ECIO '95
Proceedings
7th European Conference on Integrated Optics
with Technical Exhibition
The European Conference on Integrated Optics (ECIO) was first organized in 1981 in London and is now one of the leading conferences in the field of Integrated Optics. It is held every two years, and starting with ECIO'93 in Neuchâtel it has been combined with a technical exhibition.

The last meeting — Neuchâtel, 1993 — took place in a turbulent period for optical communication as a whole and integrated optics in particular. After the very rapid penetration of monomode fibre in the trunk network in the middle of the 80s the expected market volume growth for optical components rose to unrealistic heights. As in the early 90s it became clear that these expectations would not be realised in the near term many companies reduced their investments in research and development. This process was accelerated by the economic recession and the large-scale privatisations in the telecommunication area, refocusing attention from long-term development to short-term survival. Recent developments, however, give rise to increasing optimism for the future.

Despite these fluctuating perspectives optical communication and integrated optics continued to grow. Following the example of LiNbO₃ components integrated glass, III-V and polymer components are now reaching technological maturity, a development which is reflected in the papers presented at the conference. Complicated integration schemes have been successfully demonstrated. Fibre coupling and packaging technology are reaching a performance that which a wide spectrum of applications can be covered. Examples of successful applications are presented in a special session. Although the competition with hybrid integrated components is still stiff, the growing market volume and the increased complexity of circuits which is supported by the present state of integration technology, has widened the number of fields where integration leads to better or cheaper alternatives.

On the market side important developments are also progressing. In several places large-scale projects are being executed which bring the fibre to or very close to the home, and there is little doubt that it will reach most of the homes in urban areas in the coming decades. The demand for capacity in data-communication applications is rapidly increasing and such as Internet contribute to this demand. Multimedia services will lead to a further increase and advanced optical networks are going to provide the backbone for a novel information culture. The new European Program on Advanced Communication Technologies and Services (ACTS) will provide a platform for coordinated research and development of both the new services and the infrastructure which is required to support them.

Although telecommunications is undoubtedly the most important market for Integrated Optics, applications in other areas such as sensors, microsystems and data storage are also positively impacted by the improving technological possibilities. For these applications low-cost coupling and hybridization techniques are of even greater importance than for the telecommunication market and low-cost technologies like polymer-technology are of crucial importance for the development of the field.

The ECIO conference cycle combines a high scientific standard with a strong emphasis on applications, which is reflected in the large number of speakers and attendees from industry. Consistent with our emphasis on applications we are pleased that for the second time the ECIO conference has been combined with a full technical exhibition. As in the past an Industrial Committee has stimulated the presentation of Integrated Optics applications.

Although the Conference is a European event we are pleased that it continues to attract a large number of participants from outside Europe among its speakers and its audience. We are also happy that a considerable number of researchers from Eastern Europe are presenting their work at the conference.

The success of ECIO'95 is due to the cooperation of many individuals and institutions. The members of the local committee invested a lot of time and enthusiasm in the organization of both the conference and the exhibition. The co-sponsors and the ECIO-committees (the Standing, the Program and the Industrial Committee) helped in organizing and giving publicity to the event. The Delft University contributed with free conference facilities and many hours of personnel involved in

Foreword of the ECIO'95 Chairman
the organisation. Other sponsors helped covering the financial risk; a special word of thank is due to the Foundation for Conferences on Optical Communication and its members W. Wapenaar and J. Hodes who gave full backing to the organizers from a very early stage. Finally a word of thank is due to the city of Delft and the members of the Delft Tourist Information Office, whose help in organizing hotel accommodations was invaluable.

I hope that all the work invested in this conference will contribute to a fruitful exchange of ideas and information and to a rapid development of the field of Integrated Optics.

Meint Smit
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ECIO '95 Program Overview

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16.00-20.00 Exhibition

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10.30-11.00 Coffee Break
11.00-12.40 Semiconductor Lasers
Polymer Devices
12.40-14.00 Lunch
14.00-15.25 Optoelectronic Integration
Measurement and Characterization
15.25-17.00 Poster Session, Coffee
17.00-18.00 Optical Switches and Modulators I
Rare Earth-Doped Devices I
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Chairman: A. Carenco
France Telecom-CNET, France

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Rare Earth-Doped Devices I
Chairman: D. Ostrowsky
Nice University, France

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Chairman: M.B.J. Diemeer
Akzo Nobel Electronic Products, The Netherlands

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Optical Communication
---Today and Tomorrow---

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The impact of Optical Communication on society becomes bigger and bigger with time than we expected. Concurrently, environment of telecommunication has been changing drastically in the 90's. People recognizes that the telecommunication will be a powerful tool to make solutions for many issues in the real world and the status grades up to social infrastructure like NII or GII. Moreover, an idea of Multi-media service depicts bright future with the infrastructure. The definition of Multi-media is still in open discussion, however, the term encourage people who has been or is exploring new services other than Plain Old Telephone Services(POTS) and also encourage service providers who are trying demonstration of emerging services on test-beds. Cellular phone becomes popular and INTERNET changes from academia to public. News on disaster by earthquake in Kobe, Japan was delivered by MOSAIC and through INTERNET around the world. Under the circumstances, the paper will review Optical Communication, Today, and will touch upon the trend and technological road-map of Optical Communication towards Tomorrow.

1. Telecommunication Environment in Chaos and Transition

"Technology-oriented" to "Service/Customer-oriented"
"Telecommunication" to "Social Infrastructure"; National/Global Information Infrastructure

Motive Force; Globalization and Multi-national in Business sectors
Local Area Network (Computer networking), Merging of Teleco and CATV
PC networking, INTERNET from Academia to Public
Multi-media
Mitigation of Structural Social Issues

2. Supporting Technologies

Terminal; Personal Computer(PC) and Software
Access; Fiber, Cellular, Satellite, Cox, Copper Pair
Core Network; Flexible networking(ATM), Intelligent Network(IN), Seamless Network and Open

3. Optical Communication Technology

Optical Access Network; Fiber-to-the-home(NTT) or others
"Point to point" to "Networking"; Multi-wavelength networking(ACS)

4. Technologies supporting Multi-media Era

Bit-greedy; More Memory, Higher-speed Transmission and Routing/Switching
Higher-speed digital signal processing(DSP)
Low power devices, Cheap Price

5. Is technologies off the shelf?
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Prospects for Integrated Optics in Telecom Applications

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Abstract:
The changing world of telecommunications, with on one hand a wider penetration of photonics, and the exploitation of wavelength multiplexing on the other hand, opens perspectives for integrated optics devices. Key application areas, related devices and technologies are discussed.

1/ Introduction: trends in optical communications

Due to its acknowledged superior qualities as transmission medium, the optical fiber has introduced photonics into the telecommunication network and has initiated a rapid evolution of telecommunication technologies. Several factors are also favouring the deployment of photonic technologies. The commercial availability of high performance reliable Er doped fiber based amplifiers is allowing on one hand to bridge considerable distances without converting optical signals back to electronics, and on other hand is allowing to compensate the losses due to large splitting ratios, making thus possible the distribution of optical signals - CATV - to a large number of customers. Together with the reduction of the cost of optoelectronics devices this will facilitate a further deployment of the optical ether, and the introduction of economically viable fiber to the curb (FTTC) and fiber to the home (FTTH) systems. Additionally, the peculiar possibilities of photonics through the use of wavelength multiplexing are now envisaged as very promising future network options.

All these changes represent a number of opportunities and challenges to photonic devices in general, and to integrated optic devices in particular.

2/ Motivation for integrated optics devices in Telecom

Looking to the functionality of an optoelectronic device, one can note that a number of devices actually performs simultaneously several functions. Let us consider a simple DFB laser diode: the emission and the modulation functions are both combined in one single device. This has a large number of advantages because of the simplicity of the device realisation and control. However, the multifunctionality of a device generally results in trade off between the various parameters. Considering again the laser, the modulation induces wavelength chirp [1]. As the bitrate increases, the value of the chirp, even in an optimised DFB laser is too large for standard fibers. One solution to overcome the limitation is to separate the emission and the modulation functions. This is done by using a CW laser source, combined with an intensity modulator. Such a combination can be done using discrete components (LD and LiNbO3 modulator for instance). This combination, compared to standard directly modulated laser diode exhibits a much better performance, but inevitably is higher cost. The cost can be reduced, while
still keeping the performance advantage by increasing the degree of integration. In the particular case we are discussing, monolithic integration of a laser and the modulator (electro-absorption) is the practical solution [2].

This sequence, illustrated schematically on Figure 1, and the motivation behind (trade off of performance and cost) applies to a number of other examples mentioned below. It is however not a general rule that monolithic integration overpasses - cost and performance wise - hybrid options. This is very much depending on the overall device and technology complexity.

3/ Application areas for Integrated Optics

A schematic representation of the B-ISDN network is a layered network as depicted in Figure 2 [3]. At present, optical fibers are used for transmission (rates can range from STM 1 to STM 64) as well as in some cases for the distribution, i.e. the access layer (today mostly analog TV distribution). Submarine links, are also all fibers based and typical bitrates range from 622 Mb/s to 5 Gb/s.

![Figure 1: Rational for Integrated Optics Devices](image_url)

![Figure 2: Schematic representation of B-ISDN](image_url)
Although the today applications of integrated optics devices within the network are limited, the evolution opens new possibilities.

3.1. Access

The major motivation for introducing integrated optics devices within the access area might be the further penetration of the fiber closer to the private customers, together with the introduction of interactive services [4]. Wide dissemination of photonic technologies will put strong constraints on the cost. The interactive services require bidirectional communications, and thus need devices that can emit and receive (transceivers). One simple approach is to use a single electrode laser diode for both the emission and the detection function [5]. This can be done however only in half-duplex mode. The full duplex mode needs a dedicated laser, a separate detector and a wavelength discriminating element. Devices derived from multisection DBR lasers are one option to achieve such a functionality [6]. The wavelength discrimination function is given by the absorption edge of the III-V semiconductor. This somehow limits the wavelength allocation scheme. More general approach for the full duplex transceivers is to use wavelength demultiplexer (i.e. a duplexer) for the wavelength discriminator. Such a transceiver can be fabricated using various technological options, ranging from bulk optics micro-mechanic assemblies, to integrated optics devices which could either rely on hybrid assemblies of passive (SiO2/Si) duplexer and optoelectronic elements [7], or could use monolithic integration on InP [8]. At present, the first option still shows superior performance. However, the pressure on cost reduction and large volume gives a high chance to integrated optic solutions. The level of monolithic integration which will give the performance/cost trade off is however not yet clearly identified and will strongly depend on the manufacturability aspects.

3.2. Transport

The motivation for integrated optics in the transport layer is coming from a continuous trend to improve the performance: capacity increase and increase of the transmission distance (i.e. repeater spacing). It is interesting to note for instance that the capacity of submarine links has been roughly multiplied by 10 every 10 years, which is rule very similar to empiric Moore law followed by in Si ICs!

As already mentioned in §2, the high speed (≥10 Gb/s) TDM transmission require use of integrated laser modulator. This will be probably one of the very first monolithically integrated InP optic devices used in commercial systems. A more complex laser modulator device could be the replacement of the electro-absorption modulator by a Mach-Zehnder modulator, which brings additional advantages (variable chirp, higher saturation power).

Also the detector can benefit from the integrated optics technology. For instance, it was demonstrated that the combination of semiconductor optical amplifier and PIN detector can improve the receiver sensitivity by more than 15 dB at 10 Gb/s [9]. This combination can be done using discrete components. However, monolithic options have been envisaged too [10].
Optical time multiplexing (OTDM) is also envisaged to achieve ultra-high bitrate (40 - 100 Gb/s) systems [11]. The transmitter for such systems (for instance N×10 Gb/s OTDM) comprises a short pulse generator at 10 GHz, N delay lines, N modulators at 10 Gb/s and a combiner. Several sub-parts of such transmitter have been already demonstrated using integrated optic devices. For example mode locked lasers for the pulse generator [12], and InP integrated device including the delay lines, the modulators and the combiner [13]. Similar device has to be used also for the signal demultiplexing.

An other alternative to increase the capacity, is to use wavelength multiplexing (WDM). The key devices for WDM transmission are the multiwavelength transmitters and the multiwavelength receivers. Important efforts are spent worldwide to demonstrate integrated solutions. On the transmitters side, the first level of integration concerns laser arrays, which can be combined with SiO2/Si passive waveguides, and namely the passive combiner, using the Si mother board concept [14]. The passive combiner itself can be integrated with the laser diodes [15]. Similar approaches have been followed at the receiver part where SiO2/Si demultiplexers have been hybridized with detectors arrays [16] and also monolithic multiwavelength receivers demonstrated [17].

### 3.3. Transparent WDM Networks

The use of WDM for capacity increase is by far not the only motivation. In fact, the additional flexibility given by the WDM networks (possibility to use WDM for routing) might well be the real advantage. To exploit these unique features of photonic, a number of proposals for the so called "transparent WDM networks" have emerged during recent years [18]. A generic structure of such network is represented on figure 3. The functionality of such network is achieved using the concept of transparent node, where the node function is to route the wavelength channels. This function can be more or less complex: it can be restricted to passive wavelength routing, or it can allow, for each channel, a complete wavelength and space reallocation [19]. A schematic representation of a node that has the complete functionality is depicted on figure 4.

![Figure 3: Schematic representation of WDM all-optical network](image)

![Figure 4: Functional description of optical crossconnect node](image)

The optical cross-connect has the potential for a number of integrated optical devices which include space switches [20], tunable filters [21] and wavelength converters. The latter is another good example of the advantage of integrated optic devices. A simple wavelength converter can be realised using
semiconductor optical amplifier [22]. When injecting simultaneously a CW pump at λ1 and a modulated signal at λ2, the gain saturation of the amplifier results in a modulation of the pump wavelength. In this way, the incoming signal at λ2 is translated - by reversing the phase - to λ1 by the SOA. The two signals are separated using a filter. This wavelength converter still has imperfections; in particular the extinction ratio is degraded, which is not suitable for cascadability. Exploiting the phase cross-modulation, rather than the amplitude cross-modulation allows to improve the device. This can be done by combining two SOAs in a Mach-Zehnder structure. A Mach-Zehnder structure assembled out of discrete elements improves the extinction ratio, however it suffers from stability problems. Moving to completely monolithic Mach Zehnder wavelength converters has proven to be superior to all other versions, demonstrating thus the usefulness of integrated optic option [23].

4/ Technologies

The commercial success of the above mentioned integrated optic devices will strongly depend on the manufacturability aspects which will determine whether the cost targets can be met or not.

Despite numerous demonstrations of InP based photonic integrated circuits, the monolithic integration technology for optoelectronic devices is still lacking maturity. Integration of devices which have very different functions, such as lasers, low loss waveguides, electro-optic phase shifters, detectors,... is faced to the difficulty to combine different materials, different vertical and lateral structures on a single substrate. Feasibility has been demonstrated for almost all kinds of integration. The performance and the cost advantage have not been proven in all cases. To expand this technology to a larger family of circuits, it is mandatory to reduce the development time, the processing complexity and to improve the yield. This requires that integration process is being further rationalised. Recently, a concept of "building block" approach has been adopted to develop a large family of lasers [24]. The standardisation of these building blocks has been proven to be very effective for shortening the development time, and has in parallel allow to achieve state of the art performance, thanks to the stabilised process. Similar concept can be extended to monolithic integration of photonic circuits. Success of such an approach will depend on the early identification of main application areas, the corresponding device specifications, and a close link between the research and manufacturing entities.

As successful as monolithic integration could be, it will for sure not give a universal solution for all problems. The hybrid integration of either discrete devices or small and medium size monolithic integrated photonic circuits remains a serious candidate for devices where complexity overpasses the possibility - or the economic viability - of monolithic integration. This is already the case for instance for many of the electronics/opto-electronics integrations. The concept of hybrid integration can be extended also to the association of passive optical devices (fibres, SiO2/Si waveguides, polymers,...) and optoelectronic devices. Here, the main challenge is in reducing the assembly cost. Again, generic approaches are mandatory. The use of Si motherboards together with self-aligned processes for the positioning of the fibers and the O/E chips appears at present as being the best suitable approach for cost reduction [25].
5/ Conclusions

Photonic is expected to increase its penetration in the evolving telecommunication networks. This is creating a demand for a number of integrated optics devices which will find their application in the various part of the network, from the access to the transport layer. Most of the applications will be cost efficiency dominated. Hence, manufacturability aspects will play a major role. Several examples already exists which prove that integrated photonic devices can improve the performance and the cost. Technology wise, it is likely that monolithic integration and the planar hybrid integration will follow parallel but complementary routes.

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Abstract.

Sensors and microsystems represent the second main application field for integrated optic technologies. As compared with communication applications, this field is much more diverse, and may concern mass produced consumer goods. A large number of possibilities have been explored but few have led to commercial products so far. Except for very specific cases, most attempts face the competition with well developed and qualified non-optical technologies. These set a high cost/performance/reliability barrier for novel optical systems. This reveals again one of the main questions that integrated optic technology must solve: the access problem.

I. Introduction

Integrated optic technology owes its maturity and most of its early industrial achievements to the pull exerted by the needs of optical fibre communication systems. This is not only true for waveguide technology, which is slowly but constantly improving but also for the related hybridization and packaging techniques. The pigtailed and packaged glass and lithium niobate devices now offered on the market are all submitted to tests under harsh conditions such as repeated thermal cycling, damp heat, thermal and mechanical shocks. These recent achievements are the products of a strong, complete and qualified potential. Sensor concepts, ideas, and early experimental demonstrations were reported long ago. But it is only recently that a diversification of applications outside the communication field has become possible.

Not surprisingly, the first non-communication commercial applications of integrated optics are in optical fibre systems where the IO chip performs the same type of routing and modulation functions as in communication systems. A very significant example of such IO product is the lithium niobate gyro-chip now produced by a number of companies. The problematics of involving Integrated Optics more centrally at the core of a fibreless sensor or microsystem is quite different: the requirements on the size, geometry, sensitivity and environmental conditions may differ substantially and necessitate different waveguide materials, structures, optical circuit and guidance strength. This often requests the development of a new waveguide technology or a substantial modification of existing ones, and implies a long and costly search for reproducibility and uniformity in the fabrication processes and for stable waveguide characteristics. A difficulty for Integrated Optics to emerge in the non-communication market is the competition of established, highly reliable, and well controlled conventional technologies which have long been offering high quality devices and systems at prices which are difficult to match when light access and device packaging issues are considered as they should.

A first evidence should be recognized and repeated when speaking about guided wave optical propagation, signal processing and/or sensing: it always infers practically that light must be coupled to/from the waveguide circuit. Light coupling into single mode waveguides by end-firing or fibre pigtailling is a difficult operation which requires time, space, immobilization agents, and which is often the weak point of a packaged component. Using a grating coupler is a very attractive alternative for reasons of topological and technological compatibility, and should lead to more rugged and lower cost devices. However, in using a grating one faces the inherent problem that exciting a spatial resonance is wavelength dependent, thus the wavelength or the incidence angle must be tunable which leads to additional electronic or mechanical system complexity. The implication of the above considerations is that the advantages of using a waveguide technology in a system should a priori pay for the unavoidable difficulty of getting the light in and out. Consequently, the structure of a system must be carefully established so as to limit the impact of the access function on the full system cost. This places barriers across the wide field of possible applications.
The field of integrated optic sensors has recently been exhaustively covered in the form of extended reviews which are still up-to-date. Instead of being another one, the present contribution is an attempt to identify and isolate some of the criteria by which IO can lead to useful products, to give a few typical examples of systems, and to state what are the problems which remain to be solved before Integrated Optics emerges as an applicable sensor & microsystem technology.

II. Integrated Optics as a sensor & microsystem technology

The applicability of Integrated Optics as a practicable technology can be appreciated along three broad criteria which are described hereafter.

1. System's functional complexity

In case the functionality of an optical system is highly complex, an integrated approach may be the only way to a compact, stable and potentially low cost implementation. If in addition light is fed from a single mode fibre like in gyros and current sensors, the motivations for using an integrated optic chip are naturally reinforced. Regarding the hybridization and coupling operations, a multifunction monolithic configuration inherently saves a number of adjustment and assembling steps which a micro-optic implementation would lead to. A textbook example might be that of the acousto-optical heterodyne displacement and vibration interferometer of F. Tian et al. This Paderborn device exploits both the electro- and acousto-optical properties of LiNbO₃ as well as its birefringence in integrating all functions of an heterodyne interferometer: high isolation frequency shifting by polarization conversion, polarization splitting, phase shifting, and beam superposition. 65 dB signal-noise ratio with 300 Hz bandwidth were reported.

Much before ref. 7, a number of IO homodyne schemes have been developed in view of transposing interferometry from reference instrumentation to machine-tool control. 1ppm accuracy in a non-controlled environment was demonstrated by a twin IO interferometer on glass (CSEM). Silicon based (CSO) as well as glass (Euchner) IO technologies have successfully found a market segment. It can however be said that hybridization costs, and the extrinsic problem of laser control are still preventing the IO technological option from seriously threatening the market position of the traditional moving grating technology.

2. Light routing complexity

A comparable saving of micro-optic adjustment/immobilization steps can be obtained in multisensor systems and in systems requiring a complex multibranch signal processing circuitry as in optical bridges for instance. However multiplexed it may have to be, the sole spatial routing function performed by integrated optics is a low complexity function with high channel density in one plane only. Free space optical diffractive elements represent a more flexible technology allowing higher channel density for coherent applications such as computer interconnects, light power delivery systems, etc.

Therefore the advantages of light routing are likely to be more valuable in white light multimode plumbing applications like in parallel readout of meters and encoders, multi-readout of biochemical sensors, light barriers and triangulation techniques. Multimode Integrated Optics on glass substrates reached a very advanced status of industrial technology in the mid-eighties, before the sudden turn of optical communications towards single mode fibre technology. It was then left aside by the main industrial actors whereas university groups had already left the field earlier. Meanwhile, however, the needs for optical techniques in industrial manufacturing and control, as well as in industrial products have increased significantly. The variety, performance and quality of the related optoelectronic components available on the market have substantially progressed accordingly. A vivid example is the present availability of high power LEDs which aim at replacing light bulbs in a number of large market segments as in automotive applications;
this trend is undoubtedly bringing with it numerous needs and possibilities for compact light distribution by planar monolithic processing platforms performing complex routing functions.

The objective conditions are obviously here for a match between multimode IO technologies and real needs. However, the only waveguide technology which is presently capable of reacting to such market pull is that of organic material moulding. A single example will be mentioned here. It is the microspectrometer achieved by means of the already established and very promising LIGA technique. Such highly multimode microsystem does not only perform light guidance. It achieves the complex function of light dispersion over a large spectral range with high efficiency by means of a novel curved and blazed IO grating.

Multimode IO technology on glass has suffered a lack of interest for about ten years. Inherently more costly than plastic moulding, it is however a good candidate for very stable optical circuits which make the processing of intensity modulated sensors. Pigtailling and hybridization techniques which have recently been successfully developed for single mode IO devices can now be simplified and adapted to feedbackless and stable board-to-board assembling between the IO chip and LEDs, detectors and microlenses. However, unlike single mode glass waveguide technology, LED light plumbing in glass can not afford special glasses, wafer polishing and cautious chip edge preparation. A debate is still going on about which glass-ion pair is the most suitable. The perspectives of multimode glass integrated optics, the available technologies and their problems, as well as a list of possible producers are described at length elsewhere.

3. Exploiting specific waveguide features

Various waveguide features can offer unique advantages which may justify the price of waveguide coupling. Some of the most evident are listed hereunder.

First, these are size and weight factors which are especially important in optical systems on board of mechanical arms having to operate and react very quickly. This is the case of read/write optical modules which have a highly complex functionality. A CD reader for instance requires self-focusing, tracking and pick-up functions which call for a systematic use of gratings to keep size, weight, and assembling costs small.

Another type of feature of waveguided light in an open waveguide is its being guided along an interface while having part of its field propagating in the overlay. This enables evanescent wave sensing to be achieved in the overlay with the following advantages: the sensing field is uniquely defined and does not depend on the excitation conditions. The relative strength of the sensing field, i.e., the sensitivity, can be optimized by choosing a waveguide material with the highest refractive index (usually TiO2 or Ta2O5), and by adjusting the waveguide thickness at its prescribed value. Having a high amplitude and a well defined field at a physical interface is especially beneficial in biosensors since this allows for the local immobilization of biological species capturing another species which is distributed in the overlay analyte. Very much like SAWs which perform a weight sensing, the evanescent wave of the dielectric waveguide makes the sensing of the dielectric load that the bound species represent. Such simple label-free technique reduces the sample preparation time to below one hour and also allows a more decentralized use, thus a much shorter response time service. Although much less sensitive than fluorescence or radioactive marking techniques, and providing no proper means for species selectivity (the selectivity is at the biological level), this is clearly the extra-communication application of IO which is the most promising today. One solution has long been available (ASI) on the basis of the pioneering work of W. Lukosz. Progress in sensitivity have been made by improving the waveguide quality and by resorting to more sensitive detection schemes such as two-mode sensing. Complete instruments with an adequate distribution between manual and automated operations are available (Fisons). There are now moves to push this measurement technology from the field of still large and expensive instruments to the much wider market of sensors. With an increase of sensitivity and cost decrease it is likely that a new generation of products will appear soon for use in the doctors' practices. The same sensor concept will also find other uses in the food and environment industry and also in more general refractometric applications.
A further specific, and possibly useful feature of waveguided light is the correspondance
between a guided mode with a definite radiation direction via a grating coupler. This
characteristics of a grating waveguide has so far received very little attention\textsuperscript{24} although an
angular resolution below one arc second can easily be achieved.

There are other features of waveguided light which would be worth mentioning in
association with specific properties of the waveguide material. These could give rise to possibly
more advantageous and rugged integrated alternatives of present fibre sensors such as gyros and
electrical sensors, since IO technologies offer much larger geometrical and material tayloring
possibilities.

III. Discussion

Integrated optics is a very attractive technology for optical systems since it allows in
principle their "flattening" into a two-dimension space. As already mentioned, this operation
introduces a transverse resonance condition. The latter is responsible for all access problems
which delay the uniform emergence of IO into practical applications.

There are already commercial products which involve IO components performing
multimode light routing and it is likely that this market will steadily grow, the main driving
technology being polymer moulding. Glass multimode IO can take part in the market niche of
high stability sensor systems as soon as a high guidance and stable float or drawn glass ion
exchange technique has been selected. Although singlemode light routing has a poor
functionality/cost ratio, it would be worth investigating the possibilities offered by the multi-
waveguide WDM gratings\textsuperscript{25} for high resolution, large range monolithic beam steering systems.

Among the many proposed and demonstrated IO system schemes, only a few have emerged as viable products so far, and one only is becoming a generic technology pushing for
better performance, and driving behind it a growing number of application variants: it is the
evanescent wave (bio)chemical sensor. Several groups as well as sensor and pharmaceutical
industries are striving for better waveguides, efficient gratings, and lower cost excitation/readout
systems.

One of the application fields where integrated optics has the perspective of a wide market
is that of the flying pickup head. This concerns displacement sensors\textsuperscript{26}, and mainly data storage
in the CD-like Read function and in the more complex magneto-optical Read/Write function. If
IO can enter this market, the consequences will be a generalization of the selected technology
and a strong momentum for a large number of variations. The merits of IO in this regard are
essentially small size, low weight, and potentially low cost. The main problem again is the
access function on which very demanding requirements lie: short focal length, high coupling
efficiency, diffraction limited focus at possibly short wavelengths. In addition, the competition
is also very strong: the progress of micro-optic production and assembling techniques are very
impressive as represented by the new Sony micro-optic CD reader.

There have been several attempts to apply IO technology in this field. Very diverse opto-
geometrical implementations have been proposed. The overall feasibility was first demonstrated
by the Osaka group\textsuperscript{27} with a generalized use of waveguide gratings to perform all necessary
functions. An original magneto-optic R/W scheme was demonstrated by the LETI which uses a
high complexity polarization IO circuit with waveguide near field Read/Write without any lens or
grating\textsuperscript{28}. A compromis making the combination of free space propagation with a limited use of
waveguide grating for the whole information pickup was also proposed. Some important
activities in Japan are in the direction of laser-hybridized silicon-based waveguide circuits,
gratings and integrated detection\textsuperscript{29}.

The silicon-based IO technologies which are foreseen for these pickup applications are
derived from microelectronics and can be considered as mature. A particular care must be given
to the layer index and thickness control for high uniformity. The same cannot be said about the
coupling gratings involved; the remaining problems are: efficiency, wave front shaping,
wavelength sensitivity, and manufacturing costs. The efficiency issue is not so critical in silicon-
based waveguides: about 80 % coupling into the air can be obtained by simply re-using the
undesired substrate-reflected diffraction order with the proper phase. Concerning wave front shaping, important progress have been made in the e-beam fabricability of smooth lines, stitching-free coherent grating areas and subsequent photolithographic grating mask transfer. The wavelength sensitivity is an intrinsic property of a waveguide grating. It can be compensated for by using another, non-coplanar grating. This is not an attractive microsystem solution. The wavelength sensitivity can be decreased by playing on the magnitude of the grating radiation coefficient or by some chirping. None of these solutions are sufficient. They have to be part of a global system solution where grating design has an important role.

More generally, grating couplers have a central place in IO sensors and systems. Their being an association between a spatial resonator and a diffractive element gives them specific features which can lead to novel functional elements and sensing effects. There are major design and technology efforts at the European level and elsewhere to progress in the fabrication processes involved.

IV. Conclusion

In conclusion, the perspectives of Integrated Optics in sensors and microsystems are very uneven. The way is open for high complexity active and passive components performing the optical signal processing of fibre or free space optical sensors. Reliable industrial pigtailling and packaging techniques are available. The way is also open for multimode light circulation circuits.

There is a strong driving application in (bio)chemical sensing for the technology of high index planar waveguides from where higher quality waveguides, and progresses in grating design and technology can be expected soon with probable outcome in different application fields.

The big challenge is the data storage field. It is not possible yet to foresee when, if ever, IO will contribute. Progresses must still be made in grating technology, and the various technological bricks must be brought together. The future also depends on the coming laser characteristics. Before this challenge can be taken up, it is likely that less complex waveguide grating heads will appear in less demanding sensor applications where the wavelength is less a matter of concern as in displacement and velocity sensors.

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Integration Technology for Tunable Lasers

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Abstract:
Electronically wavelength tunable semiconductor lasers are reviewed from a technological point of view, regarding them as a basic implementation of photonic integrated circuits. The status of the techniques required for their realisation and for their incorporation into more complex optoelectronic circuits is investigated.

Introduction and motivation:
In the last few years a lot of advanced photonic applications have been suggested or realised, which need wavelength tunable laser diodes as key components. For instance, broadband multichannel optical communications, optical switching networks, wavelength dependent measurement setups and short pulse generation depend on the availability of such lasers. Because of the transmission properties of optical fibres most of the work on tuneable semiconductor lasers has been done in the wavelength range around 1.55 \textmu m based on the InGaAsP/InP material system. The development of tuneable lasers has focused on continuously tunable lasers initially, with the main target of a maximum tuning range with a minimum of spectral linewidth, yielding an optimum of addressable wavelength channels. In the last years, however, also the potential of the optoelectronic integration has been exploited for the realisation of photonic integrated circuits (PIC's) incorporating tuneable lasers with an extended functionality.

Recently, continuous tuning ranges close to the theoretical value have been reported. The activities in the field of tuneable lasers are concentrating now on structures with extremely wide, but discontinuous tuning behaviour. This trend was enforced, because for the next generation of broadband communication networks, the wavelength division multiplexing (WDM) systems with more coarsely spaced wavelength channels (about 2 nm) seem to be favoured right now. In this case, the operation with a single transverse and axial mode is not a stringent requirement. Because of the limited bandwidth of the fibre amplifiers used, not a ultimate high tuning range with a few wavelength channels, but an access to as many as possible discrete wavelength channels within the bandwidth of the fibre amplifiers ($\Delta \lambda \approx 30$ nm) is the challenge.

According to the different requirements for tuneable lasers, a variety of laser structures have been developed. Because up-to-date reviews concerning the achieved performance of tuneable lasers are available [1], the emphasis of this paper will be on some of the technological challenges and on the important technologies for the realisation of those structures.
Basic building blocks of tunable lasers:

The building blocks required for the realisation of a tunable laser are sketched schematically in Fig. 1: within a laser cavity there have to be an electronically controlled gain section, a wavelength tunable filter and for a continuous tuning operation an additional variable phase shifter, which is required to maintain a constant optical path length within the cavity. If we think of a monolithic integrated realisation of such a PIC, a closer look to this figure reveals the big difference between electronic integration based on silicon and optoelectronic integration: silicon circuits are usually based on the integration of a huge number of identical elements, namely transistors, and all other passive elements required (resistors and capacitors) are compatible with the transistor process. An increase in performance or functionality does not necessarily request the development of a new, more complex process and is often achieved with a shrinkage of the size of the elements. This is pretty different with the realisation of a PIC: here we have to deal with the interaction of a number of different elements, which have very special requirements regarding the layer properties, for instant gain in the gain section, transparency in the waveguides or phase shifter. Another challenge specific to optoelectronic integration is the need for a good optical coupling between the different parts of the PIC. Adding new functions is accompanied by a dramatic increase of the complexity of a PIC, multiplying critical steps in the overall processing. Therefore it is not easy to find the right balance between increased functionality and sufficiently high yield and low cost in order to get a device which is lucrative.

The disadvantages stated above are responsible for the difficulties to commercialise monolithically integrated optic and optoelectronic circuits. However, there are examples for a successful achievement of the expected advantages of integration - miniaturisation, higher complexity, advanced functionality and high reliability at reasonable costs - and one of these examples are the tunable semiconductor lasers.

An interesting feature of optoelectronic integration is the surprisingly large variety of technological approaches and physical solutions for a given problem. For instance, possibilities for the realisation of one of the building blocks of a tunable laser, the waveguide wavelength filter, are summarised in Fig. 2. For dynamic single mode lasers with a fixed wavelength the state of the art solution is the use of a Bragg grating, that is a coupled mode filter working in contradirectional or reflection mode. Accordingly, the first tunable lasers have been based upon this type of filters also.
The tunability of the waveguide filter is achieved via a modification of the effective refractive index $n_{\text{eff}}$ and the tuning range $\Delta \lambda$ is proportional to this index change. In the case of a contradirectional filter $\Delta \lambda/\lambda_0$ is scaled down by $n_{\text{eff}}$, whereas for a codirectional filter this factor changes to $\Delta n_{\text{eff}}$, the difference between the effective indices of the forward coupled waveguides or optical modes. Because $\Delta n_{\text{eff}}$ can be designed to be very small, the tuning range of this type of filter can be enhanced by a factor of $n_{\text{eff}}/\Delta n_{\text{eff}}$ (up to 100) compared with a contradirectional filter. Therefore, with the goal of extended tunability in mind, most of the codirectional filter schemes of Fig. 2 have been taken into consideration in the past few years. The physical effects leading to an index change and suitable to PICs are summarised in Fig. 3. Most often - because easily to achieve in semiconductors - tuning mechanism based upon current injection are used, either via the thermo-optic or via the plasma effect. A maximum index change of about 0.04 can be achieved, restricting the tuning range for devices utilising contradirectional coupling to about 15 nm. For tunable lasers incorporating contradirectional filters the tuning range of the filter can be made very large, so that the spectral width of the active region's gain peak (about 100-150 nm) is the limiting factor for the tuning range of the integrated device.

**Methods of integration:**

As mentioned above, good optical coupling between the different elements of a PIC is a stringent requirement for the realisation of high performance devices. So far, three different coupling schemes have been used for tunable lasers as sketched in Fig. 4. Most tunable lasers are based on
Required technologies:

Even for the realisation of "simple" PICs like tunable lasers, a lot of technological processes are required. Many of them have been taken over from the silicon technology and been adapted and optimised for the InGaAsP/InP material system (e.g. reactive ion etching with precise end point detection using laser reflectrometry or mass spectroscopy). Compared with the silicon technology, however, there are some special features. For instance, wet chemical etching is still extensively used in optoelectronic integration [2], taking advantage of the high or perfect selectivity achievable in this material system. Without doubt, the most striking feature is the use of multiple epitaxial growth steps and most of the progress in the development of PICs is closely related to advances in epitaxial techniques. The change from LPE to MOVPE has opened new prospects and indeed has forced the
optoelectronic integration from a laboratory pet to a fabrication technique. Only the advantages of modern epitaxial techniques - large processing areas, high uniformity, morphology improvements, excellent thickness control and the ability to grow very complex vertical layer sequences - can bring near one of the main targets of optoelectronic integration, namely cost reduction via high yield. Epitaxial regrowth has changed from a risky step to a process tool as reliable as many others needed in a fabrication sequence. This ushers a new design freedom in the engineering of PICs. Who would have believed years ago, that an optoelectronic device fabricated with nine steps of epitaxy [3] would be good for some light?

However, there are challenges remaining. The regrowth step is not trivial and the realisation of low densities of growth defects requires substantial effort not only on the epitaxial side but also on all preceding steps of technology - indeed, the mastery of this interface is a big issue: an expert in device technology has to know a lot about epitaxial growth and vice versa. Also, using MOVPE there are restrictions concerning the masked area in selective epitaxial steps and difficulties in achieving a regular growth behaviour near edges of the mask. This, in turn, causes deterioration in the succeeding steps concerning planar technology and high-resolution photolithography and requires some troublesome after-treatment. Therefore, the abilities of alternative growth techniques like MOMBE, GSMBE or VPE are taken into consideration to avoid these problems. Also, a lot of work has to be done to realise single-wafer integrated processing systems [4], which are desirable for the elimination of contamination sources and not all processes in use are very well suited for such systems.

Integration of tunable lasers into PICs:

Based upon the technological mastery of the required basic techniques, a vast variety of tunable lasers has been realised [1]. However, very early attempts for the realisation of much more complex PICs including tunable lasers have taken place, facing the challenge of integrating very different optoelectronic devices on one single chip. So far, main targets have been versatile WDM sources and heterodyne receiver circuits as schematically shown in Fig.5. Two different strategies have been implemented up to now. In the first approach [5], different optoelectronic devices are hooked up on a heterostructure waveguide serving as the backbone of the PIC. Making some cuts in the performance of a few subcomponents (for instance using laser layers for photodiodes or abstaining from a true balanced operation of the photodiodes using an n-type substrate instead of a semi-insulating one), all the critical layers can be grown in a first, rather complex epitaxial step. The local removal of unnecessary layers is performed by material selective wet chemical etching using etch stop layers, which can be positioned with very high precision and reproducibility due to the computer-controlled epitaxial growth. Sharing one or two regrowth steps with p-type or semi-insulating InP for different subcomponents of the chip allows a relatively simple process sequence for pretty complex PICs [2]. The effort required in this approach is not considerably higher than for the realisation of a simple tunable laser.

The second approach is a more modular one, arranging subcomponent by subcomponent with an optimised design and layer sequence for the achievement of the highest performance possible. This
leads to a dramatic increase of overall process complexity and the recently published monolithically integrated polarisation diversity heterodyne receiver is the leading light in this respect [6]. In this OEIC seven different types of devices - altogether 17 devices per chip of 9x0.6 mm² area- are arranged, requiring seven epitaxial growths (three selective and four full wafer) and 23 photolithographic steps. With this OEIC stable operation of an OFDM system has been demonstrated [7], proving that the employment of an integrated receiver makes the use of an optical isolator unnecessary.

Conclusion:

In the past years the techniques required for the realisation of OEICs and PICs have reached a status where simple PICs like tunable lasers are quite common and state of the art. The modularity - one of the claimed advantages of optoelectronic integration - has been exploited to realise a number of tunable laser designs mainly based upon the longitudinal integration scheme. Changing the type or implementation of the wavelength tunable waveguide filter in a DBR arrangement has led to new features without increasing the technological difficulties to much. The realisation of advanced PICs has culminated in a complexity never seen before. However, the issue of comparison with clever hybridisation is nowadays as ever a challenge and the high level of systems based on the latter technique has not yet been proofed, neither in respect to performance nor to cost.

References:

Integrated Optical Amplifiers


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Abstract

Semiconductor laser amplifiers offer the possibility of monolithic integration on a III-V substrate. After a short overview of previous work, 2 specific examples are presented. The first one is an amplifier-filter-detector module showing a 3 dB filter bandwidth of 4 GHz and a responsivity of 130 A/W, allowing a BER of $10^{-9}$ at -29.4 dBm input power for a 1.2 Gb/s PRBS signal. The second example is a single chip wavelength converter, capable of converting intensity modulated signals to a new wavelength at bitrates up to 2.5 Gbit/s. The device shows an extinction of undesired signals of better than 20 dB, approximately 15 dB conversion gain, and is nearly polarization independent.

1 Introduction

A major advantage of semiconductor laser optical amplifiers[1] (see fig. 1) over rare earth doped fiber optical amplifiers is the possibility of integration with other optoelectronic devices on the same III-V substrate. To improve the output power of a transmitter laser for use in a fiber optic system, booster amplifiers monolithically integrated with a transmitter laser have been fabricated[2-4]. The DFB transmitter lasers tend to be very sensitive to optical feedback however, and because it is not possible to insert an optical isolator between the laser and booster amplifier, these devices only perform well when extreme care is taken to avoid optical reflections from the output facet of the booster amplifier. When laser amplifiers are to be used as optical repeaters, a monitoring function both of the signal power entering the amplifier as well as of the amplified output power[5] is desirable. Integration of this monitoring function by dividing the amplifier in three sections, each with a separate contact has been suggested recently as a solution[6]. Another important application of a semiconductor laser amplifier that has caught considerable interest is as an optical preamplifier before a PIN photodiode frontend to boost the receiver sensitivity[7,8]. Here the minimum configuration consist of a semiconductor laser amplifier, a narrow bandwidth optical filter, and a photodiode. In this paper we will discuss a prototype laser amplifier filter detector module containing a monolithically integrated amplifier-filter-detector chip, which is intended as a tunable channel detector in a WDM system.

Figure 1: Example of the TE and TM fiber-to-fiber gain versus wavelength of a unidirectional laser amplifier module based on a discrete multiple quantum well laser amplifier (after ref. 1).
A specific and very attractive feature of the semiconductor laser amplifier is the possibility of modulating its carrier density and thus its gain and refractive index on timescales relevant to optical communication applications. Switching the drive current on and off, a switch with insertion gain is obtained which can compensate for the inevitable splitting losses occurring in large switching matrices. Monolithic integration of amplifiers, connecting waveguides and splitters reduces size and has the potential of significant cost reduction[9-12]. Wavelength conversion is possible when a data signal of sufficient intensity modulates the carrier density, affecting the gain of a second signal with a different wavelength which is then selected by a narrow bandwidth optical filter. A minimum configuration for this type of wavelength conversion consists of a laser amplifier, a single mode laser to provide the new wavelength and a narrow bandpass optical filter to select this new wavelength[13]. To compensate for conversion loss an additional amplifier may be added. In this paper we will present a single chip wavelength converter which integrates all functions mentioned above without the need for additional optoelectronic components.

Other applications for integrated semiconductor laser amplifiers can be found in various types of mode-locked (ring)lasers and switching elements based on nonlinear optical loop mirrors which are not treated in this paper.

2 Amplifier-filter-detector chip

2.1 Fabrication

Based on standard semi-insulating planar buried heterostructure (SIPBH) DFB technology, i.e. holographic exposure of photoresist, wet chemical etching of mesa's, and growth of semi-insulating InP current blocking layers and a p-InP contacting layer, two-section devices are formed by etching a 1.5 \( \mu \text{m} \) deep, 20 \( \mu \text{m} \) wide groove in the top contacting layer. To reduce internal losses a quantum well active layer with four compressively strained InGaAs(\( \lambda_g = 1.55 \mu \text{m} \)) quantum wells is used. The chips are cleaved to have a 300 \( \mu \text{m} \) long DFB filter/amplifier section, and a 300 \( \mu \text{m} \) long detector section (see Fig. 2). Finally, a 1/4 \( \lambda \) AR coating is applied to the chip facets to minimize reflection and increase the threshold current.

Selected chips were mounted in a 14-pin butterfly housing, which is suitable for operation at bit rates up to 2.5 Gb/s. The accurate temperature control provided by the peltier cooler is necessary because of the sensitivity of the filter wavelength to the temperature. In addition, the package is fit with a 30 dB optical isolator.

2.2 Detector performance

The test set up is depicted in Fig. 3. The signal sources used are a tunable laser to determine the wavelength response, and a 2.5 Gbit/s DFB laser module matched at the filter wavelength of the amplifier-filter-detector chip. Since the optical gain of the filter-amplifier section is polarization dependent, a polarization controller is used to adjust the polarization of the incoming light to the TE mode of the amplifier. The dashed box gives

Figure 2: Schematic view of the amplifier-filter-detector chip, which is based on a two-section DFB laser.

Figure 3: Diagram of the measurement set up.
a simplified electrical circuit model of the receiver chip, consisting of two diodes, namely the filter/amplifier section which is used under forward bias conditions, and the detector section which is not biased. A leakage resistance of approximately 15 kΩ between the two sections causes an amplifier drive current dependent offset on the detector current. Also when no input signal is present, some amplified spontaneous emission is detected. These two contributions result in a 'dark' current of about 0.16 mA at 50 mA drive current which is subtracted from the measurements. As shown in Fig. 4, the gain increases while the filter bandwidth decreases with increasing amplifier current. In addition, the central filter wavelength shifts towards longer wavelengths. This behavior is similar to that of DFB lasers. The external efficiency increases from 8 A/W at 30 mA amplifier current, up to 130 A/W at 70 mA. Since the detector efficiency will probably be less than 1, this implies an optical fibre-to-detector gain of at least 9 to 21 dB. The 3 dB filter bandwidth is very narrow, and decreases from 11 GHz at 30 mA to 4 GHz at 70 mA. The asymmetric shape results from the fact that the filter is located at the long wavelength side of the stopband.

To evaluate the performance of the module as a wavelength selective digital receiver, a fixed amplifier current of 53 mA was used, while the DFB transmitter laser was modulated with a 2^7 − 1 PRBS signal at 1.244 Gb/s. Some care had to be taken in adjusting the wavelength of the signal and the central wavelength of the module: due to the FM modulation also present in the signal, and the small filter bandwidth, both the signal and its inverse could be detected. The detector section output was fed to an electrical amplifier with a high pass filter characteristic (corner frequency 200 MHz) to achieve a flat detector response up to a frequency of 1 GHz. The output of the amplifier is sent into the Bit Error Rate (BER) tester. The BER as a function average input power is shown in Fig. 5, indicating a receiver sensitivity of -29.5 dBm at a BER of 10⁻⁹. From a scan over a larger wavelength range than that shown in fig. 4 we know that the gain of the highest secondary peak, which is the DFB resonance on the other side of the stopband at 1550.2 nm, is 16 dB less than that of the main resonance peak. This results in an effective suppression of interfering signals as was confirmed in an experiment where the tunable laser was used to simulate an interfering channel. Here no power penalties could be observed when the wavelength of the tunable laser was separated by more than 0.1 nm from the wavelength of the module.

3 Wavelength converter chip

3.1 Principle and fabrication

To reduce the large number of opto-electronic components involved in the traditional wavelength conversion scheme[13] the conversion method is simplified. Using counterpropagating signals at the source and destination wavelengths and accurate suppression of reflections in the laser ampli-
Figure 6: Operating principle of the wavelength convertor based on a polarization insensitive multiple quantum well laser amplifier and a weak DFB grating.

...fier, suppression of the source wavelength becomes unnecessary and the optical filter can be omitted. This greatly simplifies the wavelength convertor, because the optical filter would need to be matched to the destination wavelength. The laser function and the amplifier function are joined by placing a weak DFB grating on top of the near-polarization insensitive multiple quantum well active layer of a laser amplifier. The resulting wavelength convertor is shown in fig. 6. Here the input signal with the source wavelength enters the wavelength converter chip, which is lasing at the destination wavelength, through a 3 dB coupler. At the other branch of the 3 dB coupler the output signal at the destination wavelength is available. The 3 dB coupler was not integrated with the wavelength convertor chip, because it might be preferred to use an optical circulator to separate the input and output signals, thus avoiding the two times 3 dB loss of the 3 dB coupler.

Based on our 1300 nm nearly polarization insensitive multiple quantum well laser amplifier[1], 800 μm long DFB laser amplifiers were fabricated by introducing a quarter-wave shifted grating on top of the active layer using e-beam lithography[14]. Anticipating on a possible future wavelength channel allocation, an array with 8 different channels in the 1266 to 1297 nm wavelength range was fabricated. A 30 μm long window region and a 10° angled stripe were used to suppress the residual facet reflectivity down to levels below 10⁻⁵ over the entire wavelength range to ensure that the input signal is not reflected into the output signal.

3.2 Converter performance

Fig. 7 shows the threshold currents and lasing wavelengths of the wavelength convertor array. The threshold current is 135 mA for channel 1 and...
increases to 315 mA for channel 8 due to the high threshold gain for this channel. The wavelength separation of the channels is 4.5 nm ± 0.3 nm. Fig. 8 shows the conversion characteristics of channel 1 at an input wavelength of 1310 nm, excluding the losses in the 3 dB coupler. At least 10 mW of fiber coupled output power can be obtained when no input signal is present. An fiber coupled input signal of only 0.2 mW is sufficient to fully extinguish this output signal. It can be seen that for properly chosen driving conditions the extinction ratio will improve, which is not the case in the traditional wavelength conversion scheme[13]. Fig. 9 shows the output spectrum of the wavelength convertor chip with an on/off modulated 1310 nm signal applied to the input. The output spectrum shows single mode laser emission at a wavelength of 1297 nm (channel 1) with a side mode suppression ratio well over 30 dB and a suppression of the input signal of 20 dB. The small signal conversion gain is depicted in fig. 10 as a function of wavelength and channel number. Within the full 1300 to 1340 nm wavelength range a conversion gain between 10 and 18 dB can be obtained excluding the loss in the 3 dB coupler.

As can be concluded from figs. 9 and 10, the low effective facet reflectivity resulting from the angled stripe design not only minimizes the amount of input signal present in the output fiber but also reduces the gain ripple to a level where it can barely be detected. Although both tensile and compressively strained quantum wells were used in the active layer of the wavelength convertor a variation in conversion gain of about 5 dB with polarization remained. However, a few small modifications in the relative quantum well thicknesses are expected to make the wavelength convertor chip truly polarization insensitive.

The wavelength convertor chip was further tested by injecting a 2.5 Gbit/s signal from a directly modulated DFB laser. The wavelength converted response is shown in fig. 11. As can be seen, the converted datastream is inverted with respect to the input datastream. Furthermore, a strong overshoot is observed when the lasing emission is turned on. This is due to the relatively low relaxation oscillation frequency of the wavelength convertor chip, caused by its long length and its high threshold gain. At the receiver side a fourth-order Bessel-Thompson filter usually removes this overshoot making a clear reception of the wavelength converted signal possible.

4 Conclusions

In this paper a monolithically integrated amplifier-filter-detector module and a single chip wavelength convertor have been described. The amplifier-filter-detector module shows a filter bandwidth of 4 GHz and a responsivity of 130 A/W and can be used to receive a 1.244 Gb/s signal at -30 dBm input power with a BER of 10⁻⁹. The single chip wavelength convertor can deliver up to 10 mW of fiber coupled output power, with some 15 dB conversion gain, and 20 dB extinction of undesired signals. Wavelength conversion to a series of closely spaced wavelength channels
is demonstrated to be feasible up to bitrates of 2.5 Gbit/s. Both are examples of how integration of optical amplification with other elements like for instance DFB gratings allows a significant improvement in functionality, without having to divert to complicated device structures. Both chips are considered to be very useful for application in future multiple wavelength communication and distribution networks.

5 Acknowledgment

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6 References


ULTRA-SHORT PULSE GENERATION AT 1.3 μm
BY AN INTEGRATED
COLLIDING PULSE MODE-LOCKED LASER
USING ALL BULK MATERIAL

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Abstract
A 1.3 μm passively mode-locked laser is monolithically integrated on an InP substrate. A straightforward technology is used and we show that it is not necessary to employ a quantum-well device to generate ultra-short pulses. The device, using active and passive bulk material, produces 560 fs pulses at 55 GHz.

Summary
Generation of short optical pulses is essential for high bit-rate optical systems, like long distance soliton fiber transmission systems at 1.5 μm but also in the 1.3 μm optical window [1]. A method often used to generate optical pulses is passive mode-locking [2]–[4]. The shortest optical pulse reported so far had a width of 640 fs [5], generated by a passively mode-locked quantum-well laser.
We have fabricated a 1.3 μm monolithic three section CPM (Colliding Pulse Mode-locked) laser, consisting of active and passive waveguide material integrated on an InP substrate. A straightforward fabrication technology is used. A 0.12 μm InGaAsP active layer (λg = 1.3 μm) and an InP buffer layer are grown on an InP substrate by MOVPE. Amplifier sections are defined on the wafer and the rest of the active material is etched. A selective growth of a 0.35 μm InGaAsP passive waveguide layer (λg = 1.1 μm) and an InP buffer layer is then performed. A contact layer is then grown on the entire wafer. Deep ridge waveguides, etched through the active layer, are defined by Reactive Ion Etching [6], see Fig. 1. A Si3N4 dielectric layer is deposited to provide electrical isolation and on top of the ridge active sections, this layer is opened via etching. Finally, electrical contact is provided by applying metal to both sides of the wafer.

The technology used has several advantages. The use of bulk material avoids the more complex growing process of quantum-well based devices. The integration of both active and passive material on the same wafer is rather straightforward and shows good results, see Fig. 2. In contrast to buried structures, the deeply etched ridge structure, obtained by RIE, allows the use of bends and Multi-Mode Interference devices on the wafer. Bends can be used to fabricate circular devices, for example ring lasers. Deeply etched waveguide based ring lasers in combination with MMI couplers have shown very good performance [7]. Finally we demonstrate that the fabricated devices perform even better than previously reported (buried) quantum-well based laser structures.

A Scanning Electron Microscope photograph of a fabricated CPM laser and its schematic view are shown in Fig. 3 and Fig. 4 respectively. Optical gain is provided by the two amplifier sections with a length of 250 μm each, while the absorber with a length of 10 μm, situated in the middle of the cavity, causes the device to operate in the CPM mode. In Fig. 5 we have shown the background free autocorrelation trace of the light output of the device. Two main optical pulses circulate inside the cavity at the fundamental cavity repetition rate of 55 GHz. Four smaller additional pulses are caused by internal reflections at active/passive waveguide transitions and by the fact that the amplifier length is a submultiple of the cavity length. The background in the autocorrelation trace is caused by the Continuous Wave (CW) light output of the amplifier sections that partly operate as a Fabry Pérot laser due to internal reflections.

A secant hyperbolic pulse shape can be fitted to the main pulses. The width of the generated pulses equals 560 ± 10 fs, while the width of the spectrum is 3.3 nm, leading to a time-bandwidth product of 0.32, very close to the theoretical limit of 0.314 for a hyperbolic secant.

As the pulses are transform limited, their width is neither restricted by intra-cavity dispersion of the laser, nor by the absorber length (10 μm), which is not a limiting factor, because it approximately
takes 120 fs to cross it. The remaining factor for the pulse width limitation is the bandwidth of the active material used in the device [3]. Shorter pulse widths may thus be achieved by improving the technology process so that the bandwidth of the active material is enlarged.

References


Figure 1: Schematic view of the wafer after RIE processing step: deep channels are etched to define active and passive waveguide ridges. Clearly visible is the active/passive waveguide transition in the middle of the ridge.

Figure 2: SEM photograph of a cross section of the butt-joint between an active waveguide ridge and a passive waveguide ridge. The active layer and passive waveguide layer can easily be distinguished. The dark thin layer at the left of the figure is the 0.12 µm thick active layer which is butt-coupled to the 0.35 µm thick passive layer at the right of the figure.

Figure 3: SEM photograph of a 3 section CPM Fabry-Pérot laser. Clearly visible are the two gain sections at the left and right hand side of the figure (each 250 µm) and the absorber section in the middle of the figure (10 µm). The bonding wires can also be seen.

Figure 4: Schematic view of a CPM Fabry-Pérot laser with two gain sections with a length of 250 µm each and one absorber section with a length of 10 µm. The total cavity length is 1800 µm. The two main pulses and four smaller additional pulses and their place inside the cavity are shown.

Figure 5: Second order background-free-autocorrelation trace of a CPM Fabry-Pérot laser with two gain sections having a length of 250 µm each and one absorber section with a length of 10 µm and with a total amplifier current of 185 mA and an absorber reverse voltage of −0.4 V. The cavity round-trip time equals 36 ps.
Mode-locking in semiconductor ring lasers with two saturable absorbers

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We present evidence for mode-locking in integrated GaAs/AlGaAs ring lasers with two saturable absorbers, situated at opposite ends of the cavity. Measurements with a Fabry-Perot scanning interferometer reveal spectra typical of mode-locked behaviour and indicate a mode-locking frequency of 28GHz. The cavity perimeter is 3mm and the device employs a multi-mode interference (MMI) section to couple light in two directions out of the cavity. The cw threshold current of 110mA is very low considering the overall length of 4.5mm of pumped waveguide. The overall quantum efficiency is 16% (8% per output) and the emission wavelength is 860nm.

I. Introduction

Semiconductor lasers with ring cavities are attractive sources for future fibre-to-the-home systems that require affordable components. Ring resonator lasers can readily be integrated and do not require gratings or facets for feedback. They can be operated in a single transverse and longitudinal mode without the need for accurate gratings or overgrowth and hence offer themselves strongly for low-cost mass-production.

After cw [1] and single-mode operation [2] were first achieved, mode-locked [3,4] ring laser operation was demonstrated in 1992. Due to the bidirectional light circulation and the inherent symmetry, these devices are particularly suited for colliding pulse mode-locked (CPM) operation. Furthermore, the repetition rate is determined by the cavity length which, unlike the situation in cleaved Fabry-Perot cavities, can be accurately determined by lithography alone. This feature is an important requirement for applications in communication systems which need devices operating at well-defined pulse repetition frequencies.

The monolithic passive mode-locking scheme is attractive for achieving high repetition rates, since it does not require the injection of a high frequency rf signal and can be very simply implemented by integrating a saturable absorber in the laser cavity. Mode-locked operation up to several 100 GHz and sub-picosecond pulses have been demonstrated [4] but the objective in the present work is to develop devices that operate at more practical near-future pulse repetition frequencies of 10-40GHz.
II. Design and Fabrication

The strip-loaded waveguide configuration that we use has been discussed previously [5]. Its main disadvantage, the limited refractive index step (typically ∆n=0.03), implies a requirement for a minimum radius of approximately 300μm in order to reduce the bending (i.e. radiation loss) to insignificant values. The width of the waveguide is 2μm to ensure single transverse mode operation and to minimize the threshold current.

The impact of the coupler geometry on ring laser performance has also been discussed [6]. An important feature of a suitable coupler is that the coupling ratio has a large bandwidth, i.e. that it does not change with small changes of the optical properties of the coupler or the wavelength of operation. We have shown, experimentally and by the beam propagation method (BPM) [6], that multi-mode interference (MMI) couplers are the most suitable of all waveguide couplers used so far. The output waveguide facets are not intentionally coated but tilted at 4° with respect to the waveguide axis, which results in a reduction of the reflection coefficient by two orders of magnitude to <1%.

The reverse biased sections are 150μm long and separated from the main contact by 10μm gaps in order to facilitate isolation. The layout is shown in the micrograph (Fig.1).

A double quantum well GaAs/AlGaAs heterostructure was used in our experiments. We employed a self-aligned fabrication method that is based on a metal-on-polymer (MOP) process [7] (Fig.2). After deposition of the top contact (NiCr-Au) a second dry etch was performed to isolate electrically the reverse biased sections from the forward biased ones (5k Ω measured).

III. Results

A set of L-I curves with the absorber bias voltage as parameter is shown in Fig.3. If all sections are forward biased (absorber at +3V and 0V), the spectrum is single-moded between threshold and 10mW output power as shown in Fig.4a. At -0.4V absorber bias, two distinct sections with
behaviour typical of mode-locking can be distinguished that are separated by a regime of single-mode operation. At higher reverse bias, the laser operates single-mode, just above threshold, and goes into highly multimode operation shortly afterwards. Typically, 6-8 longitudinal modes could be distinguished in our measurements (Fig. 4b).

If only one of the two saturable absorber sections is reverse biased and the other one is connected to the main gain section, the mode-locking regime cannot be distinguished as clearly. The device operates single mode, multi mode and mode-locked, whereas it only operated single mode and mode-locked with both absorbers equally reverse biased.

Also, with only one absorber reverse biased, the mode spectrum does not broaden to the same degree in the mode-locked regime; typically, five or six longitudinal modes can be distinguished, so the resulting pulses are expected to be broader. This observation is consistent with the assumption that where the modes can collide twice in an absorber section during one round-trip of the cavity, sharper pulses should result, exploiting the broader spectrum of contributing modes available.

A more complex mode of operation occurs at high injection current, where a second set of modes appears between the first set (Fig. 4c). At the current stage, we cannot explain this mode of operation but suspect that it is related to a resonance in the output coupler or the combined coupler-ring resonator path.
We shall investigate the mode-locking behaviour further by using autocorrelation and time domain measurements and expect to report on these in the Conference presentation. This investigation should clarify the above observations.

IV. Conclusion

We have presented evidence for passive mode-locking at 28GHz in integrated semiconductor ring lasers with two saturable absorbers. The nature of the device allows the pulse repetition frequency to be determined by lithography alone, which is very important for systems applications. Using two absorbers instead of one improves the operation significantly; the spectra indicate that the pulses are narrower than with one absorber and the device only operates single mode or mode-locked.

In order to reduce the threshold current and the pulse repetition frequency, an extended cavity configuration would be desirable that could, for example, be realised via quantum well intermixing techniques [8].

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References

MONOLITHIC EXTENDED CAVITY GaAs/AlGaAs LASERS FABRICATED USING IMPURITY-FREE VACANCY DIFFUSION

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Abstract: Selective bandgap-widening of GaAs/AlGaAs double quantum well laser material by SiO2 capping, SrF2 masking and rapid thermal annealing at 950°C for 30s has been used to fabricate monolithic extended cavity strip-loaded waveguide lasers. With a differential shift of 21 nm in the wavelength of the photoluminescence peak, overall losses in the extended cavities were less than 6 cm⁻¹ and a red-shift of the lasing spectrum with increasing passive section length is reported. The main loss contributions are discussed and solutions to decrease them proposed.

Introduction

Monolithic extended cavity lasers (ECL) consisting of an active section and a passive one with low losses at the lasing wavelength exhibit useful and interesting characteristics:

1. Integrated cavities are mechanically stable and about a factor 4 shorter than equivalent cavities in air.
2. A longer cavity leads to a narrower linewidth of the longitudinal modes and a lower repetition frequency, determined by the cavity round trip time. Hence modelocked operation is more easily achievable with immediate applications for these devices in optical data transmission systems.
3. In single frequency lasers (DBR and DFB) very low chirp with a high modulation bandwidth is feasible if the gratings are fabricated in the passive areas.

For III-V semiconductor waveguiding structures containing quantum wells or superlattices inside the waveguide core, quantum well intermixing techniques are ideally suited to form passive bandgap-widened areas, adjacent to an active area, without the need for any regrowth step. For the GaAs/AlGaAs system, impurity-free vacancy diffusion (IFVD) using SiO2 capping and Rapid Thermal Annealing (RTA) [1] is a promising technique. Group III vacancies are created by the fast out-diffusion of Ga atoms into the SiO2 cap. These vacancies then diffuse towards the active MQW layer, leading to a change in the wells' shape from abrupt to gradual with a consequent absorption edge shift to shorter wavelengths. Furthermore, as no impurities are introduced into the active MQW region, losses due to non-radiative centres or free carriers are kept to a minimum. A thin film of SrF2 acting as a mask [2] that prevents vacancies generation in the desired areas can be used to obtain spatial selectivity. The IFVD technique has also been successfully used for the InGaAsP/InP system, although using a SiN3 cap [3]. In the following, details on the fabrication of GaAs/AlGaAs ECL using the IFVD technique together with experimental results are given.

Device fabrication

The epitaxial double quantum well pin laser structure, shown in Fig.1, was grown by MOCVD on a (100) n-doped GaAs wafer. Its 77 K photoluminescence peak was at 806 nm and oxide stripe lasers fabricated on the as-grown material emitted at 860 nm. The fabrication of the devices involved first selective IFVD and then waveguide formation and ohmic contact deposition. The IFVD process makes use of a 200 nm thick SiO2 film deposited by PECVD and removed using photolithography and wet etching only from the pump sections; following the evaporation of a SrF2 thin film 200 nm thick on the whole samples, another 200 nm of SiO2 were deposited by PECVD to protect the semiconductor surface during the subsequent RTA at 950°C for 30s. After RTA, the samples showed no significant surface damage under optical microscope inspection; this may be due to two reasons: (i)
the SrF₂ thin film deposited over the whole surface of the sample allows a more uniform interfacial stress during RTA, (ii) the top SiO₂ thin film acts as a protection layer, particularly for the active areas where the SrF₂ is in contact with the semiconductor.

![Fig. 1. Schematic of the pin double quantum well laser structure.](image)

Photoluminescence at 77 K using the 514 nm line of an Ar ion laser revealed a difference of 21 nm in the peak wavelengths, from 806 nm in the active areas (coated with SrF₂/SiO₂) to 785 nm in the passive areas (coated with SiO₂/SrF₂/SiO₂), as shown in Fig. 2. Due to the sharp absorption edge of GaAs/AlGaAs MQW of about 10 nm (90% to 10% points) at room temperature [4], this differential shift is sufficient for good operation of the devices, as we show later. However for the same annealing temperature and time, differential shifts of up to 50 nm [2] are achievable using IFVD by careful optimisation of the relevant parameters of the process (temperature, RF power and gas flux and pressure during the SiO₂ deposition by PECVD and the III-V semiconductor surface condition).

After removal of the dielectric caps by wet etching, photolithography followed by SiCl₄ dry etching was used to produce strip-loaded waveguides 2.5 μm wide and about 0.7 μm deep. The 100 nm thick GaAs p-contact layer was removed from the top of the strip-loaded waveguides, using NH₃:H₂O₂ 1:20 solution, in the passive sections only to reduce current spreading. Contact windows were then opened over the active ridges and a Ni/Au p-contact pad deposited on the laser region. After thinning and n-contact deposition on the back side of the samples, annealing of the ohmic contacts was performed and finally bars containing several devices with different passive/active length ratios Lₚ/Lₐ were scribed and cleaved.

**Results and discussion**

Extended cavity lasers (ECLs) with a total cavity length of 2250 μm and an active section ranging from 200 μm to 800 μm have been tested under pulsed operation using 1 kHz current pulses with a duration of 400 ns. For devices with 200 μm long active section Lₚ/Lₐ is more than 10 (probably the highest reported to date). Analysing the data in Table I which report the threshold currents and the emission wavelengths (spectra taken at 1.2/tₕ) we can point out some considerations.

<table>
<thead>
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<th>Lₚ(μm)</th>
<th>800</th>
<th>600</th>
<th>400</th>
<th>300</th>
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<td>Lₚ(μm)</td>
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<td>1650</td>
<td>1850</td>
<td>1950</td>
<td>2050</td>
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<tr>
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<td>1.81</td>
<td>2.75</td>
<td>4.62</td>
<td>6.5</td>
<td>10.25</td>
</tr>
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<td>Iₘ(h mA)</td>
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<td>100</td>
<td>125</td>
<td>105</td>
<td>85</td>
</tr>
<tr>
<td>λ (nm)</td>
<td>862</td>
<td>864</td>
<td>866.5</td>
<td>868</td>
<td>870</td>
</tr>
</tbody>
</table>

**Table I**
length \( L_a \) but for fixed \( L_a \), it would increase with increasing the passive section length \( L_p \) due to the higher losses in the extended cavity. From our experimental results, the increment in \( I_{th} \) due to the higher losses in the longer extended cavity is dominant for \( L_p/L_a \) less than 5 whereas the decrement due to the active section shortening is dominant for \( L_p/L_a \) greater than 5. This behaviour is indicative of losses different from zero in the extended cavities because otherwise the threshold current should increase with \( L_a \) independently of \( L_p \). Obviously, the \( L_p/L_a \) "turning value" will depend on the differential shift in the absorption spectrum between the two sections.

Secondly, we observe that, increasing \( L_p/L_a \), the emission spectrum shifts to longer wavelengths. This is due to two reasons: (i) the effective bandgap shrinkage [5] with increasing excess carrier density (an effect known as bandgap renormalisation) in the active section; (ii) the reduced contribution of the wavelength-dependent loss in the passive section for longer wavelengths which minimises the overall cavity losses.

Fig. 3 shows pulsed \( L-I \) characteristics for ECLs with 600 \( \mu \text{m} \) long active sections. It can be seen from the threshold currents that small losses are introduced by short extended cavities and even for a 1650 \( \mu \text{m} \) extended cavity, the threshold current less than doubles. Also note that the slope efficiencies of the extended cavity devices are only marginally lower than that of the conventional lasers (\( L_p=0 \)).

The determination of the passive section losses at the lasing wavelength is a very important aspect in assessing the performance of ECL devices. For this purpose we compared the amplified spontaneous emission spectra \( P_p(\lambda) \) and \( P_a(\lambda) \) measured from the active and passive device ends at a current well below the laser threshold [6]. For each wavelength the overall losses in the extended cavity (including residual absorption in the partially disordered quantum wells, free carrier absorption in the doped cladding layers and scattering loss in the waveguide), in the case of equal coupling efficiency from both ends, are expressed by

\[
\alpha(\lambda) = \alpha_{abs}(\lambda) + \alpha_{fc}(\lambda) + \alpha_{sc} = \frac{1}{L_p} \ln \frac{P_a(\lambda)}{P_p(\lambda)}
\]

For these measurements we used an optical spectrum analyser with a multimode optical fibre, maximising the signal collection at each facet by a micropositioning system. Fig. 4 shows the resulting loss spectrum for a device with 240 \( \mu \text{m} \) long active section and 900 \( \mu \text{m} \) long extended cavity. The
current injected to the laser section was 38 mA, which is well below the threshold of 60 mA. The emission wavelength of the device at $1.2 \times l_{th}$ was 869.5 nm. It can be seen that for $\lambda > 860$ nm the passive section contributes with less than 6 cm$^{-1}$ to the overall cavity losses. On the long wavelength side of the spectrum one can note a floor that is caused by non resonant losses due to scattering and free-carrier absorption. Free-carrier absorption in the doped cladding layers is the ultimate limit to the losses near the band-edge of MQW waveguides and can be decreased without degrading the laser material characteristics using graded doping profiles to reduce the doping level near the MQW region.

The same devices operated as electroabsorption modulators with reverse bias as low as 2 V for TE polarisation. Although the optical guiding was not well confined, the strip loaded waveguides 2.5 μm wide and about 0.7 μm deep were single-mode. Further, measurements of amplified spontaneous emission spectra confirmed a bandwidth of 20 nm centred at 860 nm for the same polarisation. Amplification experiments with the devices operating as injection locked lasers without antireflection coatings were also performed, showing the good potential of the IFVD technique for the fabrication of passive power splitters integrated with optical amplifiers for applications in switching, broadcasting and routing of optical signals.

Conclusions
In conclusion, the results achieved here demonstrate that the IFVD technique is suitable for the integration of active and passive devices on GaAs/AlGaAs MQW material. As it is a completely planar technique, we believe that its excellent spatial resolution, relative simplicity and low cost make it a good technique for photonic integration.

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GaAs/AlGaAs laser diodes fabricated using wet thermal oxidation of AlGaAs

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We have fabricated Fabry-Perot type GaAs/AlGaAs laser diodes using wet thermal oxidation of the upper AlGaAs cladding layer. The oxidised AlGaAs is used for the definition of an optical waveguide and as an electrical isolation. It allows the fabrication of nearly planar, self-aligned laser diodes with a single lithography step.

I. Introduction

Several fabrication schemes for the production of single-mode Fabry-Perot laser diodes in the GaAs-AlGaAs material system exist today. The simplest device structure is probably the ridge waveguide stripe laser [1], in which a narrow ridge is wet- or dry-etched in the low index upper cladding layer to provide lateral waveguiding. The device requires only one epitaxial growth step, but it has its disadvantages in that the final device is not planar (which results in e.g. contacting problems) and requires sophisticated processing to passivate and electrically isolate the exposed material.

A more sophisticated structure is the buried ridge waveguide laser [2]. Here, the ridge waveguide is selectively overgrown with cladding layer material for planarisation, and incorporates a second, reverse biased, p-n junction to provide current blocking. The injected drive current is limited to the active material below the ridge waveguide only. It results in a nearly planar device with almost no leakage current, giving a higher injection efficiency with lower threshold currents. However, this requires a non-trivial regrowth step after ridge-etching.

A third alternative is presented by the newly developed process technology [3-5] of wet thermal oxidation of AlGaAs. In this process, also known as the 'native oxide' process, one intentionally exposes the AlGaAs p-clad layers to water vapour at temperatures well above room temperature (400°C typically). At these temperatures the AlGaAs and water react to form a stable aluminum oxide. That passivates, insulates and provides a low index of refraction (~1.6) suitable for waveguide formation. An index-guiding laser diode can now be made in a single growth step maintaining planarity and with self-aligned contacts for current injection.

II. Fabrication process

The epitaxial (separate confinement heterostructure) material was grown in-house by MOCVD on n-doped GaAs [100] substrates. An n-doped 1.0 µm thick Al0.8Ga0.2As cladding layer is followed by a 140 nm thick undoped waveguide layer with a 90 Å thick quantum well. Then, a 0.9 µm thick p-doped Al0.8Ga0.2As layer is grown, and capped with a highly p-doped 100 nm thick GaAs cap-layer. After growth of the epitaxial layers, the samples are covered with photoresist, and narrow (2-8 µm wide) stripes are defined by standard lithography. These serve as etchmasks for the selective removal of the GaAs cap layer. We use a NH4OH:H2O2:H2O (1:4:100) solution, with an etch rate of 200 nm/min. After etching, the samples are rinsed in methanol, to prevent the development of a thin native hydroxide layer. The samples are dried with nitrogen immediately before they are inserted in
the oxidation furnace. This furnace consists of a quartz tube, which is heated to 450 °C. The water vapour necessary for the oxidation is supplied by saturated nitrogen carrier gas, which flows through a heated (90 °C) bath containing di-water before it enters the furnace tube.

Test-pieces are used to determine the rate of oxidation, which depends strongly on the Al-concentration of the upper cladding layer and on the furnace temperature [6]. It is typically around 10 nm/min in the vertical direction. Laterally, the oxidation is between 20 and 30% faster, probably due to the interface strain at the oxide-GaAs interface below the masking cap-material. This strain is caused by the strong lattice mismatch between the oxide and the as-grown crystal. The water vapour diffuses from the carrier gas through the oxide layer to the oxide-AlGaAs interface, where it reacts.

The whole process is diffusion limited, as is demonstrated by the SEM cross-section in figure 1. One clearly sees the elliptical interface between oxidised and non-oxidised clad material. Between the diffusion-fronts on the left- and righthandside of the GaAs cap stripe, a ridge waveguide like structure appears. Since the refractive index of the oxide is about 1.6 [7], this ridge actually does serve as a waveguiding structure, introducing a lateral index suppression in the underlying waveguiding layer (see figure) to the left and right of the buried ridge. The oxidation rate was found to be 10 nm per minute for this material at 450°C.

We observe a linear oxidation with time, after an initialisation delay of about 10 min. This may be ascribed to surface states at the wet-etched cladding layer surface, or to a thin native hydroxide layers due to air-exposure, which first has to be converted into stable oxide. After oxidation, the samples were metallized with p-type TiPtAu metals on the top and GeAuNiAu on the back, and cleaved in bars for testing.

The use of thermally oxidised AlGaAs is not only limited to Fabry-Perot type buried ridge waveguide devices. More complex laser structures such as coupled-cavity- and ring-lasers have already been demonstrated. It also has been applied to vertical cavity structures for current limiting and mirror-reflection purposes, and because of its high resistivity in the 10^{11} Ωcm range [7], it can be applied in the integration of optical and electrical devices on GaAs/AlGaAs material in a similar way as is now common in silicon electronics, provided the layer structure is appropriately designed.

III. Device results

We have fabricated and tested Fabry-Perot type laser diodes using the oxidation process described in section II. The devices show homogeneous characteristics over the processed sample area, about 2 cm². The devices lased cw, and current vs. voltage and output power vs. drive current curves were measured at room temperature. The results are plotted in figures 2. and 3. The threshold current varies between 12 and 18 mA typically, and increases with increasing stripe width. The emission wavelength was 830 nm. The IV curves show threshold voltages (voltage at threshold current) between 1.7 and 2.0 volts. The series resistance is estimated at 20 to 30 Ω from a two-point measurement. This is rather high for GaAs/AlGaAs laser diodes and is probably caused by diffusion during oxidation at 450 °C of the Zn p-doping from the highly doped p-cap into the underlying p-cladding, which increases the contact resistance at the p-side. We have recently processed lasers with improved series-resistance by employing a Zn in-diffusion after the oxide formation. In this case, the oxide also serves as an effective barrier for Zn diffusion [8].

Fig. 1: SEM Cross-section image of an oxidised laser structure. The masking cap material is 3μm wide.
IV. Conclusion

In conclusion, we have fabricated nearly planar, buried ridge waveguide fabry-perot type laser diodes using wet thermal oxidation of the upper AlGaAs cladding layer. The devices perform comparably to normal ridge waveguide laser diodes. They show low threshold currents, but a relatively high series resistance. This is attributed to diffusion of p-dopants out of the p-cap during the oxidation step where the device is kept at high temperatures for a long time.

Thermal oxidation of AlGaAs is a useful technology in the fabrication process of GaAs/AlGaAs laser diodes. It drastically simplifies this fabrication process, makes regrowth and electrical device isolation superfluous, reducing the fabrication turn-around time, and provides the developer with nearly planar devices.

V. References

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PROSPECTS FOR INTEGRATED OPTIC POLYMER COMPONENTS

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Abstract
In the middle of the last decade, polymers were introduced for the first time in active integrated optic devices. Promises were made with respect to their functional performance and low cost manufacturing methods. Nearly ten years later, the first polymer components are about to be commercialized. This paper discusses the state-of-the-art in polymer devices versus the early promises. It is concluded that most of the anticipated advantages are slowly but steadily becoming a reality in practical applications.

1. The early promises
Plastics have had a dramatic influence on every-day life since their commercial introduction, which is only a few decades ago. Nobody in the fifties would believe that high quality window frames, automotive parts, and even airplane wings could be made from plastics. We know why it became a success: low cost, design flexibility and durability without maintenance. In this context, it is not surprising that polymer experts proclaimed that the same might happen in electronics. They envisioned that all functions currently realized in electronics could be realized in polymers as well. Much of this claim has proven to be feasible: Polymeric LEDs, switches, modulators, displays, data-storage and more have all been demonstrated.

In the area of communications, a high penetration of optic technologies was (is) still hampered by prohibitively high costs, partly because devices such as modulators and switches were (are) much too expensive. Moreover, people were looking to very high bandwidth links, and to the VLSI-equivalent in optics: optical circuit boards with many functions integrated on a single substrate.

Polymers seem to intrinsically offer a solution to these issues [1].

- polymer components can be manufactured at low cost
- high speed components require a low dielectric constant active medium such as in polymers
- polymers can be deposited on large area substrates for "VLSI" optics.

With respect to active optical circuits, the point of reference in the mid-eighties clearly was Lithium Niobate. This material had shown useful properties, and the question was whether polymers could outperform this material. The prediction was 'yes, they can', mainly in terms of modulation bandwidth (the length-bandwidth product in a polymer modulator with a simple traveling wave electrode is 13 times higher than of one realized in LiNbO₃) and drive voltage (anticipated electro-optic coefficients of 50-100 pm/V, compared to ~30 for LiNbO₃). However, most polymer groups started their R&D in a chemistry environment before having an overall understanding of the requirements for integrated optic components.

The first hurdle was the technology itself. Investments in clean-room facilities and optical evaluation methods were a necessity. Next to that, numerous technical issues,
such as polarization effects, optical losses, modal properties and so on were causing unexpected problems. Also, testing these components required test-beds of an unfamiliar kind to these starting groups. All of this resulted in the formation of consortia and partnerships where 'chemists' collaborated with 'technologists' and electronic engineers. This in turn resulted in time consuming program starts. Consequently, progress in the first years was good in terms of basic understanding and improvements of the materials, but slow in terms of devices and applications. By now, trained multi-disciplinary groups exist, with a good understanding of the requirements, and adequate facilities to produce, test and evaluate their prototypes. As a result, impressive improvements in the overall performance of polymer devices has been reported in the last years.

2. State-of-the-art in polymer devices

Presently, three types of components can be identified: passive components, high speed electro-optic components (nanosecond response times) and routing components (ms response times).

The first issue to be discussed is the actually achieved functional performance of polymers. Table 1 addresses this topic, indicating 'world-record' values of individual spec's.

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<td>dB/cm</td>
<td>[2]</td>
</tr>
<tr>
<td>optical loss @1550 nm (slab)</td>
<td>0.1</td>
<td>dB/cm</td>
<td>[2]</td>
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<td>55</td>
<td>pm/V</td>
<td>[3]</td>
</tr>
<tr>
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<td>years</td>
<td>[4]</td>
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<tr>
<td>modulation bandwidth (device)</td>
<td>40</td>
<td>GHz</td>
<td>[5]</td>
</tr>
</tbody>
</table>

Table 1. Best reported functional performances in polymers

From this table, we can arrive at a few important conclusions:
- high quality passive devices are within reach
- high quality routing devices are within reach
- high quality electro-optic devices are within reach, provided that these best values are met in the same polymer

The remainder of this paper will describe the present status of polymer devices, the most important problem areas and recent efforts to tackle these problems.

2.1 Passive devices

Table 1 suggests that passive polymer devices can compete with glass in terms of performance. However, glass will remain the material with the lowest loss and the smallest dispersion. Polymers come very close to the loss values of glass, but a small difference will remain, especially in the 1550 nm window. As long as the commercial requirements are dominated by functional specifications such as the lowest loss possible, glass stays in the most favorable position. But, as soon as volumes will grow, the cost structure of the networks will become more and more important. Since polymer components are nearly as good as glass, but can be produced at lower cost in high volumes, it can be expected that companies will start commercializing polymeric couplers and other simple passive functions.
2.2 High Speed Electro-Optic devices

Originally, this has been the 'point of attack' of the first investigators. Molecules with extremely strong non-linear optical behaviour have been known for a long time. Around 1985, researchers recognized the potential of these molecules if they could be incorporated in polymer waveguides. The key parameter of an electro-optic molecule is its hyper-polarizability $\beta$. If a polymer is loaded with high-$\beta$ molecules, and these molecules are oriented in a parallel fashion, a net electro-optic effect will result. The important orientation of the molecules is obtained during 'electric field poling', a process in which the polymer is exposed to a high electric field at elevated temperatures. This electric field forces the molecules (which are also characterized by a relatively high dipole-moment $\mu$) to align with the field lines. The best known examples of high-$\beta$ molecules are dyes like DANS (di-methyl-amino-nitro-stilbene) and Disperse Red 1 (a similar molecule with nitrogen rather than carbon atoms in between the phenyl rings of the stilbene unit). These dyes have extensively been used in the early reported electro-optic devices [6], and have $\mu\beta$'s (the most important property for an electro-optic dye) of $\approx 300 \times 10^{-4}$ esu. Based on 30-40% loading of the polymer, $r_{33}$ values of 20-30 pm/V have been reported in poled devices [9].

Recently [7,8], a large number of new molecules have been identified, synthesized and measured with $\mu\beta$'s 10-30 times higher. Usually, these molecules are also larger, hence, the number density in a polymer will be reduced. The best results reported thusfar are poled slab waveguides with a $r_{33}$ of 55 pm/V at 1510 nm [2]. Based on the newest high $\mu\beta$ molecules, it looks feasible to come up with poled channel waveguides with electro-optic coefficients in the range of 50-80 pm/V, potentially even higher. The next question then is: what about the other properties of these highly active polymers, such as optical losses and thermal stability? The answer is not complete, but the indications are all in a positive direction. Low loss, thermally stable backbone polymers, to which the active molecules are chemically bonded, have been developed. Akzo Nobel reported electro-optic polymer systems which can be permanently used at temperatures of 85°C, having optical losses well below 1 dB/cm [4]. These losses are dominated by scattering at inhomogeneities, induced by the poling process. There is room for improvement in this area, since the intrinsic losses of the polymers are in the range of 0.3 dB/cm and below.

Other important issues are adequate design tools for electro-optic polymer waveguides, thick-metal-on-polymer technology for high speed traveling wave electrodes and suitable packaging for high speed applications. All of these supportive areas have been developed over the last two years, with specialized design software and a modified gold micro-plating process. The most important questions have been shifted from a technical to a commercial nature: who needs large quantities of high speed modulators and switches? Present telecom network architectures, LAN's, WAN's and computer networks largely depend on direct modulation. External modulators are used to some extent in telecom transmission systems, but numbers are still small. Perhaps, alternatives such as arrayed polymer modulators, capable of byte-wide modulation on a single chip with a single laser could lead to a break-through in external modulation applications. For the moment however, high speed device development will not likely to be transferred to product development, but resume in the research departments.

3. Routing devices

The third class of polymer devices is also identified the latest: routing devices. Rather than switching at bit rates (GHz), routing devices switch at millisecond rates. Hence,
the underlying phenomenon is of a completely different nature. Routing devices utilize thermal effects in polymer waveguides, which is limited to 0.5 ms response times, but has important advantages over competing switching technologies. Basically, the thermo-optic effect can be described as the change of refractive index of a material with varying temperature: \( \frac{dn}{dt} \). Typical values for thermo optic coefficients are \(-10^6\) for glassy materials and \(-10^4\) for polymers. In contrast to the birefringent nature of electro-optic polymers, thermo-optic materials are isotropic, leading to a polarization independent operation.

A typical example of a thermal device is the Solid State Optical Switch, a recent product of Akzo Nobel Electronic Products. Figure 1 shows the basic lay-out of the first prototypes of this switch [10]. The design consists of an adiabatic Y-branch, and two heater electrodes. The modal evolution in the multimode section is influenced by the refractive index distribution, which is subjected to the activation of the heater electrodes. This design has a digital transfer function, rather than the more conventional interferometric type waveguide switches. The digital design is possible since index changes induced by the thermo-optic effect are at least an order of magnitude larger than those induced by the electro-optic effect. Figure 2 shows the measured response curve of the switch, and figure 3 shows its dynamic response.

Wavelength routing is rapidly gaining interest in network design, and basically consists of a combination of wavelength (de-)multiplexing and space switching. The Solid State Optical Switches, available in configurations as 1x2, 2x2, 4x4, 1x8, are extremely useful for this application, facing competition only with conventional opto-mechanical devices. No other waveguide technology has been able to come with routing devices with the same potential as polymer devices. Ion-diffused glass, Lithium Niobate and glass-on-silicon, the traditional planar technologies, cannot deliver adequate solutions, due to the unfavorable thermal properties of the waveguide/substrate combination. Useful switch geometries in these technologies are of an interferometric nature, suffering from wavelength dependent operation (prohibitive for WDM applications), and requiring feedback in the drive circuitry. On the other hand, opto-mechanical devices are bulky, at least an order of magnitude slower, and consume too much power. The small insertion loss penalty for the guided wave devices versus the opto-mechanical devices appears affordable in these wavelength routers, where optical amplifiers are required anyhow.

4. Conclusions

The idea of high quality, low cost devices based on polymers is not just a promise anymore. Routing devices are the most advanced category of polymer devices, and are just being introduced into the market, offering superior performance at lower costs. Materials and designs for high speed modulators and switches are waiting to be converted into real applications. Rather than technical bottlenecks, commercial issues such as the need for volumes in high speed devices will play a major role in the future for polymer devices. As soon as a significant opportunity arises, high speed polymer modulators and switches can quickly be developed using the wide base of materials and technologies built up over the last years.

It appears likely to us that integrated optic polymer devices will become ubiquitous in opto-electronic and fiber-optic systems within the next decade.
5. References


Fig. 1 Basic layout of Solid State Optical Switch.

Fig. 2 Response curves of switch. Lower trace: drive voltage (0-7V) Upper traces: optical outputs

Fig. 3 Switching response curves. Fast switching: rise and fall times of 0.825 and 0.660 ms respectively.
OPTICAL INTENSITY MODULATION IN DIAZO-DYE-SUBSTITUTED POLYMER CHANNEL WAVEGUIDES

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ABSTRACT

Mach-Zehnder electro-optic modulators fabricated with diazo-dye-substituted polymers with microstrip electrodes are developed. An $r_{33}$ value of 26 pm/V, a half-wave voltage of 12 V, and an extinction ratio better than 10 dB are obtained at 1.32 µm with the channel waveguide fabricated by O$_2$ reactive-ion etching.

INTRODUCTION

Poled polymers have recently emerged as a promising class of electro-optic (EO) materials$^1$. Their low dielectric constant is essential to the success of high-bandwidth modulators as it leads to a lower velocity mismatch between microwaves and optical waves. 18-40 GHz EO polymer modulators have already been demonstrated$^{2-4}$. We have reported that a newly synthesized diazo-dye-substituted poled polymer (3RDCVXY) is suitable for EO applications$^5,6$. At 1.3 µm the
3RDCVXY film exhibited a large $\chi^{(2)}_{33}$ value of 183 pm/V, which corresponded to an $r_{33}$ value of 64 pm/V. Here we fabricate traveling-wave channel-waveguide modulators using 3RDCVXY polymer, and demonstrate EO modulation at 1.32 \( \mu \text{m} \).

**FABRICATION OF MODULATORS**

In order to utilize the large EO capability of 3RDCVXY, we designed traveling-wave intensity modulators with microstrip (MS) electrodes, and used this polymer to fabricate MS-electrode Mach-Zehnder channel-waveguide modulators. We investigated two types of channel waveguide. We fabricated one type using photobleaching and the other with O\(_2\) reactive-ion etching (RIE) (Fig. 1). In the photobleached waveguide both the core and the cladding layers on either side of it exhibited $r_{33}$ values. On the other hand, in the RIE-fabricated waveguide only the core ridge exhibited an $r_{33}$ value. As a result, in the RIE-fabricated waveguide, part of the electric field which overlapped the guided optical field in the cladding layers did not contribute to the phase retardation caused by the EO effect. Taking these tendencies into account, we propose the following

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Fig. 1. (a) Overview of the mounted MS-modulator, (b) cross section of RIE-fabricated waveguide, and (c) cross section of photobleached waveguide.
"effective" overlap integrals $\Gamma_{\text{TM}}$ between the optical and electric fields:

$$\Gamma_{\text{TM}}(y, z) = \int \int E_{11}^z(y, z) \Delta(y, z) F(y, z) \, dy \, dz / \int \int E_{11}^z(y, z) \, dy \, dz ,$$

where $F(y, z)$ is a step function representing the $r_{33}$ distribution in the RIE-fabricated and photobleached waveguides. $A(y, z)$ and $E_{11}^z(y, z)$ are the depth field distribution of the applied electric field and the lowest TM mode, respectively. By using eq. (1), the overlap integrals $\Gamma_{\text{TM}}$ of the RIE-fabricated and photobleached waveguides were estimated to be 0.73 and 0.88, respectively.

**ELECTRO-OPTIC MODULATION**

We measured the EO modulation of the MS-electrode 3RDCVXY-channel-waveguide modulators at 1.32 $\mu$m. The extinction ratios of the photobleached and RIE-fabricated modulators were better than 10 dB. The photobleached waveguide had a smaller half-wave voltage $V_\pi$ than the RIE-fabricated waveguide because of the existence of EO active cladding layers. However, the minimum $V_\pi$ value of 12 V was obtained with the RIE-fabricated modulator. By using the $\Gamma_{\text{TM}}$ values, the $r_{33}$ values of the MS-modulators fabricated with the RIE and the photobleaching methods as a function of the poling electric field. Open and filled circles show data for the RIE-fabricated and photobleached waveguide, respectively.
by the two methods were estimated. They are plotted in Fig. 2 as a function of the poling electric field \( E_p \). When compared using the same \( E_p \) value, the \( r_{33} \) values of the two types of waveguide are the same. Furthermore, the maximum \( r_{33} \) value (26 pm/V) of poled 3RDCVXY is obtained at \( E_p = 70 \text{ MV/m} \). This value correlates well with the electronic contribution of the \( r_{33} \) value (64 pm/V at 200 MV/m) calculated from the measured \( \chi_{33}^{(2)} \) value at 1.3 \( \mu \text{m} \). This correlation indicates that the large \( r_{33} \) values of 3RDCVXY are predominantly electronic in nature.

CONCLUSION

We demonstrated the electro-optic modulation of Mach-Zehnder channel waveguides fabricated with diazo-dye-substituted polymers with microstrip electrodes at 1.32 \( \mu \text{m} \). Two types of channel waveguide fabricated by photobleaching and \( \text{O}_2 \) reactive-ion etching (RIE) exhibited the same \( r_{33} \) values under the same poling conditions. An \( r_{33} \) value of 26 pm/V and a half-wave voltage of 12V were obtained with the RIE-fabricated waveguide. The extinction ratios of the two types of waveguide were better than 10 dB.

REFERENCES

INJECTION MOULDED 2X8 COUPLERS
FOR OPTICAL COMMUNICATIONS

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ABSTRACT

Single mode polymeric 2x8 couplers for passive optical networks are realized by using injection moulding technology which is well suited for low cost mass production. The couplers operate at 1300 nm and 1550 nm wavelengths. Excess loss figures of 4-5 dB and splitting uniformities of 1-2 dB have been achieved at both wavelengths.

INTRODUCTION

Optical couplers are essential components in actual and future passive optical networks. If both transmission windows are used, 2x8 couplers for the simultaneous distribution of signals at 1300 nm and 1550 nm wavelengths to all eight output ports are required. First devices have been realized by ion exchange in glass [1]. However, conventional fabrication technologies of IO-components like ion exchange in glass or silica-on-silicon are still cost intensive mainly because of the time consuming fibre attachment by active alignment. In this paper injection moulding has been used as mass production technique for the realization of low loss and low cost polymeric couplers. Main advantage of this technology is that only one precise mould is required for the replication of thousands of components. A further advantage of replication technologies in polymers is the capability of the simultaneous realisation of precise structures for the cost effective passive alignment of fibres and other optical or optoelectronical components.

DESIGN AND SIMULATION

The 2x8 coupler is composed of an asymmetric-symmetric adiabatic 2x2 coupler followed by two 1x4 power splitters (Fig. 1). The asymmetric input coupler (waveguides widths 5 and 7 \( \mu \text{m} \), angle 0.1°) operates as mode splitter [2] whereas the symmetric output coupler (waveguide width 6 \( \mu \text{m} \), angle 1°) acts as a conventional Y-branch power splitter. The wider input arm is intended for 1550 nm wavelength, the smaller one for 1300 nm. The BPM simulations of the coupler operation in Fig. 2 shows the perfect 3-dB power splitting for both wavelengths coupled into the respective input arms. Further simulations have demonstrated a wide tolerance of the device performance (excess loss, splitting uniformity).
to variations in design parameters such as asymmetry (+/- 0.5 \( \mu \text{m} \)), waveguide width (+/- 1 \( \mu \text{m} \)), output angle (+1°) and operation wavelength (+/- 20 nm).

**DEVICE FABRICATION**

The fabrication steps for the realisation of polymer strip waveguides is shown in Fig.3. By conventional UV-lithography on thick photoresist layers (6 \( \mu \text{m} \)) the waveguide structures are transferred into the resist in form of rectangular grooves of dimensions 6 x 6 \( \mu \text{m}^2 \) (Fig. 3b). Then the resist profile is replicated by nickel electroplating (Fig. 3c). The resulting mould insert (Fig. 3d) is used for injection moulding of the PMMA (polymethylmethacrylate) waveguide substrates (Fig. 3f). The injection moulded chips have dimensions of 10 * 40 mm\(^2\) and a thickness of approx. 2.5 mm. In a next fabrication step the waveguide grooves are filled with a monomer mixture of PFPMA (pentafluorphenylmethacrylate) and TeCEA (tetrachlorethylacrylate) in a ratio of 50:50. This monomer mixture fulfills all the requirements of a well suited waveguide core material for the described technology: it is liquid, UV curable, not dissolving PMMA, has higher refractive index than PMMA and is highly transparent at 1300 nm and 1550 nm. After filling the grooves, a plane PMMA plate is pressed against the substrate to remove the surplus liquid monomers and to protect the waveguide surface (Fig. 3g). Then the monomers are cured by UV-light. In the last fabrication step the endfaces are polished.

**EXPERIMENTAL RESULTS**

The total insertion loss (fibre-waveguide-fibre) of a 2x8 coupler with an intrinsic structure loss of 9 dB has been measured to 13.5 dB at 1300 nm and 14.2 dB at 1550 nm (Tab. 1). Pure waveguide transmission losses of the devices are in the order of 0.2 dB/cm at 1300 nm and 0.7 dB/cm at 1550 nm [3]. The splitting uniformity of the output power is within a range of 1dB at 1550 nm (except of output port 1) and about 2 dB at 1300 nm. The spectral transmission of the 2x8 coupler is shown in Fig. 4 for one path: input port 2, output port 4. The wavelength dependence of the transmission is mainly due to the material absorption showing reasonable transmission windows of +/- 20 nm around 1300 nm and 1550 nm.

**CONCLUSION**

Low loss 2x8 couplers based on an adiabatic 2x2 couplers have been realised for 1300 nm and 1550 nm using injection moulding. The results show that replication technologies on the basis of polymeric materials are well suited for the mass fabrication of high quality and
complex integrated optic circuits. The advantage of this technology will be fully exploited by the integration of passive fibre alignment structures which is under work and will be reported in the near future.

REFERENCES


Fig. 1  Structure of the 2x8 coupler (waveguide width 6 \( \mu m \), input and output pitch 250 \( \mu m \), total length 40 mm, all S-bends with \( r = 30 mm \))

Fig. 2  BPM simulated field propagation of the input 2x2 coupler for 1300 nm (a) and 1550 nm (b), inputs left, outputs right
Fabrication technology for buried polymeric waveguides

<table>
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<th>dB</th>
<th>output 1</th>
<th>output 2</th>
<th>output 3</th>
<th>output 4</th>
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Tab. 1  Total insertion loss of a 2x8 coupler at 1300 nm and 1550 nm

Spectral transmission of the 2x8 coupler
INTEGRATED OPTICAL POLARIZERS IN PMMA BY UV IRRADIATION

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ABSTRACT

The polarization characteristics of optical waveguides fabricated in PMMA by UV exposure can be adjusted by changing the total UV irradiation dose; in particular, the cut-off wavelength of the fundamental TM mode is much more sensitive to exposure than TE. By this technique integrated optical polarizers have been fabricated, operating in regions from 1.2 to 1.6 µm.

1. INTRODUCTION

Low cost passive components are key elements in integrated optics, to compete with devices made by more traditional technologies, in both telecom and sensor applications; in this respect polymer materials are extremely attractive. The polymer PMMA (Poly Methyl MethAcrylate) is among the preferred materials due to its high optical transparency and the ease of generating optical waveguides: ion implantation and photogeneration by UV-exposure are among the techniques reported in the literature [1-3].

In this paper we report the analysis of the guiding properties of waveguides made by UV irradiation of PMMA at different exposure doses, specially from the point of view of polarization behaviour. The results are of particular interest, since both polarization-insensitive waveguides and integrated optical polarizers can be manufactured, with extinction ratios exceeding 20 dB, simply by changing the exposure dose; moreover, these characteristics can be obtained in spectral regions covering the optical fibre transmission windows at 1.3 and 1.55 µm.

2. WAVEGUIDE FABRICATION

The samples are fabricated from 2 mm thick PMMA sheets [4]; plates of suitable size are cut from these sheets, packed in stacks and their end faces optically polished by standard techniques to get flat, sharp-edged optical quality facets.

Waveguides are then generated by exposing the plates in a conventional mask aligner, fitted with a mercury lamp with peak emission around 256 nm; the desired structures are defined on a chromium film on a fused silica substrate by electron beam writing, the waveguides corresponding to transparent regions in the mask. UV irradiation of the polymer at this wavelength causes a local

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increase in the refractive index of the material, due to material contraction and densification, as described in [2]. The waveguide generation process is schematically illustrated in Fig. 1.

Samples containing arrays of straight waveguides 10 μm wide have been manufactured with different exposure times and intensities, covering a range of total exposure doses from 4 to 11 J/cm² approximately.

Fig. 1. Waveguides generated in PMMA. a) schematic of the guide fabrication process by UV irradiation through a transmission mask; b) cross section of resulting waveguides.

3. WAVEGUIDE CHARACTERISATION AND RESULTS

The fabricated waveguides have been characterized to determine spectral attenuation and cut-off position of the fundamental guided mode, separately in TE and TM polarization. The measurement set-up is based on a tunable source formed by a tungsten-halogen lamp, whose radiation is filtered by a scanning monochromator and coupled to the sample under test via a single-mode, tapered and lensed optical fibre. The optical power transmitted by the waveguide is collected by a microscope objective, filtered by a Glan-Taylor polarizer (which allows polarization selection) and detected by an InGaAs photodiode; the photocurrent signal is then measured by a lock-in amplifier. A desktop computer controls wavelength scanning and data collection, and performs the necessary data processing.

Typical examples of spectral scans are shown in Fig. 2, for 10 μm wide waveguides made by 4 h UV exposure. For the guide shown in Fig. 2 a), exposed at an intensity of 0.73 mW/cm², there is practically no difference in behaviour between the TE and TM polarization, i.e. the guide is spectrally polarization independent. On the contrary, for the guide shown in Fig. 2 b), which was obtained by exposing the plate for the same time but at an intensity of 0.39 mW/cm², the TM mode goes below cut-off, and therefore is strongly attenuated, in a wavelength interval in which the TE mode exhibits no difference from the previous case. In other terms, this waveguide acts as a TE-pass polarizer in the range 1500-1580 nm.

Further examples are shown in Fig. 3: these guides, made using lower exposure doses, exhibit polarizing behaviour over wider ranges (Fig. 3 a) or different spectral regions (Fig. 3 b). This means that by suitably selecting the exposure dose it is possible to generate either waveguide
polarizers or polarisation insensitive waveguides. Further flexibility can be provided by changing also the waveguide strip width.

Fig. 2. Attenuation spectra in TE and TM polarization for waveguides 22 mm long, made by 4 h exposure at different intensities. a) 0.73 mW/cm²; b) 0.39 mW/cm². Solid line: TE; dotted line: TM. The absorption bands around 1150 nm and 1400 nm are due to intrinsic absorption of PMMA.

The positions of cut-off wavelengths for the fundamental TE and TM modes, $\lambda_C(TE)$ and $\lambda_C(TM)$ respectively, have been analyzed for a number of waveguides, exposed for different times and intensities to cover the 4–11 J/cm² range.

The results are shown in Fig. 4 as function of total exposure dose, for samples irradiated for 3 and 4 hours. Fig. 4 a) shows separately the positions of $\lambda_C(TE)$ and $\lambda_C(TM)$, while in Fig. 4 b) the difference $\lambda_C(TE)-\lambda_C(TM)$ is illustrated; as can be seen easily, $\lambda_C(TE)$ is much less sensitive to the total exposure dose than its TM counterpart.

The behaviour of $\lambda_C$ vs. UV dose is approximately linear, and at the maximum dose tested so far (about 11 J/cm²) the values for TE and TM polarization are nearly equal, so that at these levels waveguides can be made, which are polarization-insensitive over the entire spectral range of standard telecom optical fibre operation. From the curve of Fig. 4 b) the dose can be selected to make waveguides acting as TE-pass polarizers over the desired spectral bandwidth.

This characteristics of the process makes it particularly interesting, since it offers the possibility to manufacture in PMMA simultaneously, even in a single exposure step, both polarizers operating
in specific spectral bands and ordinary, polarization-insensitive guides, simply by using suitable
masks with patterned transmission features.

Work is in progress to calibrate the cut-off wavelength curves over a wider irradiation dose range,
and to determine if at higher levels the trends continue similarly and TM-pass polarizers can be
made.

Fig. 4. Behaviour of the cut-off wavelengths $\lambda_c(\text{TE})$ and $\lambda_c(\text{TM})$ for the fundamental
modes as function of total UV dose. a) Behaviour of $\lambda_c(\text{TE})$; b) behaviour of the
difference $\lambda_c(\text{TE})-\lambda_c(\text{TM})$; the dashed line is the least-squares fit to the data.

4. CONCLUSIONS

The UV irradiation process of PMMA at wavelengths below 280 nm was known as a simple
technique to generate optical waveguides for the visible and near infrared spectral domain. An
analysis has been carried out on the waveguiding properties of these structures as function of
irradiation dose. This study has shown that interesting and useful polarization-sensitive
characteristics can be obtained easily, simply by selecting the appropriate exposure conditions.
As initial results, integrated TE-pass polarizers have been made with extinction ratios better than
20 dB in ranges over 100 nm wide, at wavelengths from 1200 to 1550 nm.

Moreover, this fabrication process can be easily arranged to manufacture simultaneously, by a
single exposure in a conventional mask aligner, both the polarizers and the polarization-insensitive
optical parts of an integrated photonic circuit.

REFERENCES

4. GS 233 from Röhm GmbH, Darmstadt, Germany.
POLARIZATION INSENSITIVE PHASE MODULATOR BASED ON POLYMERS FOR HYBRID INTEGRATION

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Polymer multilayer waveguide technology on a silica/silicon substrate was used to fabricate a polarization insensitive phase modulator. Linear optical and linear electro-optic (EO) properties as well as long-term stability of the EO coefficient and DC drifts of the refractive index were investigated by various waveguide methods.

1. Introduction

In addition to anorganic crystalline materials polymers are becoming important as optical materials for Integrated Optics.\(^1\) Polymers have come to acceptable levels of performance and match with environmental Bellcore specifications.\(^1\)

Electro-optic (EO) organic polymers provide a practically unlimited switch speed due to the almost exclusively electronic origin of the NLO effects together with the minimum phase velocity difference for optical and electrical fields. Thus an improvement of more than one order of magnitude in the bandwidth-length product compared with current LiNbO\(_3\) devices is possible. EO polymers with a glass transition temperature in the range \(T_g = 210...230\) °C have been fabricated which possess chromophores as functional side-chain groups that withstand the high poling temperature.\(^2\) Over the last five years several integrated-optic devices based on EO polymers have been fabricated; e.g. an integrated-optic focal-spot intensity modulator in an EO polymer planar waveguide on a Si substrate has been demonstrated\(^3\) and a thermally stable 18 GHz bandwidth travelling wave phase modulator using cross-linked nonlinear optical polymer has been manufactured.\(^4\)

For network applications, such as phase modulators, intensity modulators, and switches polarization insensitivity is required. Such a polarization insensitive phase modulator is presented in this contribution.

2. Physical considerations on the polarization insensitive operation

In order to obtain a modulation that is insensitive to the polarization of the input light, two devices
(a) and (b) are arranged behind each other, where the first one had been poled in x-direction and the second one in z-direction by a pair of electrodes that are also used for modulation. The light propagates in the y-direction (Fig. 1).

![Diagram of polarization insensitive phase modulator](image)

**Fig. 1** Set-up of the polarization insensitive phase modulator with a lateral (a) and vertical electrode pair (b) configuration

The theory of an isotropic model delivers that the ratio of the components of the Pockels coefficients $r_{33}/r_{13} \approx 3$ is valid for realistic poling field strengths. The modulation of the light becomes polarization insensitive if $(\Delta \phi)_a = (\Delta \phi)_z$ is valid. This condition can be fulfilled if the ratio of modulation field strengths the value is adjusted according to Eqn. (1).

$$\frac{E_x^a(\Omega)}{E_x^b(\Omega)} = \frac{(n_x^a)^3 r_{33}^a - (n_x^b)^3 r_{33}^b}{(n_x^a)^3 r_{33}^a - (n_x^b)^3 r_{33}^b}$$

Here, $\Omega$ is the modulation frequency, $l^a$ and $l^b$ are the electrode lengths of the devices $a$ and $b$, respectively. It is advantageous to vary the ratio of the electrode lengths $l^a/l^b$ or the poling field strengths to fulfil Eqn. (1) so that the same amount of modulation voltage can be applied to both electrode pairs. It should be mentioned that by the linear double refraction induced by the poling the polarization plane of the light may be rotated. The modulation of the light, however, will be virtually not influenced.

### 3. Design and fabrication of the polarization insensitive phase modulator

The substrate of our modulator is a 3" Si-wafer. In order to isolate the lateral electrodes from the silicon with a relatively low electrical resistance we deposited a 8μm SiON layer by PE-CVD onto the whole wafer. The ground electrode for the vertical modulation consists of a 200 nm Cr-Ni -layer that is sputtered onto the lower SiON-layer. Then an upper 4 μm SiON layer is deposited onto
the whole wafer. The ground electrode for the vertical modulation consists of a 200 nm Cr-Ni -
layer that is sputtered onto the lower SiON-layer. Then an upper 4 μm SiON layer is deposited onto
the whole wafer. The refractive index of the SiON was chosen to be \( n = 1.55 @ \lambda = 1.32 \ \mu m \) to
avoid multimode behaviour of the guided light on the one hand and to allow a narrow electrode gap
on the other hand. In order to achieve a lateral confinement of the waveguides we etched a 4 μm
wide groove in the SiON layer by RIBE up to the ground electrode to overcome the very large
electrical resistance of SiON in the vertical direction and we buffered this groove with 1.5 μm
polyimide. \( (n = 1.529 @ \lambda = 1.32 \ \mu m) \). The lateral electrodes (100 nm thick and 100 μm wide Al-
stripes) were sputtered on the SiON. The gap of the lateral electrodes amounts to 12 μm. The lower
buffer, EO polymer (thickness \( d = 1.5 \ \mu m, n = 1.675 @ \lambda = 1.32 \ \mu m \) ), upper buffer \( (d = 3.5 \ \mu m, \ n = 1.610 @ \lambda = 1.32 \ \mu m) \), and the upper cladding Teflon AF from Du Pont \( (d = 2 \ \mu m, n = 1.303 @ \lambda = 1.32 \ \mu m) \) were spin coated. Finally, the vertical top electrode was sputtered and patterned
on the upper buffer. The lengths of the lateral electrodes and upper vertical electrode reach 15 mm.
The polymers were delivered by Sandoz Optoelectronics.

4. Characterization

The phase shift of the modulator has been measured with an accuracy of 0.02 \( \pi \) by means of an
external Mach - Zehnder interferometer. In the lateral electrode arrangement we achieved a
halfwave voltage of \( V_x = 32 \ \text{V} \) with a poling voltage of 700 V. In vertical direction a relatively high
\( V_x = 80 \ \text{V} \) was obtained because of the low electrical conductivity of the buffer polymers compared
with the EO polymer. We found no decay of the EO coefficient \( r \) of our poled polymer at room
temperature within the duration of almost one year and a decrease at \( T = 80^\circ \text{C} \) to 73% of the initial
value within 24 h. Then no further decay was measured for a period of two months.

![Room Temperature](image)

Fig. 2  Stability of the EO coefficient \( r_{33} \) of the polymer at room temperature (left) and at
\( T = 80^\circ \text{C} \) (right), respectively.
The optical loss was found to be \( \alpha = 1.7 \text{ dB/cm} \) by a modified two prism method. We found a back drift of the phase shift, initially induced by an applied DC voltage to the electrodes, of about 20%. This DC drift is due to an inhomogeneous conductivity in the region where the external field is applied. An internal space charge distribution is build up temporally which in general leads to some compensation of the external field. This formation of internal space charges depends exponentially on time with a time constant of about 12 min in our case. Then a saturation has been achieved.

5. Conclusion

A polarization insensitive phase modulator was fabricated by a 9-layer set up. Thereby a vertical and lateral electrode configuration was fabricated one behind the other. The achieved half wave voltage amounts to \( V_x = 32 \text{ V} \) in lateral direction and \( V_x = 80 \text{ V} \) in vertical direction. The waveguide attenuation is \( \alpha = 1.7 \text{ dB/cm} \). The EO coefficient of the poled device is stable within the measured period of almost one year at room temperature and after a decrease to 73% of the initial value within 24 h it is stable for at least two months at 80°C. DC drift phenomena have been investigated.

References


Second harmonic generation in organic Cerenkov-type and modematching devices

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Blue light is generated using the organic material Calix[4]arene in a second harmonic generating device. The Cerenkov device shows an efficiency of 0.23% which corresponds with values calculated using coupled mode theory. First experiments with a modematching device show visible amounts of blue light.

Introduction

In non-linear optics much effort is put in realising a compact blue laser by frequency doubling of infrared laserdiodes. This is done with inorganic materials as for example LiNbO3. Organic materials however have more potential for use in commercial devices because of their lower price and higher flexibility which eases the fabrication of various waveguide structures. The properties of the non-linear optical material required for highly efficient waveguide-devices are high non-linear optical coefficients, temporal stability, transparency for the fundamental and second harmonic (SH) wavelength and the possibility of preparing thin waveguiding films. These conditions are all satisfied by the molecule tetranitro-tetrapropoxy-calix[4]arene1,2,3 which has been used in the devices under study.

Another important aspect of efficient second harmonic generation is the phasematching condition which has to be fulfilled. This demands very homogeneous layers with thickness variations less than 1 nm on a total thickness of 0.5 to 1 μm and over a length of typically 1 cm. For the organic Calix[4]arene thin films, which are prepared with the spincoating technique, this is impossible. Therefore other methods for achieving the phasematching condition have to be found. Two fundamentally different methods are presented in this paper.

Cerenkov-type second harmonic

The principle of Cerenkov-type SH4 is that the fundamental light is propagating in a guided mode while the SH-light is radiated into the glass substrate of the waveguide as shown in figure 1. This eliminates possible destructive interference between SH-light that propagated some distance and newly generated SH as is the case in phasemismatching. Cerenkov radiation only occurs if the phase velocity of the induced SH-
polarisation, which is the same as the propagation speed of the fundamental guided mode, is above the speed of the second harmonic light in the glass substrate. The angle $\theta$, the Cerenkov angle, is given by

$$\theta = \cos^{-1}\left(\frac{N_{\text{eff}}}{N_{\text{glass}}^{2\omega}}\right)$$

Several waveguides of a mixture of the Calix[4]arene material with the polymer PPMA have been fabricated. In order to have a macroscopic non-linear coefficient $d_{33}$ the molecules are oriented in a static electric field using the corona poling technique. The resulting $d_{33}$ is 8 pm/V for $\lambda = 1064$ nm and 12 pm/V for $\lambda = 820$ nm. For the fundamental light in the Cerenkov experiment a Q-switched Nd:YAG laser in combination with a dye laser is used. The light is coupled into the waveguide as a TE- or TM- polarised mode using a prism as shown in figure 1 and after a propagation length of typically 6 mm it is coupled out of the waveguide by a second prism. The waveguide appears to be capable of generating visible amounts of Cerenkov SH with a wavelength of 532 and 410 nm when using fundamental light of 1064 and 820 nm, respectively. A coupled mode theory has been developed to be able to explain and predict the experimental efficiencies. Experimental and theoretical values for one of the experiments are given in table 1.

table 1: Cerenkov experiment for a 599 ± 10 nm thick 75 wt% Calix[4]arene/PPMA corona-polled film. For the theoretical efficiencies a correction factor of 2.0 for the fundamental beam power $P_{\omega}$ is introduced. This factor takes account of losses of fundamental light in the waveguide.

<table>
<thead>
<tr>
<th>$\lambda$ [nm]</th>
<th>mode type</th>
<th>$\theta_{\text{exp.}} \pm 0.5^\circ$</th>
<th>$\theta_{\text{theory}} \pm 0.3^\circ$</th>
<th>$P_{\omega}$ [kW]</th>
<th>$P_{2\omega}$ [W]</th>
<th>experimental efficiency $\times 10^4$</th>
<th>theoretical efficiency $\times 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1064</td>
<td>TM</td>
<td>7.5$^\circ$</td>
<td>6.8$^\circ$</td>
<td>1.21</td>
<td>0.30</td>
<td>2.5 ± 0.4</td>
<td>2.0 ± 0.3</td>
</tr>
<tr>
<td>1064</td>
<td>TE</td>
<td>6.1$^\circ$</td>
<td>6.3$^\circ$</td>
<td>3.4</td>
<td>0.12</td>
<td>0.35 ± 0.05</td>
<td>1.3 ± 0.3</td>
</tr>
<tr>
<td>820</td>
<td>TM</td>
<td>5.1$^\circ$</td>
<td>5.3$^\circ$</td>
<td>1.0</td>
<td>2.3</td>
<td>23 ± 3</td>
<td>21 ± 5</td>
</tr>
<tr>
<td>820</td>
<td>TE</td>
<td>4.7$^\circ$</td>
<td>5.3$^\circ$</td>
<td>0.78</td>
<td>0.24</td>
<td>3.1 ± 0.4</td>
<td>0.8 ± 0.2</td>
</tr>
</tbody>
</table>

The values for the Cerenkov angle $\theta$ show good correspondence between experimental and theoretical values. The values for the efficiency show also reasonable agreement with theory. The deviation is up to a factor 4, which is in our opinion acceptable for absolute second harmonic measurements. The theoretical values were calculated using the measured NLO-coefficients and the measured refractive index dispersion of the Calix[4]arene film and the glass substrate.

The highest measured efficiency was 0.23% for the $820 \rightarrow 410$ conversion with a TM-polarised fundamental mode. This is a high value for Cerenkov second harmonic generated in a planar waveguide. However the fundamental beam was a pulsed beam with high peak powers. When working with a CW laser diode of 0.1 Watt efficiencies will be limited to $10^{-4}$ - $10^{-3}$ even when channel waveguides are used.

So in spite of the non-critical dependence on the thickness of the NLO-material, which causes the easy generation of second harmonic light, the Cerenkov device is not suitable for commercial applications, which requires efficiencies considerably higher than $10^{-3}$. These high efficiencies can in theory be realised by the second method of generating second harmonic as presented in the next section.
The modematching device

The principle of modematching is that both the fundamental and second harmonic beam are guided modes in a waveguide. The problem of phasematching is still present. However by introducing an extra passive waveguiding layer the critical behaviour with respect to the NLO-material can be reduced. Figure 2 shows the waveguide configuration for this type of second harmonic generation. The fundamental light propagating in the $TM_0$-mode is converted to the SH-light which propagates in the $TM_1$-mode in this waveguide. The thickness of the passive Silicon-Nitride layer is chosen such that effective refractive index of both modes are equal (= phasematching condition) and that the light is propagating in the NLO-material as an evanescent wave. This way the electric field is negligibly small at the interface between air and NLO-material. The result is that the phasematching condition is not critical for variation in the NLO thickness. It is now critical for variation in the thickness of the $Si_3N_4$-layer. This layer can however be fabricated with a high accuracy and uniformity by means of low pressure chemical vapour deposition (LPCVD).

For the fundamental light the pulsed beam (6 ns, 10 Hz) from a dye laser is used. To improve the coupling of light in and out of the waveguide structure the Calix[4]arene film was removed at the position of the prisms. The fundamental peak power in this first experiment with a modematching device was in the order of 200 Watt. The generated blue light could be seen by eye and was measured with a photomultiplier tube as a function of the wavelength of the fundamental light as shown in figure 3. The figure shows also two theoretical curves. The first is for a perfect uniform waveguide, which is phasematched for the wavelength with maximum observed SH-power. The second curve is based on the thickness variation in the $Si_3N_4$ as has been measured with an ellipsometer and shows much better resemblance with experimental data. The deviation for longer wavelengths has not yet been explained. The absolute efficiency is in the order of $10^{-4}$. This is low for phasematching between guided modes in a waveguide. This has two reasons. First the NLO-coefficient $d_{33}$ of the poled 75wt% Calix[4]arene/PPMA layer is low because of the highly insulating $Si_3N_4$-layer. The $d_{33}$ value is estimated to be 1-2 pm/V. The second reason is that only a small part of the electric-field in the guided modes is propagating in the NLO-material where the interaction occurs. This can be improved by changing the waveguide structure in a clever way such that the field in the NLO-material is increased, without increasing the sensitivity for variation in thickness of the NLO-material.
Conclusions

Two type of devices for second harmonic generation have been fabricated and tested. They both show visible amounts of second harmonic light. The Cerenkov-type device as expected shows automatic phasematching. The experimental and theoretical values for the Cerenkov angle and efficiency show reasonable agreement. Efficiencies calculated with theory for use with CW laserdiode are somewhat low for commercial applications.

The first experiment with the modematching device shows the potential of using uniform passive layers as demonstrated with the Si$_3$N$_4$-layer. Improving the efficiency of the modematching device is subject of current and future investigations.

references


Abstract

After a brief review of realised photonic integrated circuits (PICs), the fundamental technological problems of photonic integration on InP and their solutions are discussed. A versatile fabrication process is described and results on PICs fabricated with this process are presented. Finally some prospects of future devices and technologies are given.

Introduction

Since the beginning of the work on optoelectronic integration in the early 80s different names have been used to identify photonic integrated or optoelectronic integrated circuits which were not consistently used. Hence it appears necessary to start with the definition of photonic integrated circuits (PICs), which is not necessarily the only possible definition: A device is referred to as a PIC if it includes at least one waveguide component and one optoelectronic function. Obviously, this definition excludes numerous integrated devices consisting of photodiodes or lasers integrated with electronic devices (OEICs) as these devices could be better discussed in terms of their electronic functionality. Devices with a pure optical functionality do not fulfil the above definitions either. The reason why these devices are ruled out is that they do not exploit the full advantages of the InP material system and that they therefore could be realised with other materials like SiO2/ Si, polymers etc.

According to the above definition waveguide integrated photodiodes, fabricated since 1985, were the first realised PICs\(^1\,^2\). In the following years the complexity and the functionality of PICs increased rapidly up to a monolithically integrated polarisation diversity heterodyne receiver which contains seven different functional devices (in total 18 devices), reported in 1994\(^3\). In the following, some examples of realised PICs will be briefly described. The main part will focus on some fundamental technological problems and their solutions, as well as on the presentation of an universal fabrication process for complex PICs, developed at HHI. Finally, some possible prospects will be discussed in terms of new devices and advanced technology.

Overview of realised PICs

This section will only give an enumeration of existing PICs. More detailed information can be found in other invited papers at this conference\(^4\,^5\,^6\) where the aspects of particular PIC families are discussed.

The largest PIC group in terms of different architectures are WDM devices. The integration of grating demultiplexers\(^7\) or phased arrays\(^8\) with detectors (fig. 1) as well as the integration of lasers with optical combiners for multi-wavelength sources\(^9\) was demonstrated.
Transceiver PICs also belong to the class of WDM devices, because they transmit at one and receive at another wavelength. A device which includes a wavelength duplexer, a photodetector and an electronic preamplifier is described in ref. 10. The most complex transceiver PIC fabricated so far consists of a laser, a wavelength duplexer and three detectors. This device is designed for bi-directional telephony and unidirectional broadband access (TPON/BPON) over one optical fibre (fig. 2).

Fig. 1: WDM-Receiver PIC (from 8)

Many publications report on building blocks for heterodyne receivers e.g. balanced mixer receivers. Heterodyne receivers which include a laser as the local oscillator and are suitable only for a fixed polarisation state were first published in 1989. A more complex polarisation insensitive heterodyne receiver was demonstrated in 1994 and will be described later.

Fig. 2: Transceiver PIC (from 11)

Fundamental technological problems and solutions

Evidently, the most important difference of the photonic integration as compared to the electronic (Si) integration is the higher complexity in terms of different functionality and architecture of the integrated devices. In principle, this can be overcome by using some type of "compromise-devices" e.g. taking a laser structure as a photodiode. The main drawback of this integration concept is that the individual devices cannot be optimised separately, which consequently leads to a lower performance of the PICs as compared to hybrid solutions. However, if one avoids such "compromise-devices" one has to cope with the optical coupling between different components with - in general - different layer structures. The most general coupling scheme is a straight butt coupling which, however, requires a high technological effort (selective area epitaxy) and hence should be avoided, if possible.

Fig. 3: Schematic view of an evanescent field coupled photodiode

An example of a less challenging coupling scheme is the vertical or evanescent field coupling used for example for the integration of photodiodes with waveguides (fig. 3). By optimising the complete photodiode layer stack, effective absorption coefficients of 0.5 - 1 dB per μm of photodiode length are achieved. Hence very small and therefore potentially fast photodiodes can be realised with a minimum number of epitaxial growth steps as the waveguide layers and the photodiode layers are grown in one run.
Balanced mixer receivers with photodiode bandwidths above 18 GHz\textsuperscript{17} and single waveguide integrated photodiodes with cut-off frequencies above 40 GHz\textsuperscript{18} were demonstrated.

**Tunable DBR-Laser Butt joint Network waveguide**

**Fig. 4:** Cross sectional view of the butt coupling between a DBR laser and an external waveguide

In the case of the coupling of a waveguide with a laser, butt coupling cannot be avoided without significantly degrading the performance. The internal waveguide of a laser must be heavily doped to obtain low threshold and high gain devices. In contrast the external waveguide has to be undoped or semi-insulating in order to achieve low propagation loss and avoid electrical crosstalk between optoelectronic devices. Fig 4 shows a micrograph of a DBR laser butt coupled to a semi-insulating waveguide. The exact vertical alignment of the laser layers and the external waveguide layers with high uniformity across the wafer is the most critical part in this technique. Typically coupling losses below 2 dB can be obtained\textsuperscript{19}.

**Versatile fabrication process**

The economic fabrication of PICs requires versatile processes, which enables - in principle - the development of new PICs by simply changing the lithographically masks\textsuperscript{20}. In this section an overview of a versatile PIC fabrication process, which was developed at HHI, will be given. Initially this process was developed for the fabrication of a polarisation insensitive heterodyne receiver but it was kept as general as possible to allow other device structures, which will be proved by presenting some selected results.

**Process description**

This PIC fabrication process is based on an integration concept with the following key issues\textsuperscript{21}:

- Capability of realising different PIC architectures on one wafer by a not too complicated process.
- Avoidance of "compromise-devices".
- Possibility of independent optimisation of the subcomponents.
- Utilisation of parallel processing wherever possible (e.g. contact metallisations, p-diffusion, isolation layer deposition, isolation groove etching...)
- Application of semi-insulating Fe-doped waveguide layers for optimum device isolation.
- Application of very thin (<50 nm) etch stop layers for material selective wet etching as well as for dry etching (RIE) with in-situ endpoint control.

**Fig. 5:** Schematic view of a polarisation insensitive heterodyne receiver PIC

With this process all subcomponents which are necessary for a complete polarisation insensitive heterodyne receiver were fabricated. The subcomponents are in detail (cf. Fig. 5):

- Tuneable four-section DBR lasers butt coupled to an external waveguide,
- passive polarisation transformers which rotate the TE polarisation vector by an angle of 45°,
Table 1: Compilation of results on integrated subdevices

<table>
<thead>
<tr>
<th>4-Section DBR Laser</th>
<th>Waveguide Network</th>
<th>Detector Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold current: 16 .. 24 mA</td>
<td>Polarisation ext. ratio: ≥ 19 dB</td>
<td>Photodiodes (PD)</td>
</tr>
<tr>
<td>Emission wavelength ((\lambda)): 1.55 µm</td>
<td>Deviation of 3 dB balance: ± 0.3 dB</td>
<td>Quantum. efficiency: ≥ 90%</td>
</tr>
<tr>
<td>SMSR ((\lambda)):</td>
<td>Intrinsic network losses: 3 dB</td>
<td>Dark current (-4 V): ≤ 130 nA</td>
</tr>
<tr>
<td>Linewidth ((\lambda)): 25 - 40 MHz</td>
<td>Polarisation rotator</td>
<td>Breakdown voltage: 16-20 V</td>
</tr>
<tr>
<td>Tuning range: 5.5 nm</td>
<td>Rotation angle: 35 ... 43°</td>
<td>Cut-off frequency (3 dB): 4 GHz</td>
</tr>
<tr>
<td>((\lambda)): Lasers not tuned</td>
<td>Excess losses: 1.4 ... 2 dB</td>
<td>Detector unit (PD+JFET+R)</td>
</tr>
<tr>
<td>Coupling efficiency at the</td>
<td>Gain bandwidth product: 4 GHz</td>
<td></td>
</tr>
<tr>
<td>laser/network but joint: 50 ... 65%</td>
<td>(calculated values: 75 ... 80%)</td>
<td></td>
</tr>
</tbody>
</table>

- polarisation dependent directional coupler for polarisation splitting and filtering,
- directional 3 dB coupler for power splitting and combining,
- evanescent field coupled twin balanced photodiodes for optoelectronic detection,
- junction field effect transistors together with load resistors for the first low-noise electrical pre-amplifier stage.

The entire fabrication process required for the polarisation diversity heterodyne receiver PIC involves at present 23 lithographic exposures, seven epitaxial growth steps, and 150-170 processing and inspection steps. For PICs with a lower complexity the whole process could be simplified i.e. some steps would be simply left out (e.g. a monolithically integrated transceiver PIC does not need polarisation transformers or polarisation splitters).

From the first few wafers, processed in our laboratory, some yield results shall be pointed out. About 15% of all launched 2" wafers survived the entire process. Only 20% were destroyed due to process failure e.g. in epitaxy or dry etching. 65% were broken due to human failures during handling within processing or inspection (to the honour of the technology people it should be noted that each wafer has to be picked up with tweezers some 1000 times during one complete technological run!). Obviously, this situation would be considerably ameliorated if the wafers were processed in a commercial fabrication environment with automated wafer handling systems.

In contrast, the yield of the devices on the finished wafers was quite high. About 80-90% of the subcomponents are operating within the specifications, more than 60% of the complete PICs show full functionality.

Example results
The most complicated device fabricated with the described versatile process is a polarisation insensitive heterodyne receiver. Its basic architecture is shown in fig. 5 A four-section DBR laser works as the tuneable local oscillator (LO). The light of the LO is coupled into the external waveguide and its polarisation is rotated by 45° in the polarisation transformer. In the next section the light of the LO as well as the light coming from the input fibre are splitted into the two fundamental polarisation states TE and TM by two polarisation splitters and two mode filters.

Then the incoming light and the light of the LO are combined separately for each polarisation by two 3-dB couplers. The mixed signals are detected by two balanced receivers and finally the electrical signals are amplified by two common source amplifiers realised each with a junction field effect transistor and a load resistor.

Some typical results for the integrated subdevices are summarised in tab. 1. For system experiments a few chips were packaged into first receiver modules.
Fig. 6: Bit error rate vs. received optical power

Fig. 6 shows the bit error rate versus the received optical power for different polarisation states at the input fibre of the module. Polarisation insensitive operation is demonstrated by a polarisation dependence of the BER lower than 0.5 dB. The absolute values of the receiver sensitivity are mainly determined by the non optimised packaging, in particular by a relatively high fibre to chip coupling loss.

In fig. 7 examples of somewhat simpler PICs with distinct architectures are given which were fabricated on the same wafer together with the heterodyne receivers.

They are: polarisation dependent heterodyne receivers, bi-directional transceivers and microwave signal sources. All devices were preliminarily characterised and revealed sufficient functionality. More details will be published elsewhere. The variety of realised devices demonstrates the versatility of the described fabrication process.

Prospects

Devices
The PICs reported so far are basically feasibility demonstrators. Only a few papers report on practical applications outside the laboratory. To improve this situation more studies about long term reliability and robustness e.g. in terms of temperature sensitivity are required. Obviously, polarisation dependence or high insertion loss are obstacles for a practical employment of PICs outside the laboratory - in particular as they have to compete with hybrid solutions.

Technology
To meet the requirements for high functional high performance PICs, selective epitaxie has to become more and more a standard process for PIC fabrication. This progress may be
accelerated by further development of advanced growth techniques like GSMBE (gas source molecular beam epitaxie) or MOMBE\(^{22}\) (metal organic molecular beam epitaxie). Additionally in-situ control techniques which are already applied in III-V dry etching processes\(^{23}\) will be also utilised for the different crystal growth techniques\(^{24}\).

To overcome the insertion loss dilemma spot size transformers ("waveguide tapers") and / or optically gain sections will be integrated in future PICs. Additionally the implementation of active electronic devices like HEMTs or HBTs will facilitate the connection between PICs and external electronics.

**Concluding Remarks**

Photonic integration on InP has grown to a huge field of research in the last recent years. The integration of virtually every possible sub-component was demonstrated. In the near future the application of versatile fabrication processes will provide PICs with a wide range of functionality. However, further research and development is required to fulfil the demands for mature and reliable "user friendly" devices.

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Tu A3 Optoelectronic Integration

APPLICATIONS OF QUANTUM WELLS IN INTEGRATED OPTICS

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Abstract: Quantum wells have many advantages in forming photonic integrated circuits. A quantum well intermixing method, based on laser heating, is described for integrating lasers, modulators and low-loss waveguides on a single wafer after epitaxial growth. The performance of bandgap tuned devices is reported.

1. Introduction

Quantum wells (QWs) have several significant advantages over bulk semiconductors in integrated optical devices—improved laser performance, low drive voltage modulators based on the quantum confined Stark effect (QCSE), and ease of integration. This last feature arises because the optical overlap between an active QW and a guided optical wave is small, typically only 1 to 3% per well. At the interface between a waveguide containing QWs and an otherwise identical waveguide which does not contain QWs, reflections and mode mismatches are very small.

Photonic integration requires removal of the QWs in low-loss waveguides, and modification of the bandgap to match modulator and laser spectra. There are three main routes by which this may be achieved. Firstly, the QWs can be removed by etching, and regrown with a different bandgap where needed for modulators. Successive etching and regrowth stages then allow a complete photonic integrated circuit (PIC) to be realised containing lasers, modulators and low-loss interconnect waveguides. This approach requires many stages of epitaxy and yields are low. Secondly, selective area epitaxy (SEA) techniques have recently been developed. The SEA approach relies on the fact that group III species diffuse across the surface of an SiO₂ masking layer—the growth rate in a gap between dielectric masks then depends on the width of the gap. The substrate is therefore patterned with a silica mask prior to epitaxy, the relative widths of the silica stripes to the gaps between the stripes determining the QW width in the inter-stripe regions. The bandgap is therefore varied in a controlled manner across a wafer. Thirdly, quantum well intermixing (QWI) is a powerful technique for the fabrication of PICs in which all fabrication stages take place subsequent to a single stage of epitaxy. In intermixing processes the bandgap of a QW structure is modified in selected regions by intermixing the wells with the barriers to form an alloy semiconductor. The bandgap of the intermixed alloy is generally larger than that of the original QW structure and, in addition, the refractive index is modified, thus providing a route to the formation of low-loss waveguides, gratings and other optical components. A number of intermixing techniques have been reported, most notably impurity induced disordering (IID), laser induced disordering and impurity free vacancy disordering (IFVD) in which intermixing is induced beneath a dielectric cap.

Here we discuss a particular laser induced intermixing technique which we have called photo-absorption induced disordering (PAID). PAID is a promising QWI process which takes advantage of the poor thermal stability of the GaInAsP system. Intermixing is induced by band-to-band absorption of the incident laser photons within the active region of a multi-layer structure. Subsequent carrier cooling and non-radiative recombination results in the generation of heat within the active region causing the temperature of the material to rise to a level at which thermal intermixing will occur (>520 °C). Blue-shifts, of the photoluminescence (PL) peak energy, of greater than 100 meV, measured at 300 K, in standard MQW laser structures, are typically obtainable. The method is impurity free, requires only a fraction of the power densities of existing cw techniques (1-10 W mm⁻² compared with 10⁵ W mm⁻²) and does not involve a melt phase in the semiconductor processing. Most importantly it is layer composition selective, which is additionally advantageous in that it is not restricted to near-surface layers.

PAID has previously been demonstrated to offer lateral control of intermixing in GaInAs/GaInAsP MQW structures indicating the potential for integrating devices onto a single chip. Here we report the fabrication and characterisation of bandgap tuned lasers, modulators, and
passive waveguides, the key components of any PIC. These devices retain their high performance after bandgap tuning using the PAID process, so demonstrating that PAID is a promising technique for the realisation of functional photonic integrated circuits.

2. EXPERIMENTAL PROCEDURE

During the disordering process the material is coated with a layer of plasma-deposited silicon dioxide which acts both as an anti-reflection coating and as a protective layer against surface reactions with the atmosphere. It has been found that a layer of around 500 nm ($3\lambda_{YAG}/4$) is sufficient to protect the surface during the high temperature anneal.

The material is then placed on a piece of polished ceramic and on a hotplate at around 240 °C. This increase in the background temperature of the sample reduces the incident laser power density required to heat the sample to a temperature at which disordering occurs. The use of the ceramic also reduces the required power density due to its poor thermal conductivity. The material is then irradiated with light from a CW operated Nd:YAG laser emitting at 1.064 μm with a power density of around 1 W mm$^{-2}$. Absorption of this radiation occurs within the active region of the MQW generating heat due to carrier cooling and non-radiative recombination. The temperature of the material then rises to a level at which thermal intermixing occurs between the wells and the barriers. As the process continues, the wells and barriers become less well defined as they intermix with each other. This means that the well width, barrier height and rectangular well shape change, resulting in a shift in the bandgap to higher energy.

The use of a piece of ceramic also allows the sample to be removed from the hotplate and cooled relatively quickly to a temperature at which PL measurements can be carried out. These measurements can be carried out relatively simply using the same laser (operating at a much lower power) to irradiate the sample, with the resulting luminescence being measured with a monochromator. This provides a quick way of measuring the amount of disordering which has occurred in the sample by monitoring the shift in PL peak wavelength.

3. BANDGAP TUNED OXIDE STRIPE LASERS

Broad area oxide stripe lasers were fabricated from standard MQW laser material which had been disordered by varying degrees to determine if the material still operated as a laser and, if so, to analyse some of its important properties such as threshold current density, quantum efficiency and internal losses.

The laser structure investigated was grown by metal organic vapour phase epitaxy (MOVPE) on an (100)-oriented n$^+$-type InP substrate and consisted of five 85 Å GaInAs wells with 120 Å GaInAsP barriers. The active region was bounded by a stepped graded index (GRIN) waveguide core consisting of GaInAsP confining layers. The thicknesses and compositions of these layers (from the QWs outward) were 500 Å of $\lambda_{p}=1.18$ μm and 800 Å of $\lambda_{p}=1.05$ μm. The structure, which was lattice matched to InP throughout, was completed by an InP upper cladding and a GaInAs contact layer. The first 0.2 μm of the upper cladding layer was doped with Zn to a concentration of $5\times10^{17}$ cm$^{-3}$ and the remaining 1.2 μm to $2\times10^{18}$ cm$^{-3}$. The lower cladding layer was Si doped to a concentration of $1\times10^{18}$ cm$^{-3}$. The waveguide core was undoped, thus forming a $p-i-n$ structure with the intrinsic region restricted to the QWs and the GRIN layers.

After disordering, the SiO$_2$ caps were removed and windows, 85 μm wide with a 300 μm pitch, were opened in a new 200 nm thick passivation layer of SiO$_2$ using routine photolithographic techniques. The samples were then thinned and metal contacts (p-Ti/Au, n-Au/Ge/Au/Ni/Au) were evaporated onto both surfaces and annealed in a rapid thermal processor (325 °C for 90 s). Finally, the samples were scribed and cleaved into individual lasers with lengths ranging from 200 μm to 1000 μm.

As the samples were heated using a Gaussian profile laser beam, the sample was not uniformly heated over its entire area. This resulted in less disordering around the edges of the samples compared with the more uniform central region. For this reason there was a range of
lasing wavelengths obtained from each sample, typically a spread of about 30 nm, therefore, only lasers from the centres of the samples were assessed. Fig. 1 shows output spectra from oxide stripe lasers fabricated from samples which have undergone different degrees of intermixing (blue shifted as much as 160 nm). These spectra were obtained from lasers operated in pulsed mode (400 ns pulse at a 1 kHz repetition rate) at 50% above threshold. It is apparent that the gain envelope of the material has not been measurably broadened as the wells and barriers have intermixed, indicating that all wells are disordering equally, irrespective of their depth within the epitaxial structure. This is to be expected because of the thermal nature of the disordering process and the close spacing of the wells.

The lasers with the lowest threshold currents and best external quantum efficiencies were chosen in determining the device and material parameters. The inverse of the slope efficiency was plotted against cavity length for each sample. From the slope of such plots the internal loss can be inferred and the intercept on the y-axis gives the reciprocal of the internal quantum efficiency. It is difficult to obtain precise values of the internal efficiency by this technique without a very large data set (here 5 lasers were measured for each of 5 cavity lengths at each wavelength), especially when using pulsed measurements, but trends can readily be inferred.

Fig. 2 shows the threshold currents and internal quantum efficiencies of lasers which have been fabricated from samples with different degrees of intermixing. Several factors contribute to changes in the threshold current and quantum efficiency e.g. alteration of the well shape, intermixing and dopant diffusion in the GRIN structure, and changes in the number of point defects within the material. The observed increase in threshold current is mainly due to the well shape changing and the electrons and holes becoming less confined within the wells, leading to the emission properties becoming closer to those of bulk material.

The absolute accuracy of the internal quantum efficiency data is likely to be limited, as discussed above. An initial increase in efficiency with intermixing is observed, followed by a drop. It is not clear how reliable these trends really are. It can, however, be inferred with certainty that the

\[ \text{Threshold current density} \times \text{internal quantum efficiency} \]

\[ \text{Loss (cm}^{-1}) \]

\[ \text{Wavelength (nm)} \]
internal quantum efficiency remains substantially unaffected by the PAID process, i.e., the process does not appear to induce a significant number of nonradiative recombination centres.

Fig. 3 shows how the internal losses of the laser decrease as the material is disordered. The decrease is mainly due to a reduction in Auger effects and inter-valence band absorption, as the lasing wavelength becomes shorter\(^7\). In addition, the free-carrier absorption coefficient is, to a first approximation, proportional to the square of wavelength \(\lambda^2\) and so it will be reduced by around 20\% over the range of wavelength studied. Another factor is that the guided mode will become more strongly confined within the active region of the laser as the wavelength is reduced.

Oxide stripe lasers have been fabricated from material intermixed using the PAID process, demonstrating that the threshold current density and the internal quantum efficiency of the material after disordering is still comparable to that of the as-grown material. The results demonstrate that no apparent losses are incurred because of dopant diffusion (Zn) into the active region, a conclusion which is supported by the observation that the internal loss decreases with increasing intermixing (Fig. 3). This is an important point, as a displaced \(pn\) junction due to diffusion of dopants will seriously reduce the performance of devices fabricated by intermixing, e.g., passive waveguides and modulators. The evidence that lasers work well after disordering using the PAID process, at wavelengths far removed from those of the original structure, indicates that the material is still of excellent quality for use in the integration of devices.

4. ELECTRO-ABSORPTION MODULATORS\(^8\)

The material used to fabricate the electro-absorption modulators was identical to that used to fabricate the bandgap tuned lasers with the excitonic peak of the as-grown material, measured by photoluminescence at room temperature, occurring at approximately 1580 nm. Room temperature photoluminescence and photocurrent measurements were carried out after disordering to determine the extent of bandgap shift in the samples. Depending on irradiation conditions, different amounts of shift were measured. The maximum shift used for this group of devices was about 120 nm, although larger shifts can be realised in this structure.

4 μm wide, strip-loaded, single mode waveguides were fabricated parallel to the [011] direction. When fabricating the ridges, the thick InP upper cladding layer was only partially removed by CH\(_4\)/H\(_2\) reactive ion etching, in order to prevent any possible damage to the MQW structure. InP etching was completed using a HCl wet process which, as a consequence of crystal orientation\(^9\), gave vertical and smooth waveguide sidewalls. Following the deposition of a 2000 Å thick SiO\(_2\) passivation layer, windows were opened around the ridges. The samples were then thinned and metal contacts (p-Ti/Au, n-Au/Ge/Au/Ni/Au) evaporated which were annealed at 400 °C for 60 s using a rapid thermal processor. The samples were then cleaved to a length of 500 μm.

A semiconductor laser, tuneable in the wavelength range from 1480 to 1580 nm, was used to assess the device performance. Light was end-fire coupled into the sample through a tapered microlensed single-mode fibre. A fibre polarisation rotator ensured that only the TE-mode was excited in the waveguides. The output from the sample was collected by another fibre and detected by a germanium photodiode. Transmission characteristics were investigated as a function of wavelength. Assuming a coupling loss of 6 dB at the sample facets, the estimated propagation loss of the modulators at the optimum operating wavelength with no applied bias was about 2 dB per 100 μm.

Fig. 4 shows the modulation depth versus wavelength for three different degrees of disordering, corresponding to a shift in the bandgap edge, with respect to the as-grown material, of 80 nm, 95 nm and 120 nm. Measurements have been carried out with a voltage sweep between +0.5 V and -1 V. A decrease in the modulation depth is clearly noticeable in samples which have increased disordering. Such behaviour is in good agreement with theoretical expectation, as disordering causes a reduction in quantum confinement due to the smoothing of the potential barrier shape. This effect is worthy of further investigation because the use of shallow wells is suggested as a solution for increasing the saturation intensity in electro-absorption modulators\(^10\). Moreover, shallow wells would prevent hole pile-up in the active region, allowing a higher cut-off frequency at low bias voltages and an improvement in quantum efficiency.
Fig. 4: Modulation depth when bias voltage was varied between +0.5 V and -1 V plotted as a function of wavelength for three samples which had undergone different bandgap shifts.

Fig. 5: Normalised output power as a function of bias for two samples which had undergone bandgap shifts of 120 nm, measured at 1522 nm, and 80 nm, measured at 1555 nm.

At the optimum modulation wavelength of 1522 nm for samples whose bandgap had been shifted as far as 120 nm, an ON/OFF ratio of over 20 dB (Fig. 5) was obtained when the bias voltage was varied between +0.5 V and -2.5 V. This is further evidence that the PAID process does not produce any dramatic degradation in the optical properties of the MQW structure. Samples disordered to a lesser degree (80 nm) gave higher ON/OFF ratios of at least 27 dB at 1555 nm, limited by the measuring system.

A forward bias of +0.5 V was found to increase the output power from the modulators, typically by 5 dB. Because this voltage is well below the diode turn-on voltage, only a very small current actually flows through the device. This means that no amplifying effect can account for such an increase in the output power. Most likely, the small forward bias neutralises the built-in diffusion potential between the doped layers which form the pin structure. The evidence that these devices work well after disordering demonstrates that PAID appears to be a useful technique for optimising electro-absorption modulators.

5. LOW-LOSS WAVEGUIDES

The material used to measure waveguide losses was similar to that of the standard MQW laser material except that there were no dopants introduced during growth and the upper cladding consisted of 1.5 μm of InP with no GaInAs contact layer. The material was disordered from a starting PL wavelength of 1585 nm to a final PL wavelength of 1420 nm corresponding to total intermixing between the wells and the barriers.

Single mode strip loaded ridge waveguides of width 3.5 μm were then fabricated parallel to the [011] direction on the disordered material as described previously. The waveguide losses were measured over a range of wavelengths from 1510 nm to 1570 nm using the Fabry-Perot technique. The source used was a tuneable single mode semiconductor laser.

Fig. 6 shows the single mode waveguide loss as a function of wavelength. Losses in this material should be quite low as the band-edge of the material has been shifted by a substantial amount. At higher wavelengths (lower energy) the losses will be mainly due to scattering, leakage from the guide and absorption losses from imperfections in the material. At shorter wavelengths the losses will rise as the tail of the band-edge is encountered and the absorption increases. It is evident from this graph that the losses are very low with a value of 5 dB cm⁻¹ at a wavelength of 1550 nm, the wavelength at which integrated devices in the InP system will operate. A possible reason for the low loss is that no impurities are introduced at any stage during the PAID process which could increase the absorption loss or cause damage in the crystal structure and increase the scattering losses. These results (of below 10 dB cm⁻¹) demonstrate that PAID is an effective way of producing low-loss interconnecting waveguides for the use in photonic integrated circuits.
6. CONCLUSIONS

In this paper we have discussed the advantages of quantum well structures in photonic integrated circuits. In particular, we have demonstrated that photo-absorption induced disordering is an effective quantum-well intermixing technique for producing controllable bandgap-tuning in the GaInAsP system. This bandgap-tuning has been utilised in the fabrication of different devices from standard multi-quantum well laser material.

Broad area oxide stripe lasers have been fabricated with blue shifts in the lasing spectra of 160 nm with comparable device performance to that of the as-grown material. Electro-absorption modulators have been fabricated from bandgap-tuned material demonstrating ON/OFF ratios of up to 27 dB and single mode waveguide losses of 5 dB cm⁻¹ have been measured at 1.55 μm. The performance of these devices confirm, with the lateral selectivity reported elsewhere, that PAID is a promising technique for producing photonic integrated circuits.

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8. References

Monolithically Integrated Active/Passive Cavity Mode Locked MQW Lasers Realized by Selective Area Growth


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Abstract:

We report on the realization of monolithically integrated active/passive cavity mode locked lasers operating in the 1.55 µm wavelength window. The longitudinal integration of the active/passive cavity was achieved by selective area growth (SAG) of GaInAs(P) MQWs based on low pressure MOVPE. Mode locking was achieved by absorption modulation of an intra cavity electroabsorption modulator. Pulse widths of 16 ps are observed at 10 GHz repetition rate.

Summary:

Picosecond optical pulse sources are key elements in high capacity fiber based communication systems that are based on optical time domain multiplexing techniques. InP based mode locked lasers are of particular interest due to their potential for monolithic integration. Depending on the length of the laser cavity, repetition rates between 2.2 GHz and 350 GHz have been reported with cavity lengths ranging between 20 mm and 250 µm /1,2/. Fully active resonators, mainly for short cavity high frequency lasers /1,3/, as well as integrated resonators comprising of active, passive waveguide and wavelength selective sections /2/ have been demonstrated.

In this paper the first realization of a monolithically integrated active/passive cavity mode locked laser using SAG is reported. The longitudinal integration of the laser was realized by selective area growth /4/ of 8 InGaAs(P) quantum wells on SiO₂ masked wafers with low pressure MOVPE. The geometry of the SiO₂ patterns are adapted to give a shift of the photoluminescence wavelength between the active and passive regions of 60 nm. The laser cavity with a total length of 4.17 mm consists of active and passive waveguide sections and an intra cavity electroabsorption modulator (170 µm length) located at the output facet. The laser is fabricated using BRS lateral structure. Electrical separation of segments is done by etching
the ternary contact layer and ion implantation giving segment separation of > 1 MΩ. A schematic view of the laser structure is given in fig. 1.

The lasers are at first characterized for there static behaviour. An example of the light output power versus the current in the gain section is shown in fig. 2. The threshold current of the 4.17 mm long device is 64 mA and the output power reaches 3.7 mW at 200 mA.

Mode locking operation is achieved by sinusoidal modulation of the electroabsorption intra cavity modulation segment around a reverse bias voltage with the roundtrip frequency of the laser cavity while driving the gain segment with a constant current. The short optical pulses of the mode-locked laser are measured using a fast PIN-detector and a sampling oscilloscope with a time resolution of 16 ps. An optical pulse train obtained at a modulation frequency of 9.97 GHz is depicted in fig. 3a. Intense light pulses with ~100 ps repetition are observed with very high on/off ratio. The undeconvoluted pulse width at half maximum of the laser emission is about 16 ps as shown in detail in fig. 3b. The emission wavelength of the output light is centered around \( \lambda = 1557 \) nm.

In conclusion we have realized a compact monolithically integrated mode locked laser using selective area growth of GaInAs(P) MQWs based on low pressure MOVPE. Mode locking was achieved by absorption modulation of an intra cavity electroabsorption modulator. Pulse widths of 16 ps are observed at a repetition rate compatible with the STM 64 frequency.

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References:


Figures:

Fig. 1: Schematic view of the integrated active/passive cavity mode locked laser.

Fig. 2: Static characteristic of a laser with 4.17 mm active/passive total cavity length: threshold current 64 mA, differential quantum efficiency 0.028 W/A.
Fig. 3a: Time resolved optical output of a mode locked laser with 4.17 mm cavity length: pulse train with repetition rate of 9.97 GHz. A fast PIN-detector and sampling oscilloscope were used. The lower line indicates the zero level of the PIN-detector.

Fig. 3b: Optical pulse width $\tau_{\text{FWHM}}$ (undeconvoluted) is 16.4 ps (resolution limit: 16 ps).
III-V based integrated optical chip for metrology: device and integration technology

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Abstract

We present an integration technology and devices for the fabrication of a monolithically integrated optical distance measuring circuit. A single growth-step DBR laser with a holographically-defined recessed grating coupled through a passive waveguide section made transparent by a quantum well intermixing technique to an absorbing detector is presented for the first time.

1. Introduction

The use of monolithically integrated semiconductor optical sensors for metrological applications or biochemical sensing has advantages over bulk optical approaches in that alignment of the components is simplified, robustness is enhanced and size is reduced. A waveguide-based interferometric optical sensor circuit includes an integratable laser light source, an integrated detector and a means to define selective transparency of the waveguides. We discuss in this paper the design and fabrication of the integratable devices, approaches for electrical isolation and the means by which waveguide transparency are achieved.

For optical distance measurement, the Michelson interferometer [1] depicted in figure 1 is the most suitable sensor arrangement, and for biochemical analysis, a Mach-Zehnder interferometer is attractive [2]; both of these structures share technological aspects. A distributed Bragg reflector (DBR) laser is ideal as an integrated light source since the grating mirror implies integratability with a subsequent waveguide-based circuit. In addition, a DBR laser has inherently low feedback sensitivity, implying enhanced stability for an application dependent on reflection from an external surface, and narrow linewidth, vital for a suitably long coherence length and therefore measurement distance. These latter two points represent an advantage of our current approach over previous schemes.
The grating section of the DBR laser and the waveguides are made transparent by a group-III-vacancy diffusion technique called dielectric cap annealing (DCA) [3] which permits a controlled intermixing of the quantum well (QW) with the waveguide core. The intermixing of the Ga and Al atoms blurs the QW enough to shift the bandgap energy by up to 50 meV. Through the use of different dielectric cap layers and a high-temperature anneal, transparent and absorbing regions can be defined on the same substrate. Finally, since the laser and detector must be electrically isolated, we have also incorporated a patterned implantation step in order to generate a high resistivity region between the two devices, albeit without augmenting optical loss.

2. Dielectric cap annealing

For monolithic integration of lasers and waveguides, it is necessary to increase the effective bandgap in the transparent waveguide region [4,5]; this can be achieved by quantum well disordering, requiring only a single crystal growth step. DCA employs various surface dielectrics to promote or inhibit intermixing. The pumped laser section and the absorbing photodiode are covered with a SrF$_2$ layer, the remaining waveguides with SiO$_2$ (see figure 2). The high temperature rapid thermal anneal (960 °C, 25 s) generates group-III-vacancies under the SiO$_2$ layer, while hindering this vacancy generation under the SrF$_2$ layer. These vacancies diffuse into the waveguide core during anneal and the GaAs in the QW will be intermixed with Al atoms to Al$_x$Ga$_{1-x}$As AI from the neighboring Al$_{0.3}$Ga$_{0.7}$As waveguide core.

A standard separate confinement double heterostructure layer sequence, using a 165 nm thick Al$_{0.3}$Ga$_{0.7}$As core with a single 7 nm GaAs quantum well embedded in two 1 µm thick Al$_{0.8}$Ga$_{0.2}$As barrier layers, was used for all devices. Depending on anneal time and temperature, shifts of the room temperature photoluminescence peaks under the SiO$_2$-coated surface of nearly 70 nm can be achieved. Under SrF$_2$, the maximum shift was restricted to 10 nm under the same conditions (figure 3).

Figure 2: The patterning of the surface dielectrics (SrF$_2$ left, SiO$_2$ right) is made using a self-aligned process and only one photolithography step.

Figure 3: Blue shift of the absorption edge after DCA.
3. DBR laser

The DBR laser is a ridge waveguide structure requiring no regrowth after grating fabrication and making use of a recess in order to accurately control grating position and thus coupling factor [6], as seen schematically in figure 4. Waveguide ridges and the grating recess are generated by a magnetron dry etch using SiCl₄; this recess is a region of the waveguide upper cladding thinned to 150 nm above the core. To limit the extent of the grating to the top of the recessed ridge waveguide, a photoresist layer with a reduced thickness of 250 nm only on top of the waveguide was employed. The rectangular-shaped third-order grating, with a period of 376 nm, was holographically defined and etched into the remaining upper clad, using the same dry etch chemistry. Grating depth is 0.7 times the remaining upper clad thickness. For these grating parameters, a coupling coefficient of 100 cm⁻¹ was calculated.

Figure 4: Schematic of the DBR laser with transparent recessed grating and absorbing detector

These devices operated CW at room temperature with a threshold current of 20 mA, delivering an output power of 4 mW at 820 nm at both facets. As seen in the spectrum of figure 5, sidemode suppression ratio was 25 - 30 dB; linewidth, measured by a self-heterodyne technique, was determined to be 500 kHz, implying a coherence length of 600 m. The temperature tuning coefficient was 0.07 nm/K, such that 1.4 nm of mode-hop-free wavelength tuning could be accomplished over 20⁰C.

4. Integration

Combining dielectric cap annealing with this DBR laser fabrication processes, integrated lasers with a transparent grating section, transparent passive waveguide and absorbing detector were fabricated. Processing began with a patterning of the surface dielectrics, SiO₂ or SrF₂ for the transparent (bandgap shifted) and absorbing (bandgap unshifted) regions, respectively. SiO₂ was e-beam evaporated first, to a thickness of 200 nm, and patterned by CF₄ dry etch. Using thermally evaporated SrF₂ (thickness 200 nm), patterning was then completed by lift-off of this latter dielectric. The patterning uses a self-aligned process and therefore no gap between the two dielectrics occurs. Following rapid thermal anneal in an N₂ ambient with a GaAs proximity cap, both dielectrics were stripped with 1:5 HCl:H₂O and CF₄ RIE, respectively, leaving a clean planar surface. The proximity cap is necessary to achieve an As overpressure preventing surface damage by As evaporation.

Broad-area Fabry-Pérot lasers fabricated in the nominally unshifted areas of the wafer showed an increase in threshold current density from 200 A/cm² up to 450 A/cm², with a wavelength shift of only 2 nm after anneal. This increase can be
explained by Zn diffusion into the p-n-junction. Ridge waveguide DBR lasers with transparent grating sections and long passive waveguides were fabricated; the lasers operated CW at room temperature with threshold current densities of 600 A/cm² and output powers of 5 mW. This increase in threshold current density may be due to a misalignment of the grating peak with respect to the gain peak. Optical emission from both the cleaved facet and from the end of the transparent monolithically integrated waveguide section was seen; loss measurements of DCA shifted waveguides showed losses limited by free carrier absorption in the doped materials at the wavelengths of interest.

Electrical isolation between the laser and detector can be accomplished through the use of H⁺ implantation. A thick (1.9 μm) photoresist mask defined 2 μm stripes across the waveguide; implantation was at a dose of 4×10¹⁵ cm⁻² at energies of 40, 80 and 120 keV. Isolation resistances of greater than 100 MΩ were reached with no additional optical losses.

5. Conclusions and outlook

Single-growth step DBR lasers have been monolithically integrated with transparent recessed grating and waveguide sections and an absorbing detector using quantum well intermixing. Laser performance, in terms of threshold current density, side-mode suppression ratio and linewidth, is suitable for direct inclusion in monolithically integrated interferometers for metrology and biochemical sensing. The employed integration techniques, induced transparency and electrical isolation, have been shown to be suitable for completely integrated structures.

Acknowledgments

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Optoelectronic Integration

MICROSTRUCTURE FOR WAVEGUIDE-TO-PHOTODIODE COUPLING IN SILICON OPTOELECTRONICS

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Abstract

Using a gray-tone mask technique, a waveguide-to-photodiode coupling element was designed and realized. The end of the waveguide is tapered in order to deflect by total reflection the guided light towards the silicon substrate where the photodiode is located. This microstructure realization process was added to an industrial CMOS technology, and used to realize optoelectronic circuits on silicon substrates.

Introduction

For optoelectronic technology, the coupling element between the waveguide and the photodiode must be compatible with the technology. Some ideas have been proposed using evanescent field coupling, refraction effects at the bird's beak or diffraction gratings. None appeared to be ideal, and the solution proposed here has the advantage of being fully compatible with industrial 2 μm CMOS processes, while not perturbing the waveguiding properties. The coupling structure is realized using a gray-tone mask to obtain a tilted surface in the photoresist. Then this surface is physically transferred by etching the waveguide end to form a total reflection mirror that deflects the guided light towards the photodiode. The coupling efficiency was estimated by measuring the electrical response of different structures and, as a demonstrator of the technology, an interferometric device was characterized.

The 2 μm CMOS technology

The basic technology was a standard 2 μm CMOS process, where technological steps were added for the integration of the optical circuits. The waveguide structure is formed with a 2 μm thick thermal oxide layer, a 0.5 μm thick PECVD deposited SiO2 layer with a refractive index of 1.51 and finally a 0.5 μm thick PECVD deposited SiO2 layer. A structured 0.35 μm deep RIE etch in the last layer defines rib waveguides. Figure 1 gives a cross section of the guiding structure. The added technological steps
are fully compatible with the core technology and evidently do not alter the
electrical properties of the CMOS circuits. Standard circuit libraries are
immediately usable.

The coupler fabrication technology

The coupler consists of the tapered end of the waveguide to deflect the light
into the photodiode and so to make the link between the optical signal and
the electronic processing circuit. In order to have a total reflection at the end
of the waveguide, the tapered surface angle has to be larger than 43
degrees (versus propagation axis). This three-dimensional microstructure is
not easy to realize with a standard microelectronics process. The present
approach for the realization of the three-dimensional structure consists in the
use of gray-tone masks with conventional microelectronic equipment and
only one exposure shot. Fabrication involves three steps: first, the realization
of the gray-tone mask; second, the generation of the three-dimensional
structure in the photoresist by exposure and development, and third, the
proportional physical transfer into the waveguide structure.

The gray-tone mask consists of regions with variable optical transmission
(gray level). A matrix of transparent dots with a constant pitch and a variable
surface creates the transmission levels. The electron-beam pattern
generator (EBPG) is a flexible system with high resolution and is well
adapted for the writing of gray-tone masks.

The exposure of the wafer is performed on a 5x g-line stepper. The exposure
time is chosen experimentally by observing the angle of the surface for
different exposure times. As the number of gray levels cannot be infinite, a
thermal treatment of the photoresist is carried out to smooth the effect of
digitization.

After development, the three-dimensional structure is in the photoresist. It is
conformally transferred in the optical layers using plasma etching in a RIE
reactor using fluorine-based chemistry. The process was developed to have
a resist-substrate selectivity of about 1:1. Figure 2 shows the results of tests
in a 2 μm thick resist.

Results

Figure 3 presents SEM cross-sectional micrographs of the coupler in the
photoresist and in the optical layers. The angle of the surface is 60 degrees.
To test the efficiency of the coupling structure, devices consisting of straight
or curved waveguides coupled to a photodiode and its amplifier circuit were
designed. Figure 4 shows a SEM view of the waveguide end with a 60
degree tilted surface. It can be noticed that the waveguide is not perturbed at
the limit of the photodiode region. By comparing the electrical current on
these devices with the current obtained on a device with a waveguide and a
non-integrated photodiode, the coupler loss can be estimated to be lower
than 3 dB. The bandwidth of the system was measured at 1.7 MHz, limited
by the non-optimized transimpedance amplifier.

As a demonstrator of the technology, an unbalanced interferometer was
fabricated with on-chip amplification electronics. The interferometer consists
of two 3 dB couplers linked together by two waveguides with a length difference of 26.5 μm. The circuit was tested using a temperature controlled laser diode in the wavelength range of 782 to 792 nm. Figure 5 gives the normalized interference signals versus the wavelength for TE polarization. A maximum contrast ratio of 16 dB is obtained at 783 nm. Such results show that this circuit can for instance be used for wavelength demultiplexing in sensor applications, or for the wavelength stabilization of a semiconductor laser diode.

Conclusion

The realization of a coupler between a waveguide and a photodiode using a gray-tone mask technology has been demonstrated. The advantage of this technique is that the coupling element is fabricated with only one mask, and using standard microelectronic processes. The feasibility of complex optoelectronic devices like a wavelength-sensitive unbalanced interferometer in a 2 μm industrial CMOS technology is also demonstrated.

Acknowledgement

The authors acknowledge the collaboration of Dortmund University, Germany (Prof. Voges) for the optical layer deposition.

References


Figure 1: Basic waveguide structure

Figure 2: Depth reached with gray-tone test zones in resist (1) and in silica (2)

Figure 3: SEM micrographs of the waveguide-to-photodiode coupler cross section in resist (1) and in the optical layers (2)

Figure 4: SEM micrograph of the tapered waveguide end

Figure 5: Normalized interference signals of the unbalanced interferometer circuit vs laser diode wavelength (TE polarization)
OPTICAL MODE PROPAGATION ALONG TAPERED AMPLIFIERS BY
SCANNING MICROSCOPY WITH DIELECTRIC LOCAL PROBES

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Abstract: We used the Scanning Near-Field Optical Microscopy with uncoated dielectric silica
probe to investigate the propagation of optical mode along tapered integrated semiconductor optical
amplifier devices. We show how this technique provides direct knowledge of the mode structure of
optoelectronic devices with typical sizes in the range 1 to 10 microns.

Introduction: The subject of Scanning Near-Field Optical Microscopy (SNOM) has been thriving
in the last years with resolution below the Rayleigh criterion [1, 2]. But applications of SNOM to
optoelectronics have only started to appear, providing images of the mode emitted by cleaved optical
fibers [3], and of the evanescent field above a two-waveguides coupling device [4]. We will show
here how useful data can be obtained on mode propagation with non-metallized dielectric probes, in
the case where relevant mode widths are in the micron range. We will then show how this technique
allows the measurement of intensity profiles at different sections of a device, and thus makes possible
the direct experimental reconstitution of beam propagation in complex optoelectronic devices with
spatially varying features, in the particular case of tapered semiconductor optical amplifiers. Our
results are compared to numerical simulations thus providing an evaluation of field profiling with
submicronic dielectric probes.

Description of the tapered amplifying devices: One major issue of optoelectronics is the
minimum-loss coupling of optoelectronic devices with optical fibers. This issue is particularly serious
when one considers devices such as the semiconductor optical amplifiers (SOAs). The solution
which we have developed [5] and which is shown in figure 1 consists in a 300 μm long InGaAsP
amplifying and waveguiding layer (λg = 1.6 μm) with a homogeneous cross-section, 0.6 μm wide and
0.35 μm thick, and a 250 μm long tapered section. The lateral dimensions in the tapered section are
reduced from 0.6 μm to less than 0.1 μm. Below the whole structure runs an InGaAsP coupling
waveguide with a gap wavelength of λg = 1.3 μm, a width of 6 μm and a thickness of 0.04 μm.
Along the tapered section, the mode confinement decreases with the lateral reduction of the amplifier
cross-section, and a continuously varying coupling of the energy by evanescent waves to the lower
lying homogeneous waveguide takes place. Several identical samples have been made. These have
been cleaved at four different points, in the amplifying region (Sample A1), at two different spots
along the taper, 165 μm and 30 μm before the taper end respectively (Samples A2 and A3), and
eventually in the coupling waveguide (Sample A4).

Numerical simulations: Simulations of the mode emitted in each case have been performed with a
specially devised software [6]. These simulations shown in figure 2 clearly exhibit the horizontal
expansion of the optical mode as it proceeds through the SOA devices. In the particular case of
SOAs the numerical results depend on a precise knowledge of the optical indices of variously doped
III-V layers, and therefore on the exact doping level of these layers. Since some uncertainty remains
at this level, a fitting procedure is required. We have performed this adjustment by measuring far
field intensity angular profiles. Numerical simulations have been adjusted so as to have calculated

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beamwaists agree with far-field measurements within reasonable assumptions concerning doping levels. We have reported the full width at half maximum (FWHM) of the simulated intensity profiles in table 1 for the two horizontal (x axis) and vertical (y axis) directions.

**Imaging of tapered amplifying devices intensity pattern with a dielectric probe:** The basic setup involved the scanning of a submicronic optical probe in the electromagnetic field pattern of optical devices. The probes were made by pulling a single mode optical fiber with a commercial Sutter P-2000 instrument. A convenient choice of pulling parameters allowed us to obtain reproducible tip radii between 50 and 100 nm. Such tips will be used throughout all the experiments described below. These probes are then mounted on a piezoelectric tube allowing scans of 30 microns x 30 microns in the vertical plane, coupled to a Ge photodetector, and used to generate optical image with a SNOM controlling and monitoring system which is depicted in figure 1.

![Schematic of the SNOM setup for the measurement of the near-field output of a tapered semiconductor optical amplifier](image)

**Fig. 1:** Schematic of the SNOM setup for the measurement of the near-field output of a tapered semiconductor optical amplifier. In order to study the effect of the taper on the optical mode identical samples were cleaved, before, after and in the middle of the taper.

In a typical experiment such a probe is scanned near the cleaved end of the device. The power of the SOA working at \( \lambda = 1.58 \) \( \mu \)m is adjusted thanks to the current driver to avoid saturation of the detecting device. So, the total power emitted at the cleaved end of each SOA configuration does not exceed a few tens of microwatts. The submicronic probe is then approached from the cleaved plane and scanned along this same plane so as to generate images of the field intensity in the vicinity of the cleaved end. The approach of the probe is observed with a Zeiss microscope. Since we have not implemented an additional distance regulation for these experiments, images are taken successively as the probe is brought closer to the cleaved plane, until contact is made (which often destroys the probe). The sample-probe distance for each image is then recovered through the piezoelectric devices calibrations. We have thus retained images made closer than 1 micron from the surface, that is in the near-field regime.

The raw images are shown in figure 2 and clearly depicts the mode expanding effect of the taper. The FWHM of the experimental intensity profiles have been reported in table 1. The experimental images are however widened relatively to the theoretical profile, more significantly so
Fig. 2: Comparison between experimental SNOM images of taper-SOA structures cleaved along different sections, and the numerical simulations. Scanned areas are $5.44 \mu m \times 5.44 \mu m$ (A1), $8.80 \mu m \times 8.80 \mu m$ (A2), $16 \mu m \times 16 \mu m$ (A3 and A4). On the numerical simulations we have represented the coupling waveguide (horizontal line) to show the coupling between the amplifying structure and the waveguide.

When the optical mode is more confined, this may be ascribed to the influence of the tip response. As a matter of fact, when studying smaller optical patterns, light is collected into the dielectric tip from a region much larger than the extremal tip radius with submicronic size. That's why, to take account for tip response the detected intensity can be described as the convolution product: $I(x,y) = R(x,y) * T(x,y)$ (eq. 1) where $x$ and $y$ represent the horizontal and vertical coordinates in the cleavage plane, $I$ and $R$ the experimental and real intensity profile and $T$ the dielectric tip response. As a test localized electromagnetic field pattern we have used the light emitted by the cleaved amplifying structure (sample A1) for which numerical simulations predict mode sizes of 0.53 micron in the horizontal direction and 0.65 micron in the vertical direction, in good agreement with the far-field patterns which lead to values of 0.56 and 0.60 $\mu m$ respectively. It's then possible to gain all the necessary insights within the framework of a gaussian beam model. In this case, each parameter of equation 1 may be taken with a gaussian shape: $A(x,y) = A_0 e^{-\frac{x^2}{2W_x^2} - \frac{y^2}{2W_y^2}}$; the convolution equation 1 then leads straightforwardly to: $W_x^2 = W_{xf}^2 + W_{tf}^2$ (eq. 2) where $v$ is an index standing for $x$ or $y$. It is possible to determine $W_{tf}$ from the data corresponding to the sample A1. We obtain $W_{tf} = 1.42 \mu m$ and $W_{tf} = 1.35 \mu m$. Given an experimental profile reasonably fitting the gaussian beam framework, it is then possible to determine deconvoluted beam waists using equation 2. This is what we have done in the experiments described below using the average value $W_{rf} = 1.39 \mu m$ for both the $x$ and $y$ axis. To ensure comparability of these experiments we have retained fibers with similar...
shapes and tip responses, which we found to be reproducible within the chosen fabrication parameters. Table 1 shows the deconvoluted near-field intensity profiles and theoretical profiles to be in good agreement, excepted for the shape of sample A4 along the y direction.

<table>
<thead>
<tr>
<th>SOA section</th>
<th>AXIS</th>
<th>EXPERIMENTAL FWHM</th>
<th>DECONVOLUTED FWHM</th>
<th>CALCULATED FWHM</th>
<th>ABSOLUTE DEVIATION [D - C]</th>
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<td>3.20</td>
<td>1.88</td>
<td>-</td>
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</table>

Table 1: Comparison of the FWHM values of the mode sizes in various sections of the SOA, along the horizontal (x axis) and vertical (y axis) directions. The last value in the column 4 was omitted because of a tilt in the output plane which prevented a correct tip approach.

This sample was particular in the sense that being a complete SOA structure it was prepared with a 4°-tilted end facet so as to decrease reflections back into the device. Since we were scanning perpendicularly to the output beam propagation axis, and since the beam is refracted when passing through the tilted end facet, the geometry of this particular experiment with a 16 μm by 16 μm scanning grid prevented our getting the fiber closer than 4 microns to the end facet. Beam divergence effects start to be noticeable at these distances for the y direction where the mode is much more confined. Moreover the beam propagation in the very thin coupling waveguide itself is better described by an exponential rather than a gaussian y dependence. These effects account for the discrepancy of this particular measurement.

Conclusion: In summary we have shown how the use of dielectric probes allows the direct determination of the spatial variation of the mode emitted by optoelectronic devices in the range comprised between 1 and 10 microns or more with an uncertainty which is less than or equal to 0.2 microns. Though less accurate, those probes are much easier to make than metallized probes. They therefore provide an accurate and convenient tool for the study of optical modes, particularly useful when alternative indirect techniques such as far-field angle measurements are difficult to perform, for instance in passive optical devices, waveguides or modulators.

Acknowledgements: we want to thank Michel Spajer and Daniel Courjon from the Laboratoire d'Optique P. Duffieux at the University of Besançon, for enlightening discussions and designing the piezoelectric displacement head used in these experiments.

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MEASUREMENT OF THE WELL AND FACET TEMPERATURES OF NORMALLY OPERATING QUANTUM WELL LASERS BY ANALYSIS OF THE SPONTANEOUS EMISSION FROM THE FACETS

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Analysis of the spontaneous emission from the end facet of a normally mounted and operating quantum well laser has been used to determine the active region temperature both within the device and close to the facet. The measurements were applied at high powers up to and beyond catastrophic optical damage.

Introduction

Knowledge of the temperature of the active region of a semiconductor laser and its variation with position along the length of the cavity is extremely useful for a number of reasons. Valuable information on basic physical processes such as internal loss mechanisms and also on technical issues such as the quality of the heat sink configuration can be obtained. In shorter wavelength devices the main problem at high powers is mirror degradation and here one wishes to be able to measure any increase in temperature close to the end facet in order to compare with changes in the bulk. In this paper we show how it is possible to obtain important information on these problems simply from a study of the spontaneous emission from the end facet of a laser bonded down and working in its normal configuration. The approach is non-intrusive and could easily be adapted for routine characterisation of quantum well devices. We present as an example the results of studies on 680nm double quantum well InGaAlP devices.

Results and discussion

Figure 1 shows the electroluminescent spectrum observed from the end facet of a InGaAlP/GaAs laser with an operating wavelength of 680nm. The device, which was provided by Philips Optoelectronics Centre contained two 100Å wide InGaP strained quantum wells at the centre of a 1000Å wide InGaAlP guiding region with a band gap of 2.14eV. The end facet of the laser was coated with Al₂O₃ and the laser was bonded epitaxial side down to the heat sink in an SOT header which was mounted on a Peltier temperature controller. The threshold current of the laser was approximately 30mA at room temperature. The step in the output spectrum near 2.14 eV indicates the onset of radiation from the barrier region. The spectral dependence below this energy comes from the well and is a measure of the temperature of the active region in the body of the laser while radiation above this energy is a measure of the temperature closer to the end facet.
Figure 2 shows the output intensity plotted logarithmically as a function of energy. As can be seen, both above and below the step, the results fit quite well to a straight line. Radiation with photon energies below 2.14eV will have been emitted from the well region where the absorption coefficient of the well material is of the order of $10^4$ cm$^{-1}$. However, the optical confinement factor for the two quantum wells is approximately 5%. Therefore the radiation being observed emanates from an average depth of about $20\mu$m from the end facet. This is many times the distance of the active region from the heat sink of approximately $1.5\mu$m and can therefore be considered to be representative of the quantum well temperature in a region not affected by particular effects at the facet. Because of the straight lines obtained in figure 2, we have assumed we may write the spectral dependence of the intensity $L$ in the form

$$L = A \exp(-E/kT)$$

where $E$ is the photon energy, $k$ is Boltzmann's constant and $A$ is a constant so that the gradients in figure 2 give $-1/kT$ directly.

Figure 3 shows a plot of the change in temperature of the active region deduced by this method at different laser currents as a function of the change in heat sink temperature. As can be seen, the change in temperature measured by this simple analysis of the spectrum agrees surprisingly well with that measured by the thermocouple controlling the heat sink temperature. Therefore, experimentally it seems reasonable to assume that the analysis will give an equally valid measure of the increase in temperature caused by current and photon flow within the device itself. Detailed measurements of the absolute temperature deduced for the active region at a constant heat sink temperature of 293K are shown as a function of current in figure 4. Note that the temperature point on the y-axis was determined by the heat-sink thermocouple.

Photon energies above the direct band gap of the barrier region experience an optical confinement factor close to unity and so light corresponding to an absorption coefficient of $10^4$ cm$^{-1}$ now emanates from an average distance from the facet of about $1\mu$m. Since this is less than the distance of the active region from the heat sink, it is expected to sense any excess temperature changes due to photon absorption by the facet or due to the different heat and current flow configurations in that region. The temperature rise determined by an analysis similar to that used for the well gave the facet temperatures which are also plotted in figure 4. At low powers the accuracy of the measurement is relatively poor, but for reasons not yet fully understood, below threshold the temperature of the bulk (given by the well emission) appeared to increase more swiftly than the temperature of the facet (given by the barrier emission). The temperature rise below threshold for the well is also larger than one would expect from measurements of the thermal resistance measured using the method of Pao1i. However, above threshold the situation was reversed. For the bulk the rate of change of temperature with current $\Delta T/\Delta I$ is almost constant at a value of $0.5K/mA$ while for the facet it is constant at $0.9K/mA$. We believe that the difference in these two gradients is due to heating of the facet region by photon absorption and subsequent phonon emission, while there is a cooling effect in the bulk due to the more efficient production of photons by stimulated emission. This conclusion is supported by the behaviour of the laser after catastrophic optical damage (COD) as described below.

Lasers of the type investigated here unfortunately undergo COD at very high output powers. This is believed to be due to photon absorption of the laser beam at the facet. This is consistent with the observed increase in the rate of heating of the facet above threshold shown in figure 4. COD
was observed to occur in this device as the current was being increased from 105mA to 110mA. It is extremely interesting to note that at this point, where the optical output dropped by approximately an order of magnitude, the measured temperature close to the facet drops by nearly 30 degrees. This appears to clearly illustrate the effects of facet heating by photon absorption although it is possible that some change in the current flow close to the surface was also caused by the COD process. By contrast, the bulk temperature appeared to increase slightly due to COD and there is a reversal in the absolute values of T in the two regions. The facet is cooler than the bulk above COD as observed in the low photon density regime below threshold.

Summary and conclusions

The spontaneous emission spectrum from a quantum well laser at photon energies well above the lasing wavelength has been used to obtain a measure of the lattice temperature. A very simple analytical model has been shown to yield surprisingly accurately the known changes in temperature imposed by the Peltier controlled heat sink. It should therefore give equally accurately temperature changes due to current and photon flow within the laser. It is further proposed that, because of the different optical confinement factors, radiation above the barrier energy emanates from sufficiently close to the facet that it monitors the temperature in that region, while light below that energy will be unaffected by the facet and hence more representative of the bulk. Analysis shows that in the device investigated, above the lasing threshold the temperature in the bulk increases linearly at 0.5K/mA while, closer to the facet, it increases linearly at 0.9K/mA. The difference in the two values appears to be due to the photon flux which carries away energy from within the bulk of the laser but heats the facet region due to partial absorption. This conclusion is supported by an observed temperature drop of the facet and a temperature rise of the bulk when catastrophic optical damage of the facet occurs and lasing is quenched.

The analysis used so far has been based on the simple assumption that the exponential dependence with energy of the Boltzmann tail dominates any changes with energy of the density of states etc (ie that A in equation 1 is a constant). This assumption is supported by the agreement obtained experimentally between the deduced temperature and that measured by the thermocouple. However, the success of this simple analysis is rather surprising and further detailed calculations are now in progress to try to explain this result. Nevertheless, from a pragmatic point of view, we have shown that the temperature of the active well region and the temperature of the region close to the facet may be obtained by simply looking at the spontaneous emission from the laser bonded down and in normal operation. No special processing is required in this measurement so that it allows routine, non-destructive evaluation to be carried out. Here it has been applied directly to the output of the device, but providing the absorption spectrum of the transmission medium, eg optical fibre, is known, the measurement could also be carried out remotely in order to monitor either the device or its environment.

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References

Figure 1: Spontaneous emission spectrum from the end facet.

Figure 2: Log of intensity below and above barrier energy.

Figure 3: Change in temperature deduced from the spontaneous spectrum at different currents plotted against change in heat sink temperature caused by the Peltier temperature controller.

Figure 4: Measured variation in temperature with current up to and beyond catastrophic optical damage (COD) for the bulk (well) and facet (barrier) regions.
OPTICAL IMAGING OF MULTIMODE INTERFERENCE PATTERNS WITH A RESOLUTION BELOW THE DIFFRACTION LIMIT

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Abstract

For the first time the optical interference pattern in multimode interference couplers operating at 1485 nm is made visible using an optical microscope. This is done by imaging the green light (519 and 545 nm) which is generated by upconversion at high pumping power levels in waveguides with a high erbium concentration. As the intensity of the green light is roughly proportional to the fourth power of the pump signal intensity it thus becomes possible to image the 1485 nm intensity distribution with a resolution limited by the diffraction limit for 519 and 545 nm light.

Introduction

Accurate methods for measuring two-dimensional intensity patterns in integrated optical devices are not available at present. Techniques which image the light scattered at inhomogeneities in the waveguide layer suffer from the large local inhomogeneity of the scattering sources. Another method is positioning identical devices at different distances relative to a cleaved endface. This method only provides us with one-dimensional intensity scans at different positions in the devices, provided that the excitation conditions can be reproduced. In this paper we present a method of imaging the field patterns in integrated optical devices using two-step cooperative upconversion in erbium ions incorporated in the waveguides. Cooperative upconversion is a process in which two excited Er$^{3+}$ ions exchange energy, promoting one of them to a higher energy level [1]. Two sequential upconversion processes lead to emission of green (519 and 545 nm) light. As the process depends on the concentration of excited Er$^{3+}$ ions, which in turn depends on the intensity of the field distribution, the emission of green light is a (roughly fourth-power) replica of the intensity distribution in the waveguide.

Upconversion mechanism

Figure 1 shows the energy level diagram of Er$^{3+}$, and a schematic of how cooperative upconversion proceeds. The various energy levels of the Er$^{3+}$ ion are numbered 0-6. Figure 1a illustrates the first-order process between two Er$^{3+}$ ions in the first excited state, whereby one of them transfers its energy to the other, promoting the latter to the 3$^{rd}$ excited state. This process depends quadratically on the concentration of Er$^{3+}$ in the first excited state, as two ions are
involved. The ions in the third excited state decay rapidly and non-radiatively to the second excited state. Because the lifetime of level 2 is relatively long (0.25 ms) a significant population in the second excited state is built up.

Subsequently, a second upconversion process can take place (Fig. 1b), in which two ions in the second excited state interact in a similar fashion, thereby populating the 6th excited state. Radiative decay from this state to the ground state causes emission at 519 nm. In addition, non-radiative decay can occur to the 5th excited state; radiative decay of this state to the ground state causes emission at 545 nm. The emission of this visible green light is roughly proportional to the 4th power of the concentration of Er$^{3+}$ in the first excited state, as two subsequent upconversion steps are involved. It thus becomes possible to directly image the intensity distribution of 1.48 μm pump light by monitoring the green emission. The measurement resolution is then limited by the diffraction limit for 519 and 545 nm light.

![Figure 2](image)

**Figure 2.** Principle of the measurement setup.

**Measurement principle**

Figure 2 shows the measurement setup, where a simple microscope objective placed above the waveguide is used for imaging the intensity distribution of green light as the 1485 nm light is guided through the waveguide. Accurate measurements can be made by digitizing the output on a CCD camera. The fourth power dependence between the green light and the IR light is favourable for obtaining high measurement accuracy. The short wavelength of the upconverted light makes it possible to measure with a resolution considerably below the diffraction limit for the infrared light, which allows for high accuracy imaging with medium quality objectives.
A property of multimode waveguides is self-imaging, which means that an input field is reproduced in single or multiple images at periodic intervals in the MMI-section as shown in Fig. 3. The principle can be explained as follows. An applied input field is decomposed into all guided modes of the MMI-section, each of them propagating with a different propagation constant. After a certain length $L_\pi$ all modes appear to interfere constructively, resulting in an image of the input field. At distances $L_\pi/N$ an N-fold image of the input field is obtained, so this type of MMI-coupler can be used as a power splitter. The principle of MMI-couplers is discussed in detail by Soldano [2].

**Figure 4.** Multimode interference pattern: a) BPM-simulation, and b) a microscope image, visible as green light.

Figure 4a shows the result of a simulation performed with the Beam Propagation Method (BPM) using a 21 μm wide MMI-section center-fed by a 2 μm wide input waveguide. The light coming out of the input waveguide is seen to diverge in the MMI-section and to be reflected by the sidewalls. The reflections cause the interference patterns which produce at certain distances the single and multiple images typical for MMI devices.

**Experiment**

An MMI-coupler was fabricated in an aluminum oxide ridge waveguide structure [3], implanted with erbium [4] to a peak concentration of 1.3 at.%. The device consists of a 2.0 μm wide input waveguide, center-fed to a 21.0 μm broad MMI-section. Light from a 1485 nm high
power laser was coupled into the input waveguide using a fiber taper. The power in the waveguide was 4 mW. Figure 4b shows the microscope image of the multimode interference pattern, right after the transition from the input waveguide to the MMI-section. This image appears as green light due to a two-step cooperative upconversion process as explained above. As can be seen the measured intensity profile agrees very well with the calculated profile in Fig. 4a.

Conclusion

Cooperative upconversion of Er ions pumped at 1485 nm can be used to image intensity distributions in waveguides with a high accuracy and resolution below the diffraction limit. This is demonstrated with a MMI-coupler fabricated in aluminum oxide ridge waveguide structure implanted with erbium. The calculated intensity profiles agree very well with the measured data. This method offers an unique opportunity for accurate measurements of lateral field patterns.

References

PRINCIPLES OF MODELLING OLCR SIGNATURES OF PHOTONIC DEVICES

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Abstract
Optical low-coherence reflectometry (OLCR) is now becoming an important diagnostic method for optical waveguide devices. Here we present the principles of modelling OLCR signatures by calculating the spectral dependence of the reflection coefficient of the mode of the exciting waveguide by the bi-directional mode expansion method, with subsequent Fourier transform by the FFT algorithm.

Introduction
One of the most important diagnostic methods in optical fibre systems is the well-known optical time-domain reflectometry (OTDR) [1]. Within the last few years, another but complementary approach — optical low-coherence reflectometry (OLCR), or optical coherence-domain reflectometry (OCDR) — has evolved into practical diagnostic method for integrated optical waveguides and photonic devices [2–4]. Among its most attractive features belong very large dynamic range, good spatial resolution, and relative simplicity of its optical setup. Various aspects of this method have been analyzed in detail [5–9]. Recently, commercial low-coherence reflectometers have also appeared on the market.

For modelling OLCR signatures (reflectograms) of optical waveguide devices, bi-directional methods have certainly to be used. Methods suitable for modelling back-reflections in optical waveguides have appeared only recently [10–14]. Starting point for the modelling is that the OLCR signature is the Fourier transform of the spectral dependence of the reflection coefficient of the (single) mode of the exciting waveguide. The bi-directional mode expansion and matching method (BEM) is re-formulated here to enable straightforward calculation of the reflection coefficient. Instead of the "classical" transfer matrix approach [13, 14], we use to advantage the "immitance matrix" formulation of the BEM. It has been shown recently [15] that this approach is numerically more robust. Simple examples demonstrating the applicability of the method to model the OLCR signatures with good resolution and high dynamic range are presented.

OLCR signature
Let us consider the optical setup of the OLCR shown in Figure 1. Light from a low-coherence source is split into the reference arm containing a phase modulator and a movable mirror, and the measuring arm with the device under test (DUT). Let the sarrodyne phase modulation in the reference arm introduce the light frequency shift $f$. The spectral component of the reference wave after travelling the full distance $x$ from the fibre end to the movable mirror and back can then be described by the expression $(1/\sqrt{2})E(\sigma)\exp[2\pi i \sigma (x + cct)]\exp(-2\pi if)$, where $\sigma = 1/\lambda$ is the optical wavenumber, $E(\sigma)$ is the complex amplitude of the spectral component of the source, and $c$ is the velocity of light. The wave reflected from the DUT can be similarly expressed as $(1/\sqrt{2})E(\sigma)R(\sigma)\exp(-2\pi i \sigma cct)$, where $R(\sigma)$ is the reflection coefficient 'seen' from the end of the probing (fibre) waveguide at the wavenumber $\sigma$. Both waves are guided to the photodetector.
followed by the lock-in amplifier that extracts the signal at the modulation (difference) frequency \( f \). The total complex signal at the output of the lock-in amplifier can then be expressed in the form

\[
s(x) = \int_{-\infty}^{\infty} S(\sigma) R(\sigma) \exp(-2\pi i \sigma x) d\sigma
\]  

where \( S(\sigma) \approx |E(\sigma)|^2 \) is the spectral power density of the light source. The module of \( s(x) \) is typically measured as the reflectometric (OLCR) signature. (Let us note that this result is well-known and widely used in the reflection Fourier spectroscopy).

**Calculation of the reflection coefficient by BEM**

As it is usual in the BEM method [13, 14], we subdivide the DUT waveguide structure into a number of longitudinally uniform sections. In every section, the eigenmodes and the corresponding propagation constants \( \beta_m \) are to be calculated. Instead of the amplitudes \( a_m^z(z) = a_m^z(0) \exp(\pm i \beta_m z) \) of the forward and backward \( m \)-th mode that are used in the 'transfer matrix' approach, we use their sum and difference \( p_m = a_m^z + a_m^\dagger \) and \( q_m = a_m^z - a_m^\dagger \). The relation between \( p_m \) and \( q_m \) at both sides of the waveguide segment of the length \( L \) can be expressed in the matrix form as

\[
\begin{pmatrix}
q_L \\
q_R
\end{pmatrix}
= 
e^{i \beta L} 
\begin{pmatrix}
in(\beta L) & -\tan(\beta L) \\
\tan(\beta L) & in(\beta L)
\end{pmatrix}
\begin{pmatrix}
p_L \\
p_R
\end{pmatrix},
\]

where the subscripts \( L \) and \( R \) correspond to the left (input) and right (output) side of the segment, respectively, \( p \) and \( q \) are column vectors with components \( p_m \) and \( q_m \), respectively, and \( \tan(\beta L) \) and \( \sin(\beta L) \) are diagonal submatrices with diagonal elements \( \tan(\beta_m L) \) and \( \sin(\beta_m L) \), respectively. The matching of \( p \) and \( q \) with \( p' \) and \( q' \) of the neighbouring segments is given by the transformations

\[
p_m' = \sum_n C_m^n p_n, \quad q_m' = (\sqrt{\beta_m}) \sum_n \beta_n C_m^n q_n,
\]

where \( C_{m'n'} \) is the matrix of the mode overlap integrals, and the primed symbols correspond to the neighbouring waveguide segment. We now introduce the "immitance" matrix \( u \) by the relation \( q = u \cdot p \). (For TE and TM modes of 2-D waveguides, \( u \) is the "admittance" and "impedance" matrix, respectively. The term "immitance" is thus more general.) Following [15], the relation between the values \( u_L \) at the left side and \( u_R \) at the right side of a waveguide segment may be derived from (2):

\[
u_L = i[\tan(\beta L)]^{-1} + [\sin(\beta L)]^{-1} [u_R + i[\tan(\beta L)]^{-1} [\sin(\beta L)]^{-1},
\]

and for its transformation into the neighbouring waveguide segment we find similarly from (3)

\[
u_m' = (\sqrt{\beta_m}) \sum_n C_{m'n'} C_{n'n} \beta_n u_n.
\]

The procedure of calculating reflection coefficient \( R \) of (1) is formally identical to that of a piecewise uniform transmission line: in the last (infinitely long) waveguide section, there is no backward wave there, and thus \( a_{m\infty} = 0 \). Then \( p_m = q_m \), and correspondingly, \( u_m = I \), where \( I \) is the unit matrix. Knowing \( u_m \), we use repeatedly (5) and (4) to calculate the immitance matrix at the end of the (uniform) exciting waveguide, \( u_0 \). Since \( a^z = (p \pm q) / 2 \), the matrix of reflection coefficients \( R_{mn} = a_m^- / a_n^z \) can then be expressed as

\[
R = (I + u_0)^{-1}(I - u_0); 
\]
its component $R_{00}$ is the required reflection coefficient of the fundamental mode of the exciting waveguide.

Examples of the calculated OLCR signatures

As a first example, let us consider a segment of a single-mode SiO$_2$ waveguide 8 mm long "probed" by a SiO$_2$ fibre at the distance of 50 μm from the DUT, as it is shown in Fig. 2. To keep the calculations as simple as possible, we choose both waveguide structures identical, and take into account only the fundamental modes. The summation in (5) thus reduces to a single term. We also take $C_{00} = 1$. (In fact, it corresponds to plane waves in a longitudinally piecewise uniform medium with refractive indices equal to the effective indices of the modes).

We further choose the LED source operating at $\lambda = 1.3$ μm where the chromatic dispersion of the waveguides is very small, and take the Gaussian form of the curve of spectral density with the 1/e width $\Delta \sigma = 0.03$ μm$^{-1}$ (i.e., $\Delta \lambda \approx 50$ nm). For the calculation of (1) by the FFT algorithm, the number of discretization points is to be chosen with regard to the variations of $R(\sigma)$. Fast Fabry-Perot resonances corresponding to the length of the waveguide can be shown to have the period $1/(2N_g L)$ in the wavenumber scale, where $N_g$ is the group index of the mode. We have to choose the wavenumber discretization step size $\Delta \sigma$ as a fraction of this value. It follows from the fundamental properties of FFT that the number of samples is $N = 1/(\Delta \sigma \Delta x)$, where $\Delta x$ is the step size in the spatial domain. $\Delta x$ has to be chosen as a fraction of the coherence length $L_c = 4/\Delta \sigma \sigma$ of the source. Simultaneously, both the spatial and spectral windows $D = N \Delta x$ and $D_\sigma = N \Delta \sigma$, respectively, have to be large enough to cover all the important features of $R(\sigma)$, $S(\sigma)$ and $s(x)$. In Figure 3 we show the calculated OLCR signature for $\Delta \sigma = 1/(16N_g L) = 2.7 \times 10^{-6}$ μm and several values of $N$. It is seen that the "dynamic range" increases with increasing $N$. Very large "dynamic range" corresponding to the rounding errors of the computer (about 280 dB for an 8-byte real number) can be reached. Lower "dynamic range" for smaller $N$ is a consequence of smaller spectral window together with the known aliasing effect of the FFT. Sharp reflection peaks correspond to multiple reflections from the waveguide ends. There is negligible broadening of the peaks because of nearly zero dispersion of the waveguide at $\lambda = 1.3$ μm.

The fine structure of the first reflection maximum is plotted in Figure 4 with larger spatial resolution, but calculated with twice larger $\Delta \sigma$ and half $N$. The peaks correspond to multiple reflections between the exciting waveguide and the DUT. Note that reduced "dynamic range" for lower number of discretization points does not influence the height and the shape of the reflection peaks, as long as they are above the background.
To demonstrate the effect of waveguide dispersion, we calculated in a similar way also the OLCR signature for a 2 mm long section of an InGaAsP waveguide abruptly ending inside an infinitely long InP substrate, as it is shown in Figure 5. The effective index difference between the waveguide mode and the substrate is $8.3 \times 10^{-3}$. For simplicity, only the material dispersion was taken into account since it is much larger than the waveguide dispersion. The result of calculation is shown in Figure 6. The dispersion broadening of the reflection peaks as well as their deformation by higher-order dispersion terms is clearly visible. The small broad peak at the position of about 5 mm is a numerical artefact of aliasing. It may be suppressed by increasing the number of sampling points while keeping $\Delta \sigma$ constant (see the short-dotted curve in Fig. 6). The fine structure corresponding to multiple reflections between the probe and the waveguide is also present in the first reflection peak but it is smeared out by dispersion broadening in the next peaks.

Conclusions

To conclude, we have shown the feasibility of modelling OLCR signatures of optical waveguide devices with high accuracy by the Fourier transform of the reflection coefficient of the mode of the exciting probing waveguide. We have also presented the formulation of the bi-directional mode expansion method in the form suitable for the straightforward calculation of this modal reflection coefficient. The computer code for modelling OLCR signatures of complex (2-D) waveguide devices using this method is under development. It is intended for use as a reference for the measurement of reflections, group effective indices, and waveguide dispersion by the OLCR method.

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NONDESTRUCTIVE METHOD FOR TESTING THE SHIFT BETWEEN THE GRATINGS IN THE WAVEGUIDE WITH TWO CORRUGATED BOUNDARIES

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Abstract
A method for nondestructive control of the shift between the gratings in the waveguide with two corrugated boundaries is proposed. The parameters of the waveguide are found by minimizing discrepancy between the experimental data for diffraction efficiency at different angles of incidence and theoretical approximation using multidimensional optimization procedure.

Introduction
The problem of efficient excitation of the planar waveguide by means of diffraction grating is rather old but it is still actual. Various approaches proposed for its solving have not yet been implemented in practice. Recently there was proposed a new one that due to its simplicity could result in success [1]. The main idea is to use two corrugated boundaries in the waveguide with equal periods but different phases and amplitudes. It is possible to achieve destructive interference of diffracted waves in the chosen medium. In applications it is necessary to ensure efficient excitation of the waveguide from air which corresponds to destructive interference in the substrate in the case of outcoupling. Earlier we obtained the following conditions for thin-film waveguide with two sinusoidal corrugations (Fig. 1) that lead to 100% outcoupling into the air [2]:

$$ TE: \frac{\sigma_2}{\sigma_1} = \left(\frac{n_1^2 - n_0^2}{n_2^2 - n_0^2}\right)^{1/2} \frac{G_i^{-1}}{\left[\left(G_i^{-1}\right)^2 \cos^2 \Delta + \left(G_i^{-1}\right)^2 \sin^2 \Delta\right]^{1/2}}, \ \varphi = -m\pi + \psi, \ \psi = \arctan\left(\frac{G_i^{-1}}{G_i^{-1} \tan \Delta}\right) $$

$$ TM: \frac{\sigma_2}{\sigma_1} = \left(\frac{n_1^2 - n_0^2}{n_2^2 - n_0^2}\right)^{1/2} \left[\frac{n^2 (n_1^2 + n_0^2) - n_1^2 n_2^2}{\sin^2 (\Delta + \xi) + \frac{n_i G_i^{-1}}{n_i G_i^{-1} \cos (\Delta + \xi)}}\right]^{1/2}, \ \varphi = -m\pi - \psi - \varphi = -m\pi - \psi - \arctan\left(\frac{n_i G_i^{-1}}{n_i G_i^{-1} \tan (\Delta + \xi)}\right), \ \tan \xi = \frac{n_i (n_i - N)}{G_i^{-1} |G_i|^2} $$

where $m = 0,1..$ is mode order, $N = \lambda / \Lambda$, $G_i^j = \left(n_j^2 - (n_j^* + qN)^2\right)^{1/2}, \ \Lambda_\varphi = k G_i^j h$.

To make a waveguide with two corrugated boundaries first a corrugation is created on the surface of the substrate, then a waveguide film is deposited. The waveguide-air surface also become corrugated with groove depth close to that of lower grating. However the phaseshift between the gratings can vary and depends on the conditions of waveguide film deposition. For example in [3] an angled molecular beam was used to deposit a film and to get phaseshifted gratings. Another method was used in [4]. The phaseshift was produced by etching with oblique ion beam. In both cases the
control of the grating parameters is vital for implementation of working device. In this paper we propose a method for nondestructive determination of the parameters of the film with two corrugated boundaries.

Theory

Let us consider the setup shown in Fig. 2. The thin film with high refractive index is deposited on the surface of ion-exchange waveguide. Both boundaries of the film are corrugated. Efficiency of the diffraction into the reflected ($\eta_R$) and transmitted ($\eta_T$) orders depends primarily on following parameters: incidence angle $\theta$, refractive indices $n_0$, $n_1$, $n_2$, layer thickness $h$, grating depths $\sigma_1$, $\sigma_2$ and phaseshift $\phi$. It is necessary to determine some of these parameters using experimental data for $\eta_R$ and $\eta_T$ at different incidence angles $\theta_1$. We propose the following procedure: the parameters that should be found will minimize the functional

$$S = \sum_{k=q}^{\infty} \left[ \left( \frac{\ln \eta_R^{(k)}(\theta_1)}{\eta_R^{(k)}(\theta_1)} \right)^2 + \left( \frac{\ln \eta_T^{(k)}(\theta_1)}{\eta_T^{(k)}(\theta_1)} \right)^2 \right]$$

where $\eta_R^{(k)}$ and $\eta_T^{(k)}$ are calculated diffraction efficiencies for given parameters. Since errors in the measurements of diffraction efficiencies are relative all terms in the sum will have equal weights in the functional. To minimize functional $S$ we used Davidon-Fletcher-Powell multidimensional optimization method [5].

To determine diffraction efficiency we use quasioptical approach [6]. We neglect the reflection of light on the lower waveguide boundary because in our case $\Delta n$ was very small (0.005). In our experiment $\eta_R$ and $\eta_T$ are significantly less than 1 so we can assume that incident wave amplitude is affected only by reflection on the surfaces and find the amplitudes of the 0th order waves that propagate between the gratings as

$$w^- = t^a_1 R^a_1 a_1, \quad w^+ = w^- r^a_2 \exp(2i\Delta_0)$$

where

$$r^g = \frac{G^g - G^q}{G^g + G^q}, \quad t^g = \frac{2G^q}{G^g + G^q}, \quad G^q = \left( r^q - (n_1 \sin \theta + q \lambda) \right)^{1/2} \quad \text{and} \quad R^q = \left( 1 - r^q r^q \exp(2i\Delta_0) \right)^{-1}.$$}

Then we calculate the amplitudes of the waves diffracted on each grating and after accounting for reflection receive the following formulas for diffracted wave’s amplitudes that go into the substrate

$$a^q_2 = \left[S^q (r^q a_0 + t^q w^-) r^q_2 \exp(\Delta_q) + S^q w^- \exp(i\Delta_q) r^q_1 \left( 1 + r^q_2 \exp(2i\Delta_q) \right) \right] R^q$$

and into the cover

$$a^q_3 = \left[S^q (r^q a_0 + t^q w^-) r^q_3 (1 + r^q_3 \exp(2i\Delta_q)) + S^q w^- \exp(i\Delta_q) r^q_1 \exp(2i\Delta_q) \right] R^q$$

where $S^q = q \frac{k \sigma_1}{2} \exp(\imath q \varphi)(G^q - G^q_0)$, $S^q_0 = q \frac{k \sigma_1}{2} (G^q_0 - G^q_0_0)$

Diffraction efficiency can be found as

$$\eta_R^{(q)} = \frac{G^q_0 |a_1^q|^2}{G^q_0 |a_0|^2} \quad \text{and} \quad \eta_T^{(q)} = \frac{G^q_0 |a_0^q|^2}{G^q_0 |a_0|^2}.$$}

Experiment

The sample that we investigate in this paper was prepared as follows:
1. grating with period $\Lambda = 0.4444$ mm was formed on the surface of the glass substrate by ion etching;
2. K+ single-mode waveguide was produced by ion-exchange;
3. Ta2O5 film was sputtered on the waveguide surface;
4. The film was etched by oblique ion beam to produce a phase shift between two boundaries. The efficiency of outcoupling from the waveguide into the air for this sample was about 80%.

The experimental setup is shown in Fig. 2. A triangular prism was placed with immersion on the lower surface of the substrate. This allows to extend the angular range in which the diffracted waves can be measured. Diffraction efficiency for waves that go to the cover $\eta_s^1$ can be directly calculated as ratio $P_n^1 / P_0$. To calculate the diffraction efficiency for waves that go to the substrate $\eta_s^2 = P_n^2 / P_0$ one should take into account reflections on the prism surfaces because we cannot measure light intensity in the substrate and must correct experimental values of measured intensities $P_n^2$ using known refractive indices and angles.

Results

Fig. 3 shows the experimental data and the theoretical curves. Error in the experimental measurement of the diffraction efficiency was about 3%. Theoretical fit was obtained by adjusting $\phi$, $\sigma_1$, $\sigma_2$ and $h$, while $n_0$, $n_1$ and $n_2$ were fixed. One should note that optimization over five parameters while fixing only $n_0$ and $n_2$ leads to ambiguity. It seems that exists a relation between $h$ and $n_1$ leading to almost constant values of the functional. Hence to get the parameters of the structure unambiguously it is necessary to determine either film thickness or its refractive index independently.

![Graph](image-url)
It is well known that in the symmetrical thin-film waveguide there are at least two modes: TE₀ and one TM₀. If we immerse the upper boundary of the waveguide with liquid having refractive index equal to that of substrate we can measure the effective refractive indices of these two modes that propagate in the film and calculate the thickness of the film and its refractive index. For our sample we have got \( n_{TE}^* = 1.5705, n_{TM}^* = 1.5357 \) which leads to \( n_1 = 2.1 \) and \( h = 0.04 \) mkm. In the Table the we summarize the results for different sets of optimized parameters. These results are in good agreement with data obtained from technological process.

| Parameters of the film calculated with different methods |
|---------------------------------|----|----|----|----|---|
|                                | \( n_1 \) | \( h \) (mkm) | \( \phi_1 \) (mkm) | \( \phi_2 \) (mkm) | \( \phi \) (radians) |
| from \( n_{TE}^*, n_{TM}^* \)   | 2.1 | 0.04 | — | — | — |
| optimized with \( n_1 = 2.1 \)  | — | 0.0345 | 0.0208 | 0.0204 | 0.26 |
| optimized with \( h = 0.04 \)  | 2.02 | — | 0.0210 | 0.0205 | 0.31 |
| optimized with \( n_1 = 2.1 \) and \( h = 0.04 \) | — | — | 0.0197 | 0.0177 | 0.32 |

Conclusions

The proposed nondestructive method can be used for testing the shift between the gratings in the waveguide with two corrugated boundaries as well as other parameters like grating depth and thin-film thickness. We think it is useful for elaborating technological processes for production of phase-shifted gratings.

References

Passband Engineering of Acousto-Optic Tunable Filters

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Abstract

This paper offers solutions to two serious problems encountered when acousto-optic tunable filters are used as wavelength-selective switches in WDM networks -- interchannel crosstalk and wavelength misalignment crosstalk. Passband engineering greatly reduces this interchannel coupling, using deep sidelobe suppression and passband flattening, respectively. Device modeling and fabrication suggestions are presented.

Summary

The polarization-diversity acousto-optic tunable filter (AOTF) functions as a wavelength-routing switch in demonstration dense WDM networks [1]. Various means are being developed to reduce the interchannel crosstalk which is a result of the high sidelobes and sharply-peaked transmission passband characteristic of the simple uniform-interaction-strength AOTF. Techniques of passband engineering seek to replace the sinc-squared sidelobe structure of the AOTF with the more ideal rectangular passband - one which has strictly unity transmission over a wide central wavelength band and strictly zero transmission outside. Sidelobe suppression is achieved by tapering the onset and cutoff of the acousto-optic interaction strength, often by a variation on a SAW directional coupler [2],[3].

Here we present the design of a Gaussian-weighted zero-gap SAW coupler that can lower the sidelobe skirt to -33 dB. Passband flattening is achieved using a linear-tapered-onset and cutoff, zero-gap, multiple-cycle SAW directional coupler design which has a ratio of wavelength misalignment tolerance band to channel spacing of 76% for a crosstalk criterion of -20 dB.

Background

The acousto-optic switch is a polarization-independent variant of the integrated acousto-optic tunable-filter (AOTF) which distributes a set of closely-spaced WDM input channels to either of two output ports according to whether a given channel is resonant or not resonant with a set of superimposed, electronically synthesized acoustic gratings [4]. The detailed optical transmission function of the AOTF can be modeled using coupled-mode theory. The polarization evolves along the device according to coupled-mode equations [5]. In a region of uniform acoustic interaction strength, the polarization coupling matrix M acting on the input Jones vectors (TE, TM) over a length L is

\[
M = \frac{1}{\mu} \begin{pmatrix}
\mu \cos \theta L + j \sin \theta L & j \kappa \sin \theta L \\
-j \kappa \sin \theta L & \mu \cos \theta L - j \sin \theta L
\end{pmatrix}
\]

where \(\mu = \sqrt{\delta^2 + \kappa^2}\), \(\delta\) is the detuning from resonance, \(\delta = \alpha (\lambda - \lambda_0)\), and \(\kappa\) is the polarization coupling coefficient. \(\kappa\) is proportional to the square root of the acoustic drive power. The output electric field of the AOTF is obtained by premultiplying the input Jones vector by the matrix M.

Using this formalism, the uniform AOTF cross-state optical transmission intensity is a sinc-squared function of wavelength,
which exhibits 100% conversion ($I_c = 1$) on resonance ($\delta = 0$) when $\kappa = \pi/2$. The corresponding bar state optical transmission function is given by $I_b = I - I_c$. These transmission spectra are shown for an AOTF of length 20 mm resonant at a wavelength of 1550 nm.

I Passband Engineering

In a typical WDM system, there would be considerable wavelength reuse. Fig 2 analyzes the performance of an acousto-optic switch when wavelengths $\lambda_1$, $\lambda_2$, and $\lambda_3$ appear on input port A and $\lambda_2'$ (which is really just $\lambda_2$ carrying a different signal) appears on port B. In both cases (a) and (b), the performance of the classical AOTF is compared to the performance of an ideal filter.

Fig 2(a) shows the problem of interchannel crosstalk. The ideal transmission allows all of wavelengths $\lambda_2$ and $\lambda_2'$ to crossover and retains all of $\lambda_1$ and $\lambda_3$ on the bar-state. In the case of the classical AOTF, the resonant wavelengths $\lambda_2$ and $\lambda_2'$ cross-over completely, but parts of $\lambda_1$ and $\lambda_3$ also cross over to output port B. This unwanted signal on output port B causes crosstalk between the resonant and off-resonant channels resulting in signal degradation on output port B and loss of some signal power on output port A. Interchannel spacing in WDM networks is determined by the height of the first sidelobe of the cross-state transmission function. In classical AOTFs, the first sidelobe is at a level of -9 dB. Current apodized device designs reduce the first sidelobe to -18 dB at best [2],[3]. In the following section we present a Gaussian-weighted SAW coupler design that can lower the sidelobe to -33 dB.

Fig 2(b) shows the problem of crosstalk due to wavelength misalignment. Consider the case where $\lambda_2'$ is slightly misaligned from its nominal location. In the case of an ideal switch, the exact location of a wavelength within the filter passband is irrelevant. It is seen that with the classical AOTF, such wavelength misalignment causes crosstalk on the resonant wavelength channel, i.e., some portion of the signal on the misaligned wavelength remains on the bar-state. This problem can be solved by flattening the passband of the AOTF around its resonant wavelength.

Generalized model

Using the model presented in section 1.1 and generalizing it to allow a $\kappa$ which varies along the length of the device, the optical transmission function can be tailored as required by picking suitable $\kappa$ functions. In this case, complete polarization conversion is achieved for

$$I_c(\lambda) = \left(\frac{\kappa \sin(\mu)}{\mu}\right)^2$$

The transformation matrix, $M$ (eq 1), can be used on small subsections of the device over which the $\kappa$ can be assumed to be constant and the output electric field of one sub-section can be used as the input to the next. The resultant optical transmission function is the square of the electric field at the output of the final sub-section. This model for the AOTF is the basis of a program we have developed that simulates the operation of passband-engineered AOTFs and evaluates their performance.

The apodised AOTF which has been investigated by several groups [3,6,7] uses a sinusoidally varying $\kappa$ function to reduce the high sidelobes of the classical AOTF transmission function. The sinusoidal variation is achieved by introducing a second acoustic waveguide weakly coupled to the first, analogous to an optical directional coupler, and allowing the acoustic modes to oscillate between the two acoustic waveguides. The active optical waveguide is placed in the second acoustic waveguide and sees a sinusoidally-varying $\kappa$ along the length of the filter. SAW coupler apodization represents the basis of the design of passband-engineered AOTFs. The value of the $\kappa$ function at a given
point along the length of the filter is dependent on the barrier width or gap between the two acoustic waveguides [3]. The mathematics of deriving the $\kappa$ function from the gap is the same as the derivation of the optical transmission function from $\kappa$. Our program includes this model to determine $\kappa$.

II Deep Sidelobe Suppression

In order to further reduce sidelobes, we have designed a 22 mm long AOTF with an aggressive taper at either end of the device that results in a Gaussian acousto-optic interaction function. The filter geometry and its optical transmission functions are shown in Fig. 3. It is seen from simulation that the sidelobes are suppressed to -30 dB. The cross-state transmission of the uniform and sinusoidally-weighted AOTFs are superimposed for comparison.

![Fig. 3. Deep sidelobe suppressed AOTF (a) geometry (b) optical transmission functions.](image)

III Passband Flattening

The prominent sidelobes of the AOTF passband can be effectively suppressed by techniques which tailor the acousto-optic interaction strength. However, the optical transmission function is not flat around the resonant wavelength, so the problem of signal degradation due to wavelength misalignment still exists. In this section, we describe two passband flattened AOTF designs that are viable from fabrication considerations.

It has been shown [8] that to obtain a maximally-flat passband, the $\kappa$ function is both oscillating and exponentially decaying, with a tapered onset of acousto-optic interaction and non-uniform spacing between zero-crossings. The acoustic interaction is cut-off at its third null. An exponential decay of 5.5 dB/cm is achieved by placing an attenuating overlay throughout the device.

A device incorporating the gap function suggested above is difficult to fabricate since it requires a device length of approximately 80 mm in order to complete three half-cycles of the acoustic interaction. Typical lithium niobate substrates limit device lengths to 65 mm or less. Our simulations have shown that it is possible to obtain better performance with much shorter devices using a zero-gap SAW coupler design and simple linear tapers.

![Erfc - tapered, zero-gap AOTF](image)

![Fig. 4. Erfc - tapered zero gap AOTF (a) geometry (b) optical transmission functions.](image)
By reducing the asymptotic SAW coupler gap of [8] to zero, we have arrived at a design that is only 55 mm long. This filter has a superimposed attenuation of 6 dB/cm. The filter geometry and passband are shown in Fig. 4.

**Dual-linear-tapered AOTF**

It is possible to simplify the erfc-tapered design and actually improve filter performance slightly. There is an extra advantage -- it has been shown [9] that driving alternate wavelength channels from opposite ends of the AOTF in an apodised filter results in a further reduction in crosstalk. The same can be done with this symmetric linear-tapered device. Shown below in Fig 5 are simulation results obtained for this filter which is only 49 mm long and has a barrier width that tapers linearly from 60 μm to 0 μm over 6.8 mm at both ends of the filter. The superimposed attenuation is 6 dB/cm. It turns out that the initial taper is critical. Exponential decay alone caused significant passband flattening, but the sidelobes remain very high.

(a)

![Transducer, acoustic barrier, attenuating overlay, optical waveguide, acoustic interaction profile](image)

(b)

![Cross state, bar state](image)

**IV Experiments**

All of the above-described devices are currently being fabricated on x-cut, y-propagating lithium niobate. The acoustic waveguides are formed by creating titanium-diffused barriers using ~1800 Å of Ti, diffused for a total of 30 hours at 1050° C. Optical waveguides are formed in a second titanium diffusion step, using 950 Å of Ti and a 10-hour diffusion at the same temperature. The inter-digital transducers that generate the surface acoustic wave are formed by Ti-Au evaporation. For the passband flattened filters, an additional fabrication step is required to place the attenuating overlay. The overlay is placed symmetrically along the length of the device taking care to avoid the optical waveguides. Two kinds of attenuating overlays are being investigated. The first is to apply an acoustic absorber throughout the length of the device. The second is to employ ohmic losses using either nichrome or indium tin oxide to attenuate the piezoelectric traveling wave.

**Discussion**

The designs described above have been analyzed for robustness with respect to variations in filter length. Overdesign of the filter length is necessary since the device performance improves with lengthening, but degrades drastically if fewer than three cycles are present.

Other designs for passband flattening were simulated. Radiative devices, which use leaky acoustic barriers to achieve exponential decay of the acousto-optic interaction, are being investigated because they eliminate the need for attenuating overlays.

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COUPLED LONGITUDINAL MODE MODEL FOR MODE LOCKED Er:LiNbO$_3$ WAVEGUIDE LASERS

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Abstract

Theoretical modelling of mode locked Er:Ti:LiNbO$_3$ waveguide lasers has been developed. The formulation is based on coupled longitudinal mode equations and takes into account the Er dopant and the waveguide field profiles, the longitudinal and transversal gain saturation and the distributed interaction with the integrated phase modulator.

I. Introduction

Recent advances in the LiNbO$_3$ waveguide fabrication and the improvement in the diffusion technique of dopant Er ions allowed to obtain new integrated devices based on optical amplification [1]. A great deal of interest has been devoted to the realization of optically pumped Er doped LiNbO$_3$ lasers [2] thanks to the emission properties at wavelengths used in fibre communication and the possibility of pumping with semiconductor lasers around 1.48 $\mu$m. Moreover the excellent electrooptic properties of LiNbO$_3$ crystals can be used to obtain multifunction integrated optical devices. Particularly interesting is the realization of laser sources with intracavity integrated modulators. The development of high bit rate fibre communication suggests that future improvement will depend on the possibility of obtaining reliable laser sources working in pulsed regime with high repetition rate. Ultrashort pulses at high repetition frequency can be obtained in active mode locked lasers using the phase modulator driving frequency equal to the first or higher harmonics of axial cavity FSR (Free Spectral Range). Recently the first examples of Er:Ti:LiNbO$_3$ mode locked lasers based on monolithically integrated phase modulator have been proposed [3],[4]. The aim of this work is to develop a theoretical model to simulate laser behaviour taking into account the main features of the laser cavity.

II. Basic Theory

The theoretical modelling of mode locked laser behaviour must be based on semiclassical theory in order to accurately describe the interaction of the electromagnetic field with the active medium reservoir, responsible of the signal gain along the cavity, and the electrooptical modulator, responsible of the coupling between the active axial modes [5]. The signal in the laser cavity, represented using the unperturbed cavity modes, becomes:

$$E(r,t) = C e^{i\omega_0 t} \sum_{m=-N_m}^{N_m} a_m(t) U_m(z) e^{i(m\Delta\omega t + \phi_m(t))} \sqrt{\psi(z)} + c.c.$$  (1)

where $U_m(z) = \sin((m+m_0)\pi z/L)$, $2N_m + 1$ is the number of considered longitudinal modes, $\Delta\omega$ their frequency spacing, $a_m(t)$ and $\phi_m(t)$ respectively the slowly varying amplitude and phase of the $m$-th cavity mode. $C$ is a normalization factor, $z_i$ indicates a generic point on the transversal waveguide section, $\omega_0$ the pulsation corresponding to the central emission wavelength, $m_0$ the corresponding longitudinal mode integer number and $L$ the cavity length.
The pump power time evolution $P_p(t)$ can be described using the balance equation:

$$\frac{dP_p(t)}{dt} = -v_p \left( \alpha_p^{\text{tot}} + \sigma_p^a(\lambda_p) \int_{R^1} N_0(\tau_e) \psi_p(\tau_e) d\tau_e \right) P_p(t) +$$

$$+ v_p \left( \sigma_p^a(\lambda_p) + \sigma_p^e(\lambda_p) \right) \int_{R^2} N_2(\tau_e, t) \psi_p(\tau_e) d\tau_e \frac{2v_p P_{\text{cou}}}{L(1 + R_1(\lambda_p))}$$

(2)

$\psi_p(\tau_e)$ and $\psi(\tau_e)$ are the normalized pump and signal power transversal profiles, $N_0(\tau_e)$ is the dopant distribution, $\alpha_p, \sigma_p$ are the absorption and emission saturation intensities at pump wavelength, $I_p^a = I_p^e I_p^a/(I_p^e + I_p^a)$, $\sigma_p^a(\lambda_p)$ are the absorption and emission cross sections at pump wavelength, $P_{\text{cou}}(t)$ the coupled pump power waveform, $R_1(\lambda_p)$ and $R_2(\lambda_p)$ the left and right mirror reflectivities for pump power, $\alpha_p^{\text{tot}}$ the total losses taking into account scattering losses and non ideal mirror reflectivities and $N_2(\tau_e, t)$ the population of the upper metastable laser level. Er ions have been approximated throughout the model of a quasi-two level system with homogeneous broadening of spectral line around central emission wavelength. The differential equation for the population $N_2(\tau_e, t)$ is:

$$\frac{dN_2(\tau_e, t)}{dt} = - \frac{N_2(\tau_e, t)}{\tau} \left[ 1 + \left( \Xi_a(t) + \Xi_e(t) \right) \right] \psi(\tau_e) +$$

$$+ \frac{N_0(\tau_e)}{\tau} \left( \frac{P_p(t) \psi_p(\tau_e)}{I_p^a} + \Xi_a(t) \psi_p(\tau_e) \right)$$

(3)

where

$$\Xi_{a,e}(t) = \frac{\sum_{m=-N_m}^{N_m} a_m(t) e^{i(m\Delta \omega t + \phi_m(t))}}{\sqrt{N_m}}$$

(4)

and $\tau$ is the Er ions lifetime. The signal saturation term reported in (4) introduces the square value of the coherent sum of each longitudinal mode associated phasor because of fixed phase relation between all of them. Let us now consider the evolution equation for the $m$-th signal mode amplitude $a_m(t)$:

$$\frac{da_m}{dt} = \frac{\omega_m n_\mu^2 r_\mu V_{RF} \Gamma}{LG} \left[ a_{m+1} B_{m+1,m} \sin(\phi_{m+1} - \phi_m) + a_{m+1} C_{m+1,m} \cos(\phi_{m+1} - \phi_m) +
$$

$$+ a_{m-1} B_{m-1,m} \sin(\phi_{m-1} - \phi_m) - a_{m-1} C_{m-1,m} \cos(\phi_{m-1} - \phi_m) \right] - \frac{v_m}{2} \left( \alpha_m^{\text{tot}} - g_m \right) a_m$$

(5)

and phase $\phi_m(t)$:

$$\frac{d\phi_m}{dt} = - \frac{\omega_m n_\mu^2 r_\mu V_{RF} \Gamma}{a_m LG} \left[ a_{m+1} B_{m+1,m} \cos(\phi_{m+1} - \phi_m) - a_{m+1} C_{m+1,m} \sin(\phi_{m+1} - \phi_m) +
$$

$$+ a_{m-1} B_{m-1,m} \cos(\phi_{m-1} - \phi_m) + a_{m-1} C_{m-1,m} \sin(\phi_{m-1} - \phi_m) \right]$$

(6)

g_m is the gain of the $m$-th mode, $n_\mu$ the LiNbO₃ refractive index for the considered polarization and optical axis orientation, $\Gamma$ is the overlap integral between optical and RF field profile in transversal section, $V_{RF}$ is the modulator driving voltage, $G$ the interelectrode distance, $r_\mu$ is the LiNbO₃ electrooptic coefficient depending on the chosen polarization, electrode position and crystal optical axis orientation and is responsible of the longitudinal mode coupling;
Figure 1: Laser emission output power vs. coupled pump power in CW regime (solid) and mode locked regime (dashed).

Figure 2: Output signal pulse for $P_{inc} = 57mW$ with $P_{RF} = 31.5dBm$ (solid line) and $P_{RF} = 26.5dBm$ (dashed line).

Figure 3: Spectral distribution among longitudinal modes for $P_{inc} = 57mW$ with $P_{RF} = 31.5dBm$ (solid line) and $P_{RF} = 26.5dBm$ (dashed line).

$B_{m\pm1,m}$ and $C_{m\pm1,m}$ are the mode coupling coefficients. Eqs (5) and (6) have been obtained under the condition of ideal matching between frequency mode spacing and modulation frequency (i.e. no detuning effects). The mode interaction has been approximated considering only the coupling between adjacent modes separated by the modulation frequency. Eqs (5), (6) must be solved self-consistently with Eqs (2) and (3) due to gain saturation, being $g_m$ function of $N_2$.

Since the expected mode locked pulse width $\tau_p$ is very short in comparison with Er ions lifetime $\tau$ ($\tau_p \approx 10^{-8} \times \tau$) the active medium behaves as a slow saturable absorber able to perceive mostly the mean signal value and not its instant value.

We can, consequently, write the analytic solution for $N_2$ at time $t$ starting from time $t_0$ assuming constant signal and pump power in the integration step:

$$N_2(t, t) = N_2(t, t_0) \exp\left(-\frac{t - t_0}{\tau_{eq}(t_0)}\right) + N_2,\infty(t, t_0) \left(1 - \exp\left(-\frac{t - t_0}{\tau_{eq}(t_0)}\right)\right) \tag{7}$$

\(\tau_{eq}(t_0)\) and \(N_2,\infty(t, t_0)\) are defined as in the following:

$$\tau_{eq}(t_0) = \frac{\tau}{1 + \frac{P_{p}(t_0)\psi_p(t_0)}{I_{sec}^{p}} + \sum_{m=-N_m}^{N_m} \frac{P_m(t_0)\psi(t)}{I_{sec}^{m}}} \tag{8}$$
111. Simulation results and discussion

The model described in the previous section has been implemented and applied to investigate the behaviour of an Er:Ti:LiNbO$_3$ laser with threshold pump power of 9.5mW lasing at 1.602μm. Simulation parameters relative to laser and modulator geometric structure have been taken from literature [4]. Up to now simulations have been performed with modulation frequency equal to the first harmonic of axial mode separation. For a cavity length of 5.4cm, Z-cut LiNbO$_3$ crystal and q-TM mode (π mode) the modulation frequency is 1.280GHz. The 201 longitudinal modes considered in the simulation are sufficient to cover a wavelength range of 4.75nm around central emission wavelength being the FSR equal to 0.0237nm.

In Fig. 1 we reported the average output laser characteristic in CW regime (solid line) and mode locked regime (dashed line). The incident pump power and output signal power have been calculated using a coupling efficiency of 82% for q-TM mode. The CW characteristic has been calculated using only one longitudinal mode; the output power in mode locked regime has been calculated considering the averaged signal obtained by summation of the power associated to each longitudinal mode. We have investigated the spectral and temporal features of laser emission changing the driving modulation power $P_{RF}$; the simulations have been done with $P_{RF} = 31.5dBm$ and $P_{RF} = 25.6dBm$. The obtained results for the output stationary pulse and the spectral distribution among the longitudinal modes are reported in Fig.s 2 and 3 respectively. Lowering the driving modulator power the strength of the coupling effect due to electrophoretic interaction diminishes so that the spectral width shortens and the time pulse width broadens.

IV. Conclusions

We developed a new theoretical model for mode locked Er:LiNbO$_3$ waveguide lasers based on the semiclassical laser theory taking into account the main features of the laser cavity such as dopant and field profiles, the gain saturation and the effect of a distributed phase modulator. The longitudinal modes of the cavity are coupled together through the action of the phase modulator and the gain saturation effect. Promising results in good agreement with experimental ones [4] have been obtained using 1st order harmonic modulation.

V. Acknowledgments

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POROUS SILICON FABRICATION FOR MICROCHIP INTEGRATION

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Abstract:
In this paper a modified wet-etching technique for porous silicon fabrication is discussed. This technique enables the integration of optical light emitters and VLSI circuits on one chip due to a short HF-etch step. The etching process and first results in system integration are shown.

1 Introduction

Since Canham /1/ has found the electrical stimulated emission of light in HF-treated silicon wafers, a great number of investigations has started to get a new light source for optoelectronics and OEICs. The accurate emission mechanism is still not clear up to now, but it is estimated that quantum size effects at the silicon surface are responsible for visible luminescence /2/. Nevertheless, photo- and electroluminescence have been achieved: several room temperature light emitting devices with a radiation in the energy range of 1.8 eV to 2.1 eV /3/,/4/ have been fabricated. Generally, the main etching processes for these devices can be described as a long anodic etching with low current densities. Whereas microelectronics, micromechanics and waveguides have been successfully integrated on one silicon chip /6/,/7/, there is no satisfying light source for the monolithical integration on silicon available. The introduced porous silicon LED may provide the demands for system integration.

2 Device preparation

The method of preparing porous silicon mentioned above is not suitable for system integration. Experiments with this technique showed, that adjacent - photoresist covered - microelectronic structures are destroyed because of the dissolving resist during etching time. So the way of porous silicon preparation has to be changed:

As the bulk material single-crystal p-type Si wafers with a resistivity of 20Ωcm have been used. For better current injection of the devices a pn-junction with a phosphorus implanted n-well is formed. To get a homogenous and deep well, the wafers are annealed for 150 minutes at 1170°C. Technology simulations with DIOS /5/ have shown, that this will lead to a pn-junction of 3.5 μm depth with a donor concentration of 10^{17} cm^{-3} at the surface. For the fabrication of VLSI technology compatible light emitting devices several HF-based electrolytes have been tested and finally a mixture of hydrofluoric acid (48 wt%), ethanol and deionized
water in the proportion 1:1:5 has been used. The 4"-wafer is still structured by a AZ photoresist -baked at 160°C for 30 minutes - but now etched anodically for only 4 to 7 seconds with a high current density of 600 to 900 mA/cm². The etching is done at daylight with a following dip in water. The VLSI circuits are built in a 0.8μm polysilicon gate SWAMILOCOS-CMOS-process. The active emission area is set to 100 μm x 100 μm.

Using this way of processing, no resist dissolution occurs, the microelectronic circuits are not affected. The upper electrode of the light emitting porous silicon device is made by a semitransparent, sputtered Au or Al film, concluded by an annealing at 250°C for 2h in air (Fig.1).

3 Electrical and optical measurements

The electrical and optical analyses are carried out in a light shielded box, applying a computer controlled monochromator and photomultiplier (S25). The light is chopped by a rotating sector and at least amplified by a lock-in amplifier. We made also measurements with a hamamatsu emission microscope, utilising a CCD camera in a non-photon counting mode. The electrical measurement and power supply is performed by a HP4145 semiconductor analyser.

Fig. 2 shows the well known spectral emission from a porous silicon device with an intensity maximum at 610 nm, e.g. 2.03 eV. The emission has a full width at half maximum FWHM=140 nm. The new etching technique also leads to the voltage-current characteristic as shown in Fig. 3. The threshold voltage for light emission is detected to be 6 V with a current of 3.5 mA. The observed wavelength was λ=665 nm. The samples showed no photoluminescence.

The etching time is a very critical parameter not only for save device preparation but for the light emission. For long etching times the growing porous layer acts as a limiting series resistance for current injection at the pn-junction. This behaviour has been studied in several etching steps and can be seen in Fig. 4. For increasing etching times a threshold shift of the high current injection to higher voltages can be measured. At t=30 seconds, where the I(U) tracking is linear, the device acts as a resistor. This
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is corresponding to the light emission for these devices. The threshold of optical emission is increasing and at least - for etching times greater than 20 seconds - the emission stops.

In the next step, the combined integration of these devices with optical waveguides and read-out circuits in a CMOS compatible process is planned. A general cross-section of such an microoptic chip is depicted in Fig. 5. In this figure, the porous silicon LED is connected to an optical waveguide with a high refractive index (n=2.02) to achieve a high vertical coupling efficiency. Device coupling may be performed by butt coupling or by an integrated mirror for light deflection caused by total reflection. The emitted light is guided over the chip and at least deflected into an integrated pin-diode by mirror-coupling /6/. First emission microscopy results indicate a small amount of light coupled into the waveguide. According to this first success the coupling efficiency has to be improved to get an increased photocurrent at the system output.

4 Conclusions

A special etching technique to produce porous silicon layers without damaging the neighbouring VLSI circuits has been developed. This can be achieved by short etching times at high current densities which results in a threshold voltage for optical emission below 10 V. Now the discussed LED has to be integrated with optical waveguides and photodiodes on the same chip to achieve a full optical microsystem on silicon. Applying the etching technique discussed in this paper, the porous silicon provides the silicon technology with a light source and keeps silicon in the position to get its way to be another optical material for OEICs.
5 References


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A MICRO-OPTO-MECHANICAL SWITCH IN INTEGRATED OPTICS ON SILICON

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Abstract

A Micro-Opto-Mechanical switch has been achieved using the combination of two technologies: "Integrated Optics" and "Micromachining on Silicon". The commutation is obtained by means of the mechanical deflection of a cantilever beam driven by an electrostatic force. The first devices show promising characteristics.

Introduction.

The "Integrated Optics on Silicon" technology, developed in several laboratories in the world, for instance at the LETI, enables complex optical circuits to be fabricated with good performances. The applications vary from telecommunications devices to optical sensors. Nevertheless silicon technology suffers from non activity, for instance in the electro optical domain. In order to make active devices, we thought of a very interesting way: the combination of integrated optics [1] and micromechanics [2] on silicon. From the combination of those technologies a new avenue is opening.

To explore this new field of "Opto-Mechanics" [3], we realized an attractive active component, which function is to commute an optical signal: the Micro-Opto-Mechanical Switch 1°2.

1 - Device description and modelisation.

The device structure is depicted on figure 1.
A cantilever beam bears the input waveguide. A voltage U1 or U2 applied between two adjacent electrodes creates an electrostatic force. This force makes the cantilever beam tip deflect from a distance d1 or d2. Consequently, the input waveguide faces the chosen output waveguide. In that way, the commutation function is achieved. The main advantage of this device is its insensitivity to wavelength and polarisation. Moreover electrostatic actuators, well known in the micro-electromechanical field[4], are characterised by small power consumption and high switching speed.

The waveguide structure used is made of a sandwich of 3 PECVD silica layers with different phosphorus doping levels (Figure 1). The wavelength used may be 1.3 or 1.55 microns. This configuration allows to connect the device to optical fibers with very low coupling losses (<0.5 dB).

Simulation shows that the two output waveguides have to be separated by at least 20 microns in order to get a good optical isolation. In that configuration the theoretical isolation is -25 dB. As a consequence, the deviation of the cantilever beam tip is 10 microns minimum.

The mechanical structure is mainly constituted of a cantilever beam made of silica like the optical circuit. The mechanical dimensions depend strongly on the optical and electrostatic simulations.

First, let's consider optics. The gap between the input and output waveguides near the beam tip is about 20 microns. This space causes a theoretical optical loss of 0.5 dB. Nevertheless it can be reduced, within etching quality limits. However the beam width has to be as small as possible in order to decrease the driving voltage. But the reduction of this dimension makes the metal electrode come very close to the waveguide. This situation may result in an important optical loss due to metal plasmons. In order to reduce these losses the width has to be limited to 30 microns which leads to an optical loss (at 1.55 micron) of less than 0.5 dB/cm for the studied materials (Al, Cr, Ti, Au). Beside this, it is obvious that optical losses of the whole component will be essentially due to lateral misalignments between waveguides near the free end of the cantilever.

As for electrostatic driving the desired deflection has to be obtained with the minimum voltage. With this end in view we have first to decrease the beam width, then to reduce the gap
between the electrostatic plates and finally to increase the beam length. But, the electrostatic gap is limited by two things. First, the beam has to be deflected at least 10 microns. Secondly, when the beam deflection exceeds about the third of the electrostatic gap an avalanche phenomenon occurs [5]. Then, the beam deflects spontaneously the rest of the way causing a short circuit between the two adjacent electrodes. Therefore, the minimum value of the electrostatic gap is 30 microns.

Taking all the previous remarks into account we come to the conclusion that the beam length has to be in the millimeter range to remain in a reasonable voltage domain. A cantilever beam 2 mm long, 30 microns wide with an electrostatic gap 30 microns wide, requires a driving voltage of 317 V. In the same conditions, a beam 5 mm long requires only 51 V. The length is essentially limited by the undesirable deformation of the structure.

2 - Device fabrication.

The device fabrication requires three steps. The first one is the waveguide fabrication. It is performed using LETI's usual technology.

The second is the mechanical structure etching. This step is divided in two parts: RIE anisotropic etching of the three silica layers (about 25 microns thick) and isotropic etching of silicon using an isotropic microwave etching. This step makes the mechanical structure to be free standing, liberated from the substrate.

The last step is the driving electrode fabrication using a lateral evaporation of metal to the beam sidewalls.

Fabrication of the first beams pointed out an undesirable deformation problem due to residual stress in the silica layers. This residual stress makes the beam end deflect vertically. Consequently, the waveguides are misaligned.

The problem can be solved with a dual solution: a thermal treatment suppresses most of the undesirable deflection and a compensating mechanical structure allows to suppress the eventual remaining deflection. The efficiency of this dual method has been demonstrated; it is briefly discussed in the experimental part.

Nevertheless, it can be insufficient for some particular devices. In that case, the control of the undesirable deflection can be achieved by an active system. The metallization of the beam surface results in an Aluminium-Silica thermally sensitive structure. The difference between the thermal expansion coefficient of the two materials will make the beam tip deflect if the device is submitted to a temperature variation. In controlling the temperature it is thus possible to control the beam alignment. Conversely with a good dimensioning of the device this observation allowed us to realize a temperature sensor.

Beside, we have shown that the undesirable bending of the structure couldn't be attributed to stresses at the fixed end of the beam or to a thermal stress between silicon and silica. In fact it results from an intrinsic stress gradient in silica.

3 - Experimental results.

The first micro-opto-mechanical switches have been fabricated using the different ways of controlling undesirable deflections described previously.

For beams 26 microns wide, 25 microns thick and 2 millimeters long the undesirable deflection was reduced to a tight range of +/- 5 microns around 0 owing to the heat treatment. This is very low compared to the initial deflection of 50 microns. The mechanical compensation device shows its efficiency reducing a mean deflection of 52,50 microns to a mean residual deflection of 2.80 microns. Combined, heat treatment and compensation mechanical device will allow a beam alignment with a precision better than one micron. Beside this, an active control of the vertical deflection is possible using the so-called bi-metal effect [6] existing with the Al/SiO2 sandwich structure. A specific deflection of 0,28 micron/°K at the free end has been measured in our devices.

As far as the electrostatic drive is concerned, for the beam structure described before and an electrostatic gap 34 microns large, the desired deflection (10 microns) is obtained with a driving voltage of 420 V.

Finally, the complete operation of the device was tested. Figure 3 depicts the device in its two commutation states. Figure 4 shows the working results obtained at 1,3 micron. The graph presents the fiber to fiber optical losses of the two channels during the commutation. The device exhibits optical loss of - 15 dB and isolation between the outputs of - 35 dB. The important optical losses measured on those devices are partly due to an accidental bad alignment of the beam.
Figure 5 shows the frequency working of the device. In particular the commutation between the neutral state (V=OV) and one of the output states (V=420V) is shown on figure 6. The switch response time is 0,6 ms.

Conclusion.

The feasibility of the principle of the micro-opto-mechanical switch combining the “integrated optics” and the “micromechanics” on silicon technologies, is demonstrated. It should be pointed out that this couldn’t be made without controlling undesirable deformation of the structure due to residual stress gradient in silica.

Performances obtained (driving voltage: 420 V, optical loss: -15 dB, optical isolation: -35 dB, response time: 0,6 ms) are very promising and further improvement can be expected, in particular on decreasing the driving voltage and the optical losses. The aim is to obtain a driving voltage of 12 or 24 V in a first step (later: 5V) and a fiber to fiber optical loss of a few dB.

Moreover the fabrication of the micro-opto-mechanical switch and the temperature sensor show that “Micro-Opto-Mechanics” is of a great interest in the field of optical active components and also for sensors with integrated optical read out.

Acknowledgement.

This work was partly supported by DRET under contract n° 92343.

References.

Figure 3: Imaging of the optical output of a micro-opto-mechanical switch (Wavelength: 1.3 micron).
3a: $U = U_1$. The light is commuted on Channel 1.
3b: $U = U_2$. The light is commuted on Channel 2.

Figure 4: Optical losses measured on the 2 channels of a micro-opto-mechanical switch during the commutation.
Wavelength: 1.3 micron.

Figure 6: Frequency working (100Hz) of the device.

Figure 7: Response time of the device.
OPTICAL AMPLIFICATION AND LASING AT 1054 nm IN WAVEGUIDES REALISED BY ION EXCHANGE IN A HIGH-Nd-DOPED PHOSPHATE GLASS

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Abstract

We have realized waveguides by ion exchange in a 3-wt % neodymium-doped phosphate glass. A 38 mm-long guide was placed into a resonant cavity. When pumped at 797 nm, laser oscillation occurred at 1054 nm. The threshold is 8.2 mW and the slope efficiency equals 12.7%. Using this laser as a source we characterized optical amplification in the waveguides. Thanks to the model we developed, we were able to deduce the upconversion coefficient.

Introduction:

High gains have been obtained in rare-earth doped fiber amplifiers. We transposed their principles to make active integrated optics components on rare-earth doped glasses. Ion-exchange allows for more compact devices presenting a larger number of functions. Phosphate glasses are good candidates for this technology because in such materials, rare-earth ions can be included up to several weight percents and have high cross-sections. We have realized waveguides in a 3-wt % neodymium-doped phosphate glass by a two-step silver ion-exchange in a molten bath. The components are buried by application of an electrical field during the second step [1] and present low propagation losses (< 0.1 dB/cm at 1.35 μm). The waveguides are single-mode at both pump and signal wavelengths and the 1/e near-field diameters are 4.7 x 4 μm at 780 nm.

Laser:

Laser experiment was performed using a 38 mm-long waveguide. Dielectric mirrors were butted at the two polished end faces of the glass chip and maintained by capillarity with a 1.46 index matching liquid. The reflectivity of the two mirrors is 71% at 1.054 μm and 5% at 800 nm. The pump light was focused from the laser diode into the waveguide core through a microscope objective. The coupling efficiency is estimated to 65%. Laser action was observed for an absorbed pump power of 8.2 mW at 797 nm. Just above this threshold, lasing occurs in our structure as a single line at 1053.8 nm. With increased
pump power a second line appears at 1056 nm (see figure 1). The measured FWHM of these lines is 1.1 nm and is limited by the resolution of the monochromator. The characteristics of the output power against the absorbed pump power are shown in figure 2. The slope efficiency is about 12.7%. These results are as good as those already published [2] and should be greatly enhanced by the optimisation of the waveguide length and the mirror reflectivities [3].

![Figure 1: Output spectrum of the waveguide laser](image1)

![Figure 2: Lasing characteristics of the neodymium-doped waveguide](image2)

**Amplification:**

Using this laser as a signal source we characterized the optical amplification at 1054 nm in 41.5 mm-long waveguides. The pump at 797 nm and the signal were injected into the core waveguide through a duplexor. The theoretical coupling losses between this fiber and the integrated waveguide are 0.6 dB. We have measured the gain as a function of the injected pump power (see figure 3).

![Figure 3: Dependance of the internal gain with absorbed pump power](image3)
The gain is the ratio of the pumped to unpumped signal at the waveguide output. The net gain can be obtained by deducing insertion losses which are equal to 0.9 dB. The maximum internal gain is 8.2 dB for a 52 mW-absorbed pump power. The non-linear shape of the curve is attributed to up-conversion phenomenon as attested by the white light fluorescence observed on the pump input side.

**Modeling:**

We have developed a model which takes into account the up-conversion due to the high doping concentration. The rate equation of the metastable level population of neodymium ions for pumping at 797 nm can be written as follows:

\[
\frac{dN_m}{dt} = R_{fp}.N_f - A_{mf}.N_m - W_{mf}.N_m - C.N_m^2
\]

where \(R_{fp}\), \(N_f\) is the absorption term of the ions in their fundamental level, \(A_{mf}\), \(N_m\) and \(W_{mf}\), \(N_m\) are respectively the spontaneous and stimulated emissions from the metastable level. The up-conversion term is quadratic because this phenomenon implies two ions in their metastable level. \(C\) is the up-conversion coefficient which is independent of the rare-earth concentration [4].

We have determined the spectroscopic parameters of the phosphate glass. They are summarized in table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waveguide length</td>
<td>41.5 mm</td>
</tr>
<tr>
<td>Pump wavelength</td>
<td>797 nm</td>
</tr>
<tr>
<td>1/e pump mode radius</td>
<td>2 μm</td>
</tr>
<tr>
<td>Absorption cross-section</td>
<td>(1.56 \times 10^{-24}) m(^2)</td>
</tr>
<tr>
<td>Signal wavelength</td>
<td>1054 nm</td>
</tr>
<tr>
<td>1/e signal mode radius</td>
<td>2.2 μm</td>
</tr>
<tr>
<td>Emission cross-section</td>
<td>(3.7 \times 10^{-24}) m(^2)</td>
</tr>
<tr>
<td>Neodymium concentration</td>
<td>(3.37 \times 10^{26}) m(^{-3})</td>
</tr>
<tr>
<td>Fluorescence lifetime</td>
<td>250 μs</td>
</tr>
<tr>
<td>Propagation losses</td>
<td>0 (internal gain)</td>
</tr>
<tr>
<td>Injected signal power</td>
<td>-24 dBm</td>
</tr>
</tbody>
</table>

**Table 1:** Parameter values used in the simulation

For \(C\) equals to \(4 \times 10^{-22} \text{ m}^3 \text{ s}^{-1}\), we obtain a good agreement between the experimental and theoretical curves (see figure 3). This value is relatively high and leads to a more difficult population inversion.

Without up-conversion (\(C=0\)) a gain as high as 25 dB could be reached.
Conclusion:

We succeed in the realization of ion-exchange waveguides in phosphate glasses. The lasing characteristics we have obtained with low reflective mirrors underline the good behavior of these waveguides. The optical amplification at 1054 nm is limited by up-conversion due to the high neodymium concentration. This phenomenon is well described by the model we have developed. If we also take into account the variation of the fluorescence lifetime versus the concentration, we could optimize the doping of rare-earth ions for a given pump power and get closer to the high gain values that the good spectroscopic parameters let hope.

References:

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Sub GHz Spectral Filtering and Transmission Modulation by Spectral Hole-Burning and Stark Effect

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Abstract

We have developed an integrated narrow-band (<1 GHz) programmable spectral filter, which consists of a planar waveguide covered with a thin polymer film containing molecules, which undergo persistent spectral hole-burning at liquid helium temperature. The filter transmission can be modulated by application of an electric field.

Introduction

High bit rate communication systems should be designed considering optical broadcast networks with dense frequency division multiplexing. To select efficiently different frequency channels in a multiplexed optical bus, narrow-band integrated optical filters with a selection bandwidth of less than 1 GHz are needed. Several attempts have been made to construct appropriate spectral filters [1-3] by means of distributed feedback resonators or tandem Mach-Zehnder interferometers. Unfortunately the construction of such filters is rather involved, and the performance of the filter deteriorates as the dimensions of the device become smaller.

Our approach to realize an integrated optical narrow-band spectral filter is to use the phenomena of spectral hole-burning (SHB) which is treated in detail in [4]. SHB is a process whereby normally smooth inhomogeneous absorption bands of chromophore molecules in solids are spectrally modiﬁed with very high frequency selectivity due to photochemical transitions of the molecules. At liquid helium temperatures, the spectral width of the holes is typically narrower than 0.1 - 1 GHz. Bulk SHB materials have been used as narrow-band filters [5,6] or as frequency multiplexed holographic storage media[7-12]. Because the frequency selectivity is an intrinsic property of the material, the transmission of the filter does not critically depend on the geometry of the device.

We fabricate an integrated optical filter by covering a commercial planar glass waveguide with a polymer doped with chromophore molecules which show spectral hole-burning. The transmission of the filter is programmed by illumination of the waveguide with a narrow-band laser which modifies the absorption of the SHB material.

In addition, due to linear Stark effect [7,9], the depth as well as the frequency characteristics of a spectral hole can be modiﬁed by applying an external electric field. Small electrodes are integrated on the waveguide by vapor deposition to use this effect to modulate the transmission of our filter device.
Experimental Details

The details of the construction of the waveguide filter are discussed earlier in [13,14]. As shown in the schematic of the waveguide structure in Fig. 1, two CrCuAu-electrodes have been vapor deposited on the waveguide before covering it with a polymer layer of a thickness of about 120 nm. This allows us to apply an external electric field in the y-direction.

The experimental procedure consists of three steps (see also Fig. 1). In the first step the absorption of the hole-burning layer is modified. We illuminate the waveguide structure in a transverse direction with the light of a cw diode laser (linewidth: 110 MHz) at 634.2 nm with an intensity of 33 \( \mu \text{W/cm}^2 \) for 11 minutes. In the second step we couple about 1 nW of the laser light to the TE0 mode of the waveguide and scan the frequency in a 10 GHz range around the former burning frequency. The transmitted light was collected by a cylindrical lens and detected by a photomultiplier. In a third step the light transmitted through the waveguide was measured for different applied external voltages to demonstrate modulation of the transmission intensity of the narrow-band filter device.

Results and Discussion

Fig. 2 shows the transmission of the waveguide device during a frequency scan of 10 GHz. A sharp transmission maximum is observed at the burning frequency, with a linewidth of 580 MHz and a contrast of 9.1 dB. The shape of the hole is approximately Lorentzian[15].

As we have shown [13,14], a waveguide filter constructed in this way can be freely programmed to have arbitrary transmission frequencies and ranges only limited by the homogeneous and
inhomogeneous absorption linewidth of the SHB material on the waveguide in the same way as in a bulk material. Further, it has been shown that by choosing the right concentration of the chromophores in the polymer a contrast up to 40 dB can be achieved.

In the final step the frequency of the beam coupled to the guided mode was fixed to the burning wavelength and the transmission was measured as a function of the applied voltage (Fig. 3). The transmitted intensity at 0V is taken to be unity. At the maximum applied voltage (±1kV) the transmission in the center of the hole decreases by a factor of 2.5. The maximum applied electric field is estimated to be in the order of 10 kVcm⁻¹.

![Fig. 3 Transmission of the waveguide in dependence of the applied electric field](image1)

The spectral hole was burned at 634 nm with the diode laser and the transmission was measured at the same wavelength for different applied voltages.

In addition, the spectral transmission at different applied voltages was measured and the results are shown in Fig. 4. As in the case of bulk materials [7,9] the transmission intensity decreases and the transmission linewidth increases for applied voltages unequal 0 V.

![Fig. 4 Transmission of the waveguide in dependence of the frequency for different applied voltages](image2)

The spectral hole was burned at 634 nm with a diode laser.

It should be noted that in our experiments the read beam also causes a photochemical bleaching of the SHB material proportional to the amount of light absorbed by the chlorin molecules, which gradually destroys the filter. With the actual configuration ten reading cycles reduce the contrast from 9.1 to 7.8 dB. To achieve non-destructive read-out, so-called photon-gated SHB materials can
be used [16]. With these materials two photons are needed to provide one photochemical transition. By avoiding the second photon the filter can be prevented from bleaching.

Spectral hole-burning devices work best at liquid helium temperature. Operation at higher temperatures is feasible under a loss of narrow-band performance due to increased homogeneous linewidth. New materials for high temperature SHB are under investigation [17,18].

In conclusion, due to SHB a tunable sub GHz integrated optical filter was constructed in a waveguide configuration. The advantages of such a filter are the large frequency resolution, the ease of manufacturing and the tunability of the transmission by an applied external voltage.

Obviously for current optical data transmission and processing applications, the preferred operating wavelength regions lie at 1.3 and at 1.5 μm. It will be important to extend the operation of our device into this wavelength region. However, very little is known about SHB systems absorbing at a wavelength that is larger than 700-800 nm. Nevertheless we are on the way investigating systems which show absorption at 1310 nm.

References.

GENERATION OF HUGE TUNABLE DISPERSION BY RESONANT COUPLING OF FAST AND SLOW MODES

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ABSTRACT

We show that the supermodes of two coupled waveguides may exhibit a very large tunable group-velocity dispersion, which allows for bright soliton propagation in materials with normal dispersion as well as for pulse compression and dispersion compensation in long fiber transmission lines.

1. INTRODUCTION

Pulse propagation in optical systems is tremendously influenced by the group velocity dispersion (GVD) of the excited modes. Light pulses propagating in fused silica fibers are broadened because of the different group velocities of their different frequency components.

To compensate this effect one may first increase the power to generate solitons by employing nonlinear effects. Bright solitons to exist in materials with a focusing nonlinearity require an anomalous dispersion (GVD < 0). This condition can be met beyond the zero-dispersion wavelength in optical fibers. Unfortunately, semiconductors that are fairly attractive for all-optical elements because of their large off-resonant nonlinearities (below half the band gap) exhibit a huge normal GVD (D=1000 ps²/km) thus prohibiting the formation of bright solitons. Hence, there is a great deal of interest to identify smart device concepts that allow for the compensation of the material dispersion. Such concepts could be used to avoid the experimentally observed pulse break up in nonlinear AlGaAs directional couplers by using temporal solitons [1] or to study spatiotemporal objects as e.g. light bullets [2].

A second, and at the moment much more common, way to compensate for the linear pulse broadening is to add elements with high GVD of opposite sign to the fiber transmission line. The higher the GVD of such elements the shorter the device length required. For example, 50 km standard fiber (D = −16 ps²/km) has to be compensated for by about 7 km of a highly dispersive fiber (D = +120 ps²/km) in commercial communication systems operated at λ = 1.55 μm.

Therefore, there is an urgent need for configurations with a large tunable GVD of arbitrary sign. Recently, the leaky modes of an ARROW were predicted to exhibit a huge anomalous GVD [3].

The aim of this paper is to demonstrate that a highly asymmetric directional coupler is another potential candidate to achieve that goal. To illustrate the efficiency of our envisaged device we optimize a structure to be grown from the Si-O-N system on a silicon wafer for the communication wavelength λ = 1.55 μm.
2.THEORY

The basic principle of a directional coupler is the linear coupling of two modes propagating in different waveguides (guide 1 and 2 in Fig.1).

![Fig.1 Asymmetric directional coupler](image)

To achieve phase matching the propagation constants $\beta_i$ of the fundamental modes of both guides should be equal at the central frequency $\omega_0$, but their group velocities $v_i$ should be quite different. We assume the propagation constants to depend on the frequency as (see the dashed curves in Fig.2)

$$\beta_i(\omega) = \beta(\omega_0) + \frac{\omega - \omega_0}{v_i} + \frac{D_i(\omega - \omega_0)^2}{2}$$  \hspace{1cm} (1)

where $D_i$ is the GVD of an individual mode. The absolute value of the GVD of a single waveguide is usually very close to that of the material forming the guide and does not exceed 1000ps$^2$/km. As we will show later the GVD we are looking for is orders of magnitude stronger.

The propagation constants $(B_{+/-})$ of the supermodes of the coupled system are given by

$$B_{+/-}(\omega) = \frac{1}{2} [ (\beta_1(\omega) + \beta_2(\omega)) \pm \sqrt{\frac{1}{4} (\beta_1(\omega) + \beta_2(\omega))^2 + \frac{\pi^2}{4L^2}} ]$$  \hspace{1cm} (2)

where $L$ is the half-beat length at $\omega=\omega_0$ and $B_{+/-}$ correspond to the quasi-symmetric and quasi-antisymmetric supermodes, respectively. By inserting eq.(1) into eq.(2) and differentiating twice we can obtain the dispersion of the supermodes explicitly. To simplify the resulting expression we assume the GVD in both guides to be approximately equal ($D_1 = D_2 = D_0$). The GVD of the supermodes writes as

$$D_{+/-} = \frac{\partial^2}{\partial \omega^2} B_{+/-} = D_0 \pm \frac{L}{2\pi} \left( \frac{1}{v_1} - \frac{1}{v_2} \right)^2 \left( \bar{\omega}^2 + 1 \right)$$  \hspace{1cm} (3)

where we have scaled the frequency with the characteristic bandwidth of the interaction region $\delta\omega$

$$\bar{\omega} = \frac{\omega - \omega_0}{\delta\omega} \hspace{1cm} \delta\omega = \frac{\pi}{L} \left| \frac{1}{v_1} - \frac{1}{v_2} \right|^{-1}$$  \hspace{1cm} (4)
Note, that the two supermodes may exhibit a very large GVD, which exceeds the material dispersion by orders of magnitude.

By setting $\phi = 0$ and using (3) we find the maximum GVD to be

$$D_{+/-}^{\text{max}} = D_0 \pm \frac{L}{2\pi} \left( \frac{1}{\nu_1} - \frac{1}{\nu_2} \right)^2$$

(5)

One can achieve arbitrarily large GVDs by varying the coupling strength (half-beat length). The sign of the GVD depends on the supermode one selects (normal dispersion-quasi-symmetric supermode, anomalous dispersion- quasi-antisymmetric supermode).

But it is evident that an increase of the dispersion reduces the linewidth $\Delta \omega$. Hence, the product $F_\omega$ of the maximum GVD and the bandwidth is more reliable to characterize the performance of the configuration. By using (4) and (5) we find

$$F_{+/-} = D_0 \delta\omega \pm \frac{1}{2} \left| \frac{1}{\nu_1} - \frac{1}{\nu_2} \right| = D_0 \delta\omega \pm \frac{\omega_0}{2c} \left| \frac{\partial}{\partial \omega} n_1 \right|_{\omega = \omega_0} - \left| \frac{\partial}{\partial \omega} n_2 \right|_{\omega = \omega_0}$$

(6)

Eq.(6) tells us that one mode should be far from the cut-off frequency to get a maximum $F$. The influence of the dispersion of the individual mode is negligible as far as the bandwidth of the device is not too big.

3. NUMERICAL RESULTS

![Fig. 2 Effective index vs wavelength for a spacing of 1000nm supermodes: solid lines individual modes: dashed lines](image)

![Fig.3 GVD vs wavelength of the two supermodes for different spacing](image)

Fig.2 shows the results of an exact calculation of the effective index (transfer matrix approach). The resulting GVD of the supermodes is depicted in Fig.3 for three different widths of the spacing between the two guiding layers. The individual modes selected for coupling are a TE0-mode in guide 1 and a TE2-mode in guide 2. The maximum GVD achieved in the coupler for a spacing of 1200nm is sufficient to compensate the dispersion of...
50 km of standard fiber within a distance of 20 cm. Having in mind that the spectral half width of a 10 ps pulse is about 0.35 nm the band width of the device is sufficiently large.

4. EXCITATION OF SUPERMODES

The primary problem left is how to excite selectively the supermodes. Grating or prism coupling represent the simplest methods where the spatial Fourier spectrum of the incident beam has to be narrower than the separation of the supermodes. Hence, the minimum beam width has to exceed $L/\pi$.

If the beam is more narrow or the light comes from a fiber one would prefer end-fire coupling. But, if one couples light with the frequency $\omega_0$ into one guide only, both supermodes are excited simultaneously and a well-defined GVD may not be achieved. One can overcome this drawback by using an additional but now mismatched coupler in front of the GVD generator. The mismatch of this first coupler should be $\beta_1 - \beta_2 = \pm \pi/L$ for the operating frequency $\omega_0$. If only the mode in one waveguide of the first coupler (index 1) is excited one obtains the quasi-antisymmetric mode for the negative and the quasi-symmetric for the positive sign after a propagation of a distance of $L/\sqrt{2}$, which corresponds exactly to the half beat length of this detuned coupler. Because this first coupler is detuned only half the power is transferred and thus a symmetric or an antisymmetric mode is excited according to the sign of the detuning.

5. CONCLUSION

In conclusion, we have shown that the supermodes of an asymmetric directional coupler exhibit a huge GVD which can overcome the material dispersion of all materials used in waveguide optics. The device can be tailored by changing the coupling strength between the individual modes taking into account the required band width. The modes can be excited either by distributed or end face coupling.

References

HIGH-INDEX Zn:LiTaO₃ OPTICAL WAVEGUIDES
PREPARED BY NONISOVALENT-ION EXCHANGE:
THE CRYSTAL STRUCTURE AND OPTICAL PROPERTIES

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ABSTRACT

The high-index Zn:LiTaO₃ optical waveguides formed by earlier proposed Zn²⁺ → 2Li⁺ ion exchange process have been characterized both optically and structurally. The dependences of the extraordinary and ordinary indices change on the lattice parameters of the unstrained single crystalline Li₁₋ₓZnₓ/2TaO₃ solid solutions in two observed phases were obtained.

INTRODUCTION

All known methods except the very slow process of Zn diffusion do not allow the production, in LiTaO₃ (LT), of low-loss optical waveguides supporting both modes of propagation, at the temperatures below the Curie point.

At least, there are some reports on a successful use of the proton exchange (PE) to form the waveguiding layers in LT at low temperatures. In this case, however, the surface increment of the refractive index (RI) is too small and it is impossible to manufacture the layers, supporting the propagation only of modes of extraordinary polarization.

In this paper we represent the crystal structure and optical properties of the optical waveguides formed in LT by nonisovalent ion exchange (NIIE) Zn²⁺ → 2Li⁺ and by the simultaneous processing of Zn²⁺ → 2Li⁺, H⁺ → Li⁺ and Zn²⁺ → 2H⁺ exchange (so-called double ion exchange technique (DIE)).

PREPARATION OF SAMPLES

For our experiments we have used optical grade LiTaO₃ plates of basic (X-, Y- and Z-) and rotated (02.10), (018) and (014) cuts. The experiments were carried out in the melts of K₂SO₄ (13.5 mol.%) - Na₂SO₄ (8.5 mol.%) - Li₂SO₄ (m) - ZnSO₄ (n) in the case of NIIE and in the melts K₂SO₄ (13.5) - Na₂SO₄ (8.5) - Li₂SO₄ (m) - ZnSO₄ (n) - KHSO₄ (k) in the case of DIE processes. The active ingredients in these mixtures are only the ZnSO₄, Li₂SO₄ and KHSO₄. Potassium and sodium sulphates being added to lower the temperature of the transition into the liquid state. The salt mixtures were heated in quartz crucibles to the set processing temperature. The waveguides were formed by immersing precleaned LT plates in the melts.

INVESTIGATION METHODS

We measured the mode effective indices of the planar waveguides using a standard one-prism coupling setup at a wavelength of λ=633 nm. The refractive indices profiles (RIP's) in the waveguides were reconstructed by the TWKB method.

The strained state in the ion-exchanged waveguiding layers was determined by analyzing the rocking curves (RC's) recorded by a double-crystal X-ray diffractometer DRON-3, Russia (Cu Kα₁ radiation, Si (333) and (311) monochromators). The deformations were calculated according to the method described in ref.
In most cases we observed that Zn:LiTaO$_3$ waveguides on X- and Z-cuts have only one non-zero component $\varepsilon_{33}$ of the deformation tensor in the technological coordinate system appropriate to the substrate (with the axis 3" perpendicular to the plane of the plate and 1" and 2" orthogonal axes lying in this plane). Zn:LiTaO$_3$ waveguides on Y- and rotated Y-cuts have two non-zero components of deformations $\varepsilon_{33}$ and $\varepsilon_{53}$ in this system. Therefore, the formed topotactic zinc-exchanged layers are coherent - with zero in-plane deformations $\varepsilon_{44}$, $\varepsilon_{52}$ and $\varepsilon_{42}$.

In our recent paper 9 we proposed and described in detail a new method of independent determining both the a and c lattice parameters of the unstrained solid solution whose composition is equal to that on the surface of corresponding investigated strained waveguiding layer, by examining the ion exchange processes on basic (X-, Y-, Z-) and rotated (0k1') cuts. The H$_2$Li$_{1-x}$TaO$_3$ solid solutions have been characterized. Here we shall only sketch the main principles.

It was found that lattice parameters of unstrained solid solution Li$_{1-x}$Zn$_x$/2TaO$_3$ whose composition is equal to that on the surface of corresponding strained waveguiding layer Zn:LiTaO$_3$ can be calculated as:

$$S_a = \left( \frac{\varepsilon_{33}v_{c4} - \varepsilon_{23}v_{c3}}{d} \right)$$

$$S_c = \left( \frac{-\varepsilon_{33}v_{a4} + \varepsilon_{23}v_{a3}}{d} \right)$$

where

$$S_a = \left( a_{Zn:LiTaO_3} - a_{LiTaO_3} \right) / a_{LiTaO_3}$$

$$S_c = \left( c_{Zn:LiTaO_3} - c_{LiTaO_3} \right) / c_{LiTaO_3}$$

$$d = v_{a3}v_{c4} - v_{a4}v_{c3}$$

$$v_{a3} = (t_2 + t_1v_{23} + v_{13})$$

$$v_{a4} = (t_1t_2 + t_1^2v_{24} + v_{24})$$

$$v_{c4} = (t_1 - t_1^2v_{24})$$

For the (014), (018), and (02,10) rotated cuts of LiTaO$_3$ (a =5.1543 Å, c=13.7835 Å, $\theta$=0.374) used in the present work, $t_1 = -0.112$, 0.386 and 0.617, respectively. $C_{ij}$ is the elastic stiffness tensor for zinc substituted LiTaO$_3$ solid solutions, formed by NIE process, transformed to the substrate orientation. This last is unknown and we have to use in our calculations the elastic stiffness tensor of LT$_2$.

**EXPERIMENTAL RESULTS**

It was found that the modes of both polarizations propagate in all Zn:LT waveguides. Losses, measured with a two-prism technique, were approximately 1 to 2 dB/cm at $\lambda$=633 nm. We experimentally obtained the dependences of deformation $\varepsilon_{33}$ on $\varepsilon_{33}$ in Zn:LiTaO$_3$ waveguides on (02,10), (018) and (014) rotated cuts. Two different regions were observed on such dependences which correspond, we believe, to the two different phases in the ZnTa$_2$O$_6$ - LiTaO$_3$ system: $\alpha$ and $\beta$ - zinc-substituted LiTaO$_3$ solid solutions. The $\beta$ phase characterized by higher zinc concentration than $\alpha$ phase, so as $\alpha$ phase samples can be formed by annealing of $\beta$ phase structures. From dependence $\varepsilon_{53}$ on $\varepsilon_{33}$ by using mentioned above equations, the deformations of the a and c lattice parameters have been calculated.

Fig.1 shows the dependences of $\Delta a_0$ and $\Delta c_0$ on lattice parameters of unstrained Li$_{1-x}$Zn$_x$/2TaO$_3$ solid solutions. It was observed a very good agreement
between published by Torii et al.\(^2\) and our lattice constants for \(\alpha\) phase solid solutions formed by NUE. Therefore, in the melts containing the relatively small concentration of zinc ions, the solid solutions \(\text{Li}_{1-x}\text{Zn}_{x/2}\text{Ta}_2\text{O}_5\) ([I- cationic vacancies] described by Torii et al.\(^2\) are formed in the surface region of \(\text{LiTa}_2\text{O}_5\). Note, however, that such solid solutions can be formed by NUE up to values \(S_\text{a}=2.65 \times 10^{-3}\) and \(S_\text{e}=2.0 \times 10^{-3}\) which correspond \(^2\) to concentration \(x=0.35\). This value is sufficiently smaller than the upper concentration of \(\text{Zn} \times 0.5\) \(^2\) in the equilibrium \(\text{Li}_{1-x}\text{Zn}_{x/2}\text{Ta}_2\text{O}_5\), and thus the \(\alpha-\beta\) phase transition in NUE zinc-substituted solid solutions is achieved when concentration of zinc ions exceeds the value \(x=0.35\).

We think that the Zn ions in \(\alpha\) phase solid solutions occupy the Li-site cation vacancies whereas in the \(\beta\)-phase these ions placed in the oxygen planes\(^\text{\texttt{23}}\). New zinc ion sites in the crystal lattice may be the reason of the anomalously high refractive indices in the \(\beta\) phase \(\text{Zn}:\text{LiTa}_2\text{O}_5\) waveguides\(^\text{\texttt{13}}\). The typical refractive index profiles in \(\text{Zn}:\text{LiTa}_2\text{O}_5\) waveguides, containing the \(\alpha\) and \(\beta\) phases were represented in the our last paper\(^\text{\texttt{13}}\).

The optical losses for X-cut \(\text{Zn}:\text{LiTa}_2\text{O}_5\) waveguides have been estimated by using two-prism coupler technique. For \(\beta\)-phase structures the losses for TM modes were around 1 dB/cm and for TE modes were around 2 dB/cm. The \(\alpha\)-phase waveguides show smaller light scattering and the losses for modes of both polarizations were estimated as lower than 1 dB/cm.

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Fig.1. The relationships between the refractive indices change (extraordinary $\Delta n_e$ - solid line, ordinary $\Delta n_o$ - dashed line) and the deformations of the lattice parameters $S_a(a)$ and $S_c(b)$ of unstrained Li$_{1-x}$Zn$_x$/2TaO$_3$ solid solutions.
DIRECTIONAL COUPLER SENSOR USING A LOW-INDEX FLUOROPOLYMER ISOLATION LAYER

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A novel integrated optical sensor based on an asymmetric directional coupler structure is described. A patterned low-index fluoropolymer film is used to define the sensing region. The response of the device with respect to small changes in refractive index is demonstrated, and its potential for detecting antibody-antigen reactions is considered.

Introduction

Integrated optical devices are increasingly finding application in the area of chemical sensor/biosensor technology. When used as transduction elements for specific bioreactions (such as antibody-antigen binding) the potential exists for the creation of highly sensitive, rugged and portable sensors capable of rapid screening or accurate quantitative assessment of a vast range of possible analytes. Integrated optical sensors reported so far include those based on the Mach-Zehnder Interferometer\(^1\) and on surface plasmon resonance\(^2\). The present performance of MZI devices appears to be limited by the lack of suitable low-index isolation layers. Here, we describe a new type of sensor based on the directional coupler; this sensor has the advantage of two outputs, resulting in improved signal/noise characteristics and the potential to provide simultaneous measurement of both the real and complex components of the refractive index of an analyte. Devices were fabricated in BGG31 glass using Ag\(^+\) - Na\(^+\) ion-exchange, and a new low-index fluoropolymer material (Teflon AF 1600) was deposited and patterned for use as the isolation layer. We report measurements on the characteristics of a device with respect to changes in the refractive index, and consider the response of the device to the addition of a monomolecular layer on its surface such as would occur during antigen-antibody binding in an aqueous environment.

Operating principle

The operation of the directional coupler sensor is based on adjusting the coupling condition via a sensing layer above one of the guides, which changes its effective index with respect to the second guide which has a protective cover layer and is not affected by the medium in which the sensor is immersed. Information on the sensing reaction is obtained by measuring the intensity and distribution of power at the two outputs of the coupler. The structure of the device is shown in Figure 1.

Sensor design

If a difference in propagation constant between the two guides of a directional coupler is introduced and the input waveguide is guide 1 (Figure 1), then, from coupled mode theory, the output power from guide 2 is given by

\[ P_2 = P_1 \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 \]
where $\Delta \beta = \beta_1 - \beta_2$ is the difference in propagation constants, $L$ is the length of the device and $\kappa$ is the coupling coefficient, which expresses the strength of the coupling between the two guides and depends on the overlap between the two modal fields. It can be seen from the above equation that the maximum power coupled to guide 2 is reduced as the difference in propagation constant increases, and the coupling length changes. The power emerging from guide 1 is given by $P_1 = 1 - P_2$. Complete power transfer (assuming $\Delta \beta = 0$) occurs at $\kappa L = \pi/2, 3\pi/2, 5\pi/2$ etc, with values above $\pi/2$ corresponding to light coupling fully between the guides more than once over the length $L$. However, the case $\kappa L = \pi/2$ shows the most rapid change of output with $\Delta \beta$; this case was therefore chosen for the sensor design. Note also that large values of $L$ are also advantageous. Further, the maximum of sensitivity is achieved at the point of maximum slope of the main peak of the power curve; it is therefore necessary to shift the operating point of the device to near this position. This can be achieved by introducing an initial difference in propagation constant $\Delta \beta$ by varying the width of one of the guides. The asymmetry due to the initial difference in superstrate index for the two guides also has to be considered in the calculation; in some cases (as in the example below) this asymmetry is sufficient to shift the operating point by the required amount, and the widths of the two guides can be the same.

The change in effective index of a waveguide with respect to superstrate index is greater for TE polarization and greater the more symmetric the guide in the depth direction. For the latter reason, a low index glass, BGG31 ($n = 1.4722$ at 632.8 nm), was chosen as substrate; further, the surface index change of waveguides formed in this glass following ion-exchange is controllable by varying the AgNO$_3$/NaNO$_3$ melt composition. The choice of this glass, however, imposes a limited choice of possible isolation layers, as the index of the layer must be less than that of the waveguide. After some investigation, a new material, Teflon AF 1600 amorphous fluoropolymer ($n = 1.31$ at 632.8 nm) was found to have suitable optical properties.

Taking the above considerations into account, devices were modelled fully using CAOS BPM (Beam Propagation Method) software, which is able to analyse coupling between ion-exchanged waveguides. The wavelength of operation of the device was chosen for convenience as 632.8 nm and the interaction length $L$ was set at 10 mm. Y-junctions were incorporated into the inputs of the devices to split the input signal and provide a reference to compensate for variations in input coupling. BGG31 glass and parameters for the refractive index profiles of ion-exchanged waveguides in this glass were supplied by IOT (Waghausel, Germany).

**Device fabrication**

Directional coupler structures were fabricated in BGG31 glass using titanium as the masking material for the ion exchange. The waveguide patterns were produced in the titanium using standard photolithographic techniques and etching. The ion-exchange took place in a 10 mol% AgNO$_3$/NaNO$_3$ mixture at 310°C; the exchange time was 450 s. This melt composition produces a surface index change of 0.011. Following mask removal, an 800 nm thickness layer of Teflon AF 1600 was deposited by thermal evaporation and patterned using a liftoff technique to open windows of dimensions 150 $\mu$m x 10 mm over one of the coupler waveguides as shown in Figure 1.
Results and discussion

Figure 2 shows the variation of output power from each output of a directional coupler sensor as a function of superstrate index. The dimensions of the coupler in this example were: \( w_1 = w_2 = 3 \, \mu m, \quad s = 7.4 \, \mu m \). Chopped TE polarized light from a feedback-stabilized He-Ne source was coupled into the device via a microscope objective; the three outputs (including reference) were expanded using another objective and measured simultaneously using three photodiode detectors and lock-in amplification. A flow cell was clamped to the device. Solutions of various refractive indices were pumped around the system using a peristaltic pump. Distilled water with added sucrose (0 - 25% by weight) was used to obtain indices in the range 1.334 to 1.373; refractive indices were measured using an Abbé refractometer at 589 nm. A further point below the index of water was obtained by using methanol (n = 1.329).

The measured variation with index is comparable to that predicted using the BPM model, which is shown in Figure 3. The actual device is not quite at the optimum operating point and so displays slightly reduced sensitivity; it is possible to move the device to nearer the required point by slightly varying the device dimensions or by altering the operating wavelength. The measurements demonstrate that the device offers sufficient sensitivity to detect monolayers of biomolecules adsorbed on its surface. Figure 4 shows the predicted variation in output power of output \( P_2 \) as a function of layer thickness expected when a non-absorbing layer of index 1.4 is added to the sensing region; output \( P_1 \) will show a similar variation but the power will change in the opposite direction. The values of refractive index and thickness are chosen to be typical of this type of biological material.

Conclusions

A novel type of integrated optical sensor based on the directional coupler has been demonstrated. High sensitivity has been achieved through careful choice of substrate material and design parameters. The choice of substrate necessitated the use of a new low-index material (Teflon AF) as an isolation layer and the development of techniques to pattern it lithographically; this material should be useful in many other integrated optical applications. The use of the device for detecting antibody-antigen binding reactions has been considered.

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Figure 1: Structure of directional coupler sensor

Figure 2: Measured variation of sensor output against refractive index

Figure 3: BPM simulation of sensor output against refractive index

Figure 4: Calculated change in output power (P2) of a directional coupler sensor upon addition of a biolayer (n = 1.4)
WAVELENGTH SELECTIVE DEVICES BASED ON THE ARROW SCHEME

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ABSTRACT

We describe the action of two wavelength selective devices where both are based on three coupled Anti Resonant Reflecting Optical Waveguides (ARROWS). They may be used as comb-de/multiplexer and as drop/add filter, respectively. The crosstalk ratio of these compact devices is shown to be larger than 15 dB.

1. Introduction

The increasing level of interest nowadays in wavelength division multiplexing (WDM) provides a stimulus towards the development of wavelength selective devices for separating out and combining many channels on one optical fiber. Among the devices that have been developed the conventional Fabry-Perot interferometer has attracted particular attention [1]. Unfortunately, it lacks the feasibility of an integrated optics implementation. On the other hand strongly asymmetric directional couplers (different core thicknesses and refractive indices) were used as integrated optics wavelength filters [2]. Because ARRO waveguiding relies on Fabry-Perot reflection in the interference cladding layers [3] rather than on total internal reflection we are going to show that the advantages of both schemes can be combined to form highly effective integrable wavelength selective devices. Primarily, we exploit the periodicity of the ARROW dispersion curves that leads to the peculiarities of that guiding scheme as e.g. remote coupling [4,5]. The basic idea behind the devices proposed here is to use an asymmetric coupler configuration that consists of three different ARROWS where unlike in previous filters [2] the asymmetry is caused by different cladding but constant core thicknesses. By contrast with conventional ARROWS we use very thick cladding layers (50-100 μm) to achieve the wavelength selectivity.

Although the two devices proposed rely on the same idea they may be used for different purposes. The comb demultiplexer selects from a discrete equally spaced wavelength spectrum launched into the central ARROW every other wavelength and steers it to remote output channels (right or left ARROW). The drop filter drops two different equally spaced wavelength sequences from the signal input into the central ARROW and launches them to the remote output channels.

The respective multiplex and add operations can be accomplished by simply reversing the direction of light.

The design of both configurations is based on the following rules: 1) The antiresonance condition is used for the interference cladding layers for all wavelength that are guided in order to lift the tolerances. 2) Identical core thicknesses fitting to the fiber core diameter are used to optimize the fiber-filter interconnect and to avoid tapers. 3) The distance between the output cores is large to avoid
1) The radiation losses are almost eliminated in adding additional interference cladding layers at the left and right side of the configuration.

2. THEORY

The refractive index profile for both devices together with a typical effective index of an ARROW mode is shown in Figs. 1a,b.

\[ D_{cl}^{AR} = \frac{(2N-1)\lambda_{AR}}{4\sqrt{n_{cl}^2 - n_{co}^2 + \left(\frac{\lambda_{AR}}{2D_{co}}\right)^2}} \]  

where the antiresonance condition is fulfilled for the wavelength \( \lambda_{AR} \). The order \( N \) of the antiresonance condition is determined by the integer number closest to

\[ N = \frac{\lambda_c}{\Delta \lambda} \]

where \( \lambda_c \) is the central wavelength of the signal and \( \Delta \lambda \) is either the equally spaced wavelength difference for the respective channel (demultiplexer) or the width of the communication band (drop filter). Note that the formulae (1) and (2) provide only approximate, but nevertheless quite accurate, values for \( D_{cl}^{AR} \). In ultimately designing the structure minor corrections have to be made by using the transfer matrix approach and calculating the effective index of the respective symmetric (\( n_{eff}^s \)) and antisymmetric (\( n_{eff}^a \)) supermodes involved. These effective indices yield simultaneously the device length (half beat length) as

\[ L(\lambda_c) = \frac{\lambda_c}{2n_{eff}^s - n_{eff}^a} \]
3. RESULTS

By using (1) - (3) we calculated the device parameters for typical goals to be achieved with both the demultiplexer and the drop filter. In all situations we have used $\lambda_c = 633$ nm and $D_{co} = 8 \mu$m.

A) The demultiplexer

We used a typical SiO$_2$/TiO$_2$ material system with the respective refractive indices of 1.46 (SiO$_2$) and 2.3 (TiO$_2$). The intention was to launch a discrete comb spectrum with 0.25 nm spectral width and a separation of 1 nm into channel "A". The aim is to direct the even wavelength to channel "B1" and the odd wavelength to channel "B2". This means that $\Delta \lambda (A) = 1$ nm and $\Delta \lambda (B1,B2) = 2$ nm, respectively. By using as central antiresonance wavelengths 633 nm and 634 nm we got

$$D_{cl1}^{AR} = 112.7 \mu m \quad D_{cl2}^{AR} = 56.35 \mu m \quad D_{cl3}^{AR} = 56.44 \mu m$$

The device length was calculated to be $L = 21$ mm. In using those data the output in the two outermost channels was calculated numerically and is shown in Fig.2 together with the input signal.

![Fig.2 Demultiplexing of a comb input signal](image)

For a typical linewidth of 0.25 nm a crosstalk ratio of 17 dB was achieved.

B) The drop filter

We assume a polymer material system with the refractive indices $n_{co} = 1.52$ and $n_{cl} = 1.57$. As can be seen from Fig.1b the drop filter differs from the demultiplexer by using two very thin reflectors
for the central ARROW "A". Actually, one uses $N = 1$ to calculate $D_{c1}^{AR}$ which means that the antiresonance condition is fulfilled for a broad wavelength band. Phase-matching for different wavelength to ARROW "B" or "C" is now achieved by tuning $D_{c2}^{AR}$ and $D_{c3}^{AR}$. The free spectral range $\Delta \lambda$ was designed to be 12 nm and the wavelength directed to channel "B" and "C", respectively, should differ by 6 nm. Hence, the central dropping wavelength, that is the antiresonance wavelength in (1), is 633 nm for channel "B" and 627 nm for channel "C". Using these data we got
\[
D_{c1}^{AR} = 0.436 \mu m \quad D_{c2}^{AR} = 42.06 \mu m \quad D_{c3}^{AR} = 41.71 \mu m
\]

The device length was calculated to be 50 mm. The numerically calculated output intensities of all channels are shown in Fig.3.

![Fig.3 The drop filter](image)

The peaks have a linewidth of 1.25 nm and the side lobe suppression is about 10 dB.

4. CONCLUSIONS

We have shown that coupled antiresonant waveguides with relatively large interference cladding layers may act as very efficient wavelength selective devices. Both de/multiplexing and add/drop filtering was demonstrated.

REFERENCES

A LINEAR WAVEGUIDE OPTICAL MODULATOR IN THE MODULATION RANGE ABOVE 50%

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ABSTRACT
Various coupled-waveguide modulators with Y-junction at the input are studied theoretically. Parameters of three-section modulator (two sections with electrodes of the same length separated by section without electrodes) were determined to reduce the third-order intermodulation noise to -100 and -60 dB in the modulation index range 50 and 80%, respectively. A method for compensation of technological errors in the coupling coefficient between the waveguides was developed; the method eases practical implementation of the structures.

INTRODUCTION
Analog data transmission and processing systems employ both direct modulation of laser pumping current [1] and external modulation [2] of cw laser radiation. Bodeep and Darcise [2] compared the second- and third-order intermodulation distortions for a directly modulated semiconductor laser and an LiNbO₃ external modulator and concluded that external modulation would be more attractive if one managed to expand the linearity range of external modulators.

Several groups that tackle this problem use various approaches: polarization mixing in interferometric modulators [3], integration of several interferometers [4], introduction of an interferometer between the active and passive directional couplers [5], and others [6, 7].

To our opinion, the most promising modulator is the one that is schematically drawn in Fig. 1. The combination of a symmetrical Y-junction at the input of the modulator with a tunable directional coupler (DC) automatically puts the modulator to the optimal point of amplitude characteristics. From here on, we designate the structures of this type by an abbreviation YDCM(Δk), where Δ are the scaling coefficients of a normalized driving signal \(I_0\) at corresponding sections of the modulator (the definitions of \(\Delta_i\) and \(I_0\) are given below). Modulators of this type with one section of electrodes were demonstrated on Z- [8] and X-cuts [9-11] of LiNbO₃ single crystals. Zabra and Moutrosset [12] theoretically studied an YDCM(1,-1) structure with two sections of electrodes of equal length; the driving voltage applied to these electrodes was equal in magnitude but opposite in sign. They found optimal parameters (the section lengths) of the structure that reduced the intermodulation distortion below -60 dB with the modulation depth \(m\) of the output signal up to 0.5. However, the authors noted that the structure was extremely sensitive (at a given section length) to the coupling coefficient \(K\) between the waveguides. Deviation of \(K\) from its optimal value \(K_0\) by 1% increased the intermodulation distortion by 6 dB. In this connection, the study of the possibilities to relieve tolerances on \(K\) are of particular importance for practical application.

In this work we study in detail a three-section modulator and determine its parameters that reduce the third-order intermodulation distortion below -100 dB for the optical modulation depth of the output signal more than \(m = 0.5\) and consider methods to compensate the deviation of the coupling coefficient between the waveguides; these methods expand the acceptable deviation range of \(K\) to ±20% at 6 dB level of the third-order intermodulation distortions.
CALCULATION METHODS

Amplitude Characteristics

A single-mode input waveguide of the modulator splits into two coupled waveguides A and B in symmetrical Y-junction. When describing the light propagation in the coupled-waveguide portion, we used conventional coupled mode theory. According to this method, each section of length $L$ of this portion is uniquely described by two parameters: the coupling coefficient $K$ and the difference $\Delta \beta$ in mode propagation constants in these waveguides. For a particular $k$-th section of length $L_k$, we can write the matrix $C^k$ that relates the wave amplitudes in the waveguides A and B at the section input ($A_k(0)$ and $B_k(0)$) and output ($A_k(l_k)$ and $B_k(l_k)$):

$$\begin{bmatrix} A_k(l_k) \\ B_k(l_k) \end{bmatrix} = \begin{bmatrix} C_{11}^k & C_{12}^k \\ C_{21}^k & C_{22}^k \end{bmatrix} \begin{bmatrix} A_k(0) \\ B_k(0) \end{bmatrix}$$ (1)

where elements of matrix $C^k$ are determined by the normalized section length $l_k = KL_k$ and the normalized detuning of the waveguide modes $\delta_k = \Delta \beta_k / 2K$. For ideal Y-junction the wave amplitudes at the output of the modulator with $N$ sections can be found by consecutive transformations (1):

$$\begin{bmatrix} A_N \\ B_N \end{bmatrix} = C_1 \cdot C_2 \cdots C_N \begin{bmatrix} A_0 \\ B_0 \end{bmatrix}$$ (2)

The intensity $T$ of the light wave in the output of channel A of the modulator is determined as

$$T = A_N A_N^*$$

To expand the possibilities of the study, we introduce additional parameters $\Delta_i$, which are the scaling coefficients of the driving signal amplitudes on corresponding sections of the modulator, i.e., $\delta_i = \Delta_i \delta$, where $\delta$ is proportional to the driving voltage. Thus, in general, the modulator transmission function $T(\delta)$ depends on $2N$ parameters $l_i$ and $\Delta_i$. For the structure considered in [12], the only independent parameter is $l_1$ because $l_1 = l_2$ and $\Delta_1 = -\Delta_2 = 1$. In our structure, there are two independent parameters: $l_1 = l_2$ and $l_3$ with given $\Delta_1 = \Delta_3 = 1$ and $\Delta_2 = 0$ (the last condition corresponds to absence of electrodes in the second section of the modulator).

Optimization

We optimized the parameters of the structures by minimizing the standard deviation $\sigma(l, \Delta, m)$ of the transmission function $T(\delta)$ from its linear approximation $C \delta$ for a given range of the modulation index $m$ of the output signal. Our results show that the minimal value of the functional $\sigma(l, \Delta, m)$ is an relevant measure for nonlinear distortions in a modulator because it is proportional to the ratio of the average (in the same range of $m$) amplitude of the third-order intermodulation distortion to the amplitude of the driving signal.

We optimized the functional by varying $l_k$ with fixed $\Delta_k$ using the Davidon-Fletcher-Powell multidimensional optimization method [13].

Intermodulation noise

Calculations of the intermodulation terms require special rigor [12] because their value is several orders of magnitude smaller than the output signal at the fundamental frequencies. In this work, we implemented a simple but fairly accurate algorithm for calculation of the intermodulation terms

The essence of the calculation method for intermodulation distortions is as follows. The function $\Delta T(\delta)$ of the deviation of the amplitude characteristic of the modulation from its linear fit is antisymmetrical for a symmetrical structure; therefore, it can be approximated by a odd power series of the driving signal $\delta$. Thus, without a constant, the transmission function $T(\delta)$ of the modulator can be presented as

$$T(\delta) = C_1 \delta + C_3 \delta^3 + \cdots + C_N \delta^N$$ (3)

where $N$ is the odd approximation order, $C_k$ are the series coefficients within the fitting range $[0, \delta_{max}]$. 

For the driving signal
\[ \delta = A_1 \gamma_1 \sin(\omega_1 t) + \gamma_2 \sin(\omega_2 t), \] (4)
it is easy to determine all intermodulation terms \( B_{ij} \sin(i \omega_1 t + j \omega_2 t) \) within the approximation order \( N \) by recurrent procedure (for a common third-order intermodulation term \( i = 2 \) and \( j = -1 \)). Provided the weighted coefficients are equal, \( \gamma_1 = \gamma_2 = 1/2 \), the signal-to-noise ratio (SNR) is defined as the ratio of the output signal amplitude \( C_i A \gamma_1 \) at one of the frequencies (in this case, \( \omega_1 \)) to the intermodulation signal amplitude \( B \)
\[ \text{SNR} = 20 \cdot \lg \left( \frac{C_i A \gamma_1}{B} \right), \] (5)
the modulation index \( m_{\text{out}} \) is defined as the maximal modulation index of total output signal
\[ m_{\text{out}} = \left| 2T(A) - 1 \right|. \] (6)
Within the linearity range of \( T(\delta) \), \( m_{\text{out}} \) exceeds the modulation index caused by the signal of one of the frequencies twofold. However, the modulation index determined in this way is convenient because it directly reflects the dynamic range of the linear portion of the modulation characteristics.

RESULTS

Static characteristics of modulator
Zabra and Moutrosset [12] considered a structure with no gap between the two sections of electrodes \( (l_1 = l_2 = 0.540) \). We found that introduction of a gap between the electrodes slightly improves the linearity of the amplitude characteristics: the mean-square deviation from the linear fit decreases from -79.83 dB for a structure without gap to -80.6 dB for YDCM(1,0,-1) with optimal gap \( (l_1 = l_2 = 0.383, l_3 = 0.343) \). The deviation \( \Delta T(\delta) \) of the amplitude characteristic \( T(\delta) \) of a modulator from its linear fit \( C \delta \) is an essential characteristic of the modulator. For a YDCM(1, 0, 1) three-section structure, we found a set of parameters for which the function \( \Delta T(\delta) \) is fitted by a polynomial of power not less than nine \( (N_{\text{min}} = 9) \) with very small expansion coefficients. Fig. 2 shows the functions \( \Delta T(\delta) \) for YDCM(1, -1) (curve 1) and YDCM(1, 0, 1) \( (l_1 = l_2 = 0.7510, l_3 = 1.1604, \) curve 2) modulators in the optimization range \( m = 0.5 \).

The tolerances of \( \sigma \) on the coupling coefficient between the waveguides (at given lengths and scaling coefficients of the modulator sections) is fairly narrow. Thus the problem of compensation of technological deviations of \( K \) from its optimal value \( K_0 \) is vital. In order to compensate these deviations we propose to adjust scaling coefficients. For YDCM(1, -1) and YDCM(1, 0, -1) one should fit \( \Delta_2, \Delta_1 = 1 \). Fig. 3 shows functional \( \sigma \) versus \( K/K_0 \) for uncompensated (1) and compensated (2) modulators. For YDCM(1, 0, 1) it is necessary to divide each section of the structure into two parts with equal lengths and to fit \( \Delta_1 = \Delta_0, \Delta_2, \Delta_3 \) \( (\Delta_1 = \Delta_2 = 1) \). Functional \( \sigma \) without (curve 3) and with the compensation procedure (curve 4) is also shown on Fig. 3.

Figure 2. Figure 3.
Figure 4. (1) Mach-Zehnder and single-section YDCM(1) modulators; (2) two-section YDCM(1,0) and three-section YDCM(1,0,-1) modulators; (3) YDCM(1,0,1) modulator.

Figure 5. Dependences of SNR on $m_{out}$ for YDCM(1,0,1) modulator optimized in various ranges of the modulation index. (1) $m = 0.2$, (2) $m = 0.4$, (3) $m = 0.6$, (4) $m = 0.8$.

Nonlinear distortion

Figure 4 illustrates nonlinear distortions in the modulators under consideration; it shows SNR for a combined frequency $2\omega_i - \omega_c$ versus the modulation index $m_{out}$ of the output signal. An important feature of these data is that the curves virtually coincide for substantially different but single-type functions $\Delta T(\delta)$. All the structures are optimized for the same modulation index range $m = 0.5$. The data presented on Fig. 5 show that the proposed structure expands the linearity range of the modulator to the modulation depth of the output signal more than 80% at the intermodulation noise level less than -60 dB.

CONCLUSIONS

Thus, brief analysis of various Y-junction-directional coupler modulators with linearized amplitude characteristics has shown that appropriately choosing the parameters of a three-section modulator of this type (two the same sections of electrodes separated by a region without electrodes), one can expand the dynamic range of the modulator to 60 dB for the modulation depth 80% and to 100 dB for the modulation depth 50%. In addition, we proposed a method for compensating the deviation of real coupling coefficient between the waveguides from its calculated optimal value; this method allows one to implement the structures in practice.

REFERENCES

Set of normalized scaling charts for the optimization of evanescent waveguide sensors

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Abstract

The waveguide configuration of maximum sensitivity in each case of surface and homogeneous sensing, and for each polarization is shown to be governed by a single, two-parameter transcendental equation of a single normalized variable. All possible planar step index structures have their maximum sensitivity working point defined in a single normalized chart.

1. Introduction

Evanescent wave sensing is one of the non-communication waveguide technologies which nowadays receives most attention. In its surface sensor implementation it enables the detection of the affinity between monomolecular biological species, one of them being immobilized at the waveguide surface, the other one distributed in a cover analyte. In its homogeneous sensor implementation, evanescent wave sensing is giving rise to a wide range of refractometric applications for on line process monitoring, food and beverage control, and pollutant detection, not to mention the possible measurement of physical quantities which a number of existing or new organic materials translate into a refractive index measurand. As compared with free space wave optical detection or total internal reflection, evanescent waveguide sensing is not necessarily the most advisable approach. It is therefore of prime importance to establish what this technology can best achieve. The advantages of a waveguide approach are:

- the sensing wave does not propagate into the medium under study. The guided wave licks the guide-cover interface with the Poynting vector strictly directed along the waveguide plane,
- the distribution of the sensing wave field is non-ambiguously defined by the waveguide structure and does not depend on the illumination conditions,
- the relative field strength in the sensing region can be tailored at will by a suitable choice of the waveguide structure opto-geometrical parameters,
- more than one sensing wave can be used in the very same waveguide, thus enabling diverse common rejection schemes for the cancellation of undesirable noise effects.

However, evanescent waveguide sensing also suffers from inherent limitations. A minor part only of the guided field actually interacts with the medium under study; in the case of weak guidance waveguides for instance, the relative power flowing in the cover can be as low as 0.1% at most and falls down by one or two orders of magnitude if the structure is not properly designed. Another difficulty is of practical nature: waveguide sensing is a resonant scheme; exciting the sensing wave(s) requires a strict control over the excitation angle and the optical frequency. This places a heavy cost burden on the waveguide sensing approach, implying that the choice of the waveguide route must rest on objective criteria such as its utmost achievable sensitivity. It is the aim of the present contribution to develop the methodology and to deliver the conditions for optimum sensitivity in the most condensed and normalized form in the practically meaningful case of planar step index waveguides. The results presented here are exhaustive in that they concern both cases of surface and homogeneous sensing for TE and also TM polarizations. They are new also in that they solve the problem once for all, thus preventing the designer from optimizing his sensitivity on a case by case basis as this has been made so far.
2. The methodology

The waveguide structure is sketched in figure 1. The waveguide slab of thickness w, index \(n_g\), is based on a semi-infinite substrate of index \(n_s\). In the case of homogeneous sensing (figure 1a), the measurand is the refractive index of the cover medium, \(n_c\). The only limitation imposed on the set of refractive index is \(n_g > n_s, n_c\). The case of surface sensing is illustrated in figure 1b): an ultra-thin film of thickness \(t\) >> \(\lambda\) and index \(n_f\) is immobilized at the guide-cover interface. \(\lambda\) is the wavelength of operation. In this second case, the measurand is the film thickness and/or its index; its presence will be expressed by means of the dimensionless quantity \(\eta = k_0 t (\epsilon_f - \epsilon_c), k_0 = 2\pi/\lambda,\) which is the dielectric load the film corresponds to. As from now, use will be made of the relative permittivity \(\epsilon_i = \epsilon_i^2, i = s, g, c, f, e,\) instead of the refractive index \(n_i\). \(\epsilon_c\) is the effective index of the propagating/sensing mode. The sensitivity \(S\) of a waveguide evanescent sensor is expressed as the rate of change of the mode effective index \(n_e\) with respect to the measurand: \(n_c\) in the homogeneous sensing case, \(\eta\) in the surface sensing case, \(S = \delta n_f/\delta n_c\) and \(S = \delta n_f/\delta \eta\) respectively. These will be calculated analytically as \(S^{-1}\) since then the algebraic derivation can be made explicitly.

The normalization starts on by writing the transcendental waveguide dispersion equation for mode of order \(m\) in terms of a normalized effective permittivity \(X_s\) defined as \(X_s = (\epsilon_e - \epsilon_s)/(\epsilon_g - \epsilon_e)^{1/2} ;\)

\[
k_0 w n_g ((1 - a_s)/(1 + X_s^2))^{1/2} - \arctan X_s - \arctan X_c - m\pi = 0
\]

The dependent variable \(X_c\) is related to \(X_s\) by \(X_c^2 = a (1 + X_s^2) - 1\) by means of two assymmetry parameters \(a_s, a_c ; a_s = \epsilon_g/\epsilon_s, a_c = \epsilon_c/\epsilon_g\) with \(a = (1 - a_c)/(1 - a_s).\)

The derivation leads to four analytical expressions, one for each sensing case, and for each polarization, \(S_{s,TE}, S_{s,TM}, S_{h,TE}\) and \(S_{h,TM}\) where subscripts \(s\) and \(h\) stand for the surface and homogeneous sensing cases respectively. There is not enough space here to write down all expressions. This is why one example only will be developed hereafter: it concerns TE surface sensing; a comparison with the chart of TM surface sensing will nevertheless be given. The expression of \(S_{s,TE}\) is:

\[
S_{s,TE} = (1 + X_s^2)^{-1} (\arctan X_s + \arctan X_c + m\pi + 1/X_s + 1/X_c)^{-1}
\]

\[
((1 - a_s)/(a_s + X_s^2))^{1/2}
\]

The search for the condition of maximum sensitivity is simply obtained by cancelling the derivative of \(S_{ij}\) with respect to \(k_0 w 4.\)

3. The optimization results.

This condition can again be obtained analytically and one gets the transcendental equation below which states what must be the \(X_s\) value which ensures a maximum sensitivity, in term of the assymmetry parameters \(a_c\) and \(a_s:\)

\[
(\arctan X_s + \arctan X_c + m\pi + 1/X_s + 1/X_c)(2 + (1 + X_s^2)/(a_s + X_s^2))
\]

\[-1/X_s^3 - 1/X_c^3 = 0
\]

The complete solution of (3) is represented in the chart of figure 2 showing the solution for \(X_s\) versus \(a_s\) with \(a_c\) as a parameter in the case of the TE0 mode.
Introducing these solutions into (2) gives the chart of figure 3 showing the maximum obtainable sensitivity versus $a_s$ with $a_c$ as a parameter. The solution for $X_s$ of figure 2 can now also be used to express the value of $n_g w/\lambda$ which gives rise to the maximum $TE_0$ mode sensitivity, as shown in figure 4:

$$n_g w/\lambda = ((1 + X_s^2)/(1 - a_s)^{1/2}(\arctan X_s + \arctan X_c + \pi)/2\pi$$

(4)

An example will now show how these normalized results must be used. Assuming a silica based silicon nitride waveguide ($n_s = 4, n_g = 2.1316$) and a water analyte ($n_c = 1.77$) gives $a_s = 0.533$ and $a_c = 0.44$. The chart of figure 2 gives $X_s = 0.41$ which, from figure 3, indicates a maximum sensitivity of $S_{s,TE} = 0.12$. Figure 4 says that the maximum condition takes place for $w/\lambda = 0.12$.

In the case of a thin monomolecular film of index $n_f = 1.4$ immobilized at the surface with 0.8 $\mu$m wavelength excitation, the presence of a 0.1 nm thick film provokes a maximum effective index change of $1.8 \times 10^{-4}$. Doing the same with the TM polarization leads to much more lengthy calculations. Figure 5 gives the final sensitivity chart for the $TM_0$ mode to be compared with that of figure 3. In the same example, the maximum $TM_0$ sensitivity retrieved from figure 5 is 0.28. The $TM_0$ sensitivity is significantly larger than the $TE_0$'s by a factor which increases with decreasing $a_s$ and $a_c$. This confirms the interest of using one TM and one TE mode in a common mode rejection scheme since the achievable differential sensitivity is not far from the $TM_0$ mode absolute sensitivity.

In conclusion, the design problem of optimum evanescent waveguide sensors composed of a slab step index guide is now fully solved. Complete results concerning both surface and homogeneous sensing configurations and both polarizations as well as comparisons between these different sensing schemes will be given at the conference.

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References


Figure 1 Waveguide sensor structure.

a) Homogeneous sensing of the cover's index

b) Surface sensing of a monomolecular film
Figure 2: Normalized effective index solution $X_S$ for maximum sensitivity of a surface sensor using the TE$\omega$ mode versus $a_\theta$ with parameter $a_C$.

Figure 3: Maximum achievable sensitivity of a TE$\omega$ surface sensor versus $a_\theta$ with parameter $a_C$.

Figure 4: Optical thickness $n_\theta w/\lambda$ ensuring the maximum sensitivity of figure 3 versus $a_\theta$ with parameter $a_C$.

Figure 5: Chart of maximum achievable sensitivity of a TM$\omega$ surface sensor versus $a_\theta$ with parameter $a_C$. 

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Figure 2 Normalized effective index solution $X_S$ for maximum sensitivity of a surface sensor using the TE$\omega$ mode versus $a_\theta$ with parameter $a_C$

Figure 3 Maximum achievable sensitivity of a TE$\omega$ surface sensor versus $a_\theta$ with parameter $a_C$

Figure 4 Optical thickness $n_\theta w/\lambda$ ensuring the maximum sensitivity of figure 3 versus $a_\theta$ with parameter $a_C$

Figure 5 Chart of maximum achievable sensitivity of a TM$\omega$ surface sensor versus $a_\theta$ with parameter $a_C$
ANALYSIS OF MULTILAYERED AND MULTISECTIONED CIRCULAR STRUCTURES
USING THE VECTOR-MOL-BPM IN CYLINDRICAL COORDINATES

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Abstract
Waveguides and elements for optical communication often consist of circular structures (fibres, circular bends, vertical cavity lasers, etc.). An algorithm for the analysis of such structures with the new vectorial MoL-BPM in cylindrical coordinates is described. Results are presented for the reflection coefficient of a circular Bragg-mirror.

Introduction
In this paper an algorithm for the analysis of circular structures with the vectorial MoL-BPM in cylindrical coordinates is described. As an example for such a structure a Bragg-mirror of a vertical cavity laser is sketched in figure 1.

The characteristics of the Vector-MoL-BPM in cylindrical coordinates are
- the full wave equations are used
- the refractive index may vary with \( r \) and \( \phi \)
- large refractive index steps are allowed
- reflections, inner losses and radiated fields are taken into account
- absorbing boundary conditions (ABCs) are used
- the convergence curve runs monotonically
- the calculated field is very accurate
- accurate consideration of the interface conditions at lateral index contrasts

Basic equations
The solution of the vectorial wave equation introduced by [1] is shown in detail in [2] for cylindrical coordinates, so we describe only the basic equations in this paper. But we describe the new algorithm for multiple reflections in detail. The Mol-BPM in Cartesian
coordinates works very well, so in principle we did the same in cylindrical coordinates. But there are some important differences which will explained later on.

For the discretisation we need two systems of discretisation lines: one for \( \psi \) and one for \( \phi \) with an offset of the half discretisation distance (see figure 2). The position of the discretisation lines is of great importance. In the following equations we assumed \( \varepsilon \) to be homogeneous in \( \phi \)-direction to keep the numerical effort small.

A \( \phi \)-dependence can be introduced easily. Special care has to be taken at \( r = 0 \). To take into account radiation ABCs must be used.

For the potential \( \tilde{\Pi} \) we set \( \tilde{\Pi} = \phi \tilde{\varepsilon} \psi + \psi \tilde{\phi} \) with a \( \phi \)-dependence of \( \phi \sim \cos m \phi \) and \( \psi \sim \sin m \phi \). To keep the following equations short we define

\[
\begin{align*}
\tilde{\psi} &= \hat{T}^{-1} [\psi^T, \phi^T]^T \\
E_t &= \begin{bmatrix} H_r^T & H_{\phi}^T \end{bmatrix}^T \\
H_t &= \begin{bmatrix} H_r^T & H_{\phi}^T \end{bmatrix}^T \\
\hat{T} &= \begin{bmatrix} T & T \end{bmatrix}^T
\end{align*}
\]

After discretisation the vector wave equation looks like

\[
\frac{d^2 \hat{\psi}}{dz^2} - \hat{Q} \hat{\psi} = 0
\]

with

\[
\hat{Q} = \begin{bmatrix}
\tilde{\tau}_1^{-2} \tilde{\tau}_h^{-1} \tilde{\tau}_e^{-1} D \tau_e - \varepsilon_e + m^2 r_e^{-2} & \tilde{\tau}_h^{-1} \left( \varepsilon_e D m \tau_h^{-1} \tau_e^{-1} - m \tau_h^{-2} D^2 \tau_h \right) \\
\tilde{\tau}_h^{-1} \left( -D m \tau_e^{-1} + m \tau_e^{-2} D \tau_e \right) & \tilde{\tau}_h^{-2} D \varepsilon_e D^2 \tau_h - \varepsilon_h + m^2 r_h^{-2}
\end{bmatrix}
\]

\( D \) = difference operator of the first order
\( \tilde{\tau} \) = normalized discretisation distance in \( r \)-direction
\( \tau_e \) = diagonal matrix with components of the normalized radii at the positions of \( \psi \)
\( \tau_h \) = diagonal matrix with components of the normalized radii at the positions of \( \phi \)
\( \varepsilon_e \) = diagonal matrix with components of the relative permittivity at the positions of \( \psi \)
\( \varepsilon_h \) = diagonal matrix with components of the relative permittivity at the positions of \( \phi \)

As can be seen we get the discretized radius in the matrix \( \hat{Q} \). This is an important difference to the equations in Cartesian coordinates. After diagonalization of \( \hat{Q} \) with \( \hat{T}^{-1} \hat{Q} \hat{T} = \hat{P}^2 \) we get the analytical bidirectional solution

\[
\hat{\psi} = A \cosh \{ \hat{P}(\tilde{z} - \tilde{z}_0) \} + B \sinh \{ \hat{P}(\tilde{z} - \tilde{z}_0) \}
\]

The analysis of multiple discontinuities

If we set

\[
\frac{d \hat{\psi}}{dz} = \hat{Y}_a \hat{\psi} \quad \text{at} \quad \tilde{z} = \tilde{z}_a \quad \text{and} \quad \frac{d \hat{\psi}}{dz} = \hat{Y}_b \hat{\psi} \quad \text{at} \quad \tilde{z} = \tilde{z}_b
\]
we get a transfer equation for $\bar{Y}$ from $\bar{z}_b = \bar{z}_0 + d$ to $\bar{z}_a = \bar{z}_0$

$$\bar{Y}_a = \Gamma \left( \bar{Y}_b - \Gamma \tanh(\Gamma d) \right) \left( \Gamma - \tanh(\Gamma d) \bar{Y}_b \right)^{-1}$$  \hspace{1cm} (4)

At a discontinuity in $z$-direction the tangential field components $H_r$, $H_\varphi$, $E_r$, and $E_\varphi$ must be continuous. For matching the $H$-components $\frac{d\bar{\psi}}{d\bar{z}}$ must be equal in the interface of the two different regions. The $E$-components can be written as

$$E_t = R \bar{\psi}$$

with

$$R = \text{Diag}(\bar{\varepsilon})^{-1}(M T - T \bar{r}^2) \quad M = \begin{bmatrix} m^2 \tau_z^{-2} & -m \tau_z^{-2} D^t \tau_h \\ -D m \tau_z^{-1} & D \tau_z^{-1} D^t \tau_h \end{bmatrix}$$

and must be equal in the interface of both regions, too.

With the definition of $H_t = Y^t E_t$ we obtain a relationship between $Y^t$ and $\bar{Y}$

$$Y^t = \bar{T} \bar{Y} R^{-1} \quad \text{or} \quad \bar{Y} = \bar{T}^{-1} Y^t R$$  \hspace{1cm} (5)

With equal $Y^t$ at the two sides of a discontinuity the continuity conditions are fulfilled. So we can transform $\bar{Y}$ about a discontinuity and a homogeneous section with length $d$ in the following way:

1. calculating $Y^t_i$ from $Y^t_i$ with the equation (5a)
2. setting $Y^t_{i+1}$ equal to $Y^t_i$
3. calculating $Y^t_{i+1}$ from $Y^t_{i+1}$ with the equation (5b)
4. transforming $Y^t_{i+1}$ over the distance $d$ with equation (4)

To transform $\bar{Y}$ across several discontinuities the above calculations must be done iteratively several times with different $\bar{\tau}$ and different $d$.

If the structure has several layers or sections the algorithm used in [2] becomes numerically instable if you work with all modes. The radiated fields with strong losses lead to problems for the calculation of $e^{\bar{T}d}$. So you have to work with a reduced number of modes. In this algorithm the calculation of $\tanh(\bar{T}d)$ is no problem, thus you can work with all modes.

**Calculation of the reflected field**

To get the reflected field of a multi-layered structure we set a wave in $+z$ direction

$$\bar{\psi} = \bar{\psi}_0 e^{-\Gamma N \bar{z}}$$

in the last layer of the structure. With the derivative with respect to $\bar{z}$ from (3) we obtain

$$\bar{Y}_N = -\Gamma_N$$

which can be transformed in the first layer ($\bar{Y}_1$) with the algorithm described above.
In this first layer we set a wave in $+z$ and $-z$ direction

$$\hat{\psi}_1^+ = \hat{\psi}_0 e^{-\Gamma_1 \hat{z}} \quad \hat{\psi}_1^- = r e^{\Gamma_1 \hat{z}}$$

With the coefficients $Y_1^+ = -\Gamma_1$ and $Y_1^- = \Gamma_1$ we get the reflection coefficient $r$ of the incoming field $\hat{\psi}_0$ at $\hat{z} = 0$

$$r = (I + \Gamma_1^{-1} Y_1^-) (I - \Gamma_1^{-1} Y_1^+)^{-1} \hat{\psi}_0$$

**Results**

As an example for a multi-layered structure the reflection coefficient of a Bragg-mirror (like figure 1) was calculated. The layer pairs of the mirror consists of a circular GaAs and a circular AlAs slice. The surrounding medium is air and the radii and thickness of every slice is equal.

In figure 3 the reflection coefficient as a function of the period-length (two times the thickness of one slice) is shown. The wavelength is always 1.52 $\mu$m, the radii of the layers are always 4 $\mu$m and the incoming field is the fundamental mode of a GaAs layer. Several curves are drawn for several numbers of layerpairs ($n$).

![Figure 3: Reflection coefficient of a Bragg-mirror](image)

**References**


GUIDED-WAVE MEASUREMENTS OF THE OPTICAL NONLINEARITY OF CdS-DOPED SILICA-TITANIA SOL-GEL FILMS

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Sol-gel films doped with semiconductor microcrystallites have been produced. The nonlinear characteristics of the produced films have been investigated through nonlinear grating coupling efficiency measurements. High nonlinear coefficients have been observed ($n^2 = 3 \times 10^{-8} \text{ cm}^2/\text{W}$). The dependence from the wavelength of the nonlinear coefficient is also reported.

1. Introduction

The production of integrated optical devices capable of all-optical signal processing is being pursued in many research laboratories. The possibility of optically thresholding, switching or performing logic functions would strongly enhance the speed and bandwidth of optical circuits and interconnects. The production of such devices, however, requires the availability of materials with sufficiently high nonlinearities and low absorption. This condition has not yet been fulfilled and research is still concentrating in the development of suitable materials.

In our work we have focused our attention on the class of semiconductor doped glasses (SDG), which show high third order optical nonlinearities, enhanced by the quantum confinement of the charge carriers inside the microcrystallites. Much work has already been carried out on this class of materials, but till now problems like photodarkening, control of the crystallite size and concentration of the dopant in the glass have hindered the development of high performance glasses. The sol-gel technique, which we have been using in the production of the films can in principle allow the reduction of the photodarkening effect through better control of the composition of the starting solution, as well as permit better control of the microcrystallite size and higher concentration of semiconductor dopant inside the silica glass host.

In this paper we will report on the film production and characterisation, with particular attention devoted to the measurement of the optical nonlinear characteristics by means of nonlinear grating coupling.

2. Film fabrication and characterisation

Sol-gel films have been prepared starting from a solution in ethanol of tetraethoxysilane (TEOS) and titanium butilate with 70%/30% relative molar content as precursors of silica and TiO$_2$ respectively. Alcohol for the hydrolysis of the precursors, HCl as catalyst for the reaction and acetylacetone
to stabilise the solution were also added. As precursors of the sulphur and cadmium 5% molar concentrations of thiourea (SC(NH₂)₂) and cadmium acetate were used.⁶

The films were deposited by dip-coating on silica substrates in controlled atmosphere at 30 °C temperature and 30% relative humidity. After the almost immediate gelation of the solution, the films were dried at 60 °C for 15 minutes and thereafter baked at 300 °C for 5 hours in nitrogen atmosphere. The use of nitrogen atmosphere was necessary in order to avoid the oxidation of the sulphur contained in the film, which would happen if it gets in contact with oxygen at high temperature. The resulting films are not fully densified, but baking them at higher temperature (800-900 °C) would cause a strong decrease in the semiconductor amount due to sublimation.

Following this process, films having thickness of about 0.2 μm and refractive index of 1.63 are obtained, which are suitable for guided propagation of at least one mode.

Propagation losses were measured by means of the detection by a Vidicon camera of the guided light scattered out of plain. Values of about 2-3 dB/cm were obtained at 633 nm.

In Figure 1 the comparison between the absorption spectra of an undoped film and a CdS-doped film obtained through the same sol-gel process are reported. There is an evident absorption band located approximately at 450 nm. By applying a tight band model of the band-shift (62 nm) of the absorption edge respect to the bulk (512 nm) caused by the quantum confinement, the average size of the semiconductor microcrystallites is evaluated to be about 3.5 nm.⁷,⁸

3. Nonlinear characterisation

Semiconductor-doped glasses exhibit a third order nonlinearity; we therefore expect a linear relationship between the intensity of the local electric field present in the glass and its refractive index: 

\[ n = n_0 + n_2 I \]

The experimental set-up employed to determine the \( n_2 \) coefficient is shown in Figure 2. The films were deposited on silica substrates were several grating had been previously ion-milled. Collimated light was coupled into the waveguide by means of grating coupling and the angle and shape of optimum coupling were determined by measuring the light reflected or transmitted through the coupling grating (0.7 μm period, 0.1 μm depth). At angles corresponding to light coupling a decrease in the reflected/transmitted light intensity is observed.

When the incident light intensity is high enough to induce a refractive index change in the sol-gel film, the optimum coupling condition varies accordingly. By measuring the change in shape and position of the coupling angle, the value of the \( n_2 \) coefficient can be calculated from the theory of the nonlinear distributed grating coupler.⁹

An OPO laser pumped by the third harmonic of a seeded Nd:YAG laser (8 ns duration, 10 Hz repetition rate) was used as laser source.
4. Experimental results

Measurements were carried out on a 0.2 µm thick CdS-doped film in the 500-600 nm spectral range. At 540 nm (see Figure 3) we observed a shift towards smaller coupling angles associated with a decrease in the contrast of the m-line.

The high intensity curve in Figure 3 corresponds to incident pulse energy of 0.8 mJ on a spot area of 0.7 mm², corresponding to about 100 MW/cm² irradiance. The nonlinear coefficient $n_2$, calculated from a simulation of the nonlinear grating coupler is $-2.7 \times 10^{-8}$ cm²/kW.

In order to exclude the possibility that the changes in the optimum coupling angle could be caused by damage to the film or other parameters out of our control, we cycled several times between low and high power, always getting the same results.

In Figure 4 the wavelength dependence of the measured nonlinear coefficient is shown. Unfortunately, nonlinearity out of the 530-560 range was under the sensitivity threshold of our experimental apparatus, but inside this spectral region the value of the nonlinear coefficient is very high.

Figure 5 finally shows the stability of the nonlinear coefficient as a function of a 6-months time period. A slight decrease in the value of the coefficient is actually noticeable. We are still investigating on the causes of such an undesired behaviour; a possible explanation may be given by the slow oxidation of the semiconductor particles (in particular of the cadmium) which get in contact with oxygen through the porosity of the sol-gel film.¹⁰
5. Conclusions

CdS-doped films were produced by the sol-gel technique. High negative nonlinearities were found at energies below the band gap of the semiconductors. The results seem very promising, though the nonlinear coefficient present a slow decay in the long term period.

6. Acknowledgements

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7. References

1. INTRODUCTION

Beam width converting elements are frequently needed on integrated optical chips. Beam width conversion can in principle be realised by a.o. planar lenses, adiabatic tapers and MMI (multimode interference) couplers. However, for typical waveguide index contrasts, planar lenses need a large crystal space and adiabatic tapers are relatively long [1, 2]. MMI couplers are compact and have been very successful for beam splitting [3]. However their use as beam width converters has been limited, although in principle they can be designed to perform an image magnifying function [4], in which case they tend to be very long. In this paper we propose and demonstrate experimentally a new beam width converter, which is compact, polarisation independent and index contrast insensitive. The converter is based on an elliptically shaped structure. Given the input waveguide mode, the width and position of the output beam can be controlled by proper design of the elliptic beam converter (EBC). We describe the theoretical analysis, design, fabrication and experimental results.

2. THEORETICAL ANALYSIS

A schematic drawing of the EBC is shown in Fig.1. The lengths of the half axes are denoted by a and b. The structure can be analysed by ray optics, wave optics or Gaussian beam optics. From a ray optics point of view, the left focal point of an elliptic mirror structure is focused exactly on the right focal point. This means that a diverging spherical wave produced by a point source in the left focal point is transformed into a converging beam after reflection by the elliptic interface. Because of the limited aperture of this converging beam, the image has a finite beam waist. Furthermore, if the input field is not a point source but rather the fundamental mode of a waveguide (as in Fig. 1), the converging output beam will be modified and will depend on the shape of the input waveguide mode.

To take into account all these effects accurately, the EBC has to be analysed numerically by a wave propagation algorithm (BPM or mode expansion propagation). As an example Fig.2 shows a FD-BPM analysis of an EBC with a=230 µm and b=8.0 µm. The input waveguide has a width of 2
The results are shown for two values of lateral index contrast of the elliptic region (3.31 to 1 and 3.31 to 3.21). The figure shows that the focused beam width has a rather long depth of focus with almost constant beam width of around 6 μm (FWHM of intensity). The propagation is shown to be rather independent of refractive index contrast. The small differences are partly due to physical effects (different Goos-Hanchen shift) and due to non-physical effects in the numerical BPM propagation.

Figure 1: Schematic figure of the EBC structure and the input-output beams.

Figure 2: Field amplitude of the light propagating through a half elliptic section with a=230 μm and b=8.0 μm with different lateral index contrast. The width of the input waveguide is 2 μm. (a) Index contrast is 3.31 to 1.0. (b) Index contrast is 3.31 to 3.21.

The BPM calculations do not provide a clear understanding of the behaviour of the device. We propose here an approximate three-Gaussian-beam model to explain the beam focusing properties. The input field is split in three parts: an upper beam which reflects at the upper elliptic interface, a central beam which does not reflect and a lower beam which reflects at the lower elliptic interface. The three beams can be approximated as Gaussian beams. If the input beam would be a point source, the beam waists of the focusing upper and lower beam would occur at the geometrical focus point. For an input beam of finite width however, the beam waists of both beams will occur closer to the elliptic coupler and will no longer be centralised on the axis. However due to symmetry both beams interfere constructively on axis independent of longitudinal position and this partly explains the relatively long depth of focus. Off axis one expects an interference pattern. However the fringes are just outside the main lobe of the focused beam in the example of Fig. 2 because the beam angles with
respect to the axis are so small that the fringe period exceeds the beam width. For larger \( b \) values the interference fringes show up. In this explanation the central beam has been neglected, which is reasonable for the large \( a/b \) ratios considered here.

The approximate Gaussian beam analysis can be elaborated analytically and allows to estimate the width and position of the focused beam as a function of the parameters of the elliptic beam converter and of the input beam [5]. It should be noted that the same analysis can also be used for parabolically shaped structures.

3. EBC DESIGN AND FABRICATION

On the basis of BPM calculations and the three-Gaussian-beam analysis, we have designed EBC structures that will convert the mode of a 2 \( \mu m \) wide waveguide into a 6 \( \mu m \) wide intensity pattern. The structure with \( a=230 \ \mu m \) and \( b=8.0 \ \mu m \) as described earlier (Fig. 2) is actually one of the designed structures. The beam is focused at a distance of 150 \( \mu m \) beyond the half ellipse. Apart from this structure EBC structures with other \( b \) values (6.5, 7.0, 7.5 and 8.5) are also included on the mask design. The waveguides are similar to those in [6] and consist of MOVPE-grown layers: a 1.3 \( \mu m \) InGaAsP core layer of 0.6 \( \mu m \) thickness embedded between InP layers. The lateral waveguide is produced by a deep RIE-step all through the quaternary layer. Fig. 3 shows an optical micrograph of some of the fabricated EBC structures. The devices were cleaved at a distance of 150 \( \mu m \) from the half ellipse in the slab region.

4. EXPERIMENTAL RESULTS

Light from a 1.55 \( \mu m \) laser was coupled by a microscope objective lens into the input waveguides. The light at the output facet is observed with an infrared camera. In Fig. 4 the measured near field intensity pattern of the output field at the facet is compared with BPM results for the structure with \( b=7.5 \ \mu m \). The correspondence between calculated and experimental results is very good. For the 8.5 \( \mu m \) device, the interference fringes start to be visible, whereas for the 7.0 \( \mu m \) device the focused beam is wider due to the smaller aperture, as expected theoretically. These results are independent of polarisation.
5. CONCLUSIONS

An elliptically shaped beam width converter has been proposed and analysed. The properties are explained on the basis of a three-Gaussian-beam model. Experimental results of devices made on InP show a very good correspondence with the theoretical predictions.

6. ACKNOWLEDGEMENT

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SIMPLE POLYMER TECHNOLOGIES FOR MULTIMODE INTEGRATED OPTICS

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Abstract
Economical technologies for the fabrication of multimode polymeric waveguide devices such as power splitters are presented. One approach utilizes the photolithographic delineation and UV-curing of 100 µm ethoxylated Bisphenoldimethacrylate (PLEX 6833™) layers on PMMA-substrates. For larger core cross-sections up to the mm-range high pressure injection on patterned PMMA substrates is employed.

1. Introduction
The current interest in multimode polymeric waveguide devices aims at optical data distribution and optical interconnect [1]. Various technologies for polymeric waveguides have been developed [2-4]. The substrate injection molding technology combined with groove filling is very suitable for single mode devices [5,6], but difficult to implement for multimode devices because of shrinkage effects. Here, we present two new approaches for the simple and economical fabrication of multimode waveguide devices. On one side we utilize a photolithography delineation and subsequent UV-curing of ethoxylated Bisphenoldimethacrylate on PMMA. This approach is treated in detail. On the other hand waveguides with a large core cross-section up to the mm-range are fabricated by high pressure injection of thermally curable polymers onto patterned PMMA substrates.

2. Waveguide fabrication
The main fabrication steps for UV-cured waveguides are shown in Fig. 1, which demonstrates the simplicity of this process. Best results have been achieved using PMMA-substrates (ICI, Perspex 00B™, InD 20=1.4891) spin-coated with PLEX 6833™ (RÖHM, InD 20=1.5567) containing 3% photoinitiator DAROCUR 1173™, which was cleaned by centrifugation. The dimensions of the waveguides varies between 20 µm to 100 µm in width and 20 µm to 60 µm in height, which allows a quite uncritical coupling to LED’s and photodiodes. Samples were patterned using common UV-lithography. The distance between mask and substrate was about 200 µm to protect the mask from the liquid monomer. The exposure time was in the range of 10 to 15 min. (intensity: 9,0 W/cm²). After exposure the samples were developed using acetone. This is a critical step, because it is necessary to dissolve all unexposed parts from the substrate without deteriorating the waveguides. After development the samples were fully
cured with UV-light for 20 min. Fig. 2 shows the SEM photo of an unclad PLEX 6833™
waveguide on PMMA.
To protect the waveguides a special curable cladding-mixture \((n_2=1.4975)\), which consists of
MMA/PMMA, EGDMA and DAROCUR 1173™, is used as a cladding layer. This leads to a
numerical aperture of 0.1808. The samples were cut and polished to achieve low fibre-chip
losses. The waveguides can be integrated on PCB's for e.g. optical interconnects. Another
application are low-cost fibre coupling devices such as 1x2 or 1x4 power-splitter.
For larger cross-sections we employed patterned PMMA substrates (fabricated by e.g.
injection molding) and the high pressure injection of a thermally curable acrylate. Fig. 3 shows
a microphoto of a 1 x 1 mm² waveguide core.

Characterisation of UV-cured waveguides and devices
The spectral attenuation of the waveguides was measured between 600 nm and 1000 nm using
a white-light-source/monochromator set-up. The waveguides were coupled to standard
50/125 µm GI fibers. The fibre coupling losses were eliminated by applying a cut-back
technique. The results of Fig. 4 indicate an intrinsic attenuation (absorption and scattering) of
0.2 dB/cm at a wavelength of 633 nm. The exess loss of waveguide bends was determined for
S-bends with 0.2 mm waveguide offset. The measurements at 633 nm wavelength (Fig. 5)
indicate negligible bending losses for \( R \geq 8 \) mm bending radius. Power splitters and star
couplers are the most important multimode waveguide devices. We fabricated 1x2 and 1x4
power splitters designed for a uniform splitting ratio. Fig. 6 demonstrates the output intensity
distribution of a 1x4 power splitter indicating a high level of uniformity.

Acknowledgement
We would like to thank RÖHM for supplying PLEX 6833™, CIBA-GEIGY for supplying the
UV-initiator DAROCUR 1173™ and ICI for supplying the PERSPEX 00B.

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1. Spin coating

![Spin Coating Diagram]

2. Photolithography

![Photolithography Diagram]

3. Development/UV-curing

![Development/UV-curing Diagram]

4. Cladding

![Cladding Diagram]

Fig. 1: Fabrication steps for UV-curable waveguides

Fig. 2: SEM photo of an uncladded UV-cured (60 x 70 μm²) waveguide

Fig. 3: Microphoto of a 1 x 1 mm² waveguide core (high pressure injection)
Fig. 4: Spectral attenuation of cladded PLEX 6833 waveguides with 0.2 dB/cm at 633 nm wavelength (60x70μm² waveguide core)

Fig. 5: Bending losses as a function of the bending radius at 633 nm wavelength (60x70μm² waveguide core)

Fig. 6: Nearfield of 1x4 power splitter (UV-cured waveguides)
LOW TEMPERATURE FABRICATION OF GEO₂-DOPED SILICA OPTICAL WAVEGUIDES USING MICROWAVE PLASMA.

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Abstract

A new low temperature silica deposition process based on the use of both chloride reactants and microwave plasma activation has been developed. Issued channel waveguide losses as low as 0.2dB/cm at 1.55µm have been achieved at 600°C without any additional consolidation or annealing steps. High potentialities in terms of thickness and refractive index homogeneities, reproducibility and deposition rate have been also demonstrated.

Introduction

The massive introduction of the optical fibre in the local access network will need numerous basic functions such as Y splitters, directional couplers, MUX/DEMUX, filters.... Integrated optical components, based on the silica on silicon technology [1] are very attractive in achieving low costs and mass production, as well as good performances and high functionalities in the optical telecommunication wavelength range (1.3µm-1.6µm).

To form the basic single mode channel waveguide, silica on silicon technology combines the deposition of doped silica layers (buffer, core and over-cladding) and a Reactive Ion Etching (RIE) process. Conventional deposition methods require at least one or two additional high temperature stages. In Flame Hydrolysis Deposition (FHD), consolidation at a temperature in the range 1200-1300°C is necessary to vitrify and to dry the porous glass layers [2]. In Plasma Enhanced Chemical Vapor Deposition (PECVD) and in Low Pressure Chemical Vapour Deposition (LPCVD), thermal annealing steps around 1000°C are required to remove absorption peaks associated with SiH, NH and OH bonds and to improve propagation at 1.55µm [3] [4].

This paper deals with a new low temperature deposition process based on the use of chloride reactants and microwave plasma reactor. The combination of SiCl₄ and GeCl₄ reactants with microwave plasma activation provides directly vitrified and low OH content layers at a temperature around 600°C. Other main advantages of this method which is derived from the optical fibre technology [5], are a high deposition rate and doping flexibility. Particularly the GeO₂ doping leads to low propagation losses and UV photoinduced grating capability.

Deposition technique

The principle of the microwave plasma reactor has been previously described [6] and is shown in Fig 1. An O₂ plasma is created and sustained in the plasma chamber by a 2.45GHz surface wave thanks to a microwave launcher. The reactants (SiCl₄ and GeCl₄) and the carrier gas (O₂) are fed into the deposition chamber in the O₂ plasma afterglow by a ring feeder. The silica deposition occurs by heterogeneous reactions [5] on the 4-in Si substrate which can be heated by IR lamps through a quartz window. The pressure during deposition is monitored in the range of 10 to 100 mT under a total flow up to 200 sccm by
the mean of a Turbo Molecular Pump (TMP). The typical experimental conditions are given in the table 1. Under these conditions, the deposition rate reaches 2200 A/min.

**Deposited layer properties**

Different measurements were carried out to characterize the SiO₂ on Si films deposited according to the conditions of Table 1. Results are listed in Table 2. The value of the silica refractive index, measured by the prism coupling method, is 1.457 at 632.8 nm which is similar to that of fused silica [7]. Furthermore, as shown by IR stretching frequency and wet etching rate measurements, structural properties (stoichiometry and density) are close to those of the thermal silica. Values of 300 and 450 ppm, for hydrogen and chlorine contents respectively, have been found by SIMS analysis. We assume that the lack of a loading chamber is responsible for an OH contamination because vacuum has to be broken and the reactor opened at each run. The related additional absorption loss could be estimated at a few 10⁻³ dB/cm at 1.3 μm [8] and therefore could be neglected. The Cl₂ content is due to the absorption of Cl₂ in the layers provided by the chlorides dissociation during the plasma deposition. Cl₂ content is strongly dependent on the substrate temperature but a few thousand ppm do not affect the optical properties in the interesting telecommunication wavelengths [9].

The GeO₂ doping, and consequently the refractive index value, is controlled by the GeCl₄ flow rate during the deposition. It can be deduced from Hammon data [10] that efficiency of GeO₂ incorporation is very closed to 100% at 600°C. This result agrees very well with a GeO₂ incorporation efficiency model that we have developed [11] and which shows a drop in efficiency above 800°C at 30 mT.

Thickness and refractive index uniformities are respectively better than ±1.5% and ±0.03% on a 4-in wafer. The stress, calculated from the bow measurements of the wafer, is compressive and its low value could explain why we can deposit thick layers without the formation of cracks.

**Planar and channel waveguide characteristics**

To demonstrate low loss potentialities, channel waveguides have been made. Their structure consists of a 12 μm buffer layer of 2% GeO₂ doped silica, a 7μm core layer of 8% GeO₂ doped silica and finally a 6 μm top layer with the same composition as the buffer. The two first layers are routinely deposited in one step with reproducible layer parameters from run to run. Then the core is defined by RIE using CHF₃/C₂F₆ plasma before the top layer deposition.

These channel waveguides with a refractive index difference between core and cladding of 6*10⁻³ show propagation losses of 0.3 dB/cm at 1.3 μm and 0.2 dB/cm at 1.55 μm.

**Conclusion**

We have reported a new low temperature silica on silicon deposition process. Deposited layers show low OH content without any additional high temperature stage. Waveguides losses as low as 0.2 dB/cm at 1.55 μm and deposition rates over 2000 A/min make this deposition method for passive integrated optical components very attractive for optical communications.
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References


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<th>Pressure</th>
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<tr>
<td>SiCl₄ rate</td>
<td>25 sccm</td>
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<tr>
<td>Substrate temperature</td>
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</tr>
<tr>
<td>Microwave power</td>
<td>2 kW</td>
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</table>

**TABLE 1** Typical experimental conditions
Structural properties
IR stretching frequency 1080 cm⁻¹
Stress 0.9 \(10^9\) dynes/cm
P-etch rate 3.5 A/s
[HF(40%):HNO₃(65%):H₂O=3:2:60]

Optical characteristics
Index at 0.6328 μm wavelength
vs. GeCl₄/SiCl₄ ratio
0 %  1.457
2 %  1.461
8 %  1.467

Impurity contents
Hydrogen 300 ppm
Chlorine 450 ppm

Uniformity (4-in wafer)
Thickness ±1.5 %
Index ± 0.03%

TABLE 2 Deposited Layer properties

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**FIGURE 1** Schematic diagram of the deposition system
Novel RIE-process for high quality InP-based waveguide structures

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Abstract
We have developed an alternating InP-etch (CH₄-based) and polymer descum-step (O₂-based) RIE-process using SiO₂-mask, to fabricate extremely low loss ridge waveguides in InP/InGaAsP-based material. The etch and descum-time have been optimized to obtain a smooth ridge. The optimal process parameters are influenced by the thickness of the SiO₂-mask. For low-contrast waveguide structures (shallow ridge) the damage in the etched InP-surface can be removed selectively by wet chemical treatment. High contrast waveguides (deeply etched through the InP-cladding and the InGaAsP-film) have been fabricated and characterized.

Introduction
The basic building block of integrated optics is a waveguide, hence, the quality of the circuits are determined by the quality of the waveguides. The demand on the processing increases, because by the progress of epitaxial techniques high quality material with low intrinsic loss becomes available. One of the most critical steps in the fabrication of waveguides is the reactive ion etching process (RIE) to form a ridge for the lateral confinement. Since Niggebrügge et al. [1] discovered the ability to etch InP/InGaAsP-based materials in a RIE reactor using CH₄/H₂-mixture many opto-electronic and photonic devices have been fabricated using this, or a slightly modified, technique.

Polymer deposition:
The main advantage using the CH₄-chemistry is the high etch selectivity between masking materials and InP due to deposition of hydrocarbon polymer on the mask. The deposition on the edge is not homogeneous, therefore the roughness of the sidewalls increases during etching introducing vertical striations [2, 3, 4], which strongly increases the waveguide losses by scattering. Hence, to achieve low loss, it is essential to control the amount of polymer deposition.

A method to control the polymer deposition is to apply a multiple InP-etch (CH₄-RIE) and polymer descumming (O₂-RIE) sequence [4,5]. The polymer deposited during InP-etch can be sufficiently removed by a short descum process to achieve smooth ridge.

Low-contrast waveguides and surface damage:
In the commonly used waveguides, a shallow ridge is etched in the InP cladding only (fig. 1a). In
that case there is a field along the vertical ridge and the horizontal surfaces close to the ridge. Hence, scattering on sidewall and surface-roughness contributes to the losses [6]. In addition the absorption of the on the near-surface damage, which occurs with all dry etching processes [7] contributes to the loss. An indication of this contribution is that we have observed a lower loss figure for the TE compared to the TM-polarization if the surface next to the ridge is InP [8], but this difference disappeared if the ridge is etched slightly into the InGaAsP [9]. Therefore, we have investigated the selective removal of the damage after RIE by the recovery of photoluminescence (PL) intensity by wet chemical treatment.

High contrast waveguides by deep etching:
In a high contrast waveguide (fig. 1b) etching has to be performed through the InGaAsP-film in the InP-buffer. The optical modes are fully confined by the ridge. This opens the opportunity to make very small bendings, but the attenuation is mainly determined by scattering on the sidewalls roughness. Deeply etched waveguides have been fabricated and characterized.

Experimental
Development of InP-etch
On 2"-wafers of InP (Nippon Mining) SiO2-layers of 70 or 210 nm thickness were deposited by sputtering. Lines from 1 to 20 μm wide were patterned along the <110> direction with photoresist and transferred into the SiO2 by CHF3-RIE. The resist was removed using oxygen plasma. Before etching, the substrates were dipped in 10%-H3PO4 to remove oxides from the surface. The InP etching was performed in a RIE-reactor. Deeply (~1.5 μm) etched ridges were made and the smoothness of the sidewall was deduced from SEM-micrographs.

CH4/H2 or CH4/He process:
We investigate RIE using CH4/H2- mixtures and by employing different process conditions (flow rate, pressure and power). We are able to achieve a smooth surface at an etch rate between 15-50 nm/min. The CH4-concentration window for optimum etching is very narrow (between 18-22% CH4) and is limited by two factors: Below the optimal CH4-concentration the etched surface appears to be rough due to the reactivity of hydrogen, which is preferentially removing phosphorous. Above the optimal CH4-concentration the roughness increases due to polymer deposition. Typically, we use a process CH4:H2 = 20:80 SCCM (60 mTorr, 0.5 W/cm2) with etch rate Re = 40 nm/min and a polymer deposition rate Rp = 30 nm/min.

A reduction of Re/Rp can be achieved by replacing H2 by He. The "standard" process uses CH4:He = 4:50 SCCM (60 mTorr, 0.4 W/cm2) with Re = 18 nm/min and Rp = 6 nm/min. This process produces smoother ridge compared to the CH4/H2-process but a rougher horizontal surface. The replacement of H2 by He for successful fabrication of submicron grating has been described and analyzed [12].

CH4/He-etch and O2-descum process:
The InP was etched using our "standard" CH4/He process. For descumming an O2-process with 50 SCCM under the same process condition was chosen. The maximum depth of the InP etching of each
step must be less than 200 nm (t_d = 10 min). Otherwise horizontal steps along the ridge, which correspond to the switching of etch to descum-steps, were formed. We performed deep etching with different descum-times. The SEM-micrographs (fig. 2a and 2b) are of samples with 70 and 210 nm thick SiO_2, which are simultaneously 8x etched for t_e = 10 min and descummed for t_d = 60 sec. A part of the 70 nm thick SiO_2-mask (fig. 2a) is still left. No polymer is on the top and the sidewall is very smooth. The bright striations on the side wall are residual polymer. At shorter descum-times the etched surfaces are smoother, whereas the wall is getting rougher. At longer descum-times the erosion of the SiO_2 is too high, which limits the maximum etch depth. Using thicker SiO_2-mask only can not solve this problem, because the effective polymer deposition increases too (fig. 2b).

**Removal of damaged InP-surface:**

We determined the suitable etchant to remove the damaged InP-surface selectively. Pieces (15 x 15 mm²) of InP-wafer were immersed in the chemical solutions for prolonged time. The time dependence of the mass reduction was determined gravimetrically using a micro balance. We selected concentrated sulfuric acid (H_2SO_4), which has only a very low etch rate R_e = 8.5 nm/min. The effectiveness of the damage removal was determined by photoluminescence (PL) recovery measurements, which is very sensitive for surface recombination processes. Pieces (15 x 15 mm²) were etched in the RIE to a depth of 1 μm. These samples show PL-intensities < 1% compared to untreated InP. The recovery of the PL-signal is shown in fig. 3. Treatment by H_2SO_4 for 120 sec can fully remove the near-surface damage.
Waveguide fabrication

The waveguides were fabricated in a double-heterostructure (DH) grown by MOVPE [10] on a 2 inch SI-InP substrate: 1.2 µm InP-buffer, 0.5 µm InGaAsP(\(\lambda_g=1.3\) µm) and 0.4 µm InP-cladding. Deeply etched waveguides, 0.1 µm in the InP-buffer, of different widths were fabricated and waveguide losses were measured (fig. 4). In the first experiments (deep 1) the loss is high and steeply increases as the width decreases. Recently, we have measured lower losses for deeply etched waveguides (deep 2) [11]. This result indicates, that it is possible to reach the slab loss at a width of 3 µm. The shallow etched waveguides reach the slab loss at a width of 2 µm [6].

Conclusions

We have developed an InP/InGaAsP etching process to produce very smooth ridge waveguides. The process uses alternating etching and descumming steps, which are optimized separately. High quality, low loss, devices have been fabricated with shallow etched ridges [8,9] and with deeply etched ridge [11]. This letter demonstrate the miniaturization of optical components.

References

REALISATION OF AN INTEGRATED ALL-OPTICAL NON-LINEAR MACH-ZEHNDER INTERFEROMETER


Abstract
The so-called π-conjugated polymers have promising properties for application in all-optical devices. They offer the possibility of relatively large non-linear coefficients, response times below 1 ps and the possibility to form large area thin films suitable for integrated optics. With the OANS-polymer of Akzo-Nobel, an all-optical device based on a non-linear Mach-Zehnder interferometer (MZI) is designed, realised and tested. The device exhibits correct linear behaviour. Measurement results with high intensities indicate non-linear behaviour, thermal damage however of the end-faces prevents the use of light intensities necessary for complete switching.

Introduction
In telecommunication systems, the transport of data by optical fibres is of growing importance. These fibres offer possibilities for data transport over long distances with an enormous bandwidth. Data processing performed in the electrical domain limits the bandwidth and makes translations between the optical and the electrical domain necessary. Third-order non-linear optics offer the ability of avoiding these translations and increasing the available bandwidth.

The refractive index of a non-linear medium depends on the intensity of the propagating optical field according to:

\[ n = n_0 + n_{2I} I \]

where \( n_{2I} \) is the intensity dependent refractive index (IDRI). A MZI consists of two Y-junctions which are connected as shown in figure 1. The light entering the MZI is splitted and recombines in the second junction. If the recombined modes are in phase, the zero-th order mode of the exit channel will be excited. If the two modes arrive with a phase difference of \( \pi \) radians, the first order mode will be excited or, if the output channel is monomode, the energy will be coupled to radiating modes. In this case, the transmittance of the MZI can be described by:

\[ I \propto A \left( B + \frac{1 + \cos \phi}{2} \right) \]

where \( \phi \) is the phase difference between the two modes of both arms. A and B are depicted in figure 5. The phase difference consists of three parts: a linear part due to differences between the two arms, a thermal part and a non-linear part due to the intensity of the propagating fields:

\[ \phi = \phi_0 + \Delta \phi_h + \Delta \phi_{NL} \]

The phase difference induced by the optical power of the propagating mode reads:

\[ \Delta \phi_{NL} = \frac{2 \pi}{\lambda} \left[ \int_{L_1}^{L_2} N_{2P,2} P_2(z) \, dz - \int_{L_1}^{L_2} N_{2P,1} P_1(z) \, dz \right] \]

where \( z \) is the propagation direction, \( L \) and \( P \) are the length of and the power propagating in the two branches and \( N_{2P} \) is defined according to:

\[ N_{eff}(z) = N_{eff,0}(z) + N_{2P} \cdot P(z) \]
$N_{2P}$ can be interpreted as an effective area of the propagating mode\(^3\) times the IOR.

From equations 2, 3 and 4 can be seen that the thermally induced fringes will shift if the optical power of the propagating mode changes. Alternatively, if the thermally induced phase is fixed, an optical pulse travelling through the MZI will be deformed. With the assumption of Gaussian pulses this deformation can be calculated for a range of intensities. Both effects are measured in our experiments in order to analyse the non-linear behaviour of the MZI.

Simulations of two MZI's with an extinction ratio of infinity and 10dB are given in figure 5. The pulse shape deformation of a MZI reaches its theoretical maximum for an infinite extinction ratio at $\phi=\pi$. At this point the transmission is zero. However, in general it can be stated that a large extinction ratio yields a large pulse shape deformation.

To obtain a switching behaviour in the MZI, a phase difference between the light propagating in the two arms must be introduced by designing an asymmetric MZI\(^4\,^5\). We used a MZI with a linear and a non-linear branch. In this case and with the assumption of Gaussian pulses, equation 4 can be simplified to:

$$\Delta \phi_{\text{eff}} = \frac{2\pi L N_{2P} P_{\text{eff}}}{\lambda \sqrt{2}}$$

$P_{\text{eff}}$ is the weighted average of the peak power over the length of the non-linear branch in order to take the attenuation into account.

**Realisation**

The MZI is realised\(^6\) with SiO\(_x\)N\(_y\) technology\(^7\). The cladding of one of the two branches of the MZI is removed. This window is filled with the non-linear polymer as shown in figure 1. The end faces of the devices are made by cleaving the silicon substrate along a crystal axis.

![Figure 1](image1.png)

*Figure 1* Side and top view of the window etched in the cladding of the waveguide in order to define the region where non-linear interaction takes place. The hatched region is the non-linear material. The rectangular region in the top view is the window.

![Figure 2](image2.png)

*Figure 2* The channel structure used for the Mach-Zehnder interferometer. The intensity profiles give an impression of localisation of the electrical field.

The slab waveguide is designed in such a way that a relative large amount of the propagating field is in the (non-linear) cladding. This is done by applying a high-refractive index Si\(_3\)N\(_4\) layer on top of the guiding layer which "pulls" the field towards the cladding. This layer is also helpful by etching the window because the low index PECVD SiON ($n=1.65$) is etched 50 times faster than the high index LPCVD Si\(_3\)N\(_4\) layer\(^8\). Channel waveguides with a width of 2.5\(\mu\)m are realised. The effective index contrast for the waveguide definition is 0.004. The Y-junctions are S-curved with a radius of 50mm. The DANS polymer is spin coated on top of the waveguides with a thickness of 1.5\(\mu\)m.
Results

In order to obtain information on thermal behaviour, the MZI is illuminated with a Halogen lamp in order to increase the temperature of the substrate slightly. Results are shown in figure 4. The phase is recalculated from the transmitted intensity.

![Optical response of an MZI due to a small temperature distortion applied with a halogen light source together with the calculated phase change \( \phi_0 + \Delta \phi_{th} \) between the two branches.](image)

The pulse deformation measurements are performed using the set-up of figure 3. The laser is a Q-switched mode-locked laser emitting pulses with a fwhm of 180ps at \( \lambda = 1053 \text{nm} \). Because the thermal drift of the MZI's is very large, the system can only be considered stable during a few seconds. In this small time one trace of the output pulse together with the input pulse can be recorded with a sampling oscilloscope. For this reason, time averaging is impossible. However, in the frequency domain the pulse width information is preserved. The temperature of the MZI is increased a few degrees and subsequently the heater is switched off. During this process the oscilloscope takes traces. From the ratio between the amplitude of the signal pulse and the reference pulse it is deduced at which point of the sinusoidal fringe the data is taken. The ratio of the FWHM of the reference and the signal pulse is calculated from the observed bandwidth of the pulses. The best fit to the model, is obtained for induced phase shift of 0.5 rad for a peak power 11.3W and is shown in figure 6. The non-linear interaction length was 1cm.

![Simulations of the pulse shape deformation of two MZI's. The pulse width at low intensity is 10(A.U.)](image)

![Pulse shape deformation as a function of the initial phase of an MZI. The dashed line shows the cosine behaviour of the transmission while the solid line is the best fit to the data points. The triangles are data points taken while heating the device, the circles are data points taken during cooling down.](image)
The value of $n_2 I$ can be calculated with the aid of equation 2 and 4 and results in $12 \times 10^{-18} \text{m}^2/\text{W}$ which is a reasonable value compared to the literature value $n_2 I = 7 \times 10^{-18} \text{m}^2/\text{W}$ as given by Marques\(^9\).

In the first method, from each pulse train leaving the laser one pulse is selected with the electrooptical modulator. However, it is possible to select only one out of every three pulse trains. Because the suppression by the EOM is not perfect, suppressed pulse trains will leave the EOM at a certain frequency while the high intensity pulses arrive at one third of this frequency. With two lock-in amplifiers both signals can be measured. A phase change is observed of $1.7 \pm 0.5^\circ$ for a peak power of $1.5 \text{ W}$ and a non-linear interaction length of $2 \text{ cm}$. The value of $n_2 I$ can be calculated with the aid of equation 6 and is $4 \times 10^{-18} \text{m}^2/\text{W}$ which is in the same order of magnitude of our previous value and the literature data.

During these experiments it appeared to be very difficult to avoid deterioration of the end faces of the waveguides. For these experiments we used an input peak power of $200 \text{ W}$ and the coupling efficiency was calculated to be about $5\%$. Slightly higher input powers were enough to burn holes in the end face which were observed with a microscope. V-shaped holes point to thermal damage.

**Conclusions**

We described an integrated optics non-linear Mach Zehnder interferometer. The correct working of the MZI as an optical linear device could be demonstrated by introducing a thermally induced phase shift. The extinction ratio of the MZI is $-6\text{dB}$.

For both measurement methods it can be stated that the intensity in the waveguides is quite low which makes the interpretation of the measurements difficult. The measured values for the non-linearity of $n_2 I = 4 \times 10^{-18}$ and $n_2 I = 12 \times 10^{-18} [\text{m}^2/\text{W}]$ are in good agreement with literature.

In order to perform more accurate measurements the intensity in the non-linear waveguide should be increased. During our experiments the intensity was limited by the damage of the end-face of the waveguides. The intensity can be increased without further damage in two ways. The first possibility is to make use of materials with a higher damage threshold than SiON. Second, the coupling of the optical power into the MZI could be done with the aid of a tapered channel in front of the MZI.

If a non-linear material is designed with a non-linearity two orders larger than the polymer used (there are encouraging results reported on poly-9-BCMU)\(^10\) combined with a comparable linear absorption a Mach-Zehnder interferometer can be designed which is operated by pulses with a peak power of $1 \text{ W}$ and a pulse width of $5\text{ps}$. The resulting device would be compact, cascadable, requires switching energies of $5\text{pJ}$ and is capable of handling bit rates exceeding $100\text{Gb/s}$.

**References**

Theoretical Investigation of Electro-Optical Switches with very Low Crosstalk

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Abstract
The crosstalk or switching contrast of the digital optical switch (DOS) is analysed and a new architecture to enhance the contrast from -20dB to -40dB is proposed. An electro-optical mode converter is used for compensation of the undesired mode. Some theoretical results on vertical DOS are discussed.

Introduction
The all-optical multiwavelength (WDM) network is a prime candidate for future "information highways". Space switch matrices are key components in an optical cross connect. For the construction of larger networks, switching nodes have to be cascaded. Thus coherent crosstalk of the individual switching component is a problem, where signals from sources of nominally the same wavelength can interfere coherently if their frequency separation is within the receiver bandwidth. One main disadvantage of electro-optical switches is the high crosstalk or low contrast of the output ports in the order of about -20 dB. If for example a signal has to transmit 100 stages, a crosstalk of about -40 dB is necessary. To realize a higher crosstalk suppression, cascading of identical switches is an often used solution with the disadvantage of increasing the "device length". Here we will analyze the limiting factors of the crosstalk and propose a compensating scheme for digital optical switches (DOS). The method increased e. g. a -20 dB contrast switch to -40 dB, without increasing the length dramatically.

Device Analysis
In this discussion we will focus on electro-optical switching matrices, thus excluding mechanical switches or switches with moving parts. Practically used electro-optical switches for switching matrices have to fulfill the following essential conditions among others: to be polarization independent, to have a short device length for the integration of a large number of switches on one chip, to be wavelength independent in a distinct region, to have low loss, to have very low crosstalk.

At first we have to discuss the influence of the physical switching concept on these parameters, which are two mode interference (TMI), total internal reflection (TIR) and adiabatic waveguide coupling in the digital optical switch (DOS).

<table>
<thead>
<tr>
<th>TMI</th>
<th>TIR</th>
<th>DOS</th>
<th>CRDOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>polarization independence</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>wavelength independence</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>short device length</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>low loss</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>material available</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>very low crosstalk</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Comparison of different device principles for electro-optical switches

Tab. 1 summarizes the result. The TIR switch has the possibility of very short device length and very low crosstalk by proper design of the length of the lower refractive index region, but materials with very high refractive index changes \( \Delta n_{BO} >0.3 \) and low loss are not available.

Experimental investigations show, that TMI and DOS have crosstalks in the order of -20 dB. In the first case we have to implement precise power splitting (the difference of two big numbers), which is known to be fabrication process dependent. So far we see no way to improve that switch.
Conventional DOS
The DOS uses the adiabatic coupling behaviour of a mode travelling along an asymmetric X-cross, which is composed of two different waveguides (Fig. 1a). A mode entering the waveguide with the higher mode index $n_{\text{high}}$ generates in the two mode section in the middle of the device the fundamental mode and couples to the high output port. On the other hand a mode entering the low mode waveguide generates the second mode in the middle part and leaves on the low output waveguide. Switching is performed by introducing a refractive index change $-\Delta n_{\text{ EO}}$ to invert the relation of high to low waveguide. The switch is sensible to incomplete mode conversion and to mode conversion by other reasons like waveguide disturbance due to electrodes, refractive index changes, bends and fabrication errors. Fig. 2 and 3a demonstrate the incomplete mode conversion in a DOS in a 1-dimensional BPM simulation, using waveguide parameters relevant for InP related materials. The existence of first and second order modes in the center part of the device results in a ripple in the power transfer function of the individual waveguides. (Fig. 2)

Another source of crosstalk is the well known generation of radiation modes, which will accompany the waveguides and can be captured again in bends. The DOS tends to support ARROW modes, because the parallel output waveguide section represents an ARROW waveguide. These leaky modes can be generated in an imperfect bending section of the device.

Thus a crosstalk floor can not be avoided in the conventional DOS configuration without modifications of the switch architecture.

Crosstalk Reduced DOS (CRDOS)
On the basis of the above discussed mechanism of the generation of crosstalk, we can easily give a device architecture to further reduce the crosstalk by compensation. We have to generate in a controlled way another wave of the unwanted mode of same amplitude but phase shifted by $\pi$. Thus at the end of the device both waves cancel each other, if both amplitude and phase fit to the device crosstalk. As mode converter we use an electro-optically generated and controlled refractive index change $\Delta n_{\text{ EO}}$ in form of a special grating structure, as has been described in the Synthesized Grating Structures (SYNGRA) tuning filter concept. Here we can easily control the amplitude of the generated wave by the number of grating periods (fixed) and the voltage $U$ at the electrodes. We use the fact that the coupling efficiency $\kappa$ is proportional to the voltage $U$: $\kappa \propto \Delta n_{\text{ EO}} \propto U$. As has been shown earlier, we can control the phase $\phi$ of the generated wave between $0 < \phi < 2\pi$ by using 4 electrodes per period $\Lambda$ and using the relation:

$$\kappa(i) = \frac{\kappa_0}{2} \left[ 1 + \sin \left( 2\pi \eta + \frac{\pi}{2} i \right) \right]$$

where $i$ is the number of the electrode and $\eta$ a phase control parameter. For phase control in general, we need four different voltages. This mode converter is placed in the center of the device. (Fig. 1b). Please notice, that the physical nature of the electrode cross section of both - conventional DOS and mode converter - is identical. They differ in electrode length and used voltage.

Fig. 2 shows the results of a BPM simulation of a crosstalk reduced digital optical switch (CRDOS), where less than -40 dB crosstalk have been accomplished with 2 periods and a $\Delta n_{\text{ EO}}$ of 0.003. We have to notice, that the crosstalk compensating grating depends on the input port used, which results in the necessity to adjust it if different input ports are used.

This new compensating technique has the advantage to be nearly wavelength and polarization independent, because the beat length of the periodicity is not critical due to the low number of periods. The grating has to be positioned to establish nearly identical coupling coefficients for both modes. By arguments based on bidirectional eigenmode expansion techniques we know that both overlap integrals can be made similar. The influence of wavelength variation is shown in Fig. 4 showing a flat response over the width of the EDFA window. This broadband behaviour is obvious, because the number of periods is only two.

For the introduction of the mode converter into the DOS we need only an additional length of $2 \times 18 \mu m$. The necessary length increase can be neglected.
This combination of a DOS with a mode converter has the advantage that it cascades two different physical effects, both with a switching effect in the order of $10^2$ or -20 dB leading to about -40 dB for the combination. The length of the mode converter is very short and it is used only as a correction device. Experience so far tells us, that a single physical effect with a switching resolution of -40 dB is not known.

To reduce the influence of radiation and ARROW modes we have introduced lossy regions outside and in the center between both waveguides at input and output port.

Vertical DOS

The DOS in general is a very long device due to the adiabatic mode behaviour. For integration a short device is needed. Thus we investigate the possibility of using high contrast waveguides. For technological reasons a vertical DOS configuration is preferred, where the two waveguides lie one upon the other. To build a X-cross, we have to use ramp generating techniques, as have been developed for the waveguide taper formation (e.g. dose controlled e-beam development and dry etching techniques).

A principal drawing is shown in Fig. 1. Using waveguide layers of $\lambda_G = 1.3 \mu m$ and $1.05 \mu m$ and an $\Delta n_{SO}$ of 0.030 for switching a device length of $L = 900 \mu m$ has been calculated. Using a tree structure for the matrix with mirrors to reduce the waveguide connections, a 32x32 strictly non-blocking switching matrix can be realized on a 2 inch wafer of InP.

Conclusion

We have analysed the crosstalk behaviour of electro-optical switches and we propose a new crosstalk compensating technique based on the tunable mode converter concept. It has been shown that a -20 dB crosstalk DOS device can be enhanced to -40 dB. Vertical DOS devices seem to be advantageous for the integration of larger switching matrices, if the ramp formation technology of waveguide taper devices can be accomplished.

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5. H.-P. Nolting, M. Gräwert, "Theoretical Investigation of a Tunable, Narrowband, Electro-Optical Filter with Low Crosstalk and a Large Number of Optical Channels.", Integrated Photonic Research 94, San Jose, CA, USA,
Fig. 1: Device architecture of conventional and crosstalk reduced DOS (CRDOS).

Fig. 2: Coupling behaviour of conventional and crosstalk reduced DOS (CRDOS).

Fig. 3: Switching characteristic and BPM simulation of coupling behaviour of conventional and crosstalk reduced DOS (CRDOS).

Fig. 4: Wavelength behaviour of conventional and crosstalk reduced DOS (CRDOS).
Integrated Mach-Zehnder InGaAsP BRAQWET Modulators

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Abstract

We fabricated InGaAsP BRAQWET (Barrier Reservoir and Quantum Well Electron Transfer) structures based on improved design and used them to make integrated Mach-Zehnder modulators. They have leakage current <1 A/cm$^2$ and require less than 1 V for achieving $\pi$ phase modulation in a 1 mm active length.

Introduction

The BRAQWET (Barrier Reservoir and Quantum Well Electron Transfer) modulator is an interesting alternative to quantum well modulators based on the Quantum Confined Stark Effect and the Wannier Stark Effect. The BRAQWET modulator is based on electrorefraction in a tunable electron-density quantum well. It has excellent high speed potential for low voltage modulators since it involves only one type of carriers (electrons) and the speed of the refractive index change is not limited by carrier lifetime. Realization of this structure in InGaAsP materials has potential for even higher speeds due to higher electron mobility. However, these materials have a lower bandgap offset, which increases enormously the leakage current of a BRAQWET device (tens of A/cm$^2$ at V = 0.5 V).

We have developed numerical and analytical models to accurately describe the electronic band structure of the BRAQWET. Using these models, we have optimized the layer composition and doping of the BRAQWET for higher robustness against doping level variations in the growth (up to $\pm$ 20% variations in doping levels). The optimized structure shows larger quantum well movement for a given applied voltage, reaching full dipping with less than 0.5V bias. It also has low leakage current (theoretically down to $10^{-6}$ A/cm$^2$ at V = 0.5 V). Here we present integrated Mach-Zehnder modulators that we fabricated using these new structures.

Growth and Characterization

Structures were fabricated by Chemical Beam Epitaxy based on the new design. The parameters of the growth are given in Table I. The structures include a single BRAQWET in the waveguide to
minimize the operating voltage and leakage current. The quantum well parameters have been chosen for operation close to 1.55 μm. Electrical measurements (Fig.1) using a sample of size 100x100 μm² show a leakage current of 30 mA/cm² and capacitance of 30 nF/cm² at bias V = 1 V. These values give about 7.5 μA and 0.75 pF for a device with w x l = 5 μm x 0.5 mm, values confirmed by high frequency (500 MHz) measurements.

### Table I  Parameters of the BRAQWET growth

<table>
<thead>
<tr>
<th>Layer #</th>
<th>Function</th>
<th>Layer</th>
<th>Band-gap (μm)</th>
<th>Thickness (nm)</th>
<th>Doping (cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Cladding</td>
<td>n-InP (Si)</td>
<td>-</td>
<td>30</td>
<td>2·10¹⁸</td>
</tr>
<tr>
<td>11</td>
<td>Cladding</td>
<td>n-InP (Si)</td>
<td>-</td>
<td>670</td>
<td>1·10¹⁸</td>
</tr>
<tr>
<td>10</td>
<td>Reservoir</td>
<td>n-InGaAsP (Si)</td>
<td>1.26</td>
<td>50</td>
<td>2·10¹⁸</td>
</tr>
<tr>
<td>9</td>
<td>Barrier-i</td>
<td>InP</td>
<td>-</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>Barrier-p</td>
<td>p-InP (Be)</td>
<td>-</td>
<td>20</td>
<td>3·10¹⁸</td>
</tr>
<tr>
<td>7</td>
<td>Barrier-i</td>
<td>InP</td>
<td>-</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>Barrier-n</td>
<td>n-InP (Si)</td>
<td>-</td>
<td>14</td>
<td>1·10¹⁸</td>
</tr>
<tr>
<td>5</td>
<td>Barrier-i</td>
<td>InP</td>
<td>-</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Quantum Well</td>
<td>InGaAs (58% Ga)</td>
<td>1.50</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>Spacer</td>
<td>InGaAsP</td>
<td>1.26</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Reservoir</td>
<td>n-InGaAsP (Si)</td>
<td>1.26</td>
<td>53</td>
<td>2·10¹⁸</td>
</tr>
<tr>
<td>1</td>
<td>Buffer</td>
<td>n-InP (Si)</td>
<td>-</td>
<td>200</td>
<td>1·10¹⁸</td>
</tr>
</tbody>
</table>

Fig.1/V and C/V plot of BRAQWET sample of size 100x100 μm².

**Optical properties and device fabrication**

Room temperature photoluminescence showed the quantum well exciton peak at E_g = 0.85 eV and the reservoir peak at E_g = 0.98 eV. The filling factor of the waveguide is 1%, smaller than in some BRAQWET structures, due to the relatively wide barrier which is necessary to reduce the leakage current. Differential absorption spectroscopy in the wavelength range 1-1.7 μm shows the Franz-
Keldysh effect in the reservoir, as well as Quantum Confined Stark effect (QCSE) and band-filling effect associated with the quantum well. We could observe the BRAQWET characteristics of band filling effects for positive voltages and QCSE for negative voltages.

We fabricated single rib waveguides and integrated Mach-Zehnder structures on the BRAQWET wafer. We used photo-lithography and reactive ion etching to define the $3 \mu m \times 0.5 \mu m$ ($w \times h$) rib. The guides and Mach-Zehnder structures were isolated by reactive-ion-etched trenches and planarized with polypimide. Electrical contacts were then deposited on top of each guide. The Mach-Zehnder structure used Y-couplers of $2^\circ$ angle to minimize losses.

The absorption of the BRAQWET modulator was measured on straight waveguide sections of varying lengths. A spectrum in the vicinity of $1.55 \mu m$ is shown in Fig.2a, the absorption is $9 \text{ cm}^{-1}$ at $\lambda = 1.55 \mu m$, due to the quantum well excitonic “tail”. The electroabsorption is shown in Fig.2b. It is quite strong for negative bias, and weakens for positive bias due to the band-filling effect.

The phase modulation was measured by an external Mach-Zehnder interferometer and the results are shown in fig.3. The change in the refractive index, calculated from the interference curve, is shown in the inset. A voltage change of $1 V$ is needed to change the phase by $\pi$ for a device $1 \text{ mm}$ long.

Conclusion

We fabricated InGaAsP/InP BRAQWET structures with much reduced leakage current and with refractive index changes similar to those found in InGaAs/InAlAs modulators. We used these structures to make integrated Mach-Zehnder modulators. Our results show that precise models combined with careful design for optimization of device parameters can increase the applicability of the BRAQWET modulator.

![BRAQWET Absorption Spectrum](image1)

![BRAQWET Attenuation](image2)

Fig.2 a. Absorption spectrum of the BRAQWET (no bias). b. Electroabsorption of the BRAQWET: strong for zero or negative bias, reduced for positive bias (bandfilling effect).
Fig. 4 Phase modulation, measured by Mach-Zehnder interferometer, as a function of applied bias. Inset: Calculated change of the refractive index, $\Delta n$, as function of bias.

Acknowledgements

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DIFFRACTION OF OPTICAL GUIDED WAVES BY MAGNETOSTATIC WAVES IN INCLINED MAGNETIC FIELD

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Abstract - Strong Bragg diffraction of guided optical waves (GOW) from magnetostatic waves (MSW) excited at inclined magnetization in yttrium iron garnet (YIG)/gadolinium gallium garnet waveguides at a frequency range (2-4) GHz is demonstrated for the first time. The maximum diffraction efficiency (DE) is more than two times greater than at normal magnetization of waveguide layers.

Introduction

The capability of using magnetostatic waves in waveguide optical devices such as rf spectrum analyzers, defectors, optical frequency shifters, light modulators and so on was recently reported [1]. This new class of optical devices called the guided-wave magnetooptical (MO) Bragg cells are potentially capable of providing desirable features similar to those of the now prevalent acoustooptics Bragg cell, but potentially with superior performance characteristic. For example, wide-band MO Bragg cell using pure YIG waveguide samples have been fabricated and operated at tunable carrier frequencies ranging from 2 to 20 GHz [2]. Such guided-wave MO Bragg cell possesses the unique advantages of very high and tunable carrier frequencies, tunable dispersion relation, large bandwidth and compatibility with monolithic microwave integrated circuits and hybrid integrated circuit technologies. However, both measured DE and measured linear dynamic range of this MO Bragg cell were less than desirable. The MO DE may be greatly improved by using bismuth-doped YIG layer, as such materials possess much higher MO coefficients than pure YIG layers [1].

Experiments and results

Figure 1: a) Geometry of interaction of GOW with MSW,
b) Diffacted light spots obtained by varying the carrier frequency of MSW from 2.0 to 2.6 GHz at a fixed inclined ($\gamma = 12$ deg.) magnetic field.

In this work we have solved this problem by using nontraditional inclined magnetization of YIG films, as the technology of making them is well known. Fig.1.a shows briefly the geometry of optical-guided wave interactions with MSW in inclined magnetic field. Fig.1.b. shows the diffracted light spots obtained for this case by varying the carrier frequency of MSW from 2.0 to 2.6 GHz at a fixed inclined magnetic field ($\gamma = 12$ deg.). The YIG waveguide with dimensions 1.5 x 1.5 cm.
and thickness 6.8 µm was inserted in air gap between pair of permanent magnets made of samarium-cobalt. Rotation of permanent magnet in XZ plane around Y axis provides the necessary regime of MSW excitation. The case of normal magnetization (γ = 0) provides the excitation of magnetostatic forward volume waves (MSFVW), at γ = π/2 - magnetostatic surface wave is excited. In any other cases MSWs have hybrid character. The MSW was generated over the frequency range (2-4) GHz using a single-element shorted microstrip line transducer of 20 µm width and 5 mm length. A light source at a wavelength 1.15 µm was edge-coupled into the YIG waveguide to excite either a TE-mode or a TM-mode guided light propagating in the Z-direction. The diffracted light was detected using Ge-photodiodes or imaged on infrared camera.

The measured relative DE (TE₀ → TM₀) for anti-Stokes interaction versus the angle γ is shown on Fig. 2a. In this experiment the value of wave vector K₀ for the MSW with different directions of propagation was fixed. The maximum DE in the geometry of MSFVW (γ = 0) was 0.5% (2% on the interaction length 1 cm) and MSFVW power 8 mW. The maximum DE at inclined magnetization is more than two times greater than in the case of normal magnetization. The angular dependence of DE has nonreciprocal character at different signs of longitudinal component of magnetization. After changing the direction of MSW propagation (K₀ → K₀') angular dependence of DE becomes symmetrical.

Discussion

The increase of DE at inclined magnetization of epitaxially grown YIG films can be caused by two factors. On the one hand, the presence of longitudinal component of magnetization (M_z) at inclined magnetization of YIG film leads to creation of two orthogonal elliptically polarized GOW. When the ellipticity of GOW is small such mode we call quasi-TE mode (QTE) and orthogonal to the latter quasi-TM mode (QTM). Therefore, in diffraction of GOW by MSW will take part two modes of incident light (QTE₀, QTM₀) and two modes of diffracted light (QTM₁, QTE₁), that is the scattering will occur from two optical sources. Fig.2b shows the possible processes of diffraction for which the conservation laws are true. Except of the main channel of diffraction in the geometry of MSFVW (process 1→3) in scattering now will take place three additional channels, marked on Fig.2b by figures: 1→4, 2→3, 2→4. The appearance of additional channels with new conditions of synchronism means that into diffraction will add the contribution more wide spectrum of angular harmonics of MSW. When the contribution into diffraction of the
latter processes will be in phase, the resulting DE will grow. The calculation of diffraction efficiency made in four-waved approximation using the method of couple modes, shows, that the summary

\[ \eta = \frac{i}{i_0} \ (\%) \]

Figure 3: Calculated diffraction efficiency for anti-stokes component of diffracted light versus the interaction length with MSW at normal (1a, 1b; chan. 1 → 3) and inclined (2a, 2b; \( \gamma = 12 \text{ deg.} \)) magnetization of YIG film:

1a, 1b) - interaction with single and with three space harmonics of MSW beam, accordingly.
2a) - main channel of diffraction: 1 → 3.
2b) - superposition of contributions from all channels of diffraction.

contribution of all diffraction channels into QTM diffracted mode with taking into account the wide spectrum of angular harmonics of MSW beam has oscillated character versus the length of interaction L(z): Fig. 3, curve 2b. So, there is the optimum interaction length of GOW with MSW on which the DE is maximum. Note, that taking into consideration only single plane harmonic of MSW beam and the main channel of diffraction (1 → 3) does not lead to the increase of diffraction efficiency (Fig. 3, curve 2a).

On the other hand, at inclined magnetization of YIG film, the localization of MSW in cross-section of film is changed. This leads to increase or decrease of the overlap integrals for interacted modes. This conclusion is based on the analysis of interaction symmetry of GOW with straight \( K^+ \) and reverse \( K^- \) MSW (Fig. 2a).

The sum of two above mentioned factors result, to our knowledge, the increase of DE at inclined magnetization of YIG film.

Conclusion

So, the diffraction efficiency for the process of interaction of GOW with MSW can be significantly increased by using an inclined magnetization of epitaxial YIG layers. This result can be used at elaboration of different guided-wave magnetooptical bragg cells.

References


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LOW ABSORPTION InP/InGaAs-MQW PHASE SHIFTERS FOR OPTICAL SWITCHING

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InP/InGaAs-MQW phase shifters with low absorption loss and low electroabsorption loss have been realized. Phase shift efficiency for TE-polarized light at \( \lambda = 1.55 \text{ \mu m} \) was 6.8 \( \text{°V}^{-1}\text{mm}^{-1} \) with negligible absorption loss and at \( \lambda = 1.51 \text{ \mu m} \) the efficiency was 8.9 \( \text{°V}^{-1}\text{mm}^{-1} \) with 5 dB/cm absorption loss.

Introduction

Optical switches can be made by using a Mach-Zehnder interferometer (MZI) [1,2]. For this type of switch, phase shifters with high efficiency and low absorption loss are required. For phase shifters the guiding layer is embedded in a p-i-n diode. Phase shift can be obtained by reverse biasing of the diode. High efficiency has been reported by using multiple quantum well (MQW) waveguides employing the quantum confined Stark effect [1,4], also the absorption loss are often high for MQW. For system applications polarization independence is also desired. In a bulk InGaAsP film layer polarization independence can be obtained by specially oriented waveguides [2]. With MQW the polarization dependence of the phase shift can be controlled by tensile strain in the quantum wells [1,3].

Our prime goal was to design an InP/InGaAs MQW layer with low absorption loss and electroabsorption loss (change in absorption due to applied voltages) at \( \lambda = 1.53 \text{ \mu m} \). This guiding layer will be used for passive optical components and an integrated Mach-Zehnder interferometer. Wavelength dependence of absorption loss and phase shift efficiency have been determined.

Design and Fabrication

The difference between the signal wavelength and the band-edge of the MQW film layer determines the phase shift efficiency and the absorption loss. If the signal wavelength comes closer to the band edge of the material both the electro-optical efficiency and the absorption loss increase. Earlier experiments showed that we can expect low absorption loss if the wavelength difference is more than 140 nm. For a signal wavelength of \( \lambda = 1.53 \text{ \mu m} \) the bandgap wavelength of the material should be smaller than 1.39 \( \text{\mu m} \).

Hence, the designed waveguide layer consists of a MQW structure with 4 nm lattice matched InGaAs quantum wells and 8 nm InP barriers. The calculated room temperature photoluminescence (PL)-wavelength of this structure is \( \lambda_{\text{PL}} = 1.39 \text{ \mu m} \). Experiments revealed that the PL-wavelength was
red shifted (1.48 μm) and that compressive strain occurred in the MQW-region. This is thought to be due to interfacial problems during the growth. Optimization of growth time and InGaAs composition resulted in the desired PL-wavelength with 4 nm tensile strained In_{0.50}Ga_{0.50}As quantum wells.

Fig.1 gives the cross-sectional view of the phase shifting waveguides oriented in the [011] direction. The layers were grown by LP-MOCVD on a n⁺ (100) wafer.

Fig. 1. Cross sectional view of the phase shifting waveguides.

In order to measure the phase shift efficiency of the waveguide it has been integrated in a 2x2 Mach-Zehnder interferometer structure, as shown in Fig. 2. The efficiency can be easily inferred from the switching curves. As a splitting and a combining element, MMI-couplers [5] were used.

Fig. 2. Top view of the 2x2 Mach-Zehnder interferometer.

A 140 nm SiO₂ layer served as an etching mask for the waveguides. After contact lithography, we transferred the mask in the SiO₂ layer by CHF₃/Ar reactive ion etching. For etching InP we used a CH₃/H₂ etching process. Afterwards the electrodes on the waveguide rib were fabricated by a lift-off process, for passivation we used a polyimide film. Electrical isolation between the two electrodes was obtained by partly removing the p-InP between the electrodes and the MMI-couplers.

Measurements
The optical measurements have been performed between 20× AR-coated microscope objectives. The laser source was a λ=1.53 μm Fabry-Perot laser. Light emanating from the waveguides was imaged onto an InGaAs-diode. Electro-absorption was measured with a 5 mm long electrode on a 4 μm wide waveguide. The TE-light intensity as a function of the applied reverse bias is depicted in Fig. 3. Between 0 and -20 V the electro-absorption is lower than 3 dB/cm.
The absorption peak between -5 and -10 V was measured for different waveguides. Probably it is caused by an absorption resonance in the transparent region of the MQW layer.

The measurement results of the 2x2 MZI (see Fig. 2) for TE-polarization are depicted in Fig. 4. Light was coupled in one of the input waveguides and the light intensity of the two output waveguides was recorded as a function of the applied reverse bias. The loss with respect to a reference waveguide is 12.5 dB and the crosstalk is -7.5 dB. The high loss and low crosstalk are caused by non-optimized MMI-couplers as has been confirmed by measurements on single MMI-couplers. For the determination of the phase shift efficiency the poor performance poses no problems.
For shorter wavelengths both an increase in phase shift efficiency and absorption loss can be seen. The metallization of the electrodes caused high loss for TM-polarization. A new design has been made to solve this problem.

**Discussion and Conclusions**

For the integration with other passive optical components low absorption loss is required. This low loss can be obtained by using a wavelength longer than \( \lambda = 1.53 \) \( \mu \text{m} \). Also the electro-absorption is low at this wavelength, which is desired for low loss phase shifting. The fabricated structure opens the opportunity to integrate passive waveguide structure and phase shifters in a low loss InP/InGaAs MQW structure.

**References**

2. M. Bachmann et al., “Compact polarization independent multi-leg 1x4 Mach-Zehnder switch in InGaAsP/InP,” *ECOC'94* (Firenze Italy), pp 519-522, 1994

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**Table 1: Wavelength dependence of switching voltage and absorption loss**

<table>
<thead>
<tr>
<th>( \lambda ) (( \mu \text{m} ))</th>
<th>( V_{2\pi} ) (V)</th>
<th>Efficiency ( (\text{oV}^{-1}\text{mm}^{-1}) )</th>
<th>Absorption (dB/cm)</th>
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<tr>
<td>1.51</td>
<td>10.1</td>
<td>8.9</td>
<td>5</td>
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<td>1.53</td>
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<td>7.9</td>
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<tr>
<td>1.57</td>
<td>14.8</td>
<td>6.1</td>
<td>0</td>
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</table>
OPTICAL GAIN IN ERBIUM-IMPLANTED
Al₂O₃ WAVEGUIDES

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Al₂O₃ ridge waveguides implanted with 1.3 at. % Er, pumped with 2.5 mW 1.47 μm light show 4.5 dB/cm enhancement of a 1.53 μm signal beam. The maximum gain is limited by cooperative upconversion effects. Calculations for lower Er concentrations show that 1 dB/cm net optical gain is possible at 10 mW pump power.

I. INTRODUCTION

Since the development of the erbium-doped fiber amplifier, a lot of work has been aimed at achieving optical gain in Er-doped planar waveguides. Trivalent Er is used as optical dopant because of its intra-4f transition around 1.54 μm, coinciding with the low loss telecommunications window of silica fiber. High concentrations of Er (~1 at.%) are needed in order to reach reasonable optical gain on a small length scale. However, at such high Er doping levels, concentration quenching effects come into play, in which interaction between Er³⁺ ions takes place. For example, cooperative upconversion, where two excited Er³⁺ ions exchange energy, can deplete the first excited state of Er³⁺, making it more difficult to reach population inversion and gain [1, 2]. In spite of these difficulties, several reports have demonstrated optical gain in silica-based planar devices [3, 4].

This study involves optical gain measurements on Er-implanted Al₂O₃ waveguides. Al₂O₃ is an ionic crystal with a structure similar to that of Er₂O₃ [5], enabling high concentrations of optically active Er as a dopant [6], and therefore high optical gain. Ridge waveguides fabricated on silicon substrates show a low optical loss of 0.35 dB/cm [7]. Also, the compact structure of the waveguide and the high index difference between core and cladding, allow for high confinement of the optical mode in the guide, resulting in high intensities for a given pump power, and therefore efficient pumping. Furthermore, the fabrication of the waveguides is compatible with standard silicon processing techniques, and many passive waveguide devices, such as splitters, couplers, and optical phased arrays have been demonstrated in this material [7, 8].

II. EXPERIMENTAL

Al₂O₃ waveguide films, 600 nm thick, were deposited onto thermally oxidized Si (100) substrates by sputter deposition from an Al₂O₃ target, in an oxidizing ambient. The films were implanted with 1.3 MeV Er to a peak concentration of 1.3 at.%, with the samples held at 77 K. Ridges, 0.3 μm deep, were etched into the Al₂O₃ using reactive ion etching, and the waveguide width ranged from 1.0 to 3.5 μm. Subsequently, a top SiO₂ cladding layer was deposited, and the structures were annealed at 825 °C for 1 hr in N₂ in order to achieve low loss [7], anneal out implantation damage, and activate the Er [6]. Using Rutherford backscattering spectrometry a Gaussian Er implantation profile at a depth of 270 nm with a full width at half maximum of 160 nm was measured; the profile is centred
in the middle of the waveguide, where the light intensity is highest.

Photoluminescence (PL) spectroscopy was performed using standard equipment [6] with an Ar laser to excite the samples. Optical loss measurements were done using prism coupling. For optical gain measurements the waveguides were pumped with 1.47 μm laser light from an InGaAsP diode pump laser coupled into the waveguides using a tapered optical fiber. A signal beam at 1.53 μm was included using a wavelength division multiplexer. The signal emitted at the other end of the guide was analysed with a monochromator and sensitive Ge-detector employing lock-in techniques.

III. RESULTS AND DISCUSSION

A. Er\(^{3+}\) emission and absorption

Figure 1 shows the PL spectrum of an Er-implanted slab waveguide, i.e. without ridges and top SiO\(_2\) cladding layer. The spectrum is typical for the first excited \((^4I_{13/2})\) to ground state \((^4I_{15/2})\) transition in Er\(^{3+}\). The luminescence lifetime for this sample was measured to be 4.5 ms. Figure 1 also shows the absorption spectrum of the slab waveguide (solid line, left axis), after subtraction of 0.4 dB/cm intrinsic waveguide loss. A peak absorption of 8 dB/cm is observed, due to Er\(^{3+}\). Given the implantation profile and optical mode profile of the waveguide, the absorption cross section for Er\(^{3+}\) in Al\(_2\)O\(_3\) may be derived from the absorption data in Fig. 1. This is shown on the right scale of Fig. 1. From this result, and using the Füchtbauer-Ladenburg equation [9], the emission cross section was derived from the measured PL spectrum (see righthand scale of Fig. 1). As can be seen, both absorption and emission cross section peak at \(12 \times 10^{-21}\) cm\(^2\).

B. Photoluminescence in a waveguide

Figure 2 shows the PL spectrum of a 1.5 μm wide Er-implanted waveguide pumped at 1.48 μm (~ 4 mW in the waveguide). Several luminescence peaks can be distinguished, each one characteristic of an intra-\(4f\) transition in Er\(^{3+}\), as indicated in the figure. Besides the 1.53 μm emission from the first excited state, a number of transitions originating from higher excited states is also observed. In fact, the green emission at 545 nm can be clearly seen by the naked eye. The luminescence at 800 and 980 nm is caused by cooperative upconversion, where two Er\(^{3+}\) ions in the first excited state exchange energy [2]. The emission at shorter wavelengths is due to two sequential upconversion steps.

![FIG. 1 Room temperature PL spectrum (dotted line) and absorption spectrum (solid line) of an Er-implanted Al\(_2\)O\(_3\) ridge waveguide. From these data the emission and absorption cross sections were determined as shown on the right axis.](image)
C. Optical gain

Figure 3 shows the evolution of the 1.53 μm signal intensity versus pump power, measured on a 1.5 μm wide and 9 mm long Er-implanted Al₂O₃ ridge waveguide (Er peak concentration: 1.3 at.%). At low pump powers the peak absorption due to Er³⁺ is 6 dB. The difference with the peak absorption in Fig. 1 is because of the lower overlap between Er and mode profiles in the ridge waveguide compared to the slab waveguide of Fig. 1. A maximum transmission change of 4.5 dB is observed after pumping with 4 dBm (2.5 mW) 1.47 μm light. Also shown in the figure are two calculations, using the emission and absorption cross sections derived above. The dashed line is based on a simple 2-level system including stimulated emission of pump and signal beams, excluding upconversion. The solid line is calculated by including cooperative upconversion, and taking the population of Er³⁺ in the second excited state (⁴Ι₁₁/₂) into account. The population in this level does not contribute to the optical gain, and therefore the maximum achievable gain is lower than in the case without upconversion. Also, the curve shifts to higher pump powers. The calculation fits the data for an upconversion coefficient of 8 × 10⁻¹⁸ cm³/s. Clearly, cooperative upconversion dominates the behavior of the signal at higher pump powers.
In order to reduce the effects of upconversion, the Er concentration must be reduced. This may be done without reducing the potential optical gain by redistributing the Er over a larger depth in the waveguide, resulting in a lower peak concentration. Simulations of the signal evolution for such a waveguide with 0.4 at.\% Er show that 1 dB/cm net optical gain is possible with a very modest pump power of 10 mW. Experiments are underway to achieve this result.

**V. CONCLUSIONS**

In conclusion, Er-implanted Al$_2$O$_3$ ridge waveguides show high emission and absorption cross sections at 1.5 $\mu$m, making high optical gain possible. Experiments show 4.5 dB signal enhancement for a waveguide doped with 1.3 at.\% Er. Realistic simulations including effects of cooperative upconversion show that 1 dB/cm net optical gain is possible for only 10 mW pump power at 1.47 $\mu$m.

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ANOMALOUSLY HIGH UNIFORM UPCONVERSION IN AN ERBIUM-DOPED WAVEGUIDE AMPLIFIER

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The performance of a planar Er\(^{3+}\)-doped ion-exchanged waveguide is compared to a detailed model, including uniform upconversion estimated from spectral measurements. A discrepancy between experiment and theory requires a much higher level of uniform upconversion than predicted. We consider possible explanations for this anomaly.

Introduction
In the course of developing a planar ion-exchanged glass waveguide Er\(^{3+}\)-doped amplifier, we have considered methods for rapid selection of suitable host glasses\(^1\). The parameters directly related to amplifier operation are the pump and signal cross-sections, which are readily established. However, at the high dopant levels used in short planar amplifiers, cooperative ion-ion interactions impose practical limits on the performance. A distinction can be drawn between "uniform upconversion" (UU) between randomly distributed "isolated" ions and upconversion within clusters of ions. Although clustering, which arises from imperfect rare-earth solubility in the host, has been the main problem in fibres even at relatively low dopant levels, it has recently been suggested that UU will set a fundamental limit in planar amplifiers\(^2\), even if clustering can be avoided.

We have made spectral measurements on several host glasses to permit first-principles prediction of upconversion strength, and we have estimated the clustering levels in these glasses. Using these figures and the standard spectroscopic quantities required for amplifier characterisation, we have modelled the gain and fluorescence time-dependence in doped glasses. We compare here the predicted and measured performance for one such glass, and find a substantial discrepancy, for which we consider possible explanations.

The Numerical Amplifier Model
Pump and signal evolution along a straight waveguide in a bulk-doped host are calculated using the modal intensity profiles and allowing for saturation effects and bidirectional amplified spontaneous emission. The model can also compute the decay of guided fluorescence when steady-state pumping is abruptly turned off. Ion-ion interactions are incorporated as two independent components, involving the "isolated" and the clustered ions respectively. The rate equation for the metastable population density \(N_2\) of "isolated" ions includes a term of the form \(-C_{UC}N_2^2\) to account for UU, where \(C_{UC}\) is the upconversion coefficient. A standard rate equation describes the clustered ions\(^3\).

Estimation of Ion-Ion Interaction Strengths
We estimate interaction strengths using the Förster-Dexter theory\(^4,5\), in which the fundamental quantity is an overlap integral between the spectral distributions of the two transitions involved in the interaction. We neglect phonon-assisted interactions since the relevant interactions involve direct spectral overlaps\(^6\). The distance of closest approach of Er\(^{3+}\) ions we take to be 0.35 nm, as in
crystalline $^7\text{Er}_2\text{O}_3$. An integration over space with a random distribution of ions yields the average interaction strength per excited ion, which is proportional to the excited state population density. The ion-ion interactions then contribute a quadratic term to the rate equation for the excited state population, as indicated above. The issue of representation of the inversion level by a rate equation is complicated - it is frequently asserted but not true, for example, that dipole-dipole interactions give rise to 3rd order terms. A rate equation approach with this quadratic upconversion term is appropriate provided the excitations are "shuffled" rapidly by migration.

The host glass was an aluminoborosilicate, with $3.6\times10^{19} \text{Er}^{3+}$ ions cm$^{-3}$. Waveguides 3.8 cm long were made by Ti$^+$ ion-exchange from a molten salt bath, and buried in a second step. They were single-moded at signal wavelengths, and modal profiles were determined by the near-field imaging of a polished endface. The required spectra were measured by techniques described elsewhere. We have attempted to measure the clustering level through detection of an unbleachable absorption, but the method is not very sensitive in short guides and we could specify only an upper limit.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
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<tr>
<td>Fluorescence lifetime</td>
<td>5.6 ms</td>
</tr>
<tr>
<td>Radiative lifetime</td>
<td>8.6 ms</td>
</tr>
<tr>
<td>Dopant concentration</td>
<td>$3.6\times10^{19}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Clustering fraction</td>
<td>$&lt;30%$ of ions in clusters</td>
</tr>
<tr>
<td>$Q_{\text{abs}}$</td>
<td>$1.5\times10^{-22}$ eV cm$^{-2}$</td>
</tr>
<tr>
<td>$Q_{\text{em}}$</td>
<td>$2.1\times10^{-22}$ eV cm$^{-2}$</td>
</tr>
<tr>
<td>$Q_{\text{ESA}}$</td>
<td>$0.4\times10^{-22}$ eV cm$^{-2}$</td>
</tr>
</tbody>
</table>

Table I: Measured properties of doped glass

Table I lists the properties of the doped glass, including integrated transition strengths for the $^{4}I_{15/2} \rightarrow ^{4}I_{13/2}$ absorption ($Q_{\text{abs}}$), the $^{4}I_{13/2} \rightarrow ^{4}I_{15/2}$ emission ($Q_{\text{em}}$) and the $^{4}I_{13/2} \rightarrow ^{4}I_{9/2}$ absorption ($Q_{\text{ESA}}$). The overlap integral is defined as:

$$\frac{1}{Q_{\text{em}}} \int \lambda^2 \sigma_{\text{em}}(\lambda) \sigma_{\text{x}}(\lambda) d\lambda$$

where $\lambda$ is the wavelength and $\sigma$ the cross-section, with $\sigma_{\text{x}}$ representing the absorption or ESA cross-section respectively. The overlap between the emission and ESA cross-sections leads to upconversion, whereas excitation migration or hopping involves the overlap of the emission and absorption cross-sections. Migration is much faster than upconversion, so it is plausible that the "shuffling" condition holds. The uncertainty in the calculation of $C_{\text{UC}}$ which arises from the noise on the ESA spectrum is considerable, perhaps as high as 50%, even neglecting the theoretical uncertainties. These latter include the contribution of phonon-assisted processes, other interaction modes (eg. exchange interactions) possible correlations in the orientation of close-lying ions, the influence of the magnetic dipole component of the $^{4}I_{13/2} \rightarrow ^{4}I_{15/2}$ transition, and local field corrections.
Table I also shows the minimum lifetime due to upconversion, for ions 0.35 nm apart, which presumably reflects the lifetime in clusters. Estimates in the literature\(^2\)\(^\text{10}\) for the upconversion lifetime in clusters range from 3.5 \(\mu\)s to 100 \(\mu\)s. This suggests that our calculations are reliable to within better than an order of magnitude.

**Results and discussion**

Waveguide absorption/gain was measured with the set-up in fig. 1, as a function of pump power. The time-dependence of the fluorescence decay was measured by mechanically chopping the pump and directing the waveguide output at a detector connected to a digital storage oscilloscope.

Fig. 2 shows measurements of absorption/gain versus transmitted pump power, along with two model predictions. The models differ in the upconversion coefficient; A uses the value \(7 \times 10^{-18} \text{ cm}^3 \text{s}^{-1}\) predicted as discussed above, and B, which matches the data well, uses \(120 \times 10^{-18} \text{ cm}^3 \text{s}^{-1}\), almost 20x greater. Model B also matches the instantaneous decay rate, as shown in table II. Other parameter changes which might account for the observations include reduced excited state lifetime or higher clustering levels. The numerical model has shown these not to match the data.

<table>
<thead>
<tr>
<th>Pump power</th>
<th>Expt</th>
<th>Model</th>
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<tr>
<td>14 mW</td>
<td>1.5 ms</td>
<td>1.2 ms</td>
</tr>
<tr>
<td>3 mW</td>
<td>2.5 ms</td>
<td>2.2 ms</td>
</tr>
<tr>
<td>14 (\mu)W</td>
<td>4.9 ms</td>
<td>5.2 ms</td>
</tr>
</tbody>
</table>

Table II: Instantaneous fluorescence lifetime when pump turned off

There is thus a large difference between our predicted UV coefficient and that needed to fit the data. As noted above, our prediction has large uncertainties, but it is hard to accommodate the error required to make the model parameter agree with the theory. We are now evaluating the exchange interaction and magnetic dipole contributions, and the significance of phonon-assisted upconversion.

Another possibility is energy migration from "isolated" ions to clusters where quenching is rapid. The rate is roughly proportional to the inversion level, because an excitation migrating to a cluster will be annihilated only if another is present. Macroscopically, the process mimics UU. We can estimate a quenching coefficient (for paired clusters) as \(C_Q = 0.5x\) [migration coefficient] \([\text{fraction of ions that are clustered}]\), where the migration coefficient is computed in a manner analogous to the upconversion coefficient. For this host \(C_Q\) could be as high as \(60 \times 10^{-18} \text{ cm}^3 \text{s}^{-1}\). (Note that \(C_Q\) has the same units as \(C_{UC}\) and is directly comparable). However, we need to set the minimum migration radius higher than that for upconversion, so as to count only "effective" jumps which move to a different neighbourhood. If we arbitrarily use a minimum radius twice that for \(C_{UC}\), \(C_Q\) is reduced by a factor of 8 to a value close to \(C_{UC}\), which is insufficient to account for the discrepancy.

It is also conceivable that the glass is inhomogeneous, so that the local dopant concentration seen by an individual \(\text{Er}^{3+}\) ion is substantially higher than the average value. It is perhaps noteworthy that this glass composition shows phase separation at twice the doping concentration used here. In our model, the apparent \(C_{UC}\) increases in proportion to the ratio of local to average concentrations, so a doping level of about \(5 \times 10^{20} \text{ cm}^{-3}\) would be required to account for the data.

Note that this upconversion discrepancy has not been seen in the only other host - a barium silicate - studied in detail. However, the value of \(C_{UC}\) used to model this second glass has not yet been directly determined, but inferred from another with very similar ground-state spectroscopy.
Conclusion
In developing approaches to host glass evaluation and planar amplifier modelling, we have found a discrepancy with experimental results for an Er\textsuperscript{3+}-doped glass. Our model matches data only with an anomalously large upconversion coefficient. This discrepancy has come to light because we have established an independent estimate for the upconversion coefficient. It is unclear whether its source lies in the upconversion theory or in the glass properties, and work is in progress to elucidate this.

Acknowledgements
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Optical Amplification in Cr diffusion-doped LiNbO$_3$

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Abstract: We report a process to fabricate Cr-doped lithium niobate substrates in which the active ions are introduced by thermal diffusion from a deposited film. Chromium diffusion profiles in z-cut LiNbO$_3$ were measured by SIMS. The activation energy and the effective diffusion coefficient in z-cut LiNbO$_3$ are given. The binding energy of Cr in LiNbO$_3$ was measured by XPS. Proton-exchanged and Ti in-diffused waveguides were measured at room and low temperature for fluorescence spectrum and lifetime. Finally, waveguide optical amplification has been observed.

Introduction

Laser action in chromium bulk-doped crystals with broad tuneability has been demonstrated using various hosts [1]. Bulk and film-doped lithium niobate substrates doped with the rare earths Nd and Er have provided demonstration of waveguide lasers and optical amplifiers [2-4]. Optical amplification in proton-exchanged chromium bulk-doped lithium niobate has also been observed [5]. These results indicate a significant potential for an integrated, broad-band tuneable laser in the 750-1150 nm spectral range, with the additional prospect of diode laser pumping using Cr-doped LiNbO$_3$ substrates. The potential for tuneable laser action and monolithic integration with several different devices on the same LiNbO$_3$ substrate is rather attractive, due to the well established technology involving this material.

Diffusion of the active dopant from a film into the crystal offers the possibility of tailoring the doping profiles, avoiding important limitations imposed by a bulk-doped substrate. Therefore, optical amplification and laser action in doped LiNbO$_3$ are preferably be obtained in locally diffusion-doped substrates.

A process to fabricate Cr-doped lithium niobate substrates, in which the Cr ions are introduced by thermal diffusion from a film, has been developed and characterized. Application of diffusion theory modelling in conjunction with data obtained from samples fabricated at different temperatures and diffusion times has provided estimates of the diffusion depth, the surface concentration, the effective diffusion coefficient and the activation energy for Cr diffusion into z-cut LiNbO$_3$.

Following spectroscopic characterization, optical amplification has been measured in channel waveguides fabricated in Cr planar-diffused samples.

Cr Doping Profile Measurement

All the samples fabricated used optical grade z- and x-cut LiNbO$_3$ wafers. The samples (10x5x1 mm$^3$) were coated with a 10 nm thick layer of chromium, using electron-beam thermal evaporation. Diffusion was carried out in a tubular furnace under a flow of
dry oxygen at a rate of approximately 0.5dm\(^3\)/min, using diffusion temperatures from 950°C to 1100°C and diffusion times from 1h to 24h.

The Cr concentration profile was measured by Secondary Ion Mass Spectroscopy (SIMS) with an ion microscope equipped with a normal incidence electron gun used to compensate the charge build-up. Erosion of the samples was performed by a 14.5 keV beam of Cs\(^+\) ions. The erosion speed was evaluated by measuring the depth of the erosion crater at the end of each analysis by means of a profilometer, providing a depth resolution (mainly determined by the roughness of the analysed crater) of \(\leq\)30nm.

According to diffusion theory for film layers, the Cr ion depth distribution \(C(x)\) in LiNbO\(_3\) should have the form:

\[
C(x) = \frac{C_0 \tau}{\sqrt{4\pi D t}} \exp \left( -\frac{x^2}{4Dt} \right)
\]

\((C_0:\)constant; \(\tau:\)film layer thickness; \(D:\)diffusion coefficient; \(t:\)time). By analysing a set of samples we found the dependence on the diffusion time of the parameters \(C_{\text{sur}}\) (surface concentration) and \(d\) (profile depth), using the best fit of the experimental values (obtained by SIMS) to this function \(C(x)\). The diffusion depth is plotted against the square root of the diffusion time in Fig.2. From the slopes of the straight lines we calculated the diffusion coefficients for three temperatures, Table I.

![Fig. 1: Concentration profile obtained by SIMS for a sample doped with 10.0 nm of Cr and diffused at 1000 °C for 10 hours.](image1)

![Fig. 2: Plot of the diffusion depth found by fitting gaussian functions to the experimental data (as obtained by SIMS) against the square root of the diffusion time.](image2)

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>D ((\mu)m(^2)h(^{-1}))</th>
</tr>
</thead>
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<tr>
<td>950</td>
<td>0.033</td>
</tr>
<tr>
<td>1000</td>
<td>0.098</td>
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<tr>
<td>1050</td>
<td>0.273</td>
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Table I: Calculated diffusion coefficients for three diffusion temperatures.

Using these values, an Arrhenius plot was drawn, from which we calculated a pre-exponential coefficient of \(4.7\times10^{10}\ \mu\text{m}^2\text{h}^{-1}\) and an activation energy of 2.95eV. The activation energy is approximately 8.5% larger than we have estimated previously [6] and the pre-exponential coefficient is one order of magnitude larger. The present values result from additional data as presented in this paper. It is well-known that the estimated pre-exponential coefficient value in the Arrhenius law depends very strongly on the precision of the experimental data for the diffusion coefficient versus the inverse of temperature.
Spectroscopy of Cr Doped LiNbO₃

The absorption spectrum of a Cr bulk-doped LiNbO₃ sample is plotted in Fig. 3. Two absorption bands are present with peaks at 480 nm and 650 nm, approximately.

![Absorption spectrum of Cr bulk doped LiNbO₃](image)

*Fig. 3: Absorption spectrum of Cr bulk doped LiNbO₃*

The waveguide fluorescence spectrum from a chromium diffused sample has been measured and is shown in Fig. 4. This sample was coated with 10 nm of Cr and diffused at 1050 °C for 4 h. A channel waveguide has been fabricated by Ti-indiffusion by coating the sample with a 100 nm layer of Ti and diffusing at 1050 °C for 12 h in a dry oxygen atmosphere, using a 8 µm window mask width. The fluorescence spectra of Cr-bulk doped z-cut LiNbO₃ (Cr concentration: 3.2x10²⁰ cm⁻³, supplied by Union Carbide) and of waveguides fabricated by Ti-indiffusion in the same material all presented similar features. The pump, in all cases, was the 488 nm line from an Argon-ion laser, with polarization parallel to the c-axis of the crystal for all the samples measured (no difference was noticed when the pump was polarized perpendicular to the c-axis).

The lifetime of the upper laser level has been measured for the same samples, using a Bragg cell to pulse the pump beam, together with a fast silicon detector-amplifier combination, with a time resolution better than 100 ns. In all cases, the value obtained at room temperature was 750±80 ns. We also measured the lifetime as a function of temperature for the bulk doped sample mentioned above. The results are presented in Fig. 5 and are in close agreement with published values [7].

![Waveguide fluorescence spectrum from a chromium diffused sample](image)

*Fig. 4: Waveguide fluorescence spectrum from a chromium diffused sample.*

![Lifetime of the Cr⁴⁺T₂ laser level as a function of temperature](image)

*Fig. 5: Lifetime of the Cr⁴⁺T₂ laser level as a function of temperature.*

The binding energy of chromium ions in LiNbO₃ has been measured by XPS on a completely diffused sample. We obtained 577.13 eV for the peak binding energy of line 2p₃, which is approximately equal to the binding energy of Cr in Cr₂O₃, thus suggesting that Cr diffuses into LiNbO₃ with a +3 valence.

**Optical Amplification**

We have measured optical amplification in a Ti-indiffused waveguide fabricated on a z-cut sample doped with 10 nm of Cr and diffused at
1050 °C for 24h. The waveguide fabrication parameters were as described above. The pump wavelength was 488nm from an Ar-ion laser polarized parallel to the c-axis of the sample and the signal wavelength was 804 nm from a laser diode. The signal and pump beams were mixed using a dichroic beam splitter and launched into the amplifier by a microscope objective. At the amplifier output, the pump was blocked by a filter and the signal was collected by a second microscope objective and launched into a 400 µm core optical cable connected to an optical spectrum analyser and was measured as a function of the pump power. The pump power was measured before the coupling objective and a launching efficiency of 50% is assumed. The corresponding plot is shown in Fig. 6, as obtained for a 8µm wide, 6mm long waveguide. The gain was defined as the ratio of the signal power, for a certain pump power, over the signal power for zero pump power. A gain of approximately 3dB for 5mW launched pump power was observed.

![Gain for a Cr diffused doped waveguide optical amplifier.](image)

Fig. 6: Gain for a Cr diffused doped waveguide optical amplifier.

For a pump power greater than 5mW the gain starts to decrease, probably due to photorefractive damage as absorption saturation should not occur at such relatively low values of pump power. The use of a more convenient pump wavelength (650nm) and pulsed operation in conjunction with proton-exchanged waveguides should improve the gain behaviour of these devices. We should note that a gain of only 2.2dB was obtained at 910nm (close to the peak of the fluorescence spectrum) for a Cr bulk-doped amplifier pumped at 670nm [5]; this seems to indicate that higher gain can be achieved in Cr diffusion-doped LiNbO₃ amplifiers.

Conclusions

The basic parameters for fabrication of Cr diffusion-doped z-cut LiNbO₃ amplifiers and lasers have been obtained. Measurements on the diffusion characteristics in x-cut LiNbO₃ are now under way.

An estimate of the gain behaviour has been carried out using a simple model. Research is being conducted to verify the properties of amplifiers and lasers.

Acknowledgements

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Amplification in Erbium Doped Microguides Realised on Phosphate Glass.

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Abstract
We have measured an internal gain of 21dB at \( \lambda = 1.54\mu m \) in 4.4cm long waveguides. These guides were made by ion-exchange in an erbium-ytterbium doped phosphate glass and pumped by a power of 160mW emitted by a titane-sapphire laser at 980nm.

As far as we know, it is the first time that a gain is measured in a buried waveguide made by molten-salt assisted ion-exchange in an erbium doped phosphate glass. However we can mention the works of Boulder university and Hoya Laboratories [1], [2], [3], about lasers realised on neodymium doped phosphate glasses by ion-exchange.

We have adapted our ion-exchange process, using silver ions [4] [5], to our phosphate glass doped with 2% by weight of erbium and 4% by weight of ytterbium. This gave us the possibility of making 4.4cm long microguides, simultaneously singlemode at both pump and signal wavelengths, respectively 980nm and 1540nm. The average mode diameter at \( 1/e \), \( \phi \), and the ellipticity, \( e \), of these guides for the two wavelengths are respectively: \( \phi = 4.7\mu m \), \( e = 0.81 \) at 980nm and \( \phi = 7.5\mu m \), \( e = 0.83 \) at 1540nm. These guides are buried 3.5\mu m below the surface, which gives them their good optical properties: high coupling efficiency with fibers, up to 89%, and low propagation losses, lower than 0.6dB/cm at \( \lambda = 1.3\mu m \).

Using the experimental set-up presented on figure 1 we have measured the internal gain obtained with our microguides used as travelling wave amplifiers. We launch simultaneously, through a wavelength division multiplexer, the pump and the signal at one end of a waveguide, and we analyse, at the other end, the ratio:

\[
R = \frac{\text{Signal}_{\text{pumpON}} - \text{Noise}_{\text{pumpON}}}{\text{Signal}_{\text{pumpOFF}}} = \frac{\text{Signal}_{\text{pumpON}}}{\text{Signal}_{\text{pumpOFF}}}
\]

which gives us the internal gain \( G \) in dB (using the relation \( G = 10\log R \)). The noise is the addition of the spontaneous emission and the amplified spontaneous emission (ASE), when the guide is pumped. The gain is measured at the signal wavelength of 1544nm, after a single pass into the waveguide and with a pump source which can be either a pigtailed laser-diode emitting at 982nm or a titane-sapphire laser emitting at 980nm. Figure 2 shows the evolution of the internal gain with the injected pump power, when issued of the titane-sapphire laser. As we can see, the gain saturates, this is due to the short length of the guide. Indeed when the population inversion is
obtained all along the waveguide, the excess of pump power is lost without producing any additional gain.

Figure 3 shows the evolution of the internal gain at $\lambda=1540\text{nm}$ when waveguides of different diameters are pump with $35\text{mW}$ of pump power emitted by the pigtailed laser-diode. A modification of the mask aperture from 2 to $0.8\mu\text{m}$, during the photolithographic process, induces a decrease of the waveguide diameter of less than $0.5\mu\text{m}$. And this small reduction in waveguide diameter induces a large increase in gain, more than $2\text{dB}$. We have then realised a more confined waveguide for which the mode diameters at $1/e$, measured at $\lambda=1.54\mu\text{m}$, were $\phi_x=6\mu\text{m}$ in the horizontal plane and $\phi_y=4\mu\text{m}$ in the perpendicular plane. This microguide, pumped by $160\text{mW}$ of the titane-saphire laser, shows an internal gain at $1544\text{nm}$ of $21\text{dB}$. This is relative to a net gain of $6\text{dB}$, as the insertion losses for that waveguide were measured to be $15\text{dB}$.

An optimisation of the waveguide diameter as well as of the pump and signal wavelengths, simultaneously with an optimisation of the rare-earth concentration, will allow us to make efficient optical amplifiers on compact glass substrate of less than $2.5\text{cm}^2$.

Aknowledgments
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Figure 1: Experimental set-up for internal gain measurement
Figure 2: Gain versus pump power for a 7.5μm diameter, 4cm long waveguide

Figure 3: Gain measurement on 13 different waveguides
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Integrated Optic Devices/Circuits for WDM Systems

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Abstract

The success of WDM transmission systems and networks will require the rich optical functionality offered by integrated optic devices and circuits. We present an overview of the system requirements, current status and likely early applications of these integrated optic components.
Wavelength-division-multiplexed (WDM) transmission systems, a vision of optics researchers for years, will soon become a commercial reality. The advent of WDM systems, which is due in large part to its synergy with the advantageous features of erbium doped fiber amplifiers, is great news for the field of integrated optics (IO). Because, while fiber amplifiers may provide the initial impetus for WDM systems, the rich, complex optical functionality promised by integrated-optic devices and circuits will be essential for the ubiquitous deployment and evolution of these systems. Fortunately, IO technology has also matured to the point that it is well positioned to satisfy WDM’s heavy appetite for optical circuits. In this paper we examine the IO components needs of WDM transmission systems and networks and present an overview and comparison of the key components. We also describe WDM system demonstrations that employ IO devices and circuits.

A view of the possible evolution of optical communication from simple high capacity, point-to-point transmission systems to fully connected, reconfigurable networks is shown in the figure. Also shown in the figure are the components required. The opportunities for waveguide devices and circuits, both active and passive, is clear. Integrated laser arrays and tunable lasers with integrated modulators to provide a WDM transmitter on a chip will be important. Wavelength multiplex/demultiplex components and tunable couplers and filters will be essential. Fully integrated receivers that include amplifiers, wavelength filters and photodetectors offer the cost savings potential essential for ubiquitous deployment of WDM systems, especially for access applications. WDM networks will also require integrated optic space-division switch arrays, N x N wavelength selective routers and wavelength conversion devices.

In the last several years the progress in the above integrated optic WDM components has been dramatic. A survey of these components, their current status and likely early applications will be presented.
LIGHTWAVE SYSTEM EVOLUTION: PHOTONIC CIRCUIT APPLICATIONS

Multi-channel (WDM), Point-to-Point, Amplified

Multi-channel, Multi-point Network (Bus or Star)

Multi-channel, Multi-point, Reconfigurable Network
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POSSIBILITIES OF INTEGRATED OPTICS IN OPTICAL STORAGE

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Abstract
Optical storage technology requires advanced pickup heads which can write/read pits on high-density disks with faster access and faster data transfer rate. Various possibilities and technical subjects of integrated optics for implementation of such pickup heads are discussed.

1. Introduction
Optical storage technology has been developing rapidly toward higher storage density, faster access, faster data transfer rate and lower cost, which are all required in future AV and computer data storage systems. This development is expecting advanced types of optical disk pickups. The storage capacities in the first generation disks (3.5-inch diameter) and the second generation ones are 128 MB and 230 MB, respectively. The third generation ones are presently under development [1]. The specifications, for example, are 1) Storage capacity 640 MB, resulting in track pitch of 1.1 μm, 2) 680 nm for the wavelength of light source, 3) 0.6 for the numerical aperture NA of objective lens. Digital video disks (DVD) in progress are also designed for even narrower pitch and shorter wavelength [2].

Technical subjects for such implementation are developments of pickup heads which have
1) larger NA,
2) compact light source of shorter wavelengths,
3) lighter-weight,
4) faster data transfer rate, that is, multiple beam access.

These requirements could be satisfied with integrated-optic pickup heads. In this paper, various progresses of integrated optics for future optical storage technology are discussed.

Fig. 1 Schematic view of an IO disk pickup for the first demonstration
2. To Reduce the Focusing Spot Size
2.1 Focusing Grating Coupler of IO Disk Pickup and its NA

A schematic view of integrated-optic disk pickup (IODPU) for the first demonstration [3] [4] is shown in Fig. 1. This device is quite compact (5 mm x 10 mm), and light (0.3 g). The focusing beam that is coupled out from the focusing grating coupler (FGC) is schematically shown in Fig. 2 (a). The focusing spot size \( \delta \) is determined by the wavelength \( \lambda \) of laser diode and the numerical aperture \( NA \) of FGC, and the relation is given by \( \delta = \lambda/NA \).

Assuming that FGC is designed to radiate the output beam upright for simplicity, the smallest period of FGC is located at the right-hand end. For diffraction of this wave, the phase matching condition is given by

\[
K_{\text{grating}} = n_f k_0 + k_0 \sin \theta,
\]

where \( n_f \) is refractive index of guiding film and \( k_0 = 2\pi/\lambda \). This expression is rewritten by

\[
\Lambda_s = \lambda/(n_f + NA).
\]

The relation between normalized grating constant \( K/k_0 \) and \( NA \) is shown in Fig. 2 (b).

One can obtain smaller \( \delta \) by using smaller \( \lambda \) and larger \( NA \). Then, \( \Lambda_s \) becomes smaller. The smallest period one can obtain practically is determined by electron-beam lithography, say approximately 0.2 \( \mu m \). Let examine if the IODPU can meet the specification of the third generation optical disk. In order to achieve the spot size smaller than the track pitch 1.0 \( \mu m \), \( NA \) must be larger than 0.68 for the wavelength of 0.68 \( \mu m \). This \( NA \) corresponds to the period \( \Lambda_s = 0.31 \mu m \), 0.24 \( \mu m \) and 0.17 \( \mu m \) in case of glass waveguide \((n_f = 1.5)\), LiNbO3 waveguide \((n_f = 2.28)\) and GaAs waveguide \((n_f = 3.4)\), respectively. We should say that this is comparable with the minimum fabricable period (approximately 0.2 \( \mu m \)).

2.2 Integrated-optic Light Source of Shorter (Blue/Green) Wavelength

Compact short wavelength coherent light sources are required to obtain smaller size spot. There are two directions of development, that is, II-VI semiconductor lasers and second harmonic generation devices. It will take still some time to develop the former light source.

However, the latter SHG device, based on LiNbO3 or LiTaO3 waveguide is approaching to the stage of practical use. They are designed to operate under the quasi-phase-matching (QPM) condition [5] [6] [7]. We have tried to fabricate domain-inverted gratings for QPM structures in LiNbO3 both
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by electron-beam scanning and by applying a voltage through a corrugation electrode. The domain inverted structure was successfully obtained across the thickness by both methods. The waveguide is fabricated by proton exchange techniques. We have achieved the SH power over 1 mW at a wavelength of 432 nm for a pump power of a few tens mW [8]. The output beam from such a waveguide-type device is spatially coherent, and therefore can be focused down to a diffraction-limited spot.

Combination of the wavelength 0.43 μm and LiNbO₃ waveguide can satisfy the future requirement of optical disk pickup, as schematically shown in Fig. 3.

Fig. 3 Schematical view of an IODPU with a SHG light source

3. To Increase Data Transfer Rate
3.1 Multiple Beam IODPU with Laser Diode Array

One of methods to achieve faster data transfer rate is parallel data processing techniques. Recently a monolithic array of multiple individually addressable laser diodes is under development [9]. By coupling this laser array with integrated-optic disk pickup (Fig. 1), a multiple-beam IO pickup would be implemented, as shown schematically in Fig. 4. In general multiple beams cannot be properly focused by means of a single conventional lens, since aberration takes place. To design a grating coupler such that multiple beams are all focused with allowable aberration is an interesting subject.

Fig. 4 Schematic view of a multiple-beam IODPU

3.2 IODPU for Parallel Data Readout

An integrated-optic device for parallel pickup of optical data has been also proposed and demonstrated [10]. The concept of this kind of device can be applied to parallel processing of
multiple track signals on disks and cards. The proposed device consists of linearly focusing grating coupler, a beam-splitting/imaging grating and a PD array, which are all integrated in a single-mode waveguide on a Si substrate, as shown in Fig. 5. The wave reflected by multiple digital marks on the focal line is coupled again by the same grating coupler into the waveguide. The device was designed to detect 9 μm size optical reflection marks. The working principle was successfully demonstrated. Therefore, feasibilities of parallel processing type IODPU was confirmed.

Fig. 5 Schematic view of an integrated-optic parallel pickup

4. Near-field Optical Spot Recording
Recently the near-field optics is investigated by many researchers in search for various applications [11]. One application is high density recording. The optical field is localized, for example, near the tip of optical fibers. Waveguides could be designed to provide such an extremely localized field. This might be one of nanometer recording techniques in the future.

5. Conclusion
Various possibilities of integrated optics for future development of optical storage technology have been discussed. These possibilities will be realized by progress of waveguide technology such as grating couplers, waveguide-type light sources and waveguide components.

References:
INTTEGRATED OPTICS IN THE RACE PROGRAM

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Abstract

This talk will give an overview of the current activities in integrated optics in the RACE Program.

Over 10 projects currently have activities in (or related to) integrated optics, including topics such as: OEIC modules, integration of lasers and modulators, tunable lasers and filters, wavelength converters, multiplexers and demultiplexers, integrated Er doped active components, silicon on isolator components and polymeric components.

The emphasis of the presentation will be on achievements to date in integrated optics, including examples of device performance and system applications.

A wide definition of integrated optics will be applied, and some results on components such as multisection lasers and semiconductor optical amplifiers will also be described.
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INTEGRATED OPTICS RESEARCH
IN THE FORMER SOVIET UNION

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Abstract

Integrated optics (IO) researches carried out in scientific centers of Russia and CIS Countries within last two - three years are presented.

1. Introduction

Possibility of using of last IO achievements allowed creation of more compact optoelectronic devices and improvement of their optical characteristics and reliability.

Despite rather small integration extent (less than 10), technology complexity and parameters that are worse than that of volume analogues, IO devices are widely introduced in instrument-making. There are three main directions of IO application:

1. Analogue and digital systems of information processing in different complexes, such as radio location, laser and hydro-acoustics ones.

2. Creation of IO physical values sensors on the base of different phenomena in waveguide structures of different media.

3. Creation of functional IO devices and elements for communication systems such as modulators, multiplexers and demultiplexers, amplifiers etc.

Of course, creation of IO devices on the base of different waveguide structures requires a lot of theoretical, technological and experimental investigations that are carried out in different research centers in Russia and CIS Countries.
2. IO materials and elements

Glass is one of a number of materials that are the base for waveguides creation. There are a lot of ways for such creation: ion exchange, chemical vapor deposition, ion implantation, RF sputtering, etc. A great number of passive and active glasses for IO is obtained in State Optical Institute (St.Petersburg, Russia) [1, 2]. In the last year progresses with new materials such as glasses doped with metal particles, semiconductor crystallites, rare earths etc. occur. Planar optical waveguides based on laser aluminosilicophosphate glass, activated by neodymium [3], and waveguides made of niobiophosphate glass [4] are obtained here for the first time.

LiNbO₃ and LiTaO₃ remain the point of interest. Diffusion of metal ions, inversion diffusion of LiO₂, proton exchange, liquid epitaxy, and ion implantation are the main ways of formation of waveguide structures in LiNbO₃ and LiTaO₃. New method of planar waveguides formation in LiTaO₃ by nonisovalent ion exchange in salt melts is presented in the research carried out in Moscow Institute of Electronic Technology [5]. The waveguides are formed by ion exchange reactions going on in such melts as K₂SO₄ - Na₂SO₄ - Li₂SO₄ - MeSO₄ (Me: Zn, Ni, Mn, Fe, Co, Ca, Mg) at the temperatures lower than Curie temperature of LiTaO₃.

Unique characteristics of LiNbO₃ and LiTaO₃ distinguish them from other active dielectrics. High-effective modulators, commutators, the second harmonic generators [6], acousto-optical devices for information processing etc. were created on the base of waveguide layers. The great attention is paid for calculations, investigations and verification of parameters of different devices created on the base of LiNbO₃ [7-10].

Using of monocrystals of active dielectrics such as Bi₁₂MeO₂₀, where Me is ions of Si, Ge, Fe, Ga, Zn in IO is very perspective. Dielectrics of such type have high electro- and acousto-optical parameters, great optical activity, photoconductivity and possibility of optical information record. The problems of acousto-optical interaction in gyrotropic planar waveguides are theoretically investigated in [11]. Photorefractive effect in such waveguides is investigated in Tomsk Institute of Automate Operating Systems and Radio Electronics [12], and the problems of control of polarization of optical radiation in the crystals of Bi₁₂SiO₂₀ due to the transformation of modes TE a TM is investigated in the State Optical Institute [13].

ZnO monocrystal films are very interesting due to the waveguide features and possibility of their usage as piezotransducers that may be RF sputtered on glass waveguides [14]. Isolator IO elements [15, 16] are developed on the base of magnetooptical materials in the Physical Technical Institute in St.Petersburg and in Kiev University. The problems of output waveguide couplers and their attachment with fiber waveguides, lasers and photodetectors are the most complicate and actual in IO. Investigations of prisms, output grating couplers, elements of "tapered edge" type are carried out in different research institutes in Russia [17, 18]. The patterns of holographic input elements on biochromated gelatin layers with efficiency of input into the glass waveguide about 17 percent, and gradient planar waveguide couplers based on relief-phase holograms with 40 percent efficiency were created in the State Optical Institute [19].

IO focusing systems that form the phase front of optical beams are one of the main elements of optical integrated schemes [18]. Calculations of geodezic lenses parameters and technology of their production are presented in [20].
Creation of monolithic IO schemes are as usual connected with semiconductor materials of $A^{III}-B^{V}$ group that are the base for lasers and photodetectors. Investigation and development of such schemes are carried out in Physical Technical Institute, General Physics Institute of Russian Academy of Science, Byelorussian State University. These works are mainly connected with creation of heterostructure lasers with waveguide layers, integration of lasers and photodetectors with electronic components and also with investigations of nonregular waveguides and generation of the second harmonic of semiconductor laser [21-24,27].

3. IO sensors for physical measurements

High sensitivity of waveguide to the external influence allows to create IO sensors of physical values. Sometimes application of planar waveguide structures is more preferable than application of channel waveguides. Sensor of the wave front with angular measurements error up to one second, sensor of rotation angle with 0.5 angular minute error, and the sensor of linear displacement with measurements error up to 20 nm at range 100 mm were developed on the base of IO technologies in the Institute of Applied Optics (Kazan) [25].

Sensor of index of refraction of liquid media on the base of intermode interference in the glass planar waveguides with $10^{-7}$ sensitivity (State Optical Institute).

Possibility of detection of material parameters using IO technologies is used in method of measuring of refractive index of optical materials [26], and in measuring of statistic characteristics of roughnesses of super smooth surfaces within root-mean-square deviation range 0.1 - 50 nm [27].

4. IO devices of information processing

A number of IO acousto-optical devices of location signals processing, spectroanalyzers with spatial integration with 0.3MHz frequency resolution in 100 MHz bandwidth, spectroanalyzers with time integration with frequency resolution from 10 Hz to 500 Hz depending on the signal duration, convolver with spatial integration for detection of pulse shape time integration correlator with 10 ns resolution are developed on the base of LiNbO$_3$ planar waveguides [28-30]. Acousto-optical processors providing high precision of location measurements allow to carry out signals processing in real time.

Method based on transmission of a signal being investigated through the filters system is one of possible methods of realization of signals analysis. It is known that realization of signals analysis based on using of digital methods of nanosecond range signals processing does not provide the work in real time. Realization of video-frequency orthogonal filters by means of acousto-optical methods is presented in [31]. Pulse filter reaction is set by coding mask. The results of signal analyzer investigations on the base of IO acoustic processor operating at 600 MHz frequency with 200 MHz bandwidth, proved the possibility of analysis, processing, and identification of monopulse signals with 3 - 5 nsec length. So, it is possible to create laser range finders with automatic selection and identification of the objects on the base of analysis of reflected signal shape.
Creation of optical processors carrying out multichannel time integration that allow to provide multiplying and coherent addition of signals being processed is very perspective direction. Process of multiplying of two-dimensional data matrixes is realized by means of sequence of modulators [30]. Multichannel waveguide modulators used for creation of coherent optical processors are effectively applied for correction and formation of directivity diagram of antenna gratings [32].

5. References


I. Abstract

All optical wavelength converters based on monolithic integration of Mach Zehnder interferometers with semiconductor optical amplifiers have been realized in InP/GaInAsP. Very stable wavelength conversion up to 10 Gbit/s is demonstrated. This compact device is polarization independent and shows excellent conversion performances (up- and down-conversion) within the entire 30-nm wavelength range covering the bandwidth of EDFA's (1530-1560-nm). Penalty free transmission over 60-km of non dispersion shifted fiber is demonstrated. The monolithic Mach Zehnder Interferometer is a promising component for simply implemented, high performance wavelength conversion.

II. Introduction

All optical wavelength converters are key components in flexible wavelength multiplexed networks. They can act as space switches in wavelength routed networks and allow for enhanced transmission capacity using a fixed number of wavelengths by re-using them [1]. In systems based on packet switching, wavelength conversion reduces cell loss probability by avoiding cell collisions [2]. Common required properties for most of these applications are:

- bit rate transparency up to 5-10 Gbit/s.
- signal reshaping (extinction ratio improvement)
- insensitivity to input signal polarization.
- fast switching between different wavelengths (ns).
- moderate signal input level (0 dBm).
- up and down conversion within a large wavelength window.
- ability to convert at the same wavelength.
- low chirp for transmission over long distances.

During last years intensive work has been carried out on different types of wavelength converters [3,4,5]. Among these components, all optical wavelength converters based on interferometric structures using Semiconductor Optical Amplifiers (SOA’s), as optically controlled phase-shifter elements, were demonstrated to fulfill all these requirements [6,7]. However, hybrid interferometric structures are not very easy to implement and are very sensitive to environmental fluctuations. To overcome this problem monolithic interferometric wavelength converters have been realized [8,9,10,11]. We will present here all optical wavelength converters based on monolithic integration of semiconductor optical amplifiers in the arms of a waveguide interferometer on InP. With this integrated structure on InP/GaInAsP, very stable, wavelength up-conversion as well as down-conversion up to a 10 Gbit/s bit rate is obtained. Nearly penalty-free conversion in a 30 nm optical window is obtained and possibility for same input/output wavelength is also confirmed. The sensitivity penalty on converted signal due to polarization of the input signal is below 0.5 dB.

III. Different types of interferometric wavelength converters

The common principle of operation of this interferometric converters relies on the phase shift generated by the intensity modulated input signal which, depletes the injected carrier concentration in the SOA and, induces a change in refractive index. One SOA is placed in each arm of an interferometric structure (Figure 1). The two SOA’s are driven asymmetrically either by the bias current or by signal input power. This generates a phase difference between the two interferometer branches that is proportional to the input power. The CW light entering the interferometer will experience this phase difference and be modulated according to the input.
signal power. The information from an intensity modulated input signal is consequently transferred to the CW signal which wavelength can be chosen independently from the input signal wavelength; wavelength conversion is thereby obtained. The phase change due to carrier depletion can be a few \( \pi \) radians. Therefore interferometric all optical wavelength converters can operate in a high carrier and photon density regime while maintaining high extinction ratios. Three different sort of possible wavelength converter configurations are shown on Figure-1. They differ mainly on the manner the asymmetry is introduced in the structure.

On Figure-1a, the signal is coupled directly in one arm of a Michelson interferometer (MI). The CW light is coupled in the input arm of the MI and splits equally between the two interferometer arms. The CW light is then partly reflected at the SOA's output faces. Depending on the phase delay between the two arms (induced by the signal) the CW light recombines constructively or destructively at the input arm.

On Figure-1b, the structure is a Mach Zehnder Interferometer (MZI) with asymmetric splitters/combiners. The asymmetric splitting ratio results in two different saturation regimes for the two SOA's, for increasing input signal powers.

The improved version of a MZI wavelength converter is presented on Figure-1c. This MZI has symmetric splitters/combiners, and the signal is coupled in only one arm of the interferometer by mean of a separate branch.

IV. Design and fabrication of integrated optics wavelength converters

The realization of these interferometric wavelength converters can be carried out by following different integration schemes. Monolithic MI wavelength converters (Figure-1a) have been realized by using buried ridge passive waveguide structures, integrated with a double core buried ridge amplifier section [10]. With this MI, wavelength conversion up to 10 Gbit/s have been demonstrated. In reference [11] an all active MZI is reported without any passive waveguide regions integrated in the device, which consists of a multisection active device. This approach leads to more compact structures, and the device operates up to 2.5 Gbit/s. One major difficulty is to make the device insensitive to the polarization state of the incoming signal.

In the following sections, we will present results on both asymmetric (Figure-1b) and symmetric (Figure-1c) MZI structures, the latter one including a separate injection arm. For both structures, the integration of the passive section with the amplifier is based on the double core buried stripe loaded waveguide structure, which has been demonstrated to fit the realization of polarization independent, switching matrices [12] as well as waveguide/amplifier integration [13] and 0-dB switches [14]. In the amplifier section (GaInAsP of \( \lambda_g = 1.55 \) \( \mu \)m), the active layer is directly grown on the top of the passive waveguide (GaInAsP of \( \lambda_g = 1.28 \) \( \mu \)m). Its geometry has been designed to obtain a polarization insensitive gain, by making, both the optical confinement in the active layer and the waveguide-SOA coupling efficiency, polarization independent. The complete structure is shown on Figure-2 and is obtained by three epitaxial growth steps which are described in detail in reference [13].

For the asymmetric MZI structure (Figure-1b), called DCAMZI, theoretical simulations, based on a compromise between a bias-current asymmetry of the two amplifiers (asymmetry in dynamics) and a reasonably low-signal level, led to an optimum splitting ratio of 25\% - 75\%. The designed structure is represented on Figure-3a. This 25\% - 75\% splitting ratio is obtained...
with a 700-um long directional coupler, with a 3-um wide interguide-spacing. At the device end face, two output ports S2 and S3, 200-um apart, allow to get λ_{converted}, in phase (input and converted signals with same waveform-polarity) or out of phase (input and converted signals with inverted waveform-polarity) and to proceed to signal counter propagation experiments, without any external 3dB fiber splitter. For the symmetric MZI (Figure-3b), called YSMZI, passive Y-junctions 50% splitters/combiners have been used (Y-junctions total-aperture angle being of 4-mrad).

For both structures, the length of the amplifiers is of 1200um to achieve both fast switching times and low saturation power. Out of the coupling region, the waveguides are separated via S-bends, which radii of curvature are of 15mm. The structures includes access waveguides 4-degrees titled from the cleavage plane, to reduce the coupling between the guided field and the one reflected from the cleaved end face. No anti-reflection coating was performed on the devices end-faces. Let us note that the converted signal at the two output ports S2 and S3 are complementary.

For static wavelength conversion experiments, optical powers from two DFB lasers at λ_{s}= 1545 nm and λ_{c}= 1533 nm are coupled in the MZI. At the interferometer output λ_{s} is rejected with a 1-nm bandwidth filter and λ_{c} detected. The dependency of the DCAMZI static P_{cw-out} at λ_{c}=1533-nm versus I_{1} is measured for different P_{s-in} at λ_{s}=1545-nm (Figure-4). The interferometric transfer-function is clearly observed by the periodical change in P_{cw-out} with respect to I_{1}. The device exhibits a phase-variation over 7Π for each P_{s}.

Figure-5 shows the static P_{cw-out} dependency versus P_{s-in} of the DCAMZI for conversion from 1545 nm to 1533 nm at different P_{cw-in}. From Figure-5, it can be noticed that both in-phase and out-of-phase can be obtained. Whatever is P_{cw-in} between -12 dBm and -3 dBm, the required high-level for P_{s} ranges between -2 and 0 dBm, for out-of-phase conversion. Furthermore, for P_{cw-in}=12 dBm, a static-ER regeneration of 17 dB is obtained.
The conversion performance is assessed by a system experiment at 5 Gbit/s. The converted signal at the MZI output is selected by a 100 GHz Fabry-Perot filter (Figure-6). Figure-7 shows BER curves for the converted signal (1543 nm) before and after transmission over 60-km of non-dispersion shifted fiber. Back-to-back measurements of the input signal (1531 nm) is taken as reference for estimating the device performances. Penalty-free conversion is obtained and no excess penalty is observed after transmission over 60-km of standard fiber. The improved transmission properties for the in-phase mode converted-signal is due to a red-shifted leading edge and a blue-shifted trailing edge of the incoming pulses. Pulse reshaping (extinction ratio improvement) can also increase the quality of the converted signal.

For symmetric YSMZI structures with extra arm similar interferometric and conversion curves are obtained. The BER curves at 5 and 10 Gbit/s for both the input and converted signals are shown in Figure-9. Penalty-free wavelength conversion is reached at 5-Gbit/s, whereas conversion at 10-Gbit/s results in a 1.8-dB penalty, due to a limited modulation bandwidth of the SOA’s. No excess penalty was introduced, when the signal polarization is changed. This is confirmed by an equal static fiber-to-fiber gain of the amplifier for TE and TM polarization.

As a drawback to the interferometric principle of these converters one could expect them, to be very sensitive to the input signal level. This has been verified and reported in Figure-10, where the penalty at 5-Gbit/s for both up- and down conversion is shown versus the signal input power. The dynamic range for the input power for which the penalty is below 1-dB is in the range of 3-dB. Therefore within this dynamic range no electrical feed-back is needed to readjust the performance.

Finally, this interferometric wavelength converter, as opposed to other types of converter, is able to convert the input signal at shorter as well as longer wavelengths, within a 30-nm wide window, without changing the operating points of the interferometer. This is shown on Figure-11, where the penalty (BER - 10^-9) at 5-Gbit/s is measured for conversion from 1543-nm to the whole (1530-nm-1560-nm) range.
VI. Conclusion

All optical wavelength converters based on monolithic integration of Mach Zehnder interferometers (MZI) with semiconductor optical amplifiers have been realized in InP/GaInAsP. Both asymmetric MZI and symmetric (with a separate injection arm) MZI have been fabricated. Very stable wavelength conversion at 5 and 10-Gbit/s is demonstrated. These compact devices are polarization independent and show excellent conversion performances (up- and down-conversion) within the entire 30-nm wavelength range covering the bandwidth of EDFA’s (1530-1560-nm). This output wavelength can be varied without adjustments of the MZI operating conditions. The dynamic range of input power variation without adjustment of the operating conditions is approximately 3-dB. The corresponding conversion penalty is below 1 dB. Penalty free transmission over 60-km of non dispersion shifted fiber is demonstrated. The monolithic integration of a Mach Zehnder Interferometer with Semiconductor Optical Amplifiers brings interferometric wavelength converters at the stage of a high performance, stable, wavelength converter which can be easily implemented.
VII. Acknowledgments

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VIII. References

INTEGRATED-OPTIC ARRAYED-WAVEGUIDE GRATING MULTIPLEXERS WITH LOOP-BACK OPTICAL PATHS

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Abstract
We propose and successfully demonstrate a new functional component for dense WDM networks. It consists mainly of a silica-based 1.55μm arrayed-waveguide grating 32x32 multiplexer with unique loop-back paths. We clarify the fundamental operation of new photonic components such as add-drop multiplexers, network access terminals, and channel selectors.

Introduction
Integrated-optic arrayed-waveguide grating (AWG) NxN multiplexers [2],[3] are of increasing interest for use as key devices in dense wavelength division multiplexing (WDM) networks[4] because of their unique N input and N output geometry. In addition to applications as simple add-drop multiplexers (ADM)[5] in WDM ring networks[6,7] or novel multi-channel wavelength selective switches[8] in optical ATM switching systems, silica-glass[9] based AWG multiplexers with loop-back paths are expected to be used in constructing dense WDM networks[4]. This paper proposes a new photonic component which incorporates a polarization-insensitive[10] AWG multiplexer providing an effective path between inputs and outputs. It also describes an attractive demonstration and notable results. As useful examples, new functional components such as an add-drop multiplexer, a network access terminal, and a wavelength channel selector[11] are presented.

Device Description
The proposed component consists of a silica-based 1.55μm arrayed-waveguide grating 32x32 or 16x16 multiplexer with a 0.8nm wavelength spacing. The AWG multiplexer was fabricated on a silicon substrate by using 0.75%-Δ silica-based planar lightwave circuit (PLC) technology. The chip size was about 30mm x 40mm. Polarization-insensitive operation was attained by inserting a polyimide half waveplate in the center of the arrayed-waveguide grating region. This multiplexer device is also intrinsically insensitive to temperature variations.

Component Configuration
Figure 1 shows the fundamental configuration of the AWG multiplexer with loop-back paths. It is basically a single AWG NxN multiplexer but with loop-back optical paths connecting each output port with its corresponding input port in the NxN multiplexer. The looped-back signals are automatically multiplexed again and fed out to the common output port. If required, a desired wavelength λi can be dropped or added by opening one of the loop-back paths corresponding to λi. If any elements were introduced into the loop-back paths, more attractive functions.
will be realized. Three useful photonic components, which are based on the AWG multiplexer with effective loop-back optical paths, are proposed and demonstrated.

(1) Add-drop Multiplexer

A 31-channel ADM was constructed as shown in Fig.2. The fiber-to-fiber insertion loss of this ADM was about 3.9-6.7dB for dropped or added optical signals and 8-13.5dB for other transmitting signals. The interchannel crosstalk was about -28dB. Figure 3a shows the measured transmission spectrum for the 16a-16b route in the ADM when only the loop-back path 12b-12a was open. The spectrum is characterized by 31 transmission peaks with a 0.8nm wavelength spacing and a periodicity (FSR) of 25.6nm. The peak corresponding to the λ12 channel in this spectrum has disappeared. The dropped signal λ12, which corresponds to the 16a-12b route, can be seen as a peak in the transmission spectrum of Fig.3b. This wavelength response was well matched with that of the added signal, which corresponds to the 12a-16b route. These responses were obtained even at the other grating orders n-1 and n+1. We achieved very good add-drop multiplexing.

(2) Network Access Terminal

A new network access terminal configuration is shown in Fig.4a. The proposed terminal is specially arranged in a symmetrical AWG multiplexer so that it can route optical WDM signals to any desired remote terminals. An arbitrary channel can be selected by means of the cross-connections in the loop-back paths. A different transmission response for the 16a-16b route is shown in Fig.4b. Here only two loop-back fiber paths 12 and 13 were cross-connected and the remaining 29 paths bar-connected. The transmission losses of the λ12 and λ13 lightwaves are higher than those of other single loop-back path transmissions. This is because these wavelengths occupied different channels constructed by cross-connecting loop-back paths. One channel accommodates terminals 13, 15, and 12 and then the other channel accommodates terminals 12, 17, and 13. Thus, dual channels include the common terminals (loop-back paths) 12 and 13. Here, remote terminals consist only of SC connectors. The λ12 and λ13 signals were transmitted alternately through the common loop-back fiber paths 12 and 13 of the AWG multiplexer on independent channels. The spectral response for the dropped route 16a-13b are shown in Fig.4b when loop-back fiber path 13 is open. The transmission loss of λ12 was higher than that of λ13. This is because the lightwave λ12 passes through the AWG multiplexer three times compared with only once for λ13.

(3) Wavelength Channel Selector

Figure 5a shows a tunable 15-wavelength channel selector configuration based on the 1.55μm AWG 16x16 multiplexer. Wavelength channel selective operation is successfully accomplished by inserting LD amplifiers (LDAs) into the loop-back fiber paths. Any one of the wavelength-multiplexed input signals can be selected temporarily by switching on/off the LDAs with a gate pulse as shown in trace (c) of Fig.5b. The two signals were given different repetition rates to allow them to be clearly distinguished. Trace (a) represents the multiplexed pulse stream (λ5+λ6) when the gate of LDA 5 was temporarily open and the gate of LDA 6 was continuously open, while trace (b) represents the continuously-selected λ5 channel and temporarily-selected λ6 channel. In this case of external-cavity-laser use, the signal isolation from adjacent channels was less than -40dB. The extinction ratio was 20dB depending on the active layer absorption of the LDAs.
Conclusions

We proposed and successfully demonstrated new functional components for dense WDM networks based on the integrated-optic AWG multiplexer. They will be used to construct smart wavelength-addressed networks or WDM ring networks.

Acknowledgements

We would like to thank Dr. M. Kawachi for his encouragement and Dr. Y. Ohmori and Mr. S. Suzuki for their help in fabricating the multiplexer.

References

Fig. 3 Spectral response of a 31ch add-drop multiplexer

(a) Transmission response
(b) Add-drop response

Fig. 4 Network access terminal operation
(a) Access terminal configuration
(b) Transmission spectral response

Fig. 5 Wavelength channel selector operation
(a) Channel selector configuration
(b) Two channel selective operation
a, b: selected multiplexed signals
λ5+λ6: induced gate pulse
4-CHANNEL WAVELENGTH FLATTENED DEMULTIPLEXER INTEGRATED WITH PHOTODETECTORS

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Abstract

We report the first 4-channel wavelength demultiplexer with flattened response, monolithically integrated with photodetectors. The demultiplexer is realized in InP/InGaAsP and operates around a centre wavelength of 1533 nm with a wavelength spacing of 2.0 nm. The response is flat within 1 dB for a 1.2 nm band centered around the transmission wavelength. Crosstalk remains below -20 dB. On-chip losses are estimated at -6.0 dB. Photodetector capacitances and dark currents at -5 V bias are 0.5 pF and better than 8 nA respectively.

Introduction

Wavelength Division Multiplexing (WDM) enables us to use both the electrical and optical domain for exploiting the huge bandwidth of optical fibers. A key-component in WDM-systems is a wavelength (de)multiplexer. Several wavelength demultiplexers have been reported [1, 2, 3]. A flattened response of the demultiplexer relaxes the tolerance conditions of the transmission laser wavelength. Such a flattened demultiplexer without detectors has been published recently by Amersfoort [4]. Wavelength demultiplexers without a flattened response, integrated with photodetectors have been reported [5, 6]. In this paper we report the realization of a wavelength flattened 4-channel demultiplexer integrated with photodetectors on an N+InP substrate.

Design

The presented wavelength demultiplexer is based on the phased-array concept [7]. The channel spacing was designed at 2.0 nm around a centre wavelength of 1535.0 nm. We applied multimode output waveguides in order to obtain a flattened wavelength response [4]. The light in the output waveguides is coupled into the detectors by evanescent field coupling (see Fig. 2). The layer structure was optimized for maximum detector absorption [8]. The detector capacitance was minimized for high frequency applications. Based on earlier experiments [8] the detector length was chosen 60 μm, for which 90% of the power is absorbed. The detector width was adjusted to the diffraction pattern of the optical field in the output waveguide of the demultiplexer. Since the output waveguide is multimoded and the diffraction of the highest order mode is largest (see Fig. 1), the detector width was adjusted to the diffraction pattern of the highest order mode present in the output waveguides. Taking a 2.0 μm tolerance, we ended up with a diode of 10 μm width at the beginning and 40 μm at the end (Fig. 2 a). In this way the pin area of the detector is minimized, while maintaining equal absorption for all modes. This is essential for maintaining the flattening of the wavelength response. The contact pad is placed on a 3.0 μm thick SiN$_x$ layer in order to reduce the parasitic capacitance.
Figure 1  Effective width of the diffraction of modes into a slab waveguide from a 6.0 \( \mu \text{m} \) deeply etched waveguide.

Fabrication

The layer structure was grown on an N\(^{+}\)-InP substrate by low pressure MOVPE. It consists of a 1.5 \( \mu \text{m} \) undoped InP buffer layer, a 0.6 \( \mu \text{m} \) undoped InGaAsP (Q1.3) waveguide core, a 0.3 \( \mu \text{m} \) undoped InP waveguide cladding layer, a 0.27 \( \mu \text{m} \) undoped InGaAs absorption layer, a 0.6 \( \mu \text{m} \) graded p-type InP layer (100 nm undoped, 200 nm \( 10^{17} \text{ cm}^{-3} \), 300 nm \( 10^{18} \text{ cm}^{-3} \)), and a 0.1 \( \mu \text{m} \) p-type \( 5 \times 10^{18} \text{cm}^{-3} \) InGaAs contact layer.

Detector mesa’s were formed by selective etching. The p-InGaAs/u-InGaAs and p-InP were etched by respectively \( \text{H}_2\text{O}_2:\text{H}_2\text{SO}_4:\text{H}_2\text{O} \) (1:1:10) and \( \text{HCl}:\text{H}_3\text{PO}_4 \) (1:4). Next a 140 nm PECVD SiO\(_2\) layer was deposited on the whole wafer. The waveguide pattern was defined in photoresist and etched in the SiO\(_2\) by CHF\(_3\) RIE etching. The photodiodes were covered with photoresist. By CH\(_4/\)He RIE etching a 350 nm step was etched in the InP/InGaAsP, forming the phased array waveguides (see Fig. 2b). Through a window in photoresist the output waveguides of the phased array were further etched with the SiO\(_2\) mask up to a depth of 1.0 \( \mu \text{m} \) (see Fig. 2c). This enables better confinement of the higher order modes, in order to obtain a flattened response of the wavelength demultiplexer.
After removal of the photoresist and SiO$_2$, the photodiodes were passivated by a stress free SiN$_x$ layer, which was 3.0 μm thick for reduction of the probe pad capacitance. The contact windows were etched in the SiN$_x$. The PECVD deposition process was optimized in order to obtain a V-groove type sidewall profile, which is suitable for interconnect metallization. The metallization of the p-contacs was formed by evaporation of Ti/Au, which was wet chemically etched. The n-type backside of the chip was metallized by Ti/Pt/Au. Finally, the contacts were annealed at 375 °C for 30 seconds and the chip facets were formed by cleaving. No AR-coating was applied. Fig. 2 shows the topview and cross-sections of the waveguides and detectors.

**Measurements**

The chip was characterized by coupling linearly polarized light from a HP 8168A tunable laser source into the waveguides with an AR-coated microscope objective. The light was absorbed by the integrated detectors and the photocurrent was measured. Fig. 3 shows the wavelength response for TE-polarization, measured by sweeping the wavelength of the tunable laser source. The excess losses were determined to be between -6 and -7.5 dB by comparison of straight waveguides integrated with photodetectors. The crosstalk level remains below -20 dB. Part of the cross-talk is caused by residual TM-polarization. The TE-TM shift is 5 nm, which is due to the birefringence of the array waveguides. The measured centre wavelength is 1533 nm, which is 2 nm less than the design value. The waveguide losses were determined by measuring the detector current for photodiodes with various waveguide lengths in front of the detector. The losses are estimated to be 1.5 dB/cm for both polarizations. The external efficiency was about 30% including the fiber-chip coupling losses.

![Waveguide losses](image)

**Figure 3** Wavelength response of the demultiplexer integrated with detectors. The measurements were calibrated against equal detectors integrated with straight reference waveguides.

The detector capacitance was determined at 1 MHz by CV measurements. Figure 4 shows the capacitance as a function of the bias voltage. Excellent uniformity is achieved and the capacitance is lower than 0.5 pF at -5 V bias. The dark current was below 8 nA at -5 V for all four photodiodes as depicted in Fig. 4.
Conclusions

A 4-channel phased array wavelength flattened demultiplexer integrated with photodetectors has been fabricated. The flattening occurs within a 1.2 nm band. Crosstalk levels below -20 dB have been measured. The detector capacitance is below 0.5 pF and dark current better than 8 nA for all four channels at -5 V bias.

Acknowledgements

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References

NOVEL InP-BASED PHASED-ARRAY WAVELENGTH DEMULTIPLEXER USING A GENERALIZED MMI-MZI CONFIGURATION

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Abstract

A novel type of wavelength demultiplexer is presented based on a generalized MMI-MZI configuration. This device combines the potential of low loss and high uniformity of the output channels with a small device size. Feasibility of the novel concept is demonstrated experimentally for a 4-channel demultiplexer with 4 nm channel spacing. Dimensions are 2800x106 µm, which is the smallest device size reported so far.

Introduction

Wavelength Division Multiplexing (WDM) is an effective way to exploit the huge bandwidth of optical fibres. In this paper a novel type of wavelength demultiplexer is presented. This device employs Multi Mode Interference (MMI) couplers in a Mach-Zehnder Interferometer (MZI) configuration. Due to the application of MMI-couplers the demultiplexer has the potential of low-loss and high uniformity of the output channels.

Operation principle

Figure 1 shows a generalized NxN MMI-MZI configuration. The first MMI-coupler acts as a 1 to N power splitter if the length $L_{\text{MMI}}$ is properly chosen: $L_{\text{MMI}} = 3L_{\text{N}}$, with $L_{\text{N}} = \pi/(\beta_0 - \beta_1)$, in which $\beta_0$ and $\beta_1$ are the propagation constants of the fundamental and the first order mode, respectively. Using input $i = 1$, simple equations can be obtained for the phase transfer $\phi_{ij}$ from port $i$ to port $j$ [1]:

Figure 1. Configuration of a MMI-MZI demultiplexer.

1. Now works with Microtechnology Systems Group, Swiss Federal Institute of Technology, Lausanne, Switzerland.
\[ \varphi_{ij} = \begin{cases} \varphi_0 + \pi + \frac{\pi}{4N} (j-1) (2N-j+1) & j \text{ odd} \\ \varphi_0 + \frac{\pi}{4N} j(2N-j) & j \text{ even} \end{cases} \]  

(1)

Travelling in the opposite direction, due to reciprocity light will constructively interfere into output 1 of the second MMI-coupler, if the phase relations of Eq. 1, with a minus sign, are satisfied, i.e. \( \varphi_k = -\varphi_j \). For the demultiplexer transfer the phase differences \( \Delta \varphi_k = -(\varphi_{k+1} - \varphi_1) \) between the inputs of the second MMI-coupler are important, not the absolute phases.

<table>
<thead>
<tr>
<th>Table 1. The required phase differences between the inputs of the second MMI-coupler.</th>
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<tbody>
<tr>
<td>( \Delta \varphi_k )</td>
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<td>( \Delta \varphi_1 )</td>
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<td>( \Delta \varphi_2 )</td>
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<td>( \Delta \varphi_4 )</td>
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<tr>
<td>( \Delta \varphi_9 )</td>
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<td>( \Delta \varphi_{10} )</td>
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</table>

Columns \( i = 1 \) to \( i = 4 \) from table 1 show the differences \( \Delta \varphi_k \) which are required in order to couple all the power to output 1 of a 4x4 demultiplexer. Inspection of the table shows that going from output \( i = 1 \) to \( i = 2 \), from 2 to 4, from 4 to 3, and from 3 to 1 the required phase difference \( \Delta \varphi_1 \) increases with a constant amount \( \Delta \varphi_1 = -\pi/2 \). The same holds for \( \Delta \varphi_2 \) and \( \Delta \varphi_3 \), the corresponding values of \( \Delta \varphi_k \) are listed in the last column. From this column it is seen that if we connect ports \( j \) and \( k \) by branches with lengths \( L_k \) which satisfy:

\[ \Delta L_k = L_{k+1} - L_1 = \frac{\Delta \varphi_k}{\Delta \beta}, \Delta \varphi_k = -k\frac{\pi}{2} \]  

(2)

in which \( \Delta \beta \) is the channel spacing \( \Delta \beta = \beta (\lambda_{i+1}) - \beta (\lambda_i) \), then the light will shift from output \( i = 1 \) to \( i = i+1 \) if the wavelength changes from \( \lambda_i \) to \( \lambda_{i+1} \) according to the sequence listed in the last row of table 1.

Figure 2. Layout of a 4x4 MMI-MZI demultiplexer: a) conventional, and b) with U-bend sections.

It should be noted that a minor correction \( \delta L_k \) to \( \Delta L_k \) has to be made in order to satisfy the absolute phase relations at \( \lambda_1 \), which does not affect the dispersion properties, however, due to
its small magnitude. Figure 2a shows how the required length differences $\Delta L_k$ could be realized. From the last column of the table we see that $\Delta \phi_k$ does not monotonically increase with array guide number $k$, which causes crossings in the array guides. Figure 2b shows a design in which the length differences are realized by insertion of U-bends. In this design crossings are avoided.

**Sensitivity to imbalance**

For a proper operation of the device all signals at ports $k$ should have proper phase and equal amplitude. Insertion of U-bends leads to additional losses which will be proportional to the number of U-bends inserted. If the uniformity of the signals is disturbed the imaging process will not perform properly, and power will be coupled to undesired ports leading to higher insertion loss and higher crosstalk.

**Figure 3.** Crosstalk level versus single U-bend loss.

Crosstalk values can be estimated by taking into account the U-bend losses in the simulation. If the single U-bend loss is denoted $r$, then the amplitude at input $k$ can be denoted as $a_k = (1 - r)^{n_k}$, in which $n_k$ is the number of U-bend sections for branch $k$. By approximating $a_k$ as $1 - n_k r$, which holds for small $r$, a simple equation can be derived for the resulting field amplitudes. Figure 3 shows the calculated crosstalk values. From this figure it is seen that even for losses as high as 0.5 dB per single U-bend the crosstalk is still acceptable. This is an important conclusion. It means that MMI phased-array demultiplexers are very tolerant to losses in the array branches as long as these losses depend linearly on the branch length.

**Figure 4.** Output of the realized 4x4 MMI-MZI demultiplexer: a) measured response (channel 1 defect), and b) simulated response with 1.5 dB single U-bend loss.
Experiments

The length of the MMI sections depends quadratically on the width [2], so in order to reduce the design dimensions a deeply etched waveguide structure is used [3]. Figure 5 shows the used waveguide structure. A disadvantage of these deeply etched structures are the bend losses, which lead to a non-uniform distribution of the powers in the different array guides.

![Deeply etched waveguide structure as used for the demultiplexer.](image)

A 4x4 MMI-MZI demultiplexer has been realized in a 1.5 μm deeply etched InP/InGaAsP/InP waveguide structure employing an etch/desum process for obtaining smooth and vertical sidewalls [4]. MMI-couplers with a width of 21 μm and a length of 664 μm are used, with 3 μm wide input waveguides and with 1.4 μm wide array waveguides. The demultiplexer was designed to operate at a central wavelength $\lambda_c = 1520$ nm with 4 nm channel spacing. The total device size is 2800x106 μm which is the smallest demultiplexer size reported so far. Figure 4a shows the measured wavelength response. The losses of the device are considerable (12 dB) due to problems in the mask, which resulted in rough waveguides. Measurements of single U-bends yielded 1.5 dB loss per single U-bend with a bending radius of 80 μm. Although measured crosstalk values are 5 dB worse than the simulated crosstalk values (shown in Fig. 4b), demultiplexing behaviour is clearly demonstrated and qualitative agreement between simulations and experiments is good.

Conclusion

A novel InP-based MMI-MZI demultiplexer is presented and experimentally demonstrated. Due to mask problems the realized device does not show optimal performance. The measured performance demonstrates a large tolerance to non-uniform branch losses.

References

Polarization Independent InP Grating Spectrograph for Fiber Optical Links

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ABSTRACT
An InP WDM demultiplexer that is polarization independent has been realized by means of a vertically etched diffractive grating in a n/n+ waveguide structure that leads to a very low birefringence. Measured polarization shifts of the filter passbands of a four channel demultiplexer with 4 nm channel spacing are less than 0.1 nm.

INTRODUCTION
Wavelength division multiplexing (WDM) in fiber optical links allows superior utilization of the optic fiber bandwidth and therefore attracts interest for optical communication over both long distances and in local area networks. For WDM applications demultiplexers are important devices. Grating-type demultiplexers allow the simultaneous detection of numerous wavelength channels [1]. Recently grating demultiplexers in InGaAsP/InP with integrated optoelectronic devices such as photodiode arrays [2],[3] or semiconductor optical amplifiers [4],[5] have been realized. These demultiplexers suffer from polarization birefringence and low coupling efficiency to single mode fibres. For waveguide grating arrays the polarization dependence has been reduced with special design of the grating order, but this resulted in a reduced free spectral range [6]. With a special vertical waveguide structure that consists of a repeated InP/InGaAsP stack, low polarization sensitivity has been achieved [7]. We propose a simple relatively large core n/n+ waveguide structure leading to very low birefringence and high coupling efficiency to optical single mode fibers.

DESIGN
The layout of the grating spectrograph is shown in Fig. 1. Input light coupled through a straight waveguide enters a slab waveguide. A vertically etched grating separates and couples the different wavelengths into laterally spaced waveguides, which, for coupling to fibers are separated by 250 μm. The radii of the waveguide bends are 10 mm. The grating is based on a Rowland construction with two stigmatic points [8]. Its working order is 30th. The structure of the waveguide is given in Fig. 2. The guiding film is a 3.2 μm thick undoped InP layer that eliminates the problems of lattice matching, layer composition and homogeneity of quaternary InGaAsP structures. The width of the waveguides is 5 μm. The calculated birefringence of the slab waveguide is 1.6·10^{-4}, leading to a polarization shift as low as 0.08 nm.
Fig. 1: Four channel InP WDM demultiplexer showing input waveguide coupled through planar waveguide section (black) to the vertically etched grating. The grating and the fiber alignment regions are deeply etched (grey).

Fig. 2: Slab and rib waveguide structures of the n⁻/n⁺-InP WDM demultiplexer, respectively. The rib waveguide is etched to a depth of 1.2 \( \mu \text{m} \). The given refractive indices are design values at \( \lambda = 1560 \text{ nm} \). Also shown are the calculated optical field distributions of the slab waveguide for both polarizations. For the rib waveguide the lines show equal optical field intensities spaced at 10\% for TE polarization.

**FABRICATION**

A 3.2 \( \mu \text{m} \) thick undoped InP guiding layer was grown by LP-MOVPE on a \( 2.3 \times 10^{18}/\text{cm}^3 \) sulfur doped (100) oriented InP substrate. For deep etching the waveguides and both the slab and the grating areas were masked with SiO₂ and covered with photoresist that left openings over the grating and the fiber alignment areas. Deep etching to a depth of about 6 \( \mu \text{m} \) was done by magnetron enhanced reactive ion etching with H₂/CH₄. After removal of the photoresist the areas outside of the waveguides were etched to a depth of 1.2 \( \mu \text{m} \) with H₂/CH₄ RIE. The gratings are reflection coated with Ti/Au. After cleavage the waveguide facets are antireflection coated with SiO.

**RESULTS**

Optical measurements were performed with a tunable external cavity semiconductor laser source. Output spectra of the four channels are superimposed in Fig. 3. The channel spacing of 4 nm is in agreement with the designed value. The absolute values of the wavelengths
differ only -0.65 nm from the design values. This small difference proves the very accurate control of the effective refractive index of the slab waveguide. The transmission curves can be shifted to their design positions with a slight temperature increase of 5 degrees. The 3 dB intensity widths of the WDM channels are 1.4 nm. Fig. 4 show the TE and TM transmission curves of a single channel to be equal to each other within the measurement resolution of 0.1 nm.

Fig. 3: Transmission curves of the four channels. The allocations of the channels are within 0.7 nm of the design values, corresponding to $\Delta n_{\text{eff}} = 0.0014$. They can be shifted to their design positions with a change in temperature of less than 6 degrees.

Fig. 4: Transmission curves of one WDM channel for TE and TM polarization. The shift between the two curves is within the wavelength resolution (0.1 nm) of the optical measurement system.
CONCLUSIONS
We have realized $n/n^+$-InP etched grating demultiplexers with negligible polarization dependence. The measured polarization dependence is within the resolution of the optical system. The $n/n^+$-InP waveguide structures thus allow precise control of the refractive index and of the absolute values of the channel allocations. The proposed $n/n^+$-InP grating structures are also well suited for demultiplexers with channel spacings below 1 nm.

ACKNOWLEDGMENTS
This work was in part performed within the ESPRIT Project MOSAIC. We acknowledge the support of the Swiss Federal Office for Education and Science, Berne. We thank the Swiss PTT for supplying the laser source.

REFERENCES
STRAINED InP/InGaAs QUANTUM WELL LAYERS FOR WAVELENGTH DEMULTIPLEXERS

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For the first time wavelength demultiplexers based on the phased array principle have been realized in an InP/InGaAs layer structure. The difference in spectral response for TE- and TM-polarization could be modified between 7 and 12 nm by using different strained MQW layers. The modal birefringence and thereby the polarization dependence increases for compressive strain and decreases for tensile strain.

1. Introduction

A key component in wavelength division multiplexed (WDM) systems is a demultiplexer integrated with photodetectors. For operation at \( \lambda = 1.55 \) \( \mu \)m, a demultiplexer based on a phased array (phasar) of waveguides in InP/InGaAsP material is favourable due to low loss and a relatively simple fabrication process [1].

Although in [1] the layers are optically isotropic, the mode indices of the ridge waveguide structure are different for TE- and TM-polarized light, \( N_{TE} > N_{TM} \). Hence, the spectral response of the demultiplexer for both polarizations are separated by \( \Delta \lambda_{pol} \): the TE-TM shift. Low polarization dependent response can be obtained by adjusting the free spectral range of the demultiplexer design to be equal to this \( \Delta \lambda_{pol} \) [2]. A disadvantage of this design is that all channels must be placed within \( \Delta \lambda_{pol} \), which is about 4.5 nm for an InGaAsP(\( \lambda_p = 1.3 \)) film layer. This limits the number of channels and/or channel spacing. The use of polarization independent waveguides would avoid this problem [8].

Replacing the InGaAsP film by a multiple quantum well (MQW) stack, consisting of InP-barriers and In\(_x\)Ga\(_{1-x}\)As-wells, two effects add to the optical birefringence: 1) the guiding layer is a stratified medium which gives an electromagnetic contribution, with \( N_{TE} > N_{TM} \). 2) Anisotropy of the quantum wells, i.e. energy splitting of light holes (lh) and heavy holes (hh). In the lattice matched case the electron-heavy hole (e-hh) transition energy is smaller than the electron-light hole (e-lh) transition energy. Hence this potential well contribution gives \( N_{TE} > N_{TM} \) [3]. This anisotropy can be influenced by biaxial strain in the quantum wells [4]. The energy splitting increases for compressive strain and decreases for tensile strain. At a certain amount of tensile strain (dependent on the well thickness) the energy splitting will reverse sign and also the potential well contribution to the birefringence, \( N_{TE} < N_{TM} \).

All mentioned effects increase the birefringence; only tensile strained wells can decrease the birefringence. Therefore by using tensile strained MQW waveguides it might be possible to make a polarization independent demultiplexer.
We fabricated and characterized phasars in which the film layer is composed of a strained InP/In$_{1-x}$Ga$_x$As MQW stack. The $\Delta \lambda_{\text{pol}}$ of these phasars has been adjusted between +7 and +12 nm.

2. Fabrication

All layers have been grown on semi-insulating 2° misoriented (100) InP wafers by Chemical Beam Epitaxy. Details of the growth are given elsewhere [5]. At the bottom InP/InGaAs interface approximately one monolayer InAs is present. When growing layers of lattice matched In$_{0.53}$Ga$_{0.47}$As, this interface results in a slightly positive strain, as revealed by X-ray diffraction [6]. This layer also affects the photoluminescence wavelength of the wells. Negative strain is obtained by increasing the Ga content in the wells. In Table 1, the different wafers are summarized.

A 120 nm thick sputtered SiO$_2$ layer served as an etching mask for fabricating ridge waveguides in the wafer. The pattern was defined in photoresist by projection illumination and transferred in the SiO$_2$ layer by CHF$_3$-RIE. For etching the InP we used a CH$_4$/He-RIE, employing an alternate etching/O$_2$-descumming process [7]. The cleaved facets were not anti-reflection coated. A typical waveguide structure is shown in Fig. 1. All the layers are non intentionally doped.

### Table 1: Parameters of MQW-wafers

<table>
<thead>
<tr>
<th>Top layer and etch-depth:</th>
<th>c147</th>
<th>c216</th>
<th>c224</th>
<th>c225</th>
</tr>
</thead>
<tbody>
<tr>
<td>InP cladding thickness [nm]</td>
<td>500</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Total film thickness [nm]</td>
<td>900</td>
<td>726</td>
<td>555</td>
<td>516</td>
</tr>
<tr>
<td>Etch depth $d_e$ [nm]</td>
<td>600</td>
<td>400</td>
<td>400</td>
<td>400</td>
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</table>

<table>
<thead>
<tr>
<th>MQW film:</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Well thickness (InGaAs) $t_w$ [nm]</td>
<td>1.6</td>
<td>5.0</td>
<td>3.4</td>
<td>2.6</td>
</tr>
<tr>
<td>Barrier thickness (InP) $t_b$ [nm]</td>
<td>4.3</td>
<td>7.1</td>
<td>4.0</td>
<td>6.0</td>
</tr>
<tr>
<td>$x$-fraction (In$<em>x$Ga$</em>{1-x}$As)</td>
<td>0.61</td>
<td>0.57</td>
<td>0.43</td>
<td>0.50</td>
</tr>
<tr>
<td>Strain (In$<em>x$Ga$</em>{1-x}$As) [%]</td>
<td>0.54</td>
<td>0.23</td>
<td>-0.69</td>
<td>-0.23</td>
</tr>
<tr>
<td>4K photoluminescence [J.$/\mu$m]</td>
<td>1.22</td>
<td>1.35</td>
<td>1.39</td>
<td>1.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PHASAR results:</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \lambda_{\text{pol}}$ [nm] calculated, $\Delta n=0$</td>
<td>4.9</td>
<td>8.4</td>
<td>8.2</td>
<td>5.4</td>
</tr>
<tr>
<td>$\Delta \lambda_{\text{pol}}$ [nm] measured</td>
<td>7.1</td>
<td>11.8</td>
<td>8.1</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Fig. 1. Typical waveguide geometry of the ridge waveguide.
A 4-channel phased array demultiplexer [1] with 1.8 nm channel spacing has been designed for measuring $\Delta\lambda_{\text{pol}}$, the free spectral range of this design was 15 nm. The demultiplexer exists of a dispersive and focusing waveguide array connected to slab waveguide regions for radiatively coupling light into and out of the array. All the waveguides were 2 µm wide.

3. Measurements

The optical characterization of the demultiplexers was performed with an HP 8168A tunable laser source. Light of fixed polarization was end-fire coupled into the waveguides with an (40×) antireflection coated microscope objective. The light emanating from the waveguides was imaged onto a Ge diode. The spectral responses of wafer c147 for TE- and TM-polarization are shown in Fig. 3, $\Delta\lambda_{\text{pol}}=8.1$ nm can be found from the figure.

![Fig. 2. Spectral response for TE- and TM-polarization of wafer c147. Insertion loss is not included in the figure.](image)

The crosstalk level is about -25 dB for both polarizations, which is comparable to a phased array fabricated in a bulk InGaAsP(1.3) film[1]. The measured $\Delta\lambda_{\text{pol}}$ for the other samples are given in Table 1. Straight waveguide losses were (2.3± 0.6) dB/cm for TE-polarization and (2.0± 0.2) dB/cm for TM-polarization.

4. Calculations

The refractive index of the InGaAs wells for TM- and TE-polarized light is modelled with:

$$n_{\text{InGaAs,TM}} = 3.50; \quad n_{\text{InGaAs,TE}} = 3.50 + \Delta n.$$  

$\Delta n$ is the potential well birefringence, which is dependent on the strain. The refractive index of the InP barrier is taken equal for both polarizations, $n_{\text{InP}}=3.17$. For both polarizations the refractive index of the guiding MQW layer is calculated as described in [3]. After embedding this film in the waveguide structure, the mode indices can be calculated with the effective index method. From these mode indices $\Delta\lambda_{\text{pol}}$ can be calculated as a function of the dilution factor ($d_f = \frac{n_{\text{InP}}}{d_{\text{InGaAs}}}$) of the MQW layer with $\Delta n$ as a parameter, as shown in Fig. 3.
From Fig. 3 can be concluded that for a given dilution factor the $\Delta \lambda_{\text{pol}}$ can be increased with a positive $\Delta n$ (compressive strain) and that $\Delta \lambda_{\text{pol}}$ can be reduced by a negative $\Delta n$ (tensile strain). Within the aforementioned assumptions a polarization independent waveguide ($\Delta \lambda_{\text{pol}}$) can be made by using a dilution factor of about 1.5 with $\Delta n = -0.06$. The measurement points of Sec. 3 are indicated with triangles in the figure.

5. Conclusion and Discussion

With compressive strained layers the measured $\Delta \lambda_{\text{pol}}$ was larger than the calculated one, hence compressive strain gives a positive contribution to $\Delta \lambda_{\text{pol}}$. With tensile strain a clearly reduced contribution was observed. With higher tensile strained layers the measured $\Delta \lambda_{\text{pol}}$ was even smaller than the calculated one. This effect opens the opportunity to control the polarization dependence of the transmitted response of phasar based demultiplexers by strained MQW layers.

References

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Abstract
The influence of axial strain on the refractive index of InGaAsP is studied experimentally in wavelength demultiplexers. Compressive strain is found to decrease the refractive index in the direction perpendicular to the strain as compared to the parallel direction.

Introduction
Most applications require polarisation insensitivity, i.e., a response which is independent of the state of polarisation of the input wave. In passive devices such as wavelength demultiplexers, polarisation dependence originates from the guiding structure, which has different propagation constants for TE and TM polarised waves. One way to reduce the birefringence is to use quaternary material close to InP [1], but the composition of the material is difficult to control and to reproduce accurately. We show here for the first time that birefringence can be introduced into the material itself, i.e., that material index can be made different for TE and TM polarised waves by introducing axial strain in the guiding layers. The TE and TM effective index difference can be increased or decreased according to the nature of the strain (compressive or tensile).

The effect of axial strain
Axial strain is known to modify the energy levels of the light and heavy holes as well as their peak transition energies. The TE and TM absorption are modified accordingly, the TM absorption with the heavy-hole level, the TE one with both light and heavy hole levels. Because of the Kramers-Krönig relations, the TE and TM indices should also be changed. A detailed model which would be necessary to evaluate the amount of index change that can be obtained with strain is not available at present. Therefore, our results are purely experimental.

Experimental results
Our test structure is the five-core structure described in figure 1 [2]. The guiding structure, which consists of five 600 Å thick InGaAsP ($\lambda_g=1.18 \mu m$) layers separated by
0.35 μm of InP, is grown by Gas Source Molecular Beam Epitaxy. Some strain, either tensile or compressive, can be introduced into the quaternary waveguides. The thickness of the top InP cladding layer varies between 1 and 2 μm in the different components presented here. A 4 μm wide ridge is etched down to the first quaternary layer using CH₄/H₂ Reactive Ion Etching.

Birefringence is measured in wavelength demultiplexers [2, 3] as the difference between TE and TM peak wavelengths. In the unstrained structure, the calculated TE/TM index difference of Δnₑffective=1.8 × 10⁻³ (using the index of refraction of reference [4]) gives an expected birefringence of about 0.8 nm. Measurement results are reported in Table 1.

Table 1:

<table>
<thead>
<tr>
<th>ε (%)</th>
<th>λₚₐₙ (nm)</th>
<th>Δλₘₑₐₛ (nm)</th>
<th>α (dB/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.16</td>
<td>0.80</td>
<td>1-1.5</td>
</tr>
<tr>
<td>-0.12</td>
<td>1.16</td>
<td>1.00</td>
<td>0.7-1</td>
</tr>
<tr>
<td>-0.25</td>
<td>1.18</td>
<td>1.25</td>
<td>0.5-1</td>
</tr>
<tr>
<td>+0.24</td>
<td>1.18</td>
<td>0.70</td>
<td>1-1.5</td>
</tr>
</tbody>
</table>

Table 1: ε - value of strain (- = tensile, + = compressive)
λₚₐₙ - photoluminescence wavelength
Δλₘₑₐₛ - wavelength birefringence measured on demultiplexers
α - propagation losses

It can be seen that propagation losses are kept low on the whole range of strain (below 1.5 dB/cm), showing the good quality of the material. Birefringence seems to be controlled by the importance of strain.

However, the different wafers reported here are slightly different in terms of thickness of the top InP layer and etching depth. Also, material composition varies slightly with strain,
inducing a change in refractive index. Therefore, measured birefringence can only be compared to the value calculated in the exact structure. Whereas the geometry of the structure is known precisely, the material index of the guiding layers can be deduced from measurements as follows: the peak wavelengths of the demultiplexed channels are used to measure the TE effective index \( n_{\text{eff}} \) of the guiding structure. The (TE) index of the quaternary layer \( n_{\text{quat}} \) is deduced using the effective index method (valid here because of the weak lateral confinement) to fit the measured TE effective index and assuming a refractive index of 3.169 for InP at 1540 nm [4]. Since the precision of the measured effective index is about 0.001, the precision on the calculated quaternary index is 0.007. The results are shown in Table 2.

<table>
<thead>
<tr>
<th>( \varepsilon ) (%)</th>
<th>( n_{\text{eff}} )</th>
<th>( n_{\text{quat}} )</th>
<th>( \Delta \lambda_{\text{calc}} ) (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3.181</td>
<td>3.31(1)</td>
<td>0.78</td>
</tr>
<tr>
<td>-0.12</td>
<td>3.184</td>
<td>3.32(8)</td>
<td>0.97</td>
</tr>
<tr>
<td>-0.25</td>
<td>3.184</td>
<td>3.32(6)</td>
<td>0.91</td>
</tr>
<tr>
<td>+0.24</td>
<td>3.182</td>
<td>3.31(1)</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Table 2

It appears that the variation of the TE index \( n_{\text{quat}} \) under the influence of composition is weak. The TE/TM wavelength shift \( \Delta \lambda_{\text{calc}} \) is now calculated with the corresponding material index, assuming a group index of 3.4 and no material birefringence (i.e., the same material index \( n_{\text{quat}} \) for the TE and TM polarised waves) and can be directly compared to the measured value. The difference between calculated and measured wavelength shifts, shown in figure 2, is therefore due to the difference between TE and TM material index only.

![Figure 2](image_url)

Figure 2: Difference between measured and calculated wavelength shift versus strain.

Tensile strain clearly increases the wavelength shift (i.e., the "TE" material index becomes larger than the "TM" index) whereas compressive strain decreases it (i.e., the "TM"
material index becomes larger than the "TE" index). The wavelength birefringence measured at \( \varepsilon = 0.25\% \) suggests a material index birefringence of about 0.035. However, compressive strain is limited to about 0.3 % in this structure (because of cross-hatch) and tensile strain to typically 0.5 % because of dislocations. Therefore, birefringence cannot be decreased to zero in our structure. It has nevertheless be shown that it can, to some extent, be controlled by the amount of strain.

Conclusion

The index variation with strain has been investigated for the first time. Compressive strain is found to decrease the refractive index in the direction perpendicular to the strain (TE-polarised wave) with respect to the index in the direction of the strain (TM-polarised wave). A change of 0.4 nm in birefringence can be achieved in our 5-core structure. A suitable structure remains to be found where enough compressive strain can be applied to the guiding layers to eliminate birefringence.

Acknowledgement

We wish to thank M. Erman for initiating this work, and J-Y Emery and M. Renaud for helpful discussions.

References


OXIDIZED POROUS SILICON BASED WAVEGUIDE FOR OPTICAL INTERCONNECTIONS.

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Abstract

We have realized the first integrated optical waveguide based on oxidized porous silicon. Main steps of the waveguide formation and experimental results on lightguiding in the visible range are presented.

1 Introduction

It is a common knowledge that only compound semiconductors can support all the aspects of integrated optoelectronic systems including light emission, waveguiding, and detection. Nowadays the old idea of electron and optical devices integration using silicon technology has received a strong impetus since the demonstration [1] that porous silicon (PS) has effective luminescence in the visible range. Besides, PS was shown recently to be a promising material for stable light-emitting diodes [2] and effective photodetectors [3]. So, optical waveguides are the only class of optoelectronic devices that have not been made of porous silicon [4].

This contribution presents experimental results on integrated optical waveguide made of oxidized porous silicon.

2 Experimental

Technological process of waveguide fabrication consists of the following main steps (fig.1):

a) 0.2 μm silicon nitride film deposition and patterning to form a mask of waveguide topology;

b) anodization of boron-doped Si(100) wafer of 0.01 Ohm·cm resistivity in HF/alcohol
electrolyte under anodic current density of 10-30 mA/cm² through the mask to form porous silicon. As a result, porous silicon local layers of single fiber or Y-shape waveguide topologies were formed;

c) the mask removal and thermal oxidation of porous silicon:
- low-temperature oxidation at 300 °C for 1 h in dry oxygen to stabilize porous silicon structure and to prevent PS from sintering [5];
- full oxidation of PS in steam ambient at 900 °C;
- densification of oxidized PS by temperature raise up to 1150 °C during 25 minutes and anneal of oxidized PS in wet oxygen-nitrogen atmosphere to improve optical properties of the material obtained.

These "soft" regimes together with proper choice of PS parameters provided low mechanical stress level of the waveguide structures, absence of cracks and dislocation slip lines. The waveguides had a length of 1.5-3.0 cm, a width and thickness of 5-15 μm.

Optical waveguiding in the visible range was observed by end-fire coupling into the mirror-like cleaved end of a waveguide via microscope. Tungsten lamp or He-Ne laser (λ = 633 nm) were used as a light source. The light transmitted was focused on to a liquid-nitrogen-cooled Ge:Cu photodetector via an objective. The transmittance was measured for various lengths of each sample.

3 Results

White light of tungsten lamp or red light of He-Ne laser were easily observed via microscope both on the surface near the ends of waveguide (fig.2) and at its cross section (fig.3). As seen from fig.3, the light was guided in the center part of the waveguide cross section.

4 Discussion

The lightguiding effect in oxidized PS/Si structure was surprizing: no any specially formed buffer layer was formed.

In our opinion, thermal oxide layer is formed at the oxidized PS/Si interface and acts as a confining layer preventing light leakage from waveguide into the Si substrate. Optical properties of oxidized porous silicon are very sensitive to its structure, composition, and density [6, 7]. In particular, its refractive index can be modulated by changing both thermal oxidation/densification regimes and PS porosity. The "core" part of the waveguide cross section has higher refractive index in comparison with the periferical thermal oxide confining layer.

Besides, local mechanical stress field could influence light guiding through the waveguide. Measured optical loss less than 1 db/cm seems to be due to the absence of scattering centers on sidewalls, cracks and other defects reducing optical properties of the material obtained.

Optical waveguides based on oxidized porous silicon have several advantages:
- any cross-section shape and topological design;
- buried in silicon, under microelectronic components;
- wide range of thickness (0.1-50 μm) and width (0.5-1000 μm);
- wide range of transmission (UV, visible, IR);
- variation of transmission (by rare-earth elements doping and thermal modification);
- compatible with silicon-on-insulator structures.
References


Figure 1: The main steps of fabrication process: a) masking; b) silicon anodization; c) porous silicon oxidation/densification.
Figure 2: Schematic view of optical waveguide (Y-splitter) based on oxidized porous silicon:
1 - Si substrate; 2 - oxidized porous silicon; 3 - thermal oxide; 4 - light source.

Light "OFF"  Light "ON"

Figure 3: Cross section microphotograph of the waveguide based on oxidized porous silicon.
Antiresonant reflecting optical waveguides (ARROWS) in KTiOP0 4 (KTP) were designed and fabricated by e-beam direct writing and double rubidium-potassium ion exchange. Theoretical ARROW-mode field distributions calculated by the finite element method, the refractive index profiles of the reflectors and the waveguiding layer, and measured nearfield distributions are presented.

1. Introduction: As a kind of low loss leaky waveguides antiresonant reflecting optical waveguides (ARROWS) have already shown their unique features as passive elements such as polarizers, filters and directional couplers [1,2,3,4,5]. Especially the discrimination of high-order modes and the capability of the so-called remote coupling [6] make ARROWS promising for some special applications. In order to demonstrate their potential as electrooptic modulators, switches and new confinement for second harmonic generation (SHG), one has to use a suitable nonlinear optical substrate material like KTiOP0 4 (KTP) [7]. The rubidium-potassium ion exchange in KTP allows easy fabrication of strip-ARROWS. Regarding the ARROW-concept, the main advantage of this ion exchange process is its extreme anisotropic diffusion behavior (the diffusion constant in z-direction of the crystal is several orders of magnitude higher than in the x-y plane [7]). Others are the great second-order nonlinear coefficients and low sensitivity concerning light-induced refractive index changes.

2. ARROWS in KTP: The ARROW-principle in Rb:KTP is sketched in Fig 1. While the optical field in the vertical z-direction is confined by a conventional waveguiding layer, the lateral confinement in x-direction is provided by a series of antiresonant reflectors. The refractive index increase of the reflectors (or barriers) is realized by a Rb+K ion exchange yielding an index change as large as possible. Because of the strong diffusion anisotropy of this ion exchange process, the structures in the metal mask at the surface of the substrate are identically transferred into the crystal during the exchange, thus, the barriers are well-defined. The optical field...
travelling along the y-direction with the complex propagation constant $\beta$ is mainly located in the resonant waveguiding core with the effective refractive index $n_0$ and the width $d_0$. In order to get the ARROW-based confinement, the width $d_1$ and the distance $d_2$ of the Fabry-Perot reflectors have to be chosen to fit the antiresonant conditions at the wavelength $\lambda$ ($n_1$ and $n_2$ are the corresponding effective refractive indices in the barrier regions and between them). The conditions are [8]

$$d_j \sqrt{n_j^2 - \beta^2} = \frac{\lambda}{4} (2j - 1) \quad (1)$$

for the antiresonant reflectors ($j=1,2$), and

$$d_0 \sqrt{n_0^2 - \beta^2} = \frac{\lambda}{2} m \quad (2)$$

for the resonant core, where $l$ and $m$ are integers ($l,m=1,2,...$). The imaginary part of $\beta$ is a measure for the leakage of the ARROW. A simple but efficient way to calculate $\beta$ and to optimize the design is the transfer matrix approach in combination with the effective index method [6]. Considering the material dispersion of KTP the one-dimensional field distributions of possible pump- and SHG-waves are depicted in Fig. 2.

However, in order to get more accurate calculations, one has to take into account the two-dimensional refractive index profile $n(x,z)$. Figure 3 shows the theoretical field distribution of the ARROW-mode using the vectorial finite element method (FEM). In spite of the relatively small index increase at the surface $\Delta n_{\text{max}}=0.01$ between the high index barriers and the low index regions, which was assumed in this case, the field is strongly confined in the waveguiding core.

Furthermore, from calculations of the ARROW-mode attenuation as a function of the barrier width we obtain fabrication tolerances for the barrier width of about $\pm 0.3 \, \mu m$, if we intend to achieve losses $<0.1 \, \text{dB/cm}$ for this configuration. This makes e-beam direct writing for the fabrication of the exchange mask necessary.
3. Fabrication of conventional waveguides and ARROWs in KTP: In order to realize ARROWs in KTP high-Δn channel waveguides for the antiresonant reflectors as well as a low-Δn waveguiding layer are needed, that is we have to carry out a double ion exchange. In principle, the order of the exchanges does not make any difference. However, the regions exchanged at first will be annealed during the second ion exchange. If the Rb→K ion exchange is performed in RbNO₃ melts without any fraction of potassium ions we obtain the maximum Δn of about 0.03 for this ion exchange [9]. Introducing potassium to the melt lowers the amount of rubidium incorporated in the crystal, and thus lowers the index increase. The mixed melt permits us to obtain small refractive index changes (e.g. necessary for singlemode operation at short visible wavelengths) without subsequent annealing [10] and to use relatively low exchange temperatures around 300°C, and prevents surface cracking. Barium ions in the melt increase the exchange rate, homogenize the waveguide and improve the reproducibility.

The ARROWs were fabricated in z-cut KTP substrate material (delivered by Crystal Technology, xyz dimensions: (5×25×1) mm³) in y-propagation direction. At first we performed the ion exchange for the reflectors by using a melt of [90mol% RbNO₃/0mol% KNO₃/10mol% Ba(NO₃)₂] at 350°C and an exchange mask (CrNi) fabricated by e-beam direct writing. After metal removing, the low-Δn exchange for the waveguiding layer was carried out in a mixed melt of [65mol% RbNO₃/32mol% KNO₃/3mol% Ba(NO₃)₂] at 310°C. Figure 4 shows the resultant

![Typical refractive index profiles of ARROWs in depth direction](image)

- substrate refractive index: \( n_s = 1.8417 \)
- erfc refractive index profile: \( n(z) = n_s + Δn \cdot \text{erfc} \left( \frac{z}{d} \right) \)
- Gaussian refr. index profile: \( n(z) = n_s + Δn \cdot \exp \left[ - \frac{z^2}{d^2} \right] \)
- 90/0/10 exchange melt: 90mol% RbNO₃/0mol% KNO₃/10mol% Ba(NO₃)₂
- 65/32/3 exchange melt: 65mol% RbNO₃/32mol% KNO₃/3mol% Ba(NO₃)₂
refractive index profiles at $\lambda = 850$ nm in this case, which were obtained by means of m-line spectroscopy measurements and the well-known WKB method. As already mentioned, the index change of the reflector regions is lowered by the annealing effect during the second exchange down to about 0.010. Finally, the samples were endface-polished.

We have successfully investigated the ARROWS by end-fire coupling of TM- and TE-polarized laser beams at visible and NIR wavelengths. By focus displacement of the input microscope objective either the ARROW-mode alone (focus) or all barriers (out-of-focus) can be excited. Figure 5 shows the nearfield distribution of an ARROW-mode, at $\lambda = 530$ nm in this cases, which

![Fig. 5 Measured nearfield distribution of an ARROW in Rb:KTP at $\lambda = 530$ nm; the secondary lobes are due to residual light in the four multimode channel waveguides of the barriers](image)

was detected by a Beam View Analyzer. The residual light in the multimode barrier channel waveguides is probably due to scattering or incomplete ARROW-mode excitation at the input endface. The sample length was 2.0 cm and the ARROW-core width $d_0 = 10 \mu$m.

4. Conclusion: These first results indicate that ARROWS in KTiOPO$_4$ fabricated by the technology described here appear to have a combination of properties that make it superior for efficient second harmonic generation and electrooptically controlled remote coupling.

References

LOW TEMPERATURE, NITROGEN DOPED
WAVEGUIDES ON SILICON WITH SMALL CORE
DIMENSIONS FABRICATED BY PECVD / RIE

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Abstract
A new type of low loss waveguides with small core dimensions is presented. The waveguides are mode matched to standard single mode fibres. Also integrated optical devices like 1 x 8 power splitters and 1300 / 1550 nm wavelength division multiplexers are fabricated using low temperature PECVD-deposited SiO,N ./ SiO2-layers.

Introduction
Passive integrated optic circuits provide important network elements (e.g. splitters, multiplexers) in optical communication systems. These integrated optical devices have to be mode-matched to standard single mode fibres operating at 1300 nm or 1500 nm wavelength. Many types of waveguide technologies have been employed. On one side, there are ion exchanged waveguides in special glasses [1]. Alternatively, low loss passive waveguide devices are based on silicon substrates utilizing flame hydrolysis or CVD-techniques for deposition and reactive ion etching (RIE) for waveguide delineation [2]. Here, we present the fabrication of low loss waveguides by low temperature (T = 350 °C) plasma enhanced chemical vapor deposition. Two core materials have been investigated: SiON [3] and SiO, [4]. The high Δn waveguides (Δn = 3.5 %) require very thin core layers, only. Therefore, they are easily delineated by RIE, using only resist masking and yielding a very small roughness of the sidewalls. This leads to fully CMOS-compatible low loss optical waveguides on silicon substrates which are mode matched to standard single mode fibres. Additional electronic circuits or micromechanical positioning elements for fibres (V-grooves) or for active elements (lasers, photodiodes) can be integrated on the substrate.

Waveguide design
Waveguide devices on silicon fabricated by flame hydrolysis [5] or the deposition of phosphorus doped core layers (PSG) [6,7] require high temperature processes and above all deep RIE etching for the waveguide core. Our nitrogen/silicon co-doped waveguides are fabricated by PECVD, and they have very shallow waveguide cores, only. Fig. 1 shows the waveguide cross section. We observe the small height of the waveguide core. The waveguide dimensions are designed for an high coupling efficiency to standard single mode fibres. Numerical calculations
(Method of Lines [8]) exhibited a coupling efficiency of 95 % for a core rib height of 350 nm and 3.5 % refractive index contrast. This high coupling efficiency is rather tolerant to fabrication errors allowing ± 50 nm in waveguide height and ± 1 µm in waveguide width. The residual film thickness was set at 100 nm. It was found that a residual film adjacent to the waveguide core reduces the attenuation due to edge roughnesses. Fig. 2a,b show a comparison between the calculated and measured field distributions. The bending losses are governed by the fibre matched field distribution. Our process allows a simple tapering of the waveguide width for a reduction of the bending losses. The waveguides are single mode up to 9 µm waveguide width. The minimum bending radii were determined to be 20 mm.

Waveguide fabrication

The waveguides were fabricated on standard 100 mm <100> silicon wafers which are covered with 8.5 - 11 µm thermal oxide (high pressure steam oxidation) or PECVD-oxide. A 0.35 - 0.6 µm thick core layer of silicon oxinitride is deposited using SiH₄ : Ar / N₂O / NH₃ or SiH₄ : Ar / N₂O mixtures in a 13.56 MHz parallel plate plasma reactor. The core layer is structured with a resist mask in a RIE-process using a CHF₃ - Û:l gas mixture. A layer of 5 - 8 µm PECVD-oxide is used as superstrate. The end faces of the waveguide are prepared by back-side cutting and breaking the silicon wafer.

Two different core materials have been utilized which are commonly denoted as SiON and SiOₓ. Both materials allow a refractive index which is adjustable between 1.46 (oxide-like) and nearly 2.0. Best results have been achieved for refractive index contrasts of 2 - 4 %. However, FTIR analysis showed that both materials can be identified as SiOₓNₓHₓ with varying composition. SiON contains more nitrogen linked with hydrogen than SiOₓ which itself contains more Si-H and Si-O-H bonds. Unfortunately the 2nd overtone of the Si-H and the 1st overtone of the N-H bond cause losses around 1500 nm wavelength. Therefore, both materials exhibit almost the same transmission characteristic as shown in Fig. 3. For optical communications the 1300 nm and 1550 nm wavelength regions are important. At λ = 1300 nm waveguide losses less than 0.2 dB cm⁻¹ have been determined, whereas at 1550 nm 0.5 dB cm⁻¹ are measured. A coupling loss of 0.55 dB per face has been found.

Waveguide devices

Several waveguide devices have been realised to demonstrate applications of this new type of waveguide. Power dividers (1 x 8) and 1300 / 1550 nm wavelength division multiplexers have been realised with 30 mm bending radii. The waveguide to waveguide distance at the input / output is 250 µm. This allows a direct coupling to fibre ribbons with 2, 4 or 8 fibres. The 1 x 8 power splitters use cascaded Y-junctions. The output powers are 11.6 ± 0.6 dB. Waveguide bendings and Y-junctions cause an additional loss of less than 0.5 dB at 1300 nm. A wavelength division multiplexer for 1300 / 1550 nm based on a directional coupler has been fabricated in the same way. The transmission characteristic is given in Fig. 4. The cross-talk is reduced to 30 dB. It should be noted that the fabricated multiplexer accurately agreed with the numerical design.
Conclusions

New high refractive index contrast waveguides for optical communication applications have been demonstrated which are mode matched to standard single mode fibres. The waveguide attenuation is less than 0.2 dB cm\(^{-1}\) at 1300 nm and the coupling loss could be reduced to 0.55 dB per facet. They can be produced using only ‘cold’ plasma processes at temperatures of less than 400 °C. Therefore, it is possible to integrate this waveguides with CMOS electronic circuits. The small dimensions allow short deposition and etching times. They can be fabricated in a standard equipment for integrated circuit fabrication (PECVD- and RIE systems) and they are fully CMOS-process compatible. Typical integrated optical circuits have also been demonstrated. The use of standard silicon wafers allows the integration of fibre guiding grooves or positioning of lasers or photodiodes by silicon micromachining.

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![Waveguide cross section with typical dimensions and refractive indices at 1300 nm](image-url)
Fig. 2: a) Calculated near field distribution  
b) Measured near field at 1300 nm wavelength

Fig. 3: Transmission characteristic of fibre-coupled PECVD- SiON and SiO$_x$ waveguides 
(40 mm length; 0 dB: fibre-to-fibre reference)

Fig. 4: Spectral characteristic of a 1300 / 1550 nm wavelength division multiplexer 
(0 dB-reference: 30 mm straight waveguide)
REFRACTIVE INDEX RELAXATION IN PECVD- AND LPCVD-SION-WAVEGUIDES ON SILICON SUBSTRATES

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Abstract
Mechanical properties of integrated optical waveguides like the internal stress have a profound impact on the optical their optical properties like effective refractive index and birefringence. In course of time these properties may change due to stress relaxation and thermal treatments. This paper presents the inherent stress in SiON layers deposited by PE- and LPCVD processes on silicon as function of refractive index (1.46 to 2.0) and the influence of stress relaxation due to thermal furnace annealing as well as local short time annealing with a CO₂ laser. The observed change in refractive index and its long term relaxation is investigated and a model for the observed relaxation based on glass theory is presented.

Introduction
Integrated optical waveguides based on SiO₂-SiON-SiO₂-layers deposited on silicon have found widespread applications in integrated optical circuits for optical communication and sensing [1-3]. In course of the deposition using processes like PECVD, LPCVD or flame pyrolysis mechanical stress is introduced into these films which is due to their deposition at elevated temperatures at differing thermal expansion coefficients of substrate and film and due to the formation of the film itself. As this stress has as strong impact on the film density and accordingly on the refractive index, the guiding properties of optical waveguides will also be affected. Especially devices like waveguide couplers and bends may exhibit significant variations, if these stresses are allowed to relax. Therefore the long term stability of such circuits might be impeded by this phenomenon. A defined, wishfully local relaxation of the film density on the other hand could be utilized to selectively tune such components or e.g. couple detectors buried in the silicon substrate to the waveguide via the evanescent field [4,5].

In this paper the inherent stress of the commonly used SiON-waveguides deposited by thin film techniques like PE- and LPCVD-processes as function of the film index and its temporal relaxation at different annealing conditions are investigated.

Experimental
The waveguide layers were deposited in an SiCl₄-H₂-N₂-O₂ reaction for the LPCVD at 930 °C and an SiH₄-N₂-O₂-reaction at 350 °C for the PECVD processes using standard hot wall and parallel plate reactors, respectively, on low doped 3° wafers with both sides polished. The film composition was varied between silicon dioxide and nitride with refractive indices of 1.46 to 2.0 and 1.45 to 1.8, respectively, by changing the gas composition [1,2]. The films are deposited on one side for the PECVD- and both sides for the LPCVD-layers. Immediately after removal from the reactor the refractive index and film thickness was measured by ellipsometry at HeNe-laser wavelength. These measurements were repeated after about one week with no observable change in these parameters. In addition FTIR-measurements were performed to determine the film composition and the residual hydrogen content. The internal stress in the layers was evaluated by measuring the bending in the centre of the substrate before and after film deposition (for the LPCVD-layers after removal of the backside layer) by mechanical (Tencor α-step) and a plane surface interferometer. Knowing the Young’s modulus E, and
Poisson's ratio $\nu$, of the silicon substrate and the substrate $d_s$ and film thickness $d_f$ the stress in the layers $\sigma_f$ is calculated from the bend radii before $r_b$ and after deposition $r_s$ [6]:

$$\sigma_f = E_s \left[6(1-\nu_s)\right] \frac{d_f}{d_s} \left(\frac{1}{r_s} - \frac{1}{r_b}\right)$$

These measurements were repeated directly after the annealing processes in a furnace in nitrogen at 1000°C for one hour and the local short time laser treatments and afterwards at defined time intervals for several months. For the laser annealed samples the spot size for the ellipsometer as well as for the FTIR was accommodated to the laser half width diameter, respectively. A microspot optic was used to determine the local variation within the laser annealed area. The laser annealing was performed with a 100 W CO$_2$-laser at 10.6 μm which is efficiently absorbed in the SiON-layers. Typical powers used for the annealing varied between 30 and 60W corresponding to power densities of 150 to 300 W/cm. Surface temperatures of 200 to 1000°C measured with miniature thermocouples were obtained within 10 to 40s depending on the type of substrate holder (thermal contact to quartz holder or free standing substrate).

Results and Discussion
Relevant results are summarized in Figs. 1 to 7. In Fig. 1 the inherent stress in the layers is depicted as function of the refractive index for LPCVD- and PECVD-layers. Whilst the PECVD-layer for all indices show a moderate compressive stress, if deposited at 350°C, layers deposited at about 300°C as well as the LPCVD-layers exhibit a change from compressive to tensile at an index of about 1.6. The stress in the LPCVD-layers on the average is higher, which especially for the higher indices restricts the allowed thickness for such layers. The relative variation in refractive index and corresponding change in layer thickness as function of the index, as obtained after a 60s laser annealing at 50W is shown in Fig. 2. Fig. 3 depicts the local variation of the index in the laser annealed area. This is equivalent to a 1 hour furnace anneal at 1000°C. A significant change is found for close to oxide layers with a maximum at an index of 1.55 which happens to be close to the optimum index for weakly guiding single mode waveguides. The index change vs. laser power at constant time (60s) and vs. annealing time at constant power (50W) is shown in Fig. 4. The observed change in layer thickness is not very pronounced and systematic. Whist the index varies about linearly with laser power, it saturates after several 10s, which closely relates to the temperature increase in the layer. Fig. 5 depicts the relaxation of the laser induced index variation in course of time for different laser powers. About 30% of the induced change relaxes within three days for both types of layers. A similar relaxation behaviour is observed as the dielectric layer is removed from the back of the double side coated substrates (LPCVD-process) which allows a bending of the formerly straightened substrate (Fig. 6). Fig. 7 finally shows the relevant section of FTIR-spectra of PECVD-layers before and after annealing and after relaxation. Evidently besides a small shift in the absorption characteristic no significant change in the binding energies and type of chemical bonds is observed, which could have been the cause for the changes.

In order to explain the observed results various physical models were taken into account, i.e. the removal of loosely bound hydrogen, the oxidation of SiON during the anneal, relaxation of the stress itself and relaxation of the glassy material. Only the latter model can explain all the observed phenomena, whereas one or the other finding contradicts the other theories. Fig. 8 displays the basic idea of this model. Since the deposited SiON-layers are a glassy material, a heating beyond their glass transformation temperature will give rise to an appreciable volume expansion and a corresponding decrease in refractive index. Depending on the local stress in the layers and the achieved substrate and layer temperature this volume may relax in and/or out of plane. Due to the high temperature this is a more or less instant relaxation. After the laser is switched off in contrast to the gradual cooling after the deposition processes this condition is frozen in. Because of the significant deviation from steady state their will be some relaxation also at room temperature. This relaxation vs. time $F(t,P)$ is well known for glassy materials and is usually described in a partly phenomenological equation as [7]:

$$F(t,P) = \frac{1}{\tau} \left(\frac{t}{\tau}\right)^{-n}$$
\[ F(t, P) = \exp \left[ -\frac{t}{\tau} \right] \]

with \( \tau \) the characteristic time constant, which due to its about linear dependence on the viscosity and deviation from the steady state condition (gradient), is a strong function of temperature. The exponent \( \beta \) is 0.5 for most glasses. The observed time constants at room temperature vary between 8h for the 30W and 2h for the 50W anneal, which are comparable to those found in silica rich glasses. Since these time constants are temperature dependent, a considerable speed up of the relaxation are to be expected if it takes place at elevated temperatures. The more the initial deviation from thermal equilibrium after the freeze the faster is the relaxation and the higher is the remaining deviation after relaxation as was shown in Fig.5. Furthermore the resulting change in refractive index is only a function of the actual heating condition, since former treatments are extinguished as long as the transformation temperature is surpassed. Since both pure silicidioxide and silicid nitride have high transformation temperatures, whereas even small additions of foreign phases e.g. nitrogen to the SiO\(_2\)-matrix can reduce them significantly, the observed maximum in the index change at about 1.55 results (Fig.2). The observed small differences in the behaviour of PECVD- and LPCVD-layers can be attributed to their structural differences, since due to the higher hydrogen content and lower packing density the PECVD-layers contain more nitrogen at equal refractive index. Applying this heating procedure to waveguide structures or separated small layer islands results in identical index variations, i.e. so will be the index change in locally heated integrated optic circuits or components.

**Summary and Conclusions**

The observed relaxation behaviour of SiON films for integrated optical circuits on silicon demonstrate that these layers are long time stable even if they are under stress, since they behave like any other glass. Some relaxation may occur, however, and will be observed directly after deposition, which is a function of the deposition temperature and cool down procedure. As the relaxation saturates within a few days, which can be accelerated, if the layers are stored at elevated temperatures, the properties of waveguides and components keep stable, as long as they are not heated to temperatures close to their transformation temperature, i.e. will be kept below about 400°C as derived from the threshold for the laser powers. There will, however, be a change in these properties, if the stress in the substrate is altered, e.g. by adding or removing stressed layers on its backside or bending the substrate. This will give rise to new relaxation processes. The exact index can be locally reduced by the described CO\(_2\) laser irradiation, which relaxes to about 70% of the initial change. As could be verified by multiple pulse heating at different powers and durations the resulting index change is determined by the last process. Thus this procedure is very appropriate to tune devices - e.g. waveguide couplers with respect to their coupling ratio - , since even an overtuning can be extinguished in a succeeding thermal treatment at the appropriate parameters. Since the remaining change in index after relaxation is very reproducible, the necessary overshoot directly after the treatment to obtain the desired device properties is predictable. Alternatively the elevated temperature storage may be used, to reduce the steady state condition.

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Fig. 1: Layer stress vs refractive index

Fig. 2: Relative change in index vs refractive index

Fig. 3: Relative change in index vs laser power

Fig. 4: Relative change in index vs time
Fig. 5 Index relaxation after removal of backside layer for different SiON layers.

Fig. 6 Local variation of refractive index after laser irradiation: A after annealing, B after relaxation.

Fig. 7 IR-spectra of SiON layers: A before, B after annealing, C after relaxation.
Fig. 8 Relaxation of index and layer thickness

Fig. 9 Relaxation of index as function of laser power

Fig. 10 Volume relaxation vs temperature for different pulsed heatings
PROSPECTS FOR SILICA AND GLASS-BASED IO COMPONENTS

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Abstract
The prospect of applying Integrated Optical (IO) components for telecom applications is discussed from the viewpoints of performance, reliability and productivity. Material and structural designs for waveguide blocks, fiber blocks and bonding technologies are discussed for 1x8 and 2x16 splitters from the consideration of high quality and reliability. Package designs to meet telecom reliability specifications for 1x32 splitters and long-term damp heat data are presented.

Introduction
In the Optical Access Line (OPAL) project in Germany and the Optical fiber Telecommunications Infrastructure for the Access Network (OTIAN) project in the UK, Passive Optical Networks (PON) were chosen as a general technical solution. These projects are planned to provide digital networks and analogue CATV distribution services in addition to traditional analogue telephone services. Optical splitters, both 1xN and 2xN configurations, are required as a key component for PON systems. Fiber fusion couplers have advantages of low insertion loss, high return loss and low cost for up to 1:4 split ratios. With increasing of split ratios (which is proposed up to 1:32) integrated optical (IO) circuit technology is needed to achieve cost reductions together with high performance and reliability. This paper focuses on planar optical power splitters having silica or glass waveguides. Material and structural designs for the splitters are discussed to meet telecom specifications[1,2].

Packaged IO component
Figure 1 shows the anticipated schematic diagram of a packaged IO component cross section. A waveguide block and fiber blocks including lids, which have 8 degree polished end surfaces, are bonded to each other with UV adhesive. Filler, case, seal and rubber boots are designed to protect the bare IO component under severe mechanical and environment conditions.

Waveguide block
The waveguide block consists of a planar waveguide chip and a lid. The lid has an important role to protect the waveguide during polishing and handling, since the core layer is embedded at a depth of only 20 - 30 microns below surface. The lid further increases the bonding surface area to provide additional resistance against humidity. There are two types of planar waveguides, the first type is of silica, the second of glass. In the silica waveguide group, the representative dopants are: 1)Germanium oxide doped by Flame Hydrolysis Deposition (FHD)[3], 2)Phosphorous oxide doped by Low-Pressure Chemical Vapor Deposition (LPCVD)[4] and 3)Titanium oxide doped by Plasma Chemical Vapor Deposition (PCVD)[5]. The glass waveguide is produced by the field-assisted ion exchange method in a molten salt bath. The doping ions to create the high refractive index region are: 1)Thallium+ [6] and 2)Silver+ [7].
In the case of silica waveguide on silicon substrate (silica-on-silicon), which is called "planar lightwave circuit" (PLC), the advantage is high precision processing by photolithography and dry etching. The Mach-Zehnder circuit, which is used as a wavelength insensitive coupler (WINC) in remote automatic testing system for maintaining optical subscriber lines by NTT, in Japan[8] and also for 2xN splitters, has two directional couplers in which the gap between waveguides is controlled with submicron accuracy[3]. Figure 2 shows the loss deviation measured at 1.3 microns during a temperature cycle from -40°C to 85°C for a 2x16 splitter[9]. Positive and negative deviation curves are induced from the refractive index change in the circuit due to temperature cycling. Positive values correspond to ports one through eight and negative values to ports nine through sixteen at the high temperature region. The advantages of glass waveguide are lower insertion loss, better uniformity, lower Polarization Dependent Loss (PDL) and lower coupling loss with single-mode fiber because of smoother boundary condition between the core and cladding layers and circular cross-sectional area[6]. Silica-on-silica circuits, however, have been measured to have PDL less than ±0.3 dB in 1x32 and 2x32 splitters[10].

**Fiber block**

Fiber blocks consist of V-groove parts, optical fibers and glass lids. Fiber arrays are formed in the fiber blocks, in which the core pitch depends on the V-groove period and the core displacement in the singlemode fiber. V-groove parts are made of glass, silica and silicon for both silica and glass waveguides. Fiber ribbons are used to facilitate production of fiber blocks. The pitch of the ribbon fiber is 250 microns which match the ribbon fibers. Coated fibers are stripped bare in the region touching the V-groove walls and the lids to maintain the correct position held by the adhesive. The adhesive must have enough hardness to be polished together with silica or glass. Other adhesives are used for bonding coated fiber and for protection of the bare part of the fiber behind the V-groove region.

During accelerated high temperature/humidity testing, most failures of splitters are due to deterioration of fiber blocks. Figure 3 shows the loss change before and after 5000 hours damp heat test of 75°C-90%RH for a 1x32 splitter(PLC) measured at 1.3 and 1.55 microns. Four 8-fiber ribbons were used in the output fiber block. Bigger loss changes were observed at each edge of the 8-fiber ribbon ports, where partial separation between the lid and the adhesive was observed.

**Bonding**

Bonding is one of the key technologies of IO component production. Bonding machines have mechanisms to control the vertical, lateral and tilt directions with respect to the optical axes to yield low excess loss. Bonding excess loss can be controlled within 0.2 dB per point with ± 1 micron core displacement accuracy in the fiber block. UV adhesive is used for bonding because of short cure time and reliability characteristics comparable to thermal adhesives. The glass transition temperature (Tg), of the adhesive is specified to be at least 20°C above the maximum operating temperature. This is because the adhesive will drastically soften causing the insertion loss to increase due to stresses surrounding bonded parts as the temperature becomes greater than the Tg[2].

Return loss for analogue CATV systems is required to be greater than 50 dB. The refractive index of polymeric material adhesives is temperature dependent. The UV adhesive used for 1x8 splitter (PLC), in which the refractive index is matched to that of silica optical fibers at room temperature, could not meet the 50 dB return loss requirement about at 50°C and below 0°C.
with vertically polished surfaces relative to the optical axis. To avoid the temperature dependency of return loss, the end surfaces of waveguide and fiber blocks are polished at an angle of 8 degrees. In Fig. 4 the return loss characteristics of a tilt polished 1x8 splitter (PLC) show temperature independence under a heat cycle from -40°C to 85°C measured at 1.55 microns.

Packaging

Packaged IO components need to be designed to pass the mechanical tests of vibration, bump, drop and retention\textsuperscript{[1,2]}. A robust case is needed to protect bare IO components and filler is required to absorb shock when the peak acceleration (40 G) is applied to the component during bump testing. Rubber boots are needed to protect the 250 micron diameter fiber coating during vibration testing (frequency from 6 to 200 Hz) and fiber retention testing (applied load of 5 N). Various environmental requirements: dry heat, damp heat, water immersion and heat cycle tests, must be passed by IO components for telecom applications. In the longer wavelength region fiber micro-bending loss increases with increasing stress induced by the thermal expansion difference between the case and the filler.

Reliability and lifetime

Splitters used for telecom applications must operate within optical performance specifications and have an insertion loss deviation within ±0.5 dB during a 30 year service life\textsuperscript{[3]}. Accelerated testing for splitters can be used to analyze failure mechanisms in relatively short period of time. High temperature damp heat testing is the most severe for planar waveguide splitters. Proper sealing is critical to prevent humidity from damaging critical components. IO components, however, have coated fibers which unfortunately allow moisture to come into the case. The bare IO component inside case must therefore be able to resist high temperature and high humidity.

Environmental testing of 11 sample 1x8 splitters (PLC) were performed according to Bellcore standards and the test results were successful\textsuperscript{[4]}. Figure 3 shows the loss change of the 1x32 splitter (PLC) before and after 5000 hour damp heat testing. Loss changes were measured within ±0.5 dB at all output ports at wavelengths of both 1.3 and 1.55 microns. Reliability evaluations for fused couplers and IO components (both silica and glass) were performed by damp heat testing, in which the insertion loss is continuously monitored to precisely analyze failure modes\textsuperscript{[5]}. As the failure mechanisms of IO components are not very clear, fabricating waveguide and fiber blocks and bonding with favorable contact conditions and using reliable adhesives seem to be the best ways to achieve the goal of producing reliable IO components.

Summary

Silica and glass IO components are specifically discussed for telecom applications. Material and structural designs of 1xN and 2xN splitters are presented based on Bellcore and BT specifications. Discussions of temperature insensitive return loss of 1x8 splitters, wavelength insensitive and small loss deviation of 2xN splitters, and reliability testing results of 1x32 splitters are presented. The feasibility of waveguide splitters for use in telecom PON systems is suggested as well.
Reference
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Fig. 1 Schematic diagram of packaged IO component

Fig. 2 Loss deviation during temperature change of 2x16 splitters (PLC)
(a) Loss deviation, (b) Temperature change
Fig. 3 Loss change of 1x32 splitter (PLC) between before and after 5000 hour damp heat test. 75°C-90%RH.

Fig. 4 Return loss characteristics due to temperature change of 1x8 splitter (PLC).
HIGH SIDELobe SUPPRESSION RATIO IN
A DIRECTIONAL COUPLER OPTICAL FILTER

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Abstract
The purpose of our study is to obtain high sidelobe suppression ratio in a directional coupler optical filter suitable for integration in a "1.3+/1.3- µm" duplexer. Grating-assisted and meander-type structures are theoretically and experimentally examined and compared. Finally we report, in a meander-type filter, sidelobe suppression higher than 20 dB and a reduced TE-TM dependence.

Introduction
The main objective of this study is the realization of an integrated "1.3+/1.3- µm" duplexer, associating the emission and the reception of two 10 nm channels, 40 nm spaced, in the same 1.3 µm window. To our knowledge, only 1.3/1.5 µm duplexers have been realized so far [1,2]. Reduction of the channel spacing requires single band-pass (not to perturb the 1.5 µm transmission window) isotropic filters centered either around 1.32 µm or 1.28 µm, with a 3 dB bandwidth compatible with the channels width and a high sidelobe suppression ratio (> 20 dB).

Grating-assisted directional couplers, unlike the Mach-Zehnder interferometers, offer the advantage of a single band-pass response. Horizontal directional coupler allows easier technological process than vertical coupler and yields to a wide bandwidth which is well suited to our target. This kind of structure has been realized and showed a 10 dB sidelobe suppression ratio [3] and a highly reduced anisotropy : identical central wavelength for TE and TM mode (fig. 1).

Higher sidelobe suppression ratio can be obtained by introducing a spatially varying coupling coefficient along the guided propagation axis [4]. Variation of the coupling coefficient can be either achieved by a varying duty ratio [5] or a varying inter-waveguides separation [6]. However optical filters realized so far along the latter scheme [7] showed strong anisotropy (around 20 nm shift between TE and TM central wavelength).

Here, both variation types have been studied and compared in order to optimize the sidelobe suppression ratio, the TE-TM isotropy and the power losses. Finally we report the design and realization of a weighted coupling meander-type filter exhibiting a reduced polarization sensitivity, high sidelobe suppression ratio and very low power losses.

Guide description
The coupler waveguide geometry is described in fig. 2. The technological process consisted of the following steps. The coupler epitaxial layers were grown by AP-MOCVD. Two waveguides of
respectively 200 Å and 700 Å height were achieved by RIBE and two level masking process. Afterwards the waveguides were buried with undoped InP in a second growth run. InGaAsP gap wavelength is 1.17 μm. Using a bidimensional mode computation software (included in CNET—ALCOR) [8], both waveguides have been designed in order to exhibit the same birefringence so as to obtain the same central wavelength.

Varying duty ratio

Although horizontal couplers are studied, structures with a varying duty ratio are very interesting to examine because they should be the simplest way to perform varying coupling coefficient in vertical couplers. In coupled mode theory the coupling coefficient k(z) in a grating-assisted directional coupler depends directly on the duty ratio q as sin(nzq) [5]. The variation of the duty ratio along the propagation axis is determined by a Hamming function which is assumed to be one of the most performing in terms of sidelobe suppression ratio (>20 dB in coupled mode theory) [9] (fig. 3).

Design and simulation of the device have been performed with CNET—ALCOR, a Beam Propagation Method software (BPM) [10,11] and have showed very good TE–TM isotropy but high power losses and limited sidelobe suppression ratio due to recaptured radiated power (fig. 4). Further comparisons between Fast Fourier Transform-based and Mode-Expansion BMPS have proved the influence of radiated mode in altering the theoretical filter response of the directional coupler.

The components have been measured using a pigtailed LED source centered around 1.3 μm. The output signals from both output waveguides were measured with an optical spectrum analyzer. Experimental results were in good agreement with numerical simulations, confirming a good extinction of the direct channel around 1.31 μm and highly reduced anisotropy (< 2 nm) (fig. 5). Output on the coupled channel has not been measured due to important power losses.

Varying inter-waveguide separation

In order to reduce drastically the power losses due to radiated light, a meander-type coupler [7] has been designed and realized. The variation of the coupling coefficient in this kind of structure is obtained through a variation of the inter-waveguide separation and is again chosen to follow the Hamming function (fig. 6). Simulations were carried out the same way as for the varying duty ratio coupler and exhibited very low power losses (< 1 dB), very high sidelobe suppression ratio (30 dB) and TE–TM anisotropy identical to varying duty ratio coupler (< 2 nm) (fig. 7).

Measurements (fig. 8) have showed that central wavelength and 3 dB bandwidth for TE and TM polarization are 1288 nm, 20 nm and 1280 nm, 15 nm respectively. The sidelobe suppression ratio is –27 dB in TE polarization and –22 dB in TM polarization. TE–TM anisotropy (8 nm) is very likely due to processing problems which will be eliminated in future runs.

Conclusion

Both simulations and experimental results seem to prove that varying duty ratio grating-assisted directional coupler cannot achieve high sidelobe suppression ratio and low power losses due to a large amount of recaptured radiated power. Meander-type coupler with variable inter-waveguides separa-
tion avoid these drawbacks. These devices have been modelled and realized: sidelobe suppression ratio higher than 20 dB and reduced anisotropy below 8 nm are the best results reported so far for such filter structures, to the best of our knowledge.

figure 3: Varying duty ratio coupler

figure 4: Simulations of varying duty ratio directional coupler

figure 5: Experimental results

figure 6: Varying inter-waveguide separation meander coupler

figure 7: BPM simulation of varying inter-waveguide separation coupler

figure 8: Experimental results
EFFICIENT SHORT PASSIVE POLARIZATION CONVERTER

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Abstract
A new passive polarization converter is realized on InGaAsP/InP. Using angled facets in a periodic coupler results in over 70 percent conversion and a propagation loss of less than 1 dB/mm. With an alternative technology, on which the design was based, 90 percent conversion and high propagation losses were obtained. Components are shorter than 1 mm.

1 Introduction
A fundamental problem in integrated optics is the polarization sensitivity of many components. Due to the planar geometry the two types of polarized modes, TE and TM, can behave differently in integrated switches, interferometers, amplifiers etc.. Polarization manipulating devices can be used to solve these problems. Examples are polarization splitters, which allow polarization diversity solutions. Another example is a polarization converter, which facilitates e.g. the use of an integrated laser, emitting TE-polarized light, in an integrated coherent receiver [1],[2]. In this case a fixed conversion is required, preferably achieved with a passive polarization converter. Such components are known from [3] and [4]. We have proposed to improve these components by using angled facets to enhance the coupling between TE and TM [5]. This polarization converter consists of a periodic structure containing waveguide sections with straight and angled facets (see Fig. 1). These sidewalks are interchanged in each subsequent section. Due to the local tilt of the modal fields in the section this results in high polarization conversion at the junctions between the sections. By choosing an appropriate length of the sections a build up of the converted polarization is obtained.

This paper reports on the experimental results obtained for the first realized polarization converters according to this concept.

2 Fabrication
The components are realized in a MOVPE-grown double heterostructure consisting of an InP-substrate, an InGaAsP-layer (or Q-layer) with a thickness of 460 nm and a bandgap of 1.3 µm, and a 500 nm thick InP-toplayer. The polarization converter requires combination of straight and angled sidewalks in the waveguide sections. First a mask pattern for the waveguide structure is defined in a PECVD-deposited Si\textsubscript{3}N\textsubscript{4}-layer. The position where the angled facets are to be made is covered with a resist pattern. Then the straight sidewalls are made using reactive ion etching (RIE) with CH\textsubscript{4}/H\textsubscript{2}. The etching depth is 700 nm. The angle of the straight facet deviated from the desired 90 degrees with the substrate surface and was found to be 80 degrees. For the realization of the angled sidewalk a resist pattern covering the straight side is applied. In an InP-selective wet chemical etch with

![Figure 1: Periodic polarization converter with waveguide sections containing angled facets.](image-url)
a suitable etchant (C\textsubscript{3}H\textsubscript{8}O\textsubscript{3}: HCl: HClO\textsubscript{4} \[6\]) a facet with angle of 35 degrees is obtained in the InP-toplayer. High efficiency in the polarization converter requires that the angled facet is extended 200 \textmu m into the quaternary layer. Two technologies are used to achieve this. In the first realization a second wet chemical etch (with the InGaAsP-selective etchant H\textsubscript{2}SO\textsubscript{4}: H\textsubscript{2}O\textsubscript{2}: H\textsubscript{2}O, \[7\]) is used to obtain a facet with an angle of 55 degrees in the InGaAsP-layer. The resulting waveguide profile is shown in the SEM-micrograph of Fig. 2. Some underetching in the Q-layer can be seen. After this underetch was discovered in preliminary etching tests, it was decided to base the design on an alternative technology. In this technology the angled facet in the Q-layer was obtained with a second RIE-process after the wet chemical etch of the InP-toplayer, thereby "sinking" the angled facet into the Q-layer. The waveguide profile obtained with this technology is shown in Fig. 3.

3 Analysis and results

The polarization converters are characterized with transmission measurements using a FP-laser at a wavelength of 1.5 \mu m. The converters were realized with different numbers of sections and different lengths of the sections. For every component the emanating power in the TE and the TM polarization was determined when TE polarized light was injected. Subsequently this measurement was repeated with injected TM-polarized light. In this way four results are obtained for each converter. However, these results are influenced by polarization sensitive attenuation in the input and output waveguides, caused by etching damages in the fabrication of the devices. To correct for these effects the polarization conversion \(G\) is determined as follows.

The power emanating from a converter in polarization "\(X\)" when injecting polarization "\(Y\)" can be expressed as:

\[
P_{X,Y} = P_1 A_Y F_{X,Y}(G) B_X
\]

where \(P_1\) is the injected power, \(A_Y\) an attenuation factor in the input channel for polarization "\(Y\)" and \(B_X\) an attenuation factor in the output channel for polarization "\(X\). \(F_{X,Y}(G)\) is a simple function of the polarization conversion \(G\): it equals \(G\) if "\(X\)" and "\(Y\)" are different, otherwise it equals 1-\(G\). The four experimental results for a polarization converter can be used to eliminate the attenuation factors [8]:

\[
G = \left[ 1 + \frac{P_{TE,TE} P_{TM,TM}}{P_{TE,TM} P_{TM,TE}} \right]^{-1}
\]

The conversions for the two different technologies are given in Figs. 4 and 5. For both technologies the optimum length for the sections is approximately 90 \mu m. Since the maximum conversion is found for 11 sections the total length for a converter is below 1 mm. The loss of the converters contains two major contributions: the propagation loss in the converter waveguide and the coupling loss at the junctions between the sections. The
Figure 4: Polarization conversion for wet etched Q-layer, as a function of (a) number of sections (section length 90 μm) and (b) length of sections (10 sections).

Figure 5: Polarization conversion for "sinking" of the angled facet, for (a) number of sections (section length 90 μm) and (b) length of sections (12 sections).

propagation loss was determined from converters containing one section and varying length, after correction for the polarization dependent attenuations in the input and output waveguides. The junction loss was found from $P_{TM,TE}$ and $P_{TM,TM}$, measured with the converters having the optimal section length, after correction for the propagation loss and for the measured polarization conversion. For the technology using the "sinking" of the angled facet in the Q-layer the propagation loss was however too high for the junction loss to be determined. The results for the two technologies used are summarized in table I.

Table I: Experimental results for passive polarization converters using angled facets.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Maximum conversion [percent]</th>
<th>Propagation loss (TE, TM) [dB/mm]</th>
<th>Junction loss (TE, TM) [dB/junction]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet etching of Q-layer</td>
<td>72</td>
<td>$0.8 \pm 0.2$</td>
<td>$0.3 \pm 0.1$</td>
</tr>
<tr>
<td>&quot;Sinking&quot; using RIE-etching</td>
<td>93</td>
<td>$10 \pm 1$</td>
<td>*</td>
</tr>
</tbody>
</table>

* Could not be determined due to the high propagation loss.
4 Discussion
For the technology using the wet etching of the Q-layer the realized components deviate from the design. The lateral offset between the sections therefore did not have the optimal value for low junction loss. This explains the junction loss of 0.3 dB, which is about a factor of 10 higher than for the simulations on the design [5]. Furthermore, since the waveguides used in the converter are multimoded, also conversions to higher order modes are to be expected if the lateral offset deviates from the optimal value. This limits the maximum polarization conversion. The propagation loss is sufficiently low for a component shorter than 1 mm, but it can be further improved by adjusting the technology in order to reduce the roughness of the sidewalls in the converter waveguide.

For the technology using "sinking" with RIE the resulting waveguide profile was closest to the design. The major difference is an overetching of 40 nm in the components. Nevertheless a very high conversion efficiency is found. The high loss is probably due to a damaged top layer which can appear in reactive ion etching [9]. Since the angled facet in the Q-layer is close to the waveguide core such a damaged layer on top of the facet can have a large impact on the propagation loss. This damage from the RIE-process seems unavoidable. Therefore, this technology to realize the angled facet in the Q-layer is discarded in favour of the wet-etching technology.

Adjusting the design to the first technology, which uses wet etching of the Q-layer, will result in a short component with low losses and high efficiencies.

5 Conclusions
The results presented in this paper show that polarization conversion can be obtained with short components (<1 mm), high efficiencies and low losses. Two technologies were tested. One of these yields sufficiently low propagation losses (<1 dB/mm) for both polarizations. Despite the deviation from the design the coupling loss at the junctions between the waveguide sections of the converter is low (0.3 dB) for this technology. Polarization conversion above 90 percent was obtained with the second technology, which most closely matched the design. Straightforward adjustments in both fabrication and design will result in highly efficient and short polarization converters with low losses.

References
A VERY COMPACT InP-BASED INTEGRATED OPTIC
MACH-ZEHNDER INTERFEROMETER WITH A
DELAY DIFFERENCE OF 74 ps

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Abstract

A Mach-Zehnder interferometer with 6.0 mm arm length difference was realised on InP. The
design is very compact, using deeply etched waveguides and circular bends with 50 μm radius. The
devices show a sinusoidal frequency response with 13.5 GHz period and extinction ratios up to 20
dB.

Introduction

Mach-Zehnder interferometers (MZI) have many applications in optical systems. They can be
used as phase-to-amplitude converters (in sensors, modulators, switches [1] and wavelength
converters [2]) or as building blocks of optical filters. An example of the latter is a dispersion
compensation circuit [3] consisting of a series of MZI-devices. Another example is to modify the
modulation or noise content of an optical signal by the optical filter [4]. A Mach-Zehnder
interferometer with a propagation delay difference Δt between both arms will allow to cancel the
frequency component around 1/2Δτ in the modulation or noise spectrum. If this frequency is chosen
around the resonance frequency of a laser diode it is able to flatten the frequency response or reduce
the RIN-spectrum considerably.

Integration of MZI-structures makes the fabrication of reliable components with a very precise
arm length difference and well controlled amplitude balance between both arms possible. A problem
is that some of the applications mentioned above require devices with a relatively large arm length
difference (millimetre to centimetre level) which would normally lead to an impractical large chip area.
The use of deeply etched waveguides in InP allows to make curved waveguides with very small bend
radii of the order of 50 μm [5]. Furthermore, for a given delay time difference the arm length
difference is reduced by a factor equal to the high refractive index of this material. We have therefore
used InP-technology to produce a Mach-Zehnder interferometer with an arm length difference of 6.0
mm, which corresponds with a frequency response with 13.5 GHz period. One possible application
of this device is the suppression of the RIN-spectrum of a laser diode around 6.75 GHz.
Design

The waveguide is made of InP cladding layers and a quaternary InGaAsP 1.3 μm guiding layer. The cross section is schematically given in Fig. 1. It consists of a ridge which is completely etched through the quaternary layer, thereby achieving maximum lateral index contrast. This provides a large tolerance for the etch rate. The MZI structure is shown in Fig. 2. It consists of the following waveguide components: multimode interference (MMI) couplers, circular bends, tapers, controlled loss structures and of course straight waveguides. The waveguide width is 1.3 μm in the bended regions and 3.0 μm for the straight waveguides. In the bends a small width has been chosen in order to obtain a reasonably symmetrical field profile which can be efficiently coupled to a monomode straight waveguide. As the propagation loss of these waveguides is high (7 dB/cm), 3 μm wide waveguides have been applied (0.6 dB/cm propagation loss [5]) in all parts of the structure where the narrow waveguides are not necessary. The coupling between the two different guides is achieved by a linear taper of 50 μm length.

![Waveguide cross section.](image)

Light is launched in the access waveguides (see Fig. 2) with a nominal width of 3.0 μm. A 50/50 power splitting ratio is obtained by a MMI coupler. The length equals 281 μm and the nominal width is 8.0 μm. Since the performance of the MMI coupler depends critically on its width and the tolerance of the processing steps is a few tenths of microns, five different widths ranging from 7.6 μm to 8.4 μm in steps of 0.2 μm were defined on the mask. The main advantage of a MMI coupler compared to other couplers (like Y junctions or directional couplers) is the compactness of the device and the less critical tolerance in the etching process. Furthermore, since the performance of the device for a given width is not critically dependent on its length, it is easy to obtain the desired power splitting ratio.

After the MMI section, the light enters the two arms of the asymmetric Mach-Zehnder interferometer. The longer arm consists of a folded waveguide (see Fig. 2) introducing a geometrical path difference ΔL of 6.0 mm. The total device measures about 150 μm x 4 mm. The path difference leads to time delay τ of

$$\tau = \frac{n_{\text{eff, group}} \Delta L}{c} = 74 \text{ ps}$$

where $n_{\text{eff, group}}$ is the effective group index of the waveguide mode (estimated to be 3.69) and $c$ is the speed of light in vacuum. This gives a frequency response period of $f_m = 13.5 \text{ GHz}$. The loop bends are circular arcs with a radius of 50 μm and the longest bends span an angle of 181.85°.

The shorter arm of the interferometer is provided with an extra controlled loss structure to compensate for the additional propagation losses of the longer arm. The loss structure consists of a wide waveguide region of 10 μm width in which the beam expands due to diffraction. We aimed at an additional loss of 1 dB and 2 dB, corresponding with lengths of 12.35 μm and 18.81 μm (as calculated by FD-BPM). A structure with no excess loss, where the straight waveguide is continued, was also included.
The light of both arms is finally recombined in a second MMI coupler and launched in the output waveguides.

![Schematic view of the asymmetric Mach-Zehnder interferometer and details of the input and output parts of the interferometer, showing the circular bends, the MMI couplers and a controlled loss structure of 18.8 μm long.](image)

**Figure 2:** Schematic view of the asymmetric Mach-Zehnder interferometer (upper figure, not on scale) and details of the input and output parts of the interferometer, showing the circular bends, the MMI couplers and a controlled loss structure (down right) of 18.8 μm long.

**Fabrication**

The devices were made on a SI-InP substrate with MOCVD grown undoped epilayers [6]: 600 nm InGaAsP (λg = 1.3 μm) and 300 nm InP. The devices were patterned with a 140 nm thick RF-sputtered SiO2 masking layer. 950 nm high ridges were etched with an optimised CH4/H2 RIE etching/descumming process [7].

**Experimental results**

The Mach-Zehnder structures are measured by coupling light from a tuneable 1.55 μm laser into each of the input arms and monitoring the output power in each of the output arms. Measurements were done both for TE and TM polarised light at the input. Because the Mach-Zehnder structure exhibits a small amount of polarisation conversion in the long arm a polariser was needed at the output to observe the interference pattern properly.

Fig. 3 shows a typical result for a MZI structure with a controlled loss structure of 12.35 μm length and a MMI width of 8.0 μm. The figure shows the transmitted power from each input to each output as a function of wavelength between 1550.000 nm and 1550.150 nm. The interference pattern has a period of 13.5 GHz and an extinction ratio of about 10 dB. The rippled deviation from a sinusoidal response is due to Fabry-Perot resonances between the end facets of the chip and can be easily avoided by anti-reflection coating. The best results were obtained for an MMI width of 8.0 μm which is the nominal design value. The best extinction ratio (but also the strongest Fabry-Perot ripple) was obtained for the Mach-Zehnder structure with no controlled loss structure, where it was 20 dB. This indicates that the long interferometer arm with the sharp bends has a very low loss.
Figure 3: Transmitted power from each input to each output as a function of wavelength (relative to 1550 nm). The notations A, B and a, b, labelling the input and output ports are defined in Fig. 2.

Conclusion

An integrated Mach-Zehnder interferometer with large arm length difference and sharp bends has been designed and realised in InP. The devices show a good extinction ratio indicating low losses in the folded long branch. The device can be used for cancelling the laser intensity noise around 6.75 GHz.

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References

Optical Mode-Combiners based on Planar Multi-Mode Interference Couplers in InGaAsP/InP

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Abstract
New low loss and short optical mode-combiners based on multi-mode-interference (MMI) couplers have been realized with planar InGaAsP/InP waveguides. These devices couple the fundamental mode of a first input to the fundamental mode of an output while at the same time they allow conversion of the fundamental mode of a second input into the first order mode of this same output.

Introduction
Multimode interference couplers (MMI) are increasingly explored as power splitters and combiners [1], as Multileg Mach-Zehnder Interferometers (MZI) [2] and in phase-diversity optical receivers [3]. They also play an important role in future high speed space switches [4].

Mode Converters that convert fundamental modes into higher order modes and that act at the same time as mode-combiners have interesting applications in integrated optics; they are used as adiabatic asymmetrical Y-junctions [5], in 2x2 Digital Optical (DOS)-Switches [6] and in MZI switches [5]. Recently in nonlinear MZI's they are used for the introduction and extraction of optical control signal [7].

We have realized mode-combiners using MMI's to overlap the two first order modes at the output by injecting the fundamental modes in two different inputs. Three different mode-combiners have been developed and experimentally tested. Two of them with good broadband-characteristics and with good fabrication tolerances and a third for lossless coupling. Strongly guiding MMI structures render the couplers polarization insensitive and fabrication tolerant.

Theory
Consider an MMI of length:

\[ L_N = \frac{1}{N} \cdot 3L_c, \text{ with } L_c = \frac{4nW_e^2}{3\lambda} \]  

(1)

As shown in Fig. 1 and according to [8] \( N \) is the number of input and output-arms, \( n \) is the effective refractive index, \( W_e \) is the equivalent width of the MMI, which essentially corresponds to its geometric width but takes penetration into the neighbouring material into account and \( \lambda \) is the vacuum wavelength.

An input-waveguide placed at an arbitrary position maps the input-mode onto an \( N \)-fold image of the same mode with equally split intensities provided the length of the MMI is \( L_N \). There are \( N \) input-positions that lead to the same output-intensity distribution. The case where the number \( N \) of input-positions is odd is given in Fig. 1. The parameter \( a \), which defines the position of the input-waveguide can be chosen between \( 0 < a \leq W_e/N \). Once it has been chosen, the output-positions are also determined. The situation with an even number of inputs can be treated analogously.

For conversion of the fundamental mode of an input-guide into the first order mode of an output-guide, simultaneously two characteristics of a TE01/TM01-mode have to be considered:

1.) The intensity profile of the first order mode can be realized by positioning an input arm of the MMI such, that the output-ports of the MMI touch each other to form a wider waveguide that

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transmits two beams in the form of a first order mode. Referring to Fig. 1 this implies the parameter \( a \) to take the value of one half of the rib width.

2.) The two intensity peaks of the first order mode must have a phase difference of \( \pi \). For a \( NxN \) MMI using input port \( i=1 \), the output-port \( j=2 \) and 3 automatically fulfill these phase relations.

For Mode-combiners that use MMI’s with \( N=3 \) and \( N=4 \) input and output-ports these design ideas are demonstrated in Fig. 2a) and b). The mode-converter MMI with \( N=3 \) couples a fraction of theoretically 33% of the fundamental mode of the input-waveguide into the fundamental mode of the output-waveguide \( j=1 \) and a fraction of 66% to the first order mode of the wider \( j=2,3 \) output-waveguide. The \( N=4 \) mode converter MMI couples 25% of the fundamental mode of the input-waveguide to the fundamental modes of the outer outputs and 50% to the first order mode of the central output.

These converters that couple light from one input to a first order output are of interest since, with a second input they allow a zero order mode to be exited in the same output waveguide. Fig. 3a) and b) show how, using another input-port, a zero order mode of a 3x3 respectively a 4x4 MMI combiner is mapped with 100% efficiency to the outputs [9].

A realization of superposition of two fundamental modes from two inputs into a fundamental and a higher order mode into one output is shown in Fig. 4, where a mode-combiner MMI with \( N=4 \) of Fig. 2b) and Fig. 3b) is used with a symmetrical 1x2 MMI. This allows both the fundamental and the first order mode to be combined with 100% efficiency.

**Structure**

To demonstrate these mode combiner concepts, MMI’s were realized in double-heterostructure InGaAsP/InP materials with a ridge waveguiding structure, optimized for a wavelength of 1.5 \( \mu \)m. The quaternary material has a gap wavelength of \( \lambda_g=1.20 \) \( \mu \)m.

The dimension of the 3x3 MMI-converters are 9.0 \( \mu \)m x 270 \( \mu \)m, the dimensions of the 4x4 MMI-converters are 12.0 \( \mu \)m x 340 \( \mu \)m and the 1x2 MMI were designed as small as 12.0 \( \mu \)m x 150 \( \mu \)m.

**Experimental results**

The functioning of the \( N=4 \) MMI converter is demonstrated in Fig. 5a) and b). Fig. 5a) shows how light of wavelength 1.5\( \mu \)m is mapped from input \( i=1 \) onto two fundamental modes, which are visible at the outer sides and onto a first order mode at the central output. 54% of the light is coupled into the first order mode. Each of the fundamental modes on the left and right side of the central waveguide contain 23% of the light. The total losses in comparison to a 3 \( \mu \)m straight waveguide with equal length are 0.3 dB. Fig. 5b) shows light from the input-port which maps the fundamental mode onto the central waveguide. This output has a loss of 0.1 dB.

The \( N=3 \) MMI combiner and the composed MMI-combiner show similar results.

The experimental results for the mode-combiner agree with the estimated ones.

**Summary**

We have designed and realized in InGaAsP/InP material new types of short and low-loss mode-combiners based on MMI-couplers. They allow to map a fundamental mode onto itself and a second fundamental mode onto a first order mode. Performances are close to the predictions.

**Acknowledgments**

This work was in part supported by the Swiss research programme in Optics.
Fig. 1  MMI coupler with odd number of $N$ access waveguides [8]. The positions of the inputs and outputs are given by the parameter $a$, whose value can be freely chosen between $0 < a \leq \frac{W_{eq}}{N}$.

a) $N=3$

Fig. 2  Proposed Mode-Combiner Multimode-Interferometers: a) A 3x3 MMI with light from input $i=1$. A fraction of 33% is mapped onto the fundamental mode of output $j=1$ and a fraction of 66% is mapped onto the first order mode of output $j=2,3$. b) A 4x4 MMI similarly couples 50% of the light from input $i=1$ to the first order mode of output $j=2,3$. 
Fig. 3  The same two MMI's than of Fig. 2 mapping now the fundamental mode of the second input onto the fundamental mode of the output. a) 1x1 MMI derived of a MMI with N=3; b) 1x1 MMI derived of a MMI with N=4. In both cases zero-loss is predicted.

Fig. 4  The mode-combiner composed of two different MMI's. Input 1 couples to the first order mode at the output and input 2 corresponds to the fundamental mode at the output. Zero-loss and polarization independent operation is expected in both cases.

Fig. 5  The N=4 MMI-combiner. a) Measured Intensity distribution generated by a zero order mode at input i=1 as in Fig. 2b)  b) Measured Intensity distribution of a fundamental mode at an input as in Fig. 3b)

ADIABATIC 3 dB-COUPLER REALIZED ON InGaAsP/InP

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1 Abstract
For the first time mode selectivity's larger than 45 dB for both TE- and TM-polarization is achieved in a compact (less than 3 mm long) adiabatic 3dB-coupler on InGaAsP/InP. The measured unbalance is within ± 0.23 dB for all devices at a wavelength of 1.5 μm. The excess losses are below 0.3 dB.

1 Introduction
Integrated optical power splitters are general purpose devices in optical communication. In literature mixing elements consisting of directional couplers (DC) [1], multimode interference couplers (MMI) [2] or adiabatic type 3dB-couplers [3,4] have been presented. Compared with the MMI and the DC, the adiabatic 3dB coupler (or X-junction), is less sensitive to wavelength, device parameters, and operating conditions. Furthermore adiabatic 3dB-couplers can be made polarization insensitive.

In adiabatic 3dB-couplers the asymmetrical Y-junction is essential. Such Y-junctions are realized on materials like glass and lithium niobate [3,4]. Asymmetrical Y-junctions on these materials are several cm's long. Using an InGaAsP/InP double heterostructure, well guiding single mode waveguides as well as large difference in propagation constants can be achieved. This enables design of compact adiabatic 3dB-couplers having lengths in the order of a few mm's. Furthermore InP-based devices have the advantage that they are suitable for monolithic integration. In this paper we present a compact adiabatic InP based 3dB-coupler having large mode selectivity.

2 Device Concept
The adiabatic 3dB-coupler consists of a symmetric Y-junction connected by a bimodal waveguide to an asymmetric Y-junction as shown in Fig. 1.

When light is injected into one of the branches of the symmetrical Y-junction the zero and first order mode of the bimodal channel will be equally excited. If no mode
conversion takes place, the fundamental mode will propagate through the wide branch and the first order mode through the narrow branch of the asymmetrical Y-junction [5]. This way 3 dB power splitting is obtained.

Mode conversion must be avoided in order to maintain adiabatic evolution of the modes. Therefore the performance of the 3dB-coupler depends on the quality of the mode splitter. To fulfil specifications of a coherent optical communication system [6] a coupling ratio of $3.0 \pm 0.3$ dB for all lengths of the bimodal section is required. This corresponds to a mode suppression of the unwanted mode equal to 30 dB. This large mode suppression requires use of a small angle and a sharp branching point in the asymmetrical Y-junction.

### 3 Design

The device is optimized with respect to a combination of total length and coupling ratio. All input and output waveguides are monomode, only the connection between the two Y-junctions is bimodal (TMI-section). The device is designed by use of the effective index method (EIM) and an EIM based BPM for a wavelength of $\lambda = 1.5 \mu m$.

![Figure 2: Waveguide cross-section.](image)

To enable easy integration with previously developed devices a ridge waveguide structure as shown in Fig. 2 is used. The symmetrical Y-junction has a branch width of 3.2 $\mu m$ and an opening angle of 1.5°. This keeps the excess losses low. The bimodal channel has a width of 6.4 $\mu m$ and a variation in length from 0 to 600 $\mu m$. The variation in length is used to determine the balance of the symmetrical Y-junction and the mode sorting behavior of the asymmetrical Y-junction [7]. The branches of the asymmetrical Y-junction must have a separation of 11 $\mu m$ in order to be decoupled. The length of the Y-junction is determined by the small opening angle. To reduce the length of this asymmetrical Y-junction it contains two sections.

![Figure 3: The asymmetric Y-junction](image)

The first section, starting at the branching point a small branching angle is required (0.28°) because in this section the coupling between the branches is strong. The branches are weakly coupled at the end of the first section. Hence, a larger branching angle (0.63°) can be used preventing deterioration of the mode sorting behavior. The dimensions of the asymmetrical Y-junction are shown in Fig. 3. This design results in a total device length of 2.7 mm.

Straight input and output waveguides (width 3.2 $\mu m$, pitch 25 $\mu m$) are connected to the coupler by circular S-bends (radius 10 $mm$).
BPM-simulations predict a 3dB-coupler with less than 0.3dB deviation from ideal operation in a wavelength range of 200 nm and deviations in ridge height of less than 40 nm. The excess losses are less than 0.3 dB.

Two types of 3dB-couplers are designed. One series suitable for conventional "single-mask" technique and another series making use of the so called ‘double-mask’ technique [8]. The two branches of the asymmetrical Y-junction are defined in different masking materials using the latter technique. A special mask pattern [9] is used in order to guarantee that the mode sorting Y-junction is strictly asymmetrical and that the symmetry of the symmetrical Y-junction is maintained. Furthermore the bimodal channel must support only two modes. A maximal alignment inaccuracy of 1.0 μm is tolerable. The geometry of this "double-mask" pattern is shown in Fig. 4 and described in detail elsewhere [9].

4 Device fabrication and Characterization

The photoresist etch mask is defined using contact UV exposure. The ridge waveguide structures are etched by CH₄/H₂-RIE. The obtained ridge height is 245 nm ± 5 nm. A waveguide width being 0.2μm less than the design value is realized.

The devices are characterized by transmission measurements using a FP-laser at a wavelength of 1.5 μm. The performance of the 3dB-coupler is found by using the measurement procedure described in [7]. The fractional power is given as function of TMI-section length in Fig. 5. Due to a defect, the 3dB-coupler made by ‘single-mask’ technique having a TMI-length of 500 μm was omitted from the analysis. The balance is found from the mean value of the fractional power and the mode sorting behaviour of the asymmetrical Y-junction from the amplitude of the oscillation [7]. The experimental results are shown in Table 1 and 2.

| Table 1: Measured mode selectivity of the asymmetrical Y-junction |
|------------------|------------------|------------------|
|                  | “single masked”  | “double masked”  |
| TE-pol.          | 32 ± 1 dB        | 53 ± 1 dB        |
| TM-pol.          | 35 ± 1 dB        | 46 ± 1 dB        |

| Table 2: Measured balance of 3dB-coupler |
|------------------|------------------|------------------|
|                  | “single masked”  | “double masked”  |
| TE-pol.          | 0.504 ± 0.026    | 0.505 ± 0.002    |
| TM-pol.          | 0.497 ± 0.017    | 0.501 ± 0.005    |

From those tables it is seen that the mode selectivity of all “double-masked” asymmetrical Y-junctions is larger than 45 dB. “Double-mask”-technique improves the mode selectivity with more than 11 dB for both polarizations compared to “single-mask”-technique. The experimental values are better than predicted by our BPM simulations. The balance of the 3dB-coupler is well within the specification of ± 0.3 dB. The excess losses are found to be smaller than the experimental accuracy of 0.3 dB.

5 Conclusions

For the first time according to the knowledge of the authors compact mode evolution type 3dB-couplers with mode selectivity’s larger than 50 dB for TE-polarization have been realized on InGaAsP/InP. The 3dB-couplers are polarization insensitive for mode selectivity’s larger than 45 dB. Using double masking technique, the quality of the branching points improves. This is important to insure adiabatic propagation.

6 Acknowledgments

The authors thank G. Krijnen and H. Hockstra of the University of Twente (The Netherlands) for the use of their BPM-program.
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Figure 4: Mask patterns for the double masked 3 dB-coupler. Resulting combined masks are shown for alignment errors of (a) -1, (b) 0 and (c) 1 μm. “S” and “A” indicate the symmetric and the asymmetric sides of the coupler.

Figure 5: Power fraction from one output branch as a function of the length of the bimodal waveguide for (a) the TE-polarization and (b) the TM-polarization. The dotted areas correspond with a deviation of less than 0.3 dB in the coupling ratio. Measurements: • (single mask) ° (double mask). Broken and full lines are sines fitted to the measured data.
Abstract: A large nonlinear phase shift occurs in an optical beam during second harmonic generation. It can be used for all-optical phenomena at much lower powers than those required in traditional third order nonlinear optics. Experiments in waveguides verifying this effect will be reviewed and compared against theoretical predictions.
One of the attractive possibilities offered by nonlinear optics is the application of an intensity dependent refractive index to various all-optical switching, data processing and logic operations.[1] However an intensity-dependent refractive index is not the only way to achieve the nonlinear phase shifts required for all-optical devices. It occurs during second harmonic generation (SHG) because the coupling between the fundamental and second harmonic involves continuous power exchange due to both upconversion (\(\omega + \omega \rightarrow 2\omega\)) and down conversion (\(2\omega \rightarrow \omega \rightarrow \omega\)).[2] This is shown schematically in Fig. 1. The distance which a second harmonic photon travels before returning via down conversion to the fundamental beam is typically the SHG coherence length. If the process is not phase-matched and the phase velocities are not equal, i.e. \(v_1 \neq v_2\), then the photons returning to the fundamental are shifted in phase (relative to the fundamental beam) by \(\Delta \phi = [1/v_1 - 1/v_2]L\omega\) and hence there is a net nonlinear phase shift in the fundamental. It is nonlinear because the number of second harmonic photons is proportional to the input fundamental intensity, and hence the induced phase shift is also proportional to the input intensity. It now appears that effective nonlinearities available from cascading will be orders of magnitude larger than from the best third order materials. And in fact large effects have been observed experimentally in waveguides.[3-6] This effect occurs for all parametric processes. In this paper we restrict the discussion to the results obtained in our collaborative effort to date.

The equations needed to describe cascading are just those needed for describing any second order parametric mixing process. For the simplest case of cw second harmonic generation,[2] where \(\kappa\) is proportional to the effective second order coefficient \(d(2)\), the wavevector mismatch is \(\Delta \beta = 2k_{\text{vac}}(\omega)[n(2\omega) - n(\omega)]\), and the complex field amplitudes \(a(z)\) are normalized so that \(|a(z)|^2\) is the intensity. Most practical cases require detailed solutions. Nevertheless, it is instructive to compare the magnitude of the effect relative to \(n_2\) for negligible conversion to the harmonic. For maximum phase shift,
Evaluating this equation, very large values for $n_{2,\text{eff}}$ appear possible. For example, assuming $L = 1 \text{ cm}$, for LiNbO$_3$ ($d_{33} = 36 \text{ pm/V}$) $n_{2,\text{eff}} = 2 \times 10^{-11} \text{ cm}^2/\text{W}$ which 2 orders of magnitude than $n_2$ for this material. For poled polymers, $d = 100 \text{ pm/V}$ giving $n_2 > 10^{-10} \text{ cm}^2/\text{W}$.

A number of experiments have been performed to measure nonlinear phase shifts due to cascading in waveguides.[3-6] To date, a number of wavevector matching mechanisms have been used, namely quasi-phase-matching, birefringent phase matching (Type II) and Cerenkov radiation. In addition, the propagation of spatial solitons in slab waveguides has been predicted.[7]

![Graph showing experimental and calculated frequency spectra of sub-picosecond pulses at 1600 nm in QPM KTP waveguides.][4]

A nonlinear phase shift leads to a broadening of the frequency spectrum of an incident pulse. This approach was used to study cascading in QPM KTP waveguides at 850 and 1600 nm.[3,4] The result at 1600 nm is shown in Fig. 2, along with the theoretical fit calculated from equations 1, augmented by terms to take into account group velocity dispersion, i.e. pulse walk-off. The phase shift shown corresponds to $\pi/2$. In other experiments on KTP, phase shifts $> \pi$ have been measured and the
variation in the magnitude of the nonlinear phase shift with detuning from SHG resonance have been reported.

Because all-optical switching devices require nonlinear phase shifts, it is clear that they can all be implemented with cascading nonlinearities. However, a fascinating feature of cascading is that there are new devices possible. This nonlinear process is coherent. This has its disadvantages since the phase of the interacting waves must be stable. On the other hand, the outcome of a parametric process can be controlled by "seeding" it with a weak signal, which has in fact been demonstrated experimentally. This last result suggests that an all-optical "common emitter" amplifier, with base and collector corresponding to cw and signal fundamental inputs might be possible.

References:
Cascaded Nonlinearity in Lithium Niobate Waveguides

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Abstract
Large nonlinear phase shifts caused by cascading with low fundamental depletion were measured in waveguides with nonuniform wavevector-mismatch distribution. Phase shifts of $\pi$ enabled all-optical switching in channels and spatial soliton propagation in films.

The second-order nonlinear interaction between a fundamental light wave and its second harmonic results in energy transfer between the interacting waves (second harmonic generation) and modifies their phases nonlinearly (cascaded nonlinearity) [1]. While the energy exchange has been applied to the generation of light with new frequencies since the discovery of the effect, the proposals for using the cascaded nonlinearity has gained attention just recently [2]. It has been shown that the second-order nonlinear phase distortions can be used for realizing control of light propagation by light, such as all-optical switching or soliton propagation [3]. In today's available materials the nonlinear phase shift due to cascading can be orders of magnitude larger than phase shifts produced by the third-order nonlinear refractive index. This implies that typical third-order phenomena can be implemented with Watt or even mWatt power levels in waveguide geometries on the basis of cascading.

However, the largest nonlinear phase shift is of less value when it is inseparably connected to strong depletion of the fundamental. And, in general, this is the case due to conversion of the fundamental into its second harmonic because large phase shifts appear near phase-matching [2]. Therefore, in order to benefit from the advantages of cascading we have to prevent fundamental damping while simultaneously keeping the nonlinear phase shift. This is possible in waveguides with a nonuniform phase-mismatch distribution along the propagation direction.

This idea was experimentally verified in 47mm long Ti-indiffused LiNbO$_3$ channel and film waveguides. With propagation along the X-axis in Y-cut crystals SHG can be phase-matched by coupling fundamental TM-modes to second harmonic TE-modes. For a fundamental with a wavelength of 1.32$\mu$m the two modes come into resonance around 340°C. In order to tune the wavevector-mismatch around phase-matching with temperature the crystals were placed in a temperature controlled crystal oven. Corresponding to a nonuniform oven temperature profile a wavevector-mismatch distribution was adjustable. The examples of depletion curves and SHG tuning curves from a channel waveguide in Fig. 1 show a strong asymmetry around the phase-matching temperature $T_{pm} \approx 336.65^\circ$C. Simultaneously, in an interferometer, we measured nonlinear phase changes of the fundamental mode which are shown in Fig. 2. Large phase shifts were measured in regions of low conversion and depletion on the low temperature side of $T_{pm}$. These large nonlinear phase shifts of the fundamental detune the phase-matching conditions depending on power which yields to the strongly power-dependent tuning and depletion curves in Fig. 1.
For applications of cascading with low depletion all-optical switching in a hybrid Mach-Zehnder and the propagation of spatial solitons in film waveguides were demonstrated. Fig. 3 shows the output intensity profile of a beam with an input FWHM of 70μm. Depending on the phase-mismatch diffraction can be completely balanced by cascading with low beam depletion.

We thank Dr. W. Sohler from the University-GH-Paderborn for providing the Ti:LiNbO₃ waveguides and the crystal oven.

References

Fig. 1: Temperature-dependence of the throughput fundamental power and generated second harmonic: (a) low power 80W, (b) high power 300W.
Fig. 2: Temperature-dependence of the nonlinear phase shift: theory (smooth curves) and experiment.

Fig. 3: Output beam intensity for different wavevector-mismatch (input peak power: 1500W, input beam FWHM: 70μm).
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QUASI-PHASE-MATCHED PARAMETRIC FLUORESCENCE IN ROOM TEMPERATURE LITHIUM TANTALATE WAVEGUIDES

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Abstract:
We report the first observation of quasi-phase-matched parametric fluorescence in the 1.2 to 2.3 micron region, at ambient temperature, in lithium tantalate waveguides using a pump wavelength between 805 and 845 nm. Fluorescence signals of up to 7 pW have been observed for guided pump powers of 70 mW.

To date, parametric fluorescence and oscillation in integrated optics have been demonstrated only in lithium niobate waveguides. The first experiments used crystal temperatures above 200°C and pump wavelengths in the visible region (514 to 615 nm) (1,2). Phase matching was achieved using crystal birefringence, imposing the use of the d31 nonlinear coefficient for the parametric interaction. In a recent experiment (3), we reported the use of first-order quasi-phase-matching (QPM) (4,5,6), i.e. periodically inverted crystal domains, with a resultant periodic modulation of the sign of the nonlinear coefficient. This has permitted the generation of parametric fluorescence in the 1.2 to 2.3 μm window at ambient temperature, using an 800 nm pump, and the d33 coefficient of lithium niobate which is approximately 6 times greater than the d31 coefficient. The parametric efficiency was improved by three orders of magnitude compared to the birefringent phase matching experiment mentioned above. More recently (7), this configuration has been used by Bortz et al. to realize a pulsed parametric oscillator.

In this paper, we will present the first observation of parametric fluorescence (from 1.2 to 2.3 μm) in the QPM configuration in PE LiTaO3 waveguides (8,9) pumped between 805 and 845 nm. Compared to LiNbO3, LiTaO3 is attractive because it is expected to present a greater resistance to the photorefractive effect (10) and techniques to produce periodic poling in this material can lead to inverted domain shapes closer to the ideal rectangular case. We will show that the signal wavelength is nearly independent of the injected pump power, but the measured conversion efficiency is lower by a factor of 130 than the predicted value.

For the formation of the periodically inverted domains, we used a Z- substrate, and started with proton exchange through a periodic Ta mask (periods = 20, 21 and 22 μm, width of the openings: 250 μm in the Y direction) using a phosphoric acid bath heated to 260°C in which the sample was immersed for 70 min. This induces a periodic doping with a very high maximum proton concentration. This step is followed by a flash annealing at 600°C for 13 min, during which the electrical field induced by the concentration gradients combined with the elevation of temperature to around the Curie temperature, causes the orientation of the e axis of the crystal to flip forming semi-cylindrical inverted domains (12). The residual protons are then further diffused by a long annealing (4h00) at 500°C. Within each domain inverted region, a group of seven proton exchanged guides with mask widths ranging from 1 to 7 microns in one micron steps were then fabricated, for propagation along the x-axis. One additional group of guides was fabricated on a region of the crystal having no domain inversion to permit comparison.

<table>
<thead>
<tr>
<th>Index profile</th>
<th>Initial waveguide</th>
<th>After first annealing</th>
<th>After second annealing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial waveguide</td>
<td>Gaussian</td>
<td>Gaussian</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Δn_e (λ = 632.8 nm)</td>
<td>0.0216</td>
<td>0.0182</td>
<td>0.0152</td>
</tr>
<tr>
<td>Depth at 1/e</td>
<td>3.7 μm</td>
<td>4.2 μm</td>
<td>5.0 μm</td>
</tr>
</tbody>
</table>

Table 1: Characteristics of the waveguides realized through the 3 μm openings.
The sample was immersed in a 330°C benzoic acid bath, containing 0.5% by weight of lithium benzoate, for 2h 45mn. This was followed by annealing at 350°C for 1 hour. After mask removal the sample was polished to permit end-fire coupling. The sample was in this processing stage, called the initial stage, when the first nonlinear fluorescence measurements were performed. It then underwent two 1h annealings at 375°C after each of which, the nonlinear fluorescence was again monitored. At each processing stage, the guiding structures were characterized and the properties of the waveguides obtained with a mask opening of 3 μm are reported in table 1. The sample was excited by a chopped Ti:sapphire laser beam and the parametric fluorescence observed with synchronous detection using a liquid nitrogen cooled germanium photodetector-preamplifier (NEP = 1x10^-15 WHz^-1/2) placed after a spatial filter, permitting isolation of light issued from the guide extremity, and a monochromator of 0.2 m focal length and 1mm slit width. A series of pump rejection-signal pass filters with an overall pump rejection factor of 10^-10 were placed in front of the monochromator input.

![Figure 1: Experimental (points) and calculated (lines) tuning curves of the sharp fluorescence peak signal and idler wavelengths versus pump wavelength at ambient temperature for a 20 μm domain inversion period and 3 μm wide guide after each of the three processing stages. The injected pump power was 10±2 mW.](image)

In figure 1, we trace the tuning curves of the sharp fluorescence peak4 which corresponds to the completely guided interaction, versus pump wavelength, in a 3 μm wide waveguide presenting a 20 μm domain inversion period. Signal and idler fluorescence wavelengths have been experimentally measured up to 1.7 μm (sensitivity limit of the Ge detector). Above this limit, idler frequencies are determined by imposing the conservation of energy condition, ω_i = ω_p - ω_s where ω_p, ω_s and ω_i represent the pump, signal, and idler pulsations, respectively. These curves indicate that, as in LiNbO3 waveguides, we can obtain a fluorescence between 1.2 and 2.3 microns using a pump wavelength around 0.8 μm, and that the fluorescence range can be covered by varying the pump wavelength less than 20 nm, which is possible to achieve with a temperature - tuned laser diode13. The translation towards the shorter wavelengths after the annealings is due to the reduction of the index increase, and is perfectly predictable by our model13.

In figure 2 we see that taking into account the error factor on the signal wavelength, the signal (and idler) wavelength can be considered to be independent of the injected pump power in both initial and annealed waveguides, even at ambient temperature. This was not the case for LiNbO313, where the signal wavelength variation was well explained by invoking the photorefractive effect. In this particular LiTaO3 sample, the absence of signal wavelength variation is due to a combination of two effects:
- LiTaO3 presents a smaller intrinsic photorefractive effect10 than LiNbO3
- in this sample, as we will see in the next paragraph, a proton - induced reduction of the electro-optic coefficient is to be expected
At the "initial" stage, the parametric fluorescence efficiency, defined as $\eta = \frac{P_s}{P_p}$ where $P_p$ is the input pump power and $P_s$ the signal power, is approximately $0.3 \times 10^{-10}$ which is 4 orders of magnitude lower than what we could expect theoretically, neglecting the influence of the protons on the nonlinear coefficient. Indeed, before the annealings at $375^\circ$C, the waveguides present a relatively high proton concentration, and the characterization of planar waveguides realized in similar conditions permits concluding that this sample was in the $\beta$ phase, in which a reduction of the electro-optic and nonlinear coefficients is to be expected.

The annealings allow significantly improving this efficiency (Fig. 3). We believe these improvements are related to the reduction of the proton concentration and the subsequent phase transition, which brings the sample to the $\alpha$ phase, a transition which is correlated with a partial recovery of the electro-optic and nonlinear coefficients. After the second annealing, the measured efficiency is $1.1 \times 10^{-10}$. As can be seen in Table 2, this figure is one order of magnitude lower than what we measured on LiNbO$_3$, but still two orders of magnitude lower than what can be expected from a sample presenting no degradation of the periodic domains and no reduction of the nonlinear coefficient.

<table>
<thead>
<tr>
<th></th>
<th>LiTaO$_3$</th>
<th>LiNbO$_3$</th>
<th>LiTaO$_3$ / LiNbO$_3$</th>
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<tbody>
<tr>
<td>Calculated $\eta_c$</td>
<td>$14.2 \times 10^{-9}$</td>
<td>$5.5 \times 10^{-9}$</td>
<td>2.6</td>
</tr>
<tr>
<td>Measured $\eta_m$</td>
<td>$1.1 \times 10^{-10}$</td>
<td>$9.8 \times 10^{-10}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$\eta_c + \eta_m$</td>
<td>130</td>
<td>5.6</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Comparison between calculated and experimentally measured parametric efficiencies in LiTaO$_3$ and LiNbO$_3$ periodically poled waveguides.

In conclusion, we have demonstrated that efficient guided wave QPM parametric fluorescence at ambient temperature is possible in LiTaO$_3$, using pump wavelengths and powers attainable with laser diodes. The measured efficiency is lower than the numerically predicted value, and we are now trying to determine whether this limitation is due to a reduction of the nonlinear coefficient or a degradation of the periodic grating.
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Nonlinear Properties of Disordered GaAs/AlGaAs MQW structures at 1.55 μm

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Abstract.

We report on the use of a novel impurity free vacancy disordering technique for the realisation of samples with selective nonlinear regions. The technique used relies on standard SiO2 dielectric caps to promote disordering, a hydrogen plasma treatment to suppress disordering and results in band gap shifts of around 35 nm and changes in n2 of up to 60%.

The use of nonresonant nonlinearities as a potential mechanism for realising ultrafast all-optical switches and modulators has been the subject of an increasing amount of research. One of the major reasons is the potential increase in speed possible if nonresonant nonlinearities could be effectively utilised. To date a number of discreet devices have been reported using the half band gap nonlinearities in the AlGaAs material system, for example, nonlinear directional couplers[1], Mach-Zehnders[2] and X-junctions[3]. However, to fully realise the potential of such devices they must be integrated with both passive linear waveguides and ideally with semiconductor lasers. Disordering of quantum well structures has been used to produce a range of integrated devices[4] and has been proposed as a possible technique for integrating...
linear and nonlinear devices onto the same chip[5]. In this paper we report on the use of a novel impurity free vacancy disordering (IFVD) technique for producing samples with selective nonlinear regions[6].

Samples were produced from an MBE grown wafer with the following structure. The waveguide core consisted of a 1 \( \mu \)m thick multiple quantum well (MQW) layer, composed of 78 periods of 2.8 nm thick GaAs wells and 10 nm thick Al\(_{0.4}\)Ga\(_{0.6}\)As barriers. Optical confinement was provided by a 4 \( \mu \)m thick lower cladding and a 0.8 \( \mu \)m thick upper cladding both of Al\(_{0.4}\)Ga\(_{0.6}\)As. The top layer of the structure consisted of a 10 nm GaAs cap. Using a relatively thick lower cladding minimised radiation losses to the GaAs substrate, while the upper cladding allowed stripe loaded waveguides to be formed.

Regions with different nonlinearities were produced using IFVD. Initially a 200 nm cap of SiO\(_2\) was deposited across the whole sample using E-beam evaporation. Standard photolithography and wet etching with buffered HF was used to remove half of the SiO\(_2\). The sample was then subjected to a hydrogen plasma in a Plasmatech \( \mu \)P80 dry etch machine for 40 minutes[6].

Once the hydrogen treatment was complete the sample was then thermally processed in a rapid thermal processor. The sample was placed face down on a fresh piece of GaAs, to minimise As loss during the processing and then raised to 900°C for 60 s. This processing resulted in the disordering of the MQW under the SiO\(_2\) as a result of Ga absorption into the cap. While under the region subjected to the hydrogen plasma treatment the disordering was suppressed The resulting bandgap shifts were characterised using low temperature, 77 K, photoluminescence. Typical bandgap shifts are shown in fig. 1. After the thermal processing the remaining SiO\(_2\) was removed. Finally, stripe loaded waveguides were produced using photolithography and dry etching with SiCl\(_4\) gas.
The losses of the resulting waveguides were measured by the standard Fabry-Pérot technique using a 1.55 μm DFB laser. Waveguides formed in the undisordered portion of the sample had a loss of 2.9 dBcm⁻¹, while those in the disordered portion of the sample had a loss of 6 dBcm⁻¹. These figures should be compared to the losses measured in waveguides formed in the initial material, with no thermal processing, of ~ 1 dBcm⁻¹.

Nonlinear measurements were performed using a synchronously pumped, mode-locked NaCl:OH⁺ colour centre laser producing ~10 ps pulses. The waveguides were excited by end-fire coupling using a 40X microscope objective at the input and a 25X objective at the output. The nonlinear coefficients were measured by recording the power required to produce a $3\pi/2$ phase shift in the self-phase modulation (SPM) spectra in both the disordered and undisordered portions of the sample, a typical spectra is shown in fig. 2. The transmitted power levels were recorded, rather than the input power levels, thereby eliminating any differences in coupling efficiencies and allowing account to be taken of the different linear losses.
Fig. 2. Shows the input spectrum from the colour centre laser and a typical SPM spectrum.

Table 1. shows the measured $\Delta n_2$ for both TE and TM polarised modes at three different wavelengths. The change in nonlinear coefficient, $\Delta n_2$ is defined as $\frac{n_2^d - n_2^u}{n_2^u}$, where $n_2^u$ and $n_2^d$ are the nonlinear indices in the undisordered and disordered regions, respectively. The change in $n_2$ can be attributed to several factors, a) an increase in the effecting bandgap results in a decrease in $n_2$ since the nonlinearity scales as $E_g^{-\alpha}$, b) loss of quantum confinement and c) and increase in detuning after disordering.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>$\Delta n_2$ TE (%)</th>
<th>$\Delta n_2$ TM (%)</th>
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<td>1510</td>
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In conclusion we have reported a novel IFVD technique relying on a hydrogen plasma treatment, to suppress disordering. This technique was successfully used to produce samples with a 35 nm shift in the band edge and a corresponding change in the magnitude of the half bandgap $n_2$ of around 60%. This technique has many potential applications in the field of nonlinear optics.

References:
GIANT OPTICAL NONLINEARITY IN WAVEGUIDING AMORPHOUS SUPERLATTICES

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ABSTRACT
Giant optical second-order nonlinearity has been observed in waveguiding amorphous superlattices. Second-order susceptibility exceeding $10^{-11}$ m/V has been measured in experiments on frequency doubling in multilayer optical waveguide composed by ultrathin amorphous silicon dioxide and tantalum pentoxide films. Optical nonlinearity degradation has been observed during second harmonic generation (SHG).

INTRODUCTION
Waveguiding nonlinear optical interactions are very attractive due to effective beam confinement over long interaction lengths providing high conversion efficiencies of laser diode radiation. SHG in optical waveguides has been demonstrated in a variety of materials and configurations. Multilayer thin film optical waveguides are almost ideal for nonlinear interactions because they can easily provide high conversion efficiency due to their adjustable dispersion characteristics and form birefringence. Amorphous dielectric waveguiding superlattices are of great interest as new artificial media for efficient nonlinear interactions for a large variety of different and transparent in UV-IR region materials can be used for their design. In this paper we report on extremely efficient SHG by TM-TM mode conversion in multilayer optical waveguides composed by ultrathin amorphous silicon dioxide and tantalum pentoxide films.

EXPERIMENTAL
Multilayer periodical structures have been proposed to design an optical waveguide form birefringent core to increase nonlinear interaction efficiency [1,6]. It has been shown in our previous investigations that built-in electrostatic field asymmetry in each layer of an amorphous multilayer periodic waveguiding structure is the essential requirement to obtain non-zero nonlinear response. It can be build in by means of deposition techniques used for fabrication of such multilayer [2]. We found that RF sputtered multilayer boundaries SiO$_2$-Ta$_2$O$_5$ and Ta$_2$O$_5$-SiO$_2$ had nonidentical surface defect...
densities providing electrostatic potential profile asymmetry in each layer. As a consequence, efficient SHG has been observed in a multilayer planar optical waveguide composed by periodically alternating amorphous Ta$_2$O$_5$ and SiO$_2$ films [3]. Another way to achieve required asymmetry is an appropriate arrangement of the different material layers in the structure period. This technique can provide the possibility to control the nonlinear coefficient sign of the ‘artificial’ medium period. For instance, optical SHG has been observed in a 3-layer-in-period amorphous dielectric heterostructure described in Ref.[4,7,8]. All of the 2- and 3-layer-in-period multilayer structures were deposited by reactive RF sputtering on fused silica substrates. X-ray measurement showed that all fabricated multilayers were amorphous. The optical birefringence of the periodic stratified waveguiding structures provided phase matching of the lowest order waveguide modes TE$_{00}$ and TM$_{00}$. SHG in a 700 nm thick 15 period planar multilayer waveguiding structure [4] has been performed with a Nd:YAG laser at $\lambda=1064$ nm. Each period consisted of Ta$_2$O$_5$, Al$_2$O$_3$, SiO$_2$ films with thickness 19.0 nm, 12.0nm and 15.7 nm respectively. For 130 mW fundamental input power $P_0$ the measured SHG efficiency $\eta = P_2/P_0$ was $1.7 \times 10^{-6}$. Assuming that field-induced second-order susceptibility was localized in amorphous tantalum pentoxide layers we have calculated $\chi^{(2)}$ nonlinear coefficient of Ta$_2$O$_5$. Its value was estimated to be $1 \times 10^{-13}$ m/V which almost equalled that of KDP crystal.

In our latest experiments we studied SHG in multilayer waveguides using TM-TM mode conversion. In this case the nonlinear conversion is attributed mainly to $\chi^{(3)}$ nonlinear coefficient. We suspected nonlinear response to be much higher in this case because fundamental wave electrical field had component collinear to a superlattice built-in electrostatic field vector. One of the possible waveguide configurations to achieve phase matched TM-TM SHG is a 4-layer planar optical waveguide [5].

High conversion efficiency can be obtained for TM$_{1} -$ TM$_{1}$ modes interaction when only one of the core layers is nonlinear. Our detailed investigations showed that the amorphous superlattice nonlinearity strictly depended on layer thickness and reached its maximum at 30 nm thick Ta$_2$O$_5$ and SiO$_2$ layers in superlattice period. The nonlinearity of 2 nm thick layer in period superlattices was negligibly small while their refraction indices equalled those of 30nm thick layer superlattices.

For SHG experimental observation quasi-4-layer waveguiding structure was fabricated by RF sputtering. The first highly nonlinear core layer deposited on a fused silica substrate consisted of 12 periodically alternating Ta$_2$O$_5$ and SiO$_2$ films with total thickness 334 nm. The second layer was composed by 146 periodically alternating Ta$_2$O$_5$ and SiO$_2$ films with total thickness 320 nm.
Non Q-switched Nd:YAG laser radiation at wavelength 1064 nm was coupled into waveguiding superlattice using a prism coupler. We estimated the fundamental wave power density in waveguide as $10^5$-$10^6$ W/cm$^2$. Every laser pulse was followed by bright green streak of TM$_{0}$ -TM$_{1}$ phase matched SHG propagating through the whole 5 cm length waveguide. We faced substantial difficulties in experimental measurement of SHG efficiency because after several dozens of pulses its value became considerably small and the green streak became shorter and shorter. Experimentally measured SHG efficiency on the 5 mm interaction length was $3\times10^{-2}$. On the basis of these data the value of amorphous waveguiding superlattices second order susceptibility was estimated to be more than $10^{-11}$ m/V which was close to that of LiNbO$_3$. These results correspond only to the first 3-5 pulses. We believe that extremely high ‘artificial’ nonlinearity we have observed in experiment was caused by resonant interactions of fundamental wave radiation and band gap localized states. Second-order susceptibility degradation can be probably considered as a result of the localized states and charge density redistribution originated from resonant interactions mentioned above.

In our opinion to avoid the multilayer second-order susceptibility degradation profound research is needed to design an appropriate potential profile of waveguiding amorphous superlattice.

ACKNOWLEDGEMENT

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146 periodically alternating 2.2 nm thick Ta$_2$O$_5$ and SiO$_2$ layers

24 periodically alternating 28 nm thick Ta$_2$O$_5$ and SiO$_2$ layers
Soliton switching in a Mach-Zehnder device via cascading of second-order nonlinearities

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Abstract
We numerically demonstrate the operation of a Mach-Zehnder all-optical switch based on temporal solitary waves propagating in a second-order nonlinear medium.

All-optical switching devices have been largely investigated, both theoretically and experimentally, in the framework of intensity-dependent effects due to a Kerr-like nonlinearity. Recently, however, the possibility of achieving large phase shifts via cascading of second-order effects such as Second-Harmonic Generation (SHG) has opened up new scenarios where non-centrosymmetric media could provide the long sought solution to ultrafast all-optical processing at low powers. [1-2] While the initial work has concentrated on cw phenomena in bulk and in integrated optics configurations, [2-8] the interest is now moving towards time-dependent effects which link the inherent dispersion of the material to the pulsed character of realistic excitations. In particular, dispersion and nonlinearity can be exploited in order to perform signal processing on pulses as bits or wave-particles, beating the detrimental effect of the otherwise unavoidable pulse break-up characteristic of any device (also of the Kerr-type) operating with regular pulses. In this Communication we numerically demonstrate the operation of a typical all-optical switch, the nonlinear Mach-Zehnder interferometer, based upon the propagation of soliton-like or simulon pulses in a non-centrosymmetric medium and in the presence of cascading effects due to phase-mismatched SHG.

Considering a scalar interaction and assuming that a fundamental frequency (FF) wave and its second-harmonic (SH) component propagate in the same direction with matched group velocities but with unequal phase velocities \(\omega/\beta_f\) and \(\omega/\beta_s\) and unequal group-velocity dispersion (GVD), the coupled equations describing the evolution of slowly-varying envelopes \(U_f\) and \(U_s\) at frequencies \(\omega\) and \(2\omega\), respectively, can be cast in the form:

\[
\frac{i}{\partial \xi} \frac{\partial U_f}{\partial \tau} + \frac{1}{2} \frac{\partial^2 U_f}{\partial \tau^2} + U_f^* U_s = 0
\]

\[
\frac{i}{\partial \xi} \frac{\partial U_s}{\partial \tau} - \frac{\beta_s}{2} \frac{\partial^2 U_s}{\partial \tau^2} + \delta k U_s + U_f^2 = 0
\]

(1)
having defined $\xi = z / z_d$ the propagation length normalized to the dispersion length, $\tau = (t - \beta_r z) / T_0$ the time normalized to the pulse length $T_0$ in a temporal frame moving with the FF group velocity $1 / \beta_r$, $\beta_s = \beta_r / \beta_0$ a ratio between the GVDs at the two frequencies and $\delta k = z_d (\beta_s - 2 \beta_r)$ a normalized wavevector mismatch. The sign + or - applies in the first of (1) according to the sign of $-\beta_r$. Equations (1), regardless the sign of the dispersion, exhibit solitary wave solutions in the form of mutually sustained fields at $\omega$ and $2\omega$, also called simultons. [9] Such solutions take the form:

$$U_1 = \pm 3\alpha^2 \sqrt{2\beta_r \beta_0} e^{iz_0 \beta_r} \text{sech}^2(\alpha \tau)$$

$$U_2 = -3\alpha^2 \text{sgn}(\beta_r) e^{i(\delta k z_0 - 3 \alpha^2 \tau)} \text{sech}^2(\alpha \tau)$$

provided that

$$2[\beta_s / \beta_0^2 - 2 \text{sgn}(\beta_s)] \alpha^2 = \delta k$$

Even though the simulton is composed of two pulses traveling at the same group velocity, it is apparent from eqns.(2) that the amplitudes corresponding to the fundamental frequency and its second harmonic are related via the ratio of their respective GVDs, such that the larger the GVD at $2\omega$ the smaller the solitary pulse propagating at that frequency with respect to the FF pulse. For $\beta_s \rightarrow 0$ the simulton tends to a single frequency one component soliton. Nevertheless, in most material systems $|\beta_s| \gg |\beta_0|$, and a single FF pulse can propagate as a solitary wave without seeding the interaction with the corresponding second-harmonic component. This is shown in Fig. 1, demonstrating nearly undistorted propagation of an FF quasi-soliton over a length $L = 50 z_d$. The dispersion helps suppressing the SH component, even for small wavevector mismatches, or at phase-matching. The FF pulse, however, does experience a nonlinear phase shift upon propagation, and this shift can be used in order to all-optically switch an interferometric device such as, for instance a Mach-Zehnder.

Let us consider a typical Mach-Zehnder interferometer formed by a couple of Y-junctions connected by straight channel waveguides, with a slight asymmetry introduced in the branching factor at the stems in order to allow for a differential phase term between the fields propagating along the two otherwise identical arms. The nonlinear phase term characterizing the FF quasi-solitons propagating in the interferometer can be then utilized to switch the device from the "on" (transmissive) to the "off" states, only acting upon the input power launched in the form of a suitable FF quasi-soliton and split at the first stem in the ratio $\sigma / (1-\sigma)$. Figure 2 (left) is a sketch of the device. When the pulses, after propagation in the two arms, recombine at the second stem according to the inverse ratio $(1-\sigma) / \sigma$, they interfere with each other converting the phase change into an amplitude modulation. Fig.2 (right) shows a typical power dependent input/output characteristic, obtained for $\sigma=0.55$, $\delta k = -50$, and $|\beta_s| / |\beta_0| = 10$. Similar results are obtained in a wide range of mismatches, and different values of the splitting ratio. The integrated power
throughput varies periodically according to the amount of differential phase shift induced by the cascading process.

Several inorganic and organic crystals are potential candidates for the demonstration of this device, provided a waveguide can be realized and a substantially larger GVD is present at $2\omega$. A simple estimate, considering a 4 cm-long $z$-propagating channel fabricated by Ti indiffusion in $y$-cut Lithium Niobate, for an effective area $\approx 100 \mu m^2$ [10] and $\beta_r=100$ ps$^2$/km, 30 fs pulses lead to a switching energy of 3.7 nJ (peak power $\approx 120 kW$) for a normalized switching amplitude $U_f=50$. This switching energy is comparable to that required by a Kerr soliton switch in a fiber interferometer which, however, would be approximately one order of magnitude longer [11]. It is reasonable to expect much lower switching thresholds with suitable organic crystals in waveguide format.

In conclusion, efficient all-optical switching can be obtained employing simultons in materials exhibiting a cascaded 2nd-order nonlinearity in a guided-wave Mach-Zehnder configuration. Such operation could be an effective approach towards the experimental verification of solitary wave propagation in media for SHG.

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References
Fig. 1 Nearly undistorted propagation of a quasi-soliton over fifty dispersion lengths (z is in units of dispersion length), with no seed at second-harmonic, $\delta k = -20$, and $|\beta_2^"/\beta_f^"| = 50$.

Fig. 2 Schematic of the device: $t$ denotes the splitting ratio of the junctions (left); Energy transmissivity vs. peak amplitude of the fundamental frequency input pulse for $\delta k = -20$, $|\beta_2^"/\beta_f^"| = 10$, and splitting ratio $t=0.55$ (right).
We Po Poster Session

FLUORESCENCE LIFETIME OPTIMISATION
OF A LOW THRESHOLD, HIGH EFFICIENCY, PROTON EXCHANGED
WAVEGUIDE LASER in Nd:LiTaO₃

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Abstract
Correlating the Nd³⁺ excited state lifetime in proton exchanged waveguides and the phase diagram
of the HₓLiₙ-xTaO₃ compound allows optimizing waveguide laser fabrication parameters. Using
these results, we have fabricated a Nd:LiTaO₃ waveguide laser with a threshold of 2.9 mW
(previously 24 mW) and a slope efficiency of 33 % in good agreement with the predicted values.
Nevertheless this component suffers from instabilities due to the photorefractive effect.

Introduction
During the last five years, integrated optical waveguide lasers have been demonstrated in a variety
of rare earth doped materials. Different techniques were used to fabricate such devices: ion exchange
in neodymium doped glass¹, ion implantation in crystals such as Nd:YAG² and Nd:LiNbO₃³,
titanium diffusion in Nd:LiNbO₃⁴, Er:LiNbO₃⁶ and Nd:LiTaO₃⁶, and proton exchange in
Nd:MgO:LiNbO₃⁷ and Nd:LiTaO₃⁸. Due to their electro-optic and nonlinear properties, rare earth
doped lithium niobate and tantalate are very attractive for realizing mode-locked and Q-switched
devices as well as intracavity frequency doubled sources. Following the recent success in realizing
such functions in annealed proton exchanged Nd:MgO:LiNbO₃ waveguides⁹, we tried to transpose
this technique to Nd:LiTaO₃ waveguides¹¹ as this material has the reputation of having a higher
optical damage threshold¹² than LiNbO₃, and has been used to produce efficient guided-wave
frequency doublers¹³ using the periodic domain inversion technique¹⁴. For these reasons, this
material seems to be more appropriate for the realization of a visible, self-doubled integrated source.

The first attempt to get laser action in Nd:LiTaO₃, using proton exchanged waveguides, was not
very successful, due to a strong reduction of the neodymium ⁴F₃/₂ level lifetime which induces a high
oscillation threshold, although laser performances was improved by annealing the sample. In this
paper, we will show how correlating the Nd³⁺ fluorescence lifetime and the crystallographic phase of
the HₓLiₙ-xTaO₃ host matrix, allows explaining these facts and allows determining waveguide
fabrication parameters achieving the best compromise between wave confinement and the Nd³⁺
fluorescence properties.

The paper is divided into four sections. In the first, we present the phase diagram of the exchanged
layer in undoped X-cut lithium tantalate, showing that we observe a very similar behaviour on X- and
Z-cut samples. In the second section, we present the spectroscopic properties and the performances
of our first laser and the improvement observed after annealing. In the third section, we detail the
influence of the successive annealings on both the lifetime and the crystalline structure of the
exchanged layer. Knowing the correlations between these two characteristics, as well as the
influence between the crystalline structure and the index profile¹⁵, we deduce optimised fabrication
parameter of a Nd:LiTaO₃ waveguide laser. In the fourth section we will show that the threshold and
the slope efficiency of such a waveguide laser, are very near the predicted values, and discuss the
stability problem.

1- Phase diagram of HₓLiₙ-xTaO₃ layers
In another paper¹³, we detailed the correlation between the index profile and the crystallographic
properties of proton exchanged layers on Z-cut substrate. Similar work has been done for X-cut
substrates, and again, at least four phases were identified (see figure 1): α, β, γ, δ. The main
difference between the two substrate orientations lays in the fact that the deformations (ε"₃₃) observed
perpendicular to the substrate surface are higher for the X-cut samples, which limits the possibility of
having good quality high proton concentration layers.
This explains why in the δ phase, which corresponds to the highest proton concentration phase, it was not possible to have more than one point. Any further increase of the proton concentration in the crystal leads to surface fissures during the exchange. As observed for Z-cut crystals, in each phase, the index variation is a linear function of the H⁺ concentration, the slope of this function being either positive or negative. Note that passing from the δ phase to the γ and β phases, leads to an annealing induced increase of the δnₑ. For the very low proton concentration layers, the limit between the α and the α' phase is less well defined than on Z-cut samples, and it is not clear whether the substrate can accept some protons, leading to a δnₑ of up to 4.10⁻³, without presenting a crystallographic phase change.

2. Nd³⁺ lifetime and laser performances of Nd:HXLi₁₋ₓTaO₃ waveguides

To produce our first PE Nd:LiTaO₃ waveguide laser, we used an X-cut substrate doped with 0.1 mole % of Nd³⁺. The exchange was carried out through a mask presenting 1 to 7 μm wide openings, during 3.5 hours in a benzoic acid bath melted at 330 °C and diluted with 0.5 % lithium benzoate. These fabrication conditions lead to a HₓLi₁₋ₓTaO₃ layer in the δ phase (point 1 in fig.1) and the laser obtained by depositing mirrors having a 90 % transmittivity at the pump wavelength (λ₀ = 0.81 μm) and a reflectivity of 99% at the laser wavelength (λ = 1.08 μm) for the input, and a reflectivity of 70% at 1.08 μm for the output exhibited a threshold of 58 mW. The reason for this high threshold is a strong reduction of the excited state lifetime which goes from 100 μs in the substrate down to 2.9 μs for 60 % of the ions and to 34 μs for the others. This reduction is due to rapid nonradiative relaxation via the phonons associated to the OH⁻ formed during the exchange. As the only efficient contribution to the laser oscillation comes from the Nd³⁺ ions with the longer lifetime, it is not surprising to find a very high threshold in this case.

Annealing the Nd:LiTaO₃ waveguide for 1 hour at 350 °C, in an oxygen rich atmosphere modifies the index profile of the waveguide (figure 2) which exhibits an increase of both the surface index and the depth of the exchanged layer. Placing this result (point 2) in the phase diagram of figure 1 indicates that this evolution is due to a transition from the δ to the γ phase. The annealing also increases the two observed lifetimes and the proportion of ions having the longer lifetime (57 μs) becomes 68 % (see table 1). This is consistent with a phonon induced lifetime reduction, as the annealing diminishes the proton concentration and the number of OH⁻ associated phonons. The laser
performance obtained with a similar set of mirrors is also improved, threshold being reduced to 24 mW.

![Waveguide index graph](image)

Figure 2: Variation of index profile induced by the first annealing at a temperature near from the exchange temperature

3- Correlation between crystallographic phases and Nd$^{3+}$ fluorescence lifetime.

In order to see how far the effective fluorescence lifetime could be recovered without excessively reducing $\delta n_e$, we annealed the neodymium waveguide step by step monitoring simultaneously these two parameters. The results are reported in table 1 where we see that during the first three annealings the waveguide is in the $\beta$ or $\gamma$ phase (points 2 and 3 in fig.1) with a $\delta n_e$ of 2.35x10$^{-2}$ and presents a long fluorescence lifetime of 60 ± 10 $\mu$s for 60% of the ions. Increasing the annealing temperature allows a further phase transition to the $\alpha$ phase where the fluorescence lifetime can be as high as 82 $\mu$s for 93 % of the Nd$^{3+}$ ions in a layer which still presents an index variation of 1.15x10$^{-2}$ (point 4 in fig.1), enough to maintain good light confinement.

<table>
<thead>
<tr>
<th>ref. Nb.</th>
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<th>$A_1$(%)</th>
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</table>

Table 1: Index increase $\delta n$ and lifetime values $\tau_1$ at different stages of annealing

4- Realisation of an optimized waveguide laser in Nd:LiTaO$_3$

In order to realise a waveguide laser in the $\alpha$ phase we used an 0.1 mole%, Z-cut Nd doped substrate provided by Crismatec. Guides were fabricated by proton exchange at 330° C for 70 minutes, in benzoic acid diluted with 1 mole % lithium benzoate through the same titanium mask. The exchange was followed by one hour annealing at 385 °C. We then butted against the sample faces the same dielectric mirrors, and upon application of the pump, obtained from a Ti:sapphire laser tuned to 0.81 $\mu$m, laser oscillation was obtained in the 7 $\mu$m wide waveguide.
Unfortunately this laser presented an unstable behaviour due to the photorefractive effect. Heating the sample up to 50°C was not sufficient to suppress these instabilities. We then modulated the pump with an acousto-optic modulator using a low duty cycle and measured the peak output power versus the absorbed pump power for a laser fabricated from a 7 μm wide mask (figure 3).

We can see that the threshold absorbed pump power is as low as 2.9 mW and the slope efficiency is 33%, figures which are very close to the best results obtained on Nd:MgO:LiNbO₃ with similar cavities.

We are now addressing the stability problem, due to an unexpectedly high photorefractive effect which we are trying to correlate with the doped crystal drawing conditions. Moreover, recent results¹⁶ show that the periodic poling necessary for frequency doubling, may solve the stability problem as well.

In conclusion, we have now identified the correlation existing between the crystallographic structure, the fluorescence properties and the index profile of proton exchanged layers on Nd:LiTaO₃ substrates. This allows determining optimized waveguide fabrication parameters and demonstrating for the first time an efficient waveguide laser action in this material. Instabilities continue to be observed, due to an unexpectedly high photorefractive effect at the pump wavelength. Efforts are underway to determine the source of this strong photorefractive effect and a way to reduce it.

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CONTROL OF PROTON EXCHANGE FOR LiTaO$_3$ WAVEGUIDES AND CRYSTAL STRUCTURE OF H$_x$Li$_{1-x}$TaO$_3$

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Abstract
In this paper, we show how the phase diagram of the H$_x$Li$_{1-x}$TaO$_3$ waveguiding layer on top of a crystal of a given orientation allows to understand, and thus to control, the proton exchange (PE) process in lithium tantalate.

Introduction
Lithium tantalate (LiTaO$_3$), which presents electro-optical and non-linear coefficients similar to those of Lithium Niobate (LiNbO$_3$), has the reputation of presenting a much higher resistance to optical damage. Realizing waveguides in this material is therefore particularly interesting for applications where the power density is very high, such as in integrated non-linear optics and lasers. Today, one of the most convenient waveguide fabrication procedures is proton exchange (PE) and in the last few years, various studies have been made to characterize this process in LiTaO$_3$, but none gave a good explanation of all the observed effects, such as the annealing induced increase of the extraordinary refractive index.

In this paper, we demonstrate how the knowledge of the phase diagram of the H$_x$Li$_{1-x}$TaO$_3$ layer allows us to establish correlations between fabrication parameters and optical properties, which leads to a good understanding and control of the process.

Phase diagram
During the exchange, the crystalline cell expands, but in order to satisfy the boundary conditions, elastic deformations occur and expansion takes place only perpendicular to the surface.

Figure 1: Phase diagram of H$_x$Li$_{1-x}$NbO$_3$ on Z.L substrate. It gives the dependence of the index variation measured at $\lambda = 632.8$ nm versus the deformations. Samples 1, 3 and 4 are prepared by exchange in high temperature benzoic acid melts diluted with lithium benzoate. Samples 2a and 5a to 7a are obtained by annealing.

This induces stresses in the exchanged layer which, via the elastooptic effect and the combination of the piezo electric and the electrooptic effects create index variations which add to the index increase due to composition variation. Both compositional and elastic deformation depend on the...
proton concentration in the exchanged layer. In the following, we make the assumption that the differences between the exchanged layer and the substrate lattice parameters (subsequently noted $\varepsilon''_{ij}$) are proportional to the proton concentration in the exchanged layer. In previous papers\textsuperscript{10,11}, Fedorov and Korkisho have identified four crystalline phases named $\alpha$, $\beta$, $\delta$ et $\gamma$ of the exchanged layer on Z-cut substrates ($Z\parallel$) leading to the phase diagram shown in Figure 1. The phase transitions are characterized by a discontinuity of either the index variation ($\delta n_e$), or the deformations ($\varepsilon''_{ij}$ with $i=j$) and the shearings ($\varepsilon''_{ij}$ with $i\neq j$).

Moreover, this diagram shows that in each crystalline phase there is a linear dependence between the index increase ($\delta n_e$) and the deformations ($\varepsilon''_{ij}$) and, therefore, the proton concentration, but that the slope changes dramatically from one phase to the other (Table 1). Based on these facts, we shall now show how this diagram permits us to understand the PE process on LiTaO$_3$ and explain the optical properties of the different waveguides obtained with different exchange and annealing conditions.

**Table I** Dependence of the extraordinary index changes $\delta n_e$ versus the relative cell deformation $\varepsilon''_{33}$

<table>
<thead>
<tr>
<th>Phase</th>
<th>$\delta n_e = f(\varepsilon''_{33})$</th>
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<tbody>
<tr>
<td>$\alpha$</td>
<td>$\delta n_e = 8 \cdot \varepsilon''_{33}$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$\delta n_e = 7.4 \cdot \varepsilon''_{33} + 0.0072$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$\delta n_e = 2.1 \cdot \varepsilon''_{33} + 0.0218$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>$\delta n_e = 0.028$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>$\delta n_e = -5.1 \cdot \varepsilon''_{33} + 0.0385$</td>
</tr>
</tbody>
</table>

**Direct exchange**

Using the sealed ampoule technique\textsuperscript{3} and a high exchange temperature (330°C), we prepared $H_xLi_{1-x}TaO_3$ layers varying the proton concentration in the Benzoic Acid (BA) melt by varying the percentage of Lithium Benzoate (LB) incorporated (Table 2).

![Figure 2: Index variation obtained on Z-parallel substrates at $\lambda = 0.6328$ μm versus the lithium benzoate quantity in the melt. Two different waveguides profiles were obtained for two thresholds for $p$. The numbers identify the waveguides which were analysed by DCXRD and reported in the phase diagram (fig-1).](image)

Varying the ratio $p = 100(LB / BA + LB)$, between 0 and 5, we have identified two kinds of index profiles and two discontinuities in the dependance of $\delta n_e$ on $p$ (Figure 2). A step index profile is observed for $0 < p < p_1 = 0.05 \pm 0.05$ with $\delta n_e = 2.10^{-2}$, and for $p_1 < p < p_2 = 3.55 \pm 0.05$ with $\delta n_e = 3.10^{-2}$. For $p > p_2$, we observed a gradient index profile with a maximum index increase at the surface on the order of $4.10^{-3}$. Four of these samples, identified by a number in figure 2 and chosen in different regions of $p$, were also analysed by DCXRD. The results obtained ($\delta n_e$ and $\varepsilon''_{33}$) were reported in the phase diagram where they are identified by the same numbers as in Figure 2.
Table 2: Fabrication conditions and results corresponding to our samples studied and placed in figures 1 and 2.

| Sample number | Sample      | %BL | T (°C) | Time | $\delta n$ | depth (µm) | $E_{13}$
<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>TZ+220-15</td>
<td>3.6</td>
<td>330</td>
<td>30 h</td>
<td>0.004</td>
<td>5.6</td>
<td>5x10^{-4}</td>
</tr>
<tr>
<td>2</td>
<td>TZ+220-6</td>
<td>0.5</td>
<td>330</td>
<td>4 h</td>
<td>0.030</td>
<td>2.8</td>
<td>1.84x10^{-3}</td>
</tr>
<tr>
<td>2a</td>
<td>TZ+220-6</td>
<td>0.5</td>
<td>330</td>
<td>1 h</td>
<td>0.026</td>
<td>4.8</td>
<td>3.65x10^{-3}</td>
</tr>
<tr>
<td>3</td>
<td>T3-7</td>
<td>0.5</td>
<td>330</td>
<td>2 h</td>
<td>0.029</td>
<td>2.6</td>
<td>3.55x10^{-3}</td>
</tr>
<tr>
<td>4</td>
<td>T3-9</td>
<td>0.5</td>
<td>330</td>
<td>5 h</td>
<td>0.028</td>
<td>3.2</td>
<td>3.55x10^{-3}</td>
</tr>
<tr>
<td>5</td>
<td>TZ+220-13</td>
<td>1</td>
<td>330</td>
<td>5 h</td>
<td>0.028</td>
<td>2.2</td>
<td>8x10^{-4}</td>
</tr>
<tr>
<td>5a</td>
<td>TZ+220-13</td>
<td>1</td>
<td>330</td>
<td>3 h</td>
<td>0.012</td>
<td>7.2</td>
<td>9.5x10^{-4}</td>
</tr>
<tr>
<td>6</td>
<td>TZ+220-12</td>
<td>0.5</td>
<td>330</td>
<td>4 h</td>
<td>0.030</td>
<td>2.8</td>
<td>9.5x10^{-4}</td>
</tr>
<tr>
<td>6a</td>
<td>TZ+220-12</td>
<td>0.5</td>
<td>400</td>
<td>3 h</td>
<td>0.016</td>
<td>8.3</td>
<td>9.5x10^{-4}</td>
</tr>
<tr>
<td>7</td>
<td>TZ+220-8</td>
<td>1</td>
<td>330</td>
<td>5 h</td>
<td>0.028</td>
<td>2.2</td>
<td>4.1x10^{-3}</td>
</tr>
<tr>
<td>7a</td>
<td>TZ+220-8</td>
<td>1</td>
<td>380</td>
<td>3 h</td>
<td>0.018</td>
<td>4.8</td>
<td>1.39x10^{-3}</td>
</tr>
</tbody>
</table>

They allow us to draw the following conclusions:

- by varying $p$ between 0 and $p_2$, it is possible to obtain three of the four previously identified $H_xLi_{1-x}TaO_3$ crystallographic phases.
- for $p = 0$, samples prepared using pure BA present a $\delta$ phase.
- for $p_1 \leq p \leq p_2$, the proton exchanged layers are in the $\gamma$ or $\beta$ phases, leading to the highest possible index variations ($\delta n_\gamma = 3 \times 10^{-2}$) and intermediate values of deformations ($2 \times 10^{-3} \leq E_{13} \leq 4 \times 10^{-3}$). Our samples 2, 3 and 4, although fabricated with the same %LB ($p = 0.5$), present different crystalline phases. Nevertheless, the differences between $\beta$ and $\gamma$ phases are relatively subtle and could be explained by different substrate qualities.
- for $p > p_2$, (sample no. 1), the proton exchanged layers are in none of the four previously identified phases. They present a much lower index increase ($\delta n_\alpha = 4 \times 10^{-3}$) and rocking curves showing only a gradually distorted substrate peak with maximum relative deformation lower than $0.5 \times 10^{-3}$. In the figures we identify them as the $\alpha$ phase.

The $\alpha$ phase was not observed on samples prepared by direct exchange. It was obtained only by annealing samples realized in $\beta$, $\gamma$ or $\delta$ phases, a process that we now discuss.

**Annealing effects**

On $LiTaO_3$, the effect of this fabrication step on the index profile appears to be rather complicated, sometimes leading to an increase and sometimes to a decrease of the $\delta n_\alpha$. But this complicated behaviour can be easily understood by considering the phase diagram and the fact that an annealing always causes a reduction of the proton concentration. Due to the annealing, the $H_xLi_{1-x}TaO_3$ layer may either evolve into a given phase or experience one or several phase transitions. The effect of the annealing on the index profile can then be complicated but perfectly understood if we know exactly the phase of the original layer. For example, for an initial exchange leading to $\delta$ phase, index variation ($\delta n_\alpha$) and depth will first increase during annealing due to an evolution in the $\delta$ phase followed by a transition to $\gamma$ or $\beta$ phase (Fig.3). Continuing the annealing will then lead to a decrease of $\delta n_\alpha$ and an increase of the depth, which corresponds to the evolution through the $\gamma$, $\beta$ and $\alpha$ phases.

This technique allows producing very good quality waveguides in the $\alpha$ phase (samples n°5, 6 and 7) which cannot be obtained by direct exchange and have perfectly stable index profiles, which have been verified over a one year period of time. As will be explained elsewhere, this result is very important because this phase would be the most interesting for many applications.
Figure 3: Annealing effects
(a) initial exchange conditions: 0 %LB / 330°C / 4 h, lead to a waveguide in the δ phase. With successive annealings, $\delta_e$ increases and the waveguide experiences phase transition to γ or β phase
(b) initial exchange conditions: 0.1 %LB / 330°C / 4 h, lead to a waveguide in the γ or β phase. With successive annealings, $\delta_e$ decreases and the waveguide experiences phase transition to α phase

Conclusion
Exploiting to the phase diagram of $H_xLi_{1-x}TaO_3$, we are able to control the proton exchange process on $LiTaO_3$ and realize waveguides on this material presenting a given crystalline phase, either by direct exchange varying the proton source composition, or by annealing. Previously observed index increase induced by annealing are explained and guide lines are given for realizing high quality waveguides for various applications\textsuperscript{12,13}.

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ANALYSIS OF NONLINEAR WAVEGUIDES
IN THE TIME DOMAIN

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Abstract
A novel Finite Difference Time Domain (FDTD) method is presented for the analysis of nonlinear optical waveguides. It is based on an implicit algorithm and selfconsistently includes reflections and radiation fields. The main advantage of the presented method is its unconditional stability compared to standard FDTD methods based on Yee's algorithm.

I. Introduction
Guided waves in nonlinear planar optical waveguides have received considerable attention with regard to their potential application in optical signal processing devices for optical communications and optical computation. In general coupled-mode theories provide a good insight on nonlinear devices. However, they are unreliable for the analysis of the detailed behaviour and quantitative predictions. Therefore numerical methods are necessary [1]. In nonlinear waveguides the orthogonality relation between modal fields does not hold. Therefore, optical pulses cannot be expanded into harmonic waves, and the application of beam propagation techniques [2-6] is questionable. On the other hand, time domain propagation algorithms allow to simulate the propagation of pulses [7] and have the general advantages of full vectorial formulation, calculation of transmission characteristics in one step, and the automatic and accurate inclusion of reflections.

Yee's algorithm described in [7] has been extensively used in microwave techniques and was introduced in integrated optics by [8]. This algorithm has been extended to the analysis of nonlinear waveguides [9-12]. One significant disadvantage restricts the application of this method. That is, a stability condition has not yet been derived for the analysis of nonlinear waveguides. In this paper, we present an unconditionally stable method which allows the analysis of nonlinear waveguides.

II. Theory
The wave propagation in the time domain is described by Maxwell's curl equations

\[ \nabla \times \vec{H} = \frac{\partial \vec{B}}{\partial t}, \]

\[ \nabla \times \vec{E} = -\frac{\partial \vec{D}}{\partial t}. \]  

with \( \vec{B} = \mu_0 \cdot \vec{H} \) and \( \vec{D} = \varepsilon_0 \left( \varepsilon_r \vec{E} + \vec{P}_{NL} \right) \), when neglecting dispersion effects and considering isotropic media. Otherwise one has to introduce an appropriate dielectric function and tensor properties. \( \vec{P}_{NL} \) denotes the polarization due to nonlinear effects. Neglecting dispersion effects, considering a Kerr medium and TEM-waves, a nonlinear relative dielectric constant \( \varepsilon_{rel} \) is introduced with
\[ \varepsilon_{\text{rel}} = n^2(z) + 3 \chi^{(3)}(z) E_p^2. \]  

Here, \( n^2(z) \) represents the axial variation of the index distribution and \( \chi^{(3)}(z) \) describes the nonlinearity of the medium. In a first step \( \varepsilon_{\text{rel}} \) is assumed to be constant, because actually the known initial field \( E_p \) is inserted. The FDTD method is formulated by discretization of Maxwell's curl equations over a finite volume and approximating the derivatives with centered difference approximations. Therefore the discretization in space coincides with Yee's algorithm. Due to the natural choice of the grids and the allocation of the unknown components in space, the conditions \( \nabla \cdot D = 0 \) and \( \nabla \cdot B = 0 \) hold, i.e., spurious modes cannot occur \[13\]. In contrast to Yee's algorithm all field vectors are determined at the same time step. The discretization in space and time are indicated by the index \( v \) and \( k \), respectively. Stability problems can be avoided, if the field values are approximated by the averaged field values at time steps \( k \) and \( k+1 \). Hence, with the central difference approximation we have

\[
\begin{align*}
\frac{\varepsilon_{\text{rel},v}^k E_{p,v}^{k+1} - E_{p,v}^k}{\Delta t} &= \frac{1}{2 \varepsilon_0 \Delta z} \left( H_{s,v+0.5}^{k+1} - H_{s,v-0.5}^{k+1} + H_{s,v}^{k+1} - H_{s,v}^k \right) \\
\frac{H_{s,v+0.5}^{k+1} - H_{s,v-0.5}^k}{\Delta t} &= \frac{1}{2 \mu_0 \Delta z} \left( E_{p,v+1}^{k+1} - E_{p,v}^{k+1} + E_{p,v}^k - E_{p,v}^{k} \right)
\end{align*}
\]

\( \Delta t \) and \( \Delta z \) are the discretizations widths in time and space. \( c_0 \) is the velocity of light in vacuum. A uniform discretization pattern is assumed. \( \varepsilon_{\text{rel},v}^{k,0.5} \) is a constant dependent on the known field \( E_{p,v}^k \) at time step \( k \). Then the coupled differential equation (8) is transformed into a system of linear equations described by a matrix equation

\[ [A] \cdot \vec{\mathbf{v}}^{k+1} = [B] \cdot \vec{\mathbf{v}}^k, \]

where the vector \( \vec{\mathbf{v}} \) is defined by

\[ \vec{\mathbf{v}} = \left( E_{p,v}, H_{s,v+0.5}, E_{p,v+1}, H_{s,v+1}, \ldots, E_{p,v'}, H_{s,v'+0.5} \right)^T. \]

containing the discretized field values. Now we consider the nonlinearity by an iterative calculation of \( \varepsilon_{\text{rel}} \). After the field \( E_{p,v}^{k+1} \) is calculated for the first time, the relative dielectric constant is modified with the aid of the initial field and the propagating field in the first step. Afterwards the field \( E_{p,v}^{k+1} \) is recalculated again with respect to the modified relative dielectric constant and the known field \( E_{p,v}^k \). This procedure is repeated until the change in the field distribution remains under an established tolerance limit. For this purpose equation (3) is solved repeatedly. A simple first order approximated continuous absorbing boundary condition \[14,15\] is applied to prevent reflections from the computational window.
Nonlinear and linear dispersive effects can be incorporated, so that the modelling of optical solitons featuring a large instantaneous bandwidth is possible. Physical models are described in [9], which allow the description of time retardation or memory. Losses are incorporated by physical dispersion models. The inclusion of all these effects does not affect the fundamental structure of our proposed algorithm. If dispersion effects must be included, the presented formula have to be rearranged in the following way. Within the system of coupled differential equations (1) the dielectric flux $\vec{D}$ has to be incorporated. Then of course an adequate dispersion relation combining $\vec{D}$ and $\vec{E}$ has to be inserted into Maxwell's equations. The above presented implicit method considers nonlinearities iteratively. As linear matrix equations are employed within the algorithm unconditional stability can be proved when a uniform discretization pattern is used.

### III. Results

For a nonlinear grating device the intensity-dependent change in the propagation constant modifies the Bragg condition when the input power is increased. Because of the distributed character of this effect, the feedback allows a multivalued dependence of the transmitted power on the input, leading to bistability and multibistability and for large detunings, to instability. Fig. 1 shows a grating structure dimensioned for a center wavelength of $\lambda_0=1.55\mu m$ with a grating period $\Lambda=0.236\mu m$. A grating with 20 unit cells is applied. The discretization width in z-direction is $h_z=23.684nm$, i.e. resulting in 200 discretization points, whereas the propagation step in time is chosen as $\Delta t = 41,12$ as. The grating structure is excited with the pulse described by

$$E(t) = \bar{E}_0 \cdot e^{-\left(\frac{t}{\tau_0}\right)^2} \cdot \cos\left(\frac{2 \pi c_0}{\lambda_0} t\right),$$

with a carrier wavelength $\lambda_0=1.55\mu m$, a 1/e$^2$-pulse width of 27.3fs, and an amplitude $\bar{E}_0 = 10^5 V/m$ of the gaussian pulse. This pulse is injected into a nonlinear Kerr medium for different nonlinearity parameters NL defined by $NL = \chi^{(3)}(z) \bar{E}_0^2$ and the transmission and reflection spectra are calculated. Within the calculation a transient phenomenon has to be taken into account until the pulse completely leaves the computational window. Considering the transient phenomena Fig. 2 and Fig. 3 present the reflection and transmission spectra, respectively. From these figure the detuning effect can be seen, since the center wavelength is shifted to lower wavelengths.

**Fig. 1 Nonlinear grating device**
Fig. 2 Reflection spectrum for different non-linearity parameters

Fig. 3 Transmission spectrum for different non-linearity parameters

References

SiO$_2$-TiO$_2$ RIB WAVEGUIDES
FOR ELECTROSTATICALLY ACTUATED
IO NANOMECHANICAL DEVICES

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Rib waveguides and Mach-Zehnder interferometers are produced by wet etching of 150-160 nm thick SiO$_2$-TiO$_2$ films, dipcoated (sol-gel process) on oxidized silicon wafers (SiO$_2$/Si) as substrates. Bridges (made of SiO$_2$/Si) spanned over a rib waveguide are used as electrostatically actuated effective-refractive-index-shifting elements; interferometric intensity modulators based on the IO nanomechanical effect are demonstrated.

Introduction

In this paper, we demonstrate that:
1.) rib waveguides - and Mach-Zehnder interferometers - can be fabricated by chemical etching of SiO$_2$-TiO$_2$ films (which are planar waveguides), the films being produced by dipcoating with the sol-gel process on oxidized silicon wafers as (SiO$_2$/Si) substrates,
2.) with embossed surface relief gratings, light (\(\lambda = 633\) nm) can be coupled into and out of the rib waveguides, from the in/outcoupling angles the effective refractive indices of the guided modes are determined, and from the latter the optical parameters of the rib waveguide, in particular its width \(w\),
3.) bridges (made of SiO$_2$/Si by etching of oxidized silicon wafers) spanned over a rib waveguide can be used as electrostatically actuated effective-refractive-index-shifting elements; interferometric intensity modulators based on the nanomechanical IO effect are demonstrated.

By the IO nanomechanical effect changes \(\Delta N\) of the effective refractive indices of guided modes are induced by varying the gap width \(d\) of an air gap between the waveguide and an effective-refractive-index-shifting element E [1]. Previously, the IO nanomechanical effect had been experimentally demonstrated only for guided modes propagating in planar waveguides [2-5].
Fabrication of rib waveguides

First, SiO$_2$-TiO$_2$ films were fabricated by dipcoating with the sol-gel process from Liquicoat® solutions (Merck, Darmstadt) on SiO$_2$/Si substrates. The SiO$_2$ buffer layers of thickness $d_{BL} = 3.5$ $\mu$m were grown by wet oxidation at $T = 1100$ °C. For SiO$_2$-TiO$_2$ films fired for 1 hour at a temperature of 800 °C, typical values of thickness $d_F$ and refractive index $n_F$ (at $\lambda = 633$ nm) are $d_F = 155$ nm and $n_F = 1.817$.

Rib waveguides of width $w = 1.5 - 10$ $\mu$m were produced by etching in buffered hydrofluoric acid (BHF), the waveguide area was protected by a positive photoresist (Shipley, Microposit® SP25-15) irradiated in contact exposure through a chromium mask.

A scanning electron micrograph (Fig. 1(d)) shows a 7.4-$\mu$m-wide rib waveguide with a step height of $\Delta d_E = d_F - d_{FE} = 25.8$ nm ($d_F = 157.6$ nm, $d_{FE} = 131.8$ nm); it proves that the edge roughness is very low. The etch rate $r_{BHF}$ at room temperature was determined with two independent methods: 1.) Scanning with a mechanical stylus instrument (Alpha-Step 200 from Tencor Instruments) the step height between the etched and the non-etched area (i.e., the waveguide) gave the value $r_{BHF} = 6.7$ nm/min. 2.) With the grating coupler method, applied to the etched area FE of the SiO$_2$-TiO$_2$ film as a planar waveguide, the value $r_{BHF} = 6.5$ nm/min was obtained. This method also gave the refractive index values $n_{FE}$ of the etched film FE, which were found to decrease with increasing etching time $t_E$. Values obtained for $\Delta n_{FE} = n_{FE} - n_F$ are $\Delta n_{FE} = -(2.5, 7.2, 9.6,$ and $13.8) \times 10^{-3}$ after $t_E = 30, 60, 120,$ and 240 seconds, respectively. This indicates that the films either become more microporous or that the surface roughness increases.

Characterization of rib waveguides

Optionally a surface relief grating can be provided on the rib waveguide (see Fig. 1). We fabricated such gratings with $1/\Lambda = 2400$ lines per mm (where $\Lambda$ is the grating period) by embossing a diffraction grating as a die into the dipcoated film in its gel-state. The grating can be used to couple light into and out of the rib waveguide; we are planning to use them also as Bragg reflectors.

![Fig. 2. Characterization of rib waveguide by outcoupling. Schematic and photograph of the 'm-lines' of the five guided modes GW (of transverse orders $m_y = 0 - 4$) propagating in the rib waveguide and of the mode in the etched film (planar waveguide) FE. TE-polarization. Width $w = 6.0$ $\mu$m; step height $\Delta d_F = 10.6$ nm. $\lambda = 633$ nm. ML, microscope lens.](image-url)
We use the grating coupler to characterize the rib waveguides, i.e., in particular to determine their widths \( w \). Figure 2 shows an outcoupling experiment. Laser light is endcoupled into the rib waveguide and partly into the etched film \( \text{FE} \). The 'm-lines' consist of straight lines corresponding to the rib-waveguide modes of the same polarization \( \text{TE} \) and of different transverse orders \( m_y = 0, 1, \ldots \), and the curved line to the \( \text{TE}_0 \) mode in the etched film (planar waveguide) \( \text{FE} \). Figure 3 illustrates an incoupling experiment. The incoupled power versus angle of incidence shows the excitation of the modes of different even transverse orders \( m_y = 0, 2, \ldots \) and of the \( \text{TE}_0 \) mode in the etched film \( \text{FE} \).

![Figure 3](image)

Fig. 3. Characterization of rib waveguide by incoupling.
(a) By varying the angle of incidence \( \alpha \) of the s-polarized laser beam \( \text{LB} \) (\( \lambda = 633 \text{ nm} \)), the modes of even transverse orders \( m_y = 0, 2, 4, \) and 6 in the rib waveguide and the mode in the etched film (planar waveguide) \( \text{FE} \) are sequentially excited.
(b) Incoupled power measured by detector \( D_1 \) versus \( \alpha \) (schematically). TE-polarization.

Width \( w = 8.5 \mu \text{m} \); step height \( \Delta d_p = 10.6 \text{ nm} \). \( D_1, D_2 \), detectors.

The effective refractive indices \( N \) are determined from the coupling angles \( \alpha \) with the in/outcoupling condition \( N = n_{\text{air}} \sin \alpha + \ell \Delta n/\lambda \), where \( \ell = 1 \) is the diffraction order. The effective indices \( N \) of the modes in the rib waveguide satisfy the relation \( N_{\text{FE}} < N < N_{\text{F}} \), where \( N_{\text{FE}} \) and \( N_{\text{F}} \), respectively, are the effective indices of the modes in the planar waveguides \( \text{FE} \) and \( \text{F} \), i.e., in extended etched and non-etched film areas. From the \( N \)-values of the modes of different transverse orders \( m_y \), the width \( w \) of the rib waveguide was determined - in good agreement with direct microscopic measurements.

Examples of multimode rib waveguides are given in Figs. 2 and 3. We also fabricated monomode rib waveguides in which only the mode of transverse order \( m_y = 0 \) (for both polarizations \( \text{TE} \) and \( \text{TM} \)) can propagate, by reducing the width to \( w = 1.5 \mu \text{m} \) and the step height to \( \Delta d_p = 6.5 \text{ nm} \).

Electrostatically actuated IO nanomechanical devices: interferometric intensity modulators

Bridges made of \( \text{SiO}_2/\text{Si} \) are spanned over the (preferably monomode) rib waveguide; they function as electrostatically actuated effective-refractive-index-shifting elements \( \text{E} \), i.e., the variation of the air-gap width \( d(t) \) induces changes \( \Delta N(t) \) of the effective index \( N \) of a guided mode and thus of its phase \( \Delta \Phi(t) = 2\pi(n_x/\lambda)\Delta N(t) \) in the rib waveguide [1]. The configuration shown in Fig. 4(a) is primarily a phase modulator; in combination with a polarizer \( \text{P} \) and an analyzer \( \text{A} \) it becomes a difference (or polarimetric) interferometer [3,5], where two orthogonally polarized modes are excited; the output power is determined by their nanomechanically induced phase difference. In the Mach-Zehnder interferometer shown in Fig. 4(b) the bridge is spanned over both legs - but the air-gap width only over one rib waveguide is small enough (\( d < \lambda \)) to induce effective-
Refractive-index changes $\Delta N$. (Alternatively, with wider separations of the two rib waveguides, a bridge spanned only over one leg could be used.) Experimental results for interferometric intensity modulators are shown in Fig. 4(c). The input signal is the voltage $U(t) = U_0 + \Delta U(t)$ applied to the two electrodes. The output power is proportional to $\sin(\Delta \Phi(t) + \Delta \Phi_0)$, where $\Delta \Phi_0$ is a constant phase difference, which can be adjusted, for example, by varying the dc voltage $U_0$.

**Fig. 4. IO Electro-nanomechanical devices.** An electrostatically actuated 'effective-refractive-index-shifting element' $E$ in the form of a bridge made of $\text{SiO}_2$/Si is spanned over a rib waveguide. $L_x$, interaction length; $L_y$, span-width of bridge; $d(t)$, air-gap width; $U(t)$, time-dependent voltage.

(a) Phase modulator and (with polarizer $P$ and analyzer $A$ at 45°) difference- or polarimetric interferometer.

(b) Mach-Zehnder interferometer.

(c) Experimental result of intensity modulation with set-up (a): output power is I) in phase, III) 180° out of phase, and II) quadratic with respect to the sinusoidal input voltage at three different values $\Delta \Phi_0 = 0$, $\pi$, and $\pi/2$ of the constant phase difference. Modulation frequency $f = 10$ kHz; dc voltage $U_0 = 58$ V, ac voltage $\Delta U_{pp} = 1.8$ V. $L_x = 4.0$ mm, $L_y = 6.5$ mm.

**Conclusions**

We showed that (monomode) rib waveguides and Mach-Zehnder interferometers can be fabricated by wet etching of dipcoated (sol-gel-derived) $\text{SiO}_2$-$\text{TiO}_2$ films on oxidized silicon wafers as substrates. We demonstrated an electrically driven interferometric intensity modulator based on the IO nanomechanical effect.

**References**


EXPERIMENTAL AND THEORETICAL STUDY THE SWITCHING RESPONSE OF SEMICONDUCTOR OPTICAL AMPLIFIERS

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ABSTRACT

In this paper we present the results of an experimental and theoretical study of the switching response of TWSOAs. The model is based on a traveling wave description of the optical field in the active medium, which is imaginarily divided into longitudinal sections of constant carrier density. The dependence of switching times on the current bias and input power appears to be more subtle than was previously foreseen or analysed. A realistic analysis of the dynamic response requires a detailed study of the carrier density distribution. Experimental measurements confirm the simulation results.

I. Introduction

Semiconductor optical amplifiers (SOAs) find straightforward applications in optical switching for example in optical networks and broadband video transmission systems, since their intrinsic characteristics are very near the required features: low insertion loss < 5 dB, broad bandwidth ~10 THz, high switching rate > 1 GHz, ability to switch wavelength multiplexed optical signals, optical integration possibility, gain > 15 dB, extinction ratio > 15 dB, delay < 100 ps, rise time and fall time < 500 ps, instantaneous deviation frequency < 20 GHz.

The switching characteristics of semiconductor laser amplifiers (SLAs) have been the object of research for a number of years.[1] Consistent theory and dynamic models which explain the behavior of this devices have been developed. With the mastering of anti-reflection coating and the development of sophisticated technology, appears the traveling-wave semiconductor optical amplifier (TWSOA). Several groups have made use directly of SLA theory to explain the switching behavior of TWSOA.[2] It has generated a erroneous description of performances of these devices, since the theory did not account for a non-uniform carrier density distribution in the longitudinal direction.

II. Model Description

Recently, efforts[3] had been made to develop a correct representation of carrier density distribution within a TWSOA. However, essential parameters that intervene in the switching response are still incorrectly described, notably the differential gain and the differential index, which are considered constant causing a wrong description of phase modulation, spectral broadening, response time, gain, extinction ratio, etc. during Amplitude Modulation.

In this paper we present the results of an experimental and theoretical study[4] of the switching response of TWSOAs based on a traveling wave description of the optical field in the active medium, which is imaginarily divided into sections, each with a constant carrier density. The boundary conditions are established for the stimulated and spontaneous emissions in each section. On the amplifier's facets the residual reflectivities have been considered. In each section a rate carrier equation is established assuming a plane wave propagation. In order to consider a differential gain dependant of the carrier density, we have used the parabolic band approximation which assumes an absorption coefficient as a function of the Fermi levels. The differential index is found from the application of Kramers-Kronig formula.
III. Experiments
The SOA investigated here is a 0.35 μm thick and 0.5 μm broad bulk structure developed in Alcatel Alsthom Recherche, with an active medium length of 380 μm. The device is AR-coated on both facets giving a reflectivity of approximately 10^{-5} and the peak gain wavelength is around 1550 nm for 80 mA current bias.

In the experiment we used a 1 Gbit/s one-zero sequence as modulation signal. A 50 Ω matched line has been used for avoid electrical reflection between the SOA and the wideband amplifier placed after the sequences generator. A current source coupled through a "bias T" produces the offset necessary to obtain the off-level required.

The optical input and output signal are coupled by two lensed optical fibres. The AM is converted to an electrical signal in a wideband photodetector and a sampling oscilloscope digitalizes the signal. The PM is reassured via an optical interferometric technique[5]

IV. Results and discussion
Figure 1 illustrates the output power rise time when a current step is applied to the amplifier. The facet reflectivities are 10^{-5}.

When the input power is weak, the stimulated emission requires a delay to get started, since it is directly proportional to the photon density. Experimentally this delay is accompanied of jitter. On the other hand, when the input power is sufficiently high, the stimulated emission can start immediately, leading to a smaller rise time. For the same reason the OFF-state DC bias current affects the rise time as can be seen in Figure 1.

This delay is not observed in the phase response (will be presented in conference). This is due to the local inverse proportionality relation between the carrier density fluctuations and the refractive index fluctuations. Whereas efficient photon creation requires the setting up of the stimulated emission process, the carrier increase is a more regular process: the current injects carriers while the non radiative recombinations (Auger process) and later the radiative recombinations consume them. As the separation between the OFF and ON states is increased, the phase excursion increases, since the excursion in carrier density is larger.

Increasing the input power generates a reduction in the phase rise time, inasmuch as the gain is more rapidly saturated and so the final value of the carrier density is reached after a shorter time. The same explanation is valid for an increase of the OFF-level polarisation current. The gain saturation is due to carrier density reduction which reduces the phase excursion.

It is interesting to note that for a 1 mW input power together with 10 to 100 mA current step the start of the rise is slower than for a 1 μW input power together with 50 to 100 mA current step. This phenomenon is due to the weak carrier density that exists in the sections near the output of the amplifier when a 10 to 100 mA current step is applied. Then, when the input power is strong there is a big carrier consumption notably in the sections near the output, creating a considerable overall output.

Figure 2 illustrates the output power fall time of the amplifier output for two different input powers, two modulation level ranges and a 10^{-5} residual facet reflectivity at each extremity. On one hand the response of the amplifier for high and low input power are nearly the same for a current range going from 100 to 10 mA. On the other hand, the increase of the OFF-state level does not result necessarily in a faster response. Both phenomena can be explained by a careful study of the values and the decreasing behavior of the carrier density.

In the front end of the amplifier, stimulated emission has a weak effect since the power density is always rather small. The carrier density is only a function of the bias current. The Auger recombination dominates. In the case of a strong input (1 mW) the action of stimulated emission is quickly noticeable. It results in a reduction of the carrier density and consequently gain compression as one progresses within the amplifier (see figure 3). (A simple calculation shows that this amplifier is almost transparent at the back end). The Auger rate reduces while the stimulated emission increases. It is interesting to notice that both effects can compensate one another within the amplifier. This
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happens when the amplifier is switched down from 100 to 10 mA which explains why the rate of decrease is the same as the one obtained for a 1 μW input where the Auger is the only noticeable effect all along (see the carrier distribution in figure 4). This similarity between the rate of carrier decrease in the 1 μW and 1 mW cases is confirmed by the phase response (will be presented in conference). The falling behavior of the phase which is directly related to that of the carriers is very similar in both cases. When the amplifier is switched down to 50 mA only, the behavior for high and low input power is different (see figure 2). Even though at the beginning the Auger and the stimulated emission rate are equivalent, they decrease in a very different manner in time. The Auger rate decreases with N⁵ whereas the stimulated emission decrease with the product of N times the photon density. Since the amplifier is partially saturated for a 100 mA bias, the photon density is not very much reduced when the bias is reduced to only 50 mA. Thus the Auger rate decreases the fastest and therefore the response is slower in the case of a 1 μW. Again this is confirmed in the phase response (will be presented in conference), where one can notice the phase decrease more slowly for a 1 μW input.

It may look paradoxical that for a 1 μW input the fall time is smaller when the amplifier is switched down to 50 mA than when it is switched down to 10 mA. Actually, in terms of carrier consumption rate the first case is faster than the second. This apparent contradiction lies with the fact that the relation between carrier number and optical output power is not linear (it is exponential at first, then saturates) and that the rate of decrease of the carrier density slows down with time. A simple calculation shows that in order to get down to an optical power equal to 10% of the total power range, the normalised carrier density (defined in the same way as the normalised output power) must take a value smaller than the one corresponding to an off-state of 50 mA.

V. Conclusion

SOAs ON-OFF switching characteristics have been analysed under several input power levels. The switching time response depends on the bias and input power levels in a rather complicated way. It appears that the analysis of the dynamic response requires a detailed study of the carrier density distribution.

The measured switching behavior corresponds with good accuracy to our model prediction.

References

Fig. 1: Output power rise time.
Above: Numerical results.
Below: Experimental results

Fig. 2: Output power fall time.
Above: Numerical results.
Below: Experimental results

Fig. 3: Carrier density evolution during the fall time for a 1 mW input power

Fig. 4: Carrier density evolution during the fall time for a 1 μW input power
DEVELOPMENT OF AN INTEGRATED OPTICAL CURRENT SENSOR FOR LARGE AC CURRENT SENSING

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Abstract

We have developed a Faraday effect integrated optical current sensor for measurements of large AC currents. The optical waveguides of the sensor head have been optimized to reduce optical losses and intrinsic linear birefringence. Preliminary results show a good linearity of the sensor response over a wide range of currents.

Introduction

For more than 20 years, numerous research and development studies have been conducted to implement Faraday effect current sensors in power electric systems, measurements of large AC currents in medium and high voltage lines being one of the main motivations. These magneto-optical sensors have some definite advantages against classical current transformers. For example, they are less sensitive to electromagnetic interferences and free of saturation effects, they are electrically passive and they exhibit a high bandwidth, suitable for measurements of large transient currents.

Two types of Faraday effect sensors have been developed so far. Bulk current sensors are usually made of a glass that have a strong sensitivity to the Faraday effect and a low residual stress-birefringence. These sensors present good characteristics under environment conditions (temperature changes and vibrations) [1][2] but their cost is still very high partly because of the large size of the glass sensing head. Optical fiber current sensors offer more design versatility and are much cheaper but have not reached yet expected levels of accuracy. This is due to strong variations of linear birefringence in the fiber under external perturbations [3]. The use of integrated optics could offer an alternative solution to these sensors, taking advantages from both bulk sensors (low-stress glass substrate, high sensitivity to Faraday effect and low sensitivity to external perturbations) and optical fiber sensors (design versatility and low cost).

Already, one integrated optical current sensor has been proposed using birefringent waveguides and screening pads to get rid of birefringence quenching effects [4]. We present in this paper a new IO current sensor with a more classical detection principle. We will first describe the optical sensing principle and design, and then the way we optimized the optical waveguides. Finally, we will give preliminary experimental results.

Principle of operation

As for the previous optical current sensors, the IO sensor makes use of the Faraday effect. This effect is observed when a magnetic field is applied to a dielectric material in which a light beam propagates in the direction of the field. This results in a non reciprocal optical activity with a rotation of the plane of polarization proportional to the line integral of the magnetic field, H, along the optical path, L. The proportionality coefficient is a material parameter known as the Verdet constant, V. If the light path encircles N times a
conductor that carries a current, $I$, the Ampère's law applies and the net Faraday rotation, $\theta_F$, is given by:

$$\theta_F = V \int_L \vec{H}(t) \cdot d\vec{l} = VNI.$$

The rotation of polarization is detected using a polarimetric readout scheme (Fig. 1).

A linearly polarized wave, oriented at $90^\circ$ with respect to the glass surface, is launched in the waveguide by means of a polarizing single-mode fiber. The input waveguide separates into two waveguides that encircle the conductor once. The intensities coming out of the waveguides are sent to photodetectors using multimode fibers. The reference beam (left) is directly sent to photodetector 1. This channel is used to stabilize the laser diode output intensity $I_0$. The signal beam (right) is analyzed by a dichroic sheet polarizer oriented at $45^\circ$ with respect to the input beam orientation. This polarizer is inserted between the glass and the multimode fiber that carries the beam to photodetector 2.

Since the Verdet constant for silicate glass is small and since we use a single turn design, the net Faraday contribution is always much smaller than the accumulated intrinsic linear birefringence of the waveguides, $\delta \beta L$. Therefore, using Jones calculus, the expression of the light intensity received by photodetector 2 simplifies to [5]:

$$I_2 = \alpha_p \frac{I_0}{2} (1 + 2\theta_F \frac{\sin \delta \beta L}{\delta \beta L})$$

where the $\alpha_p$ term is a transmission coefficient that takes into account all the losses along the optical path. After filtering of the DC part, the Faraday signal, $S$, is then given by:

$$S = \alpha_p \frac{I_0}{2} 2\theta_F \frac{\sin \delta \beta L}{\delta \beta L} = \alpha_p I_0 V \sin c(\delta \beta L) I.$$

The signal is directly proportional to the Faraday rotation and thus the electrical current to be measured.
Optical waveguides for Faraday effect sensing

The sensor head is made of a specific glass developed for silver/sodium ion-exchange. The optical waveguiding structure is fabricated using a two-step ion-exchange process developed at GeeO [6]. During the first step, a surface channel waveguide is created by thermal diffusion of silver ions through an aluminum mask deposited on the glass surface. The exchange occurs between Ag⁺ ions present in a molten salt bath and Na⁺ ions present in the glass, leading to a local increase of the refractive index. During the second step (after removal of the mask), all the Ag⁺ are pulled below the surface by application of an electric field between the sides of the glass wafer.

In order to get large Faraday signals, opto-geometrical parameters of the buried waveguide were optimized to maximize the optical transmission $\alpha_p$ and to minimize the intrinsic linear birefringence $\delta\beta$. This led to the following set of parameters (numerical values estimated using diffusion simulation programs):

- maximum index increase: $\Delta n = 2.10^{-3}$,
- burying depth: $p = 7\ \mu m$,
- average size of the waveguide: $p = 3.4\ \mu m$,
- index ellipticity ($e_i = \pi y / \pi x$): $e_i > 85\%$.

With these parameters, we have achieved propagation and input coupling losses as low as -0.15 dB/cm and -0.5 dB, and critical bending radii lower than 10 mm. No bending loss occurs during light propagation around the conductor. The close-to-circular shape and the large burying depth of the waveguide (Fig. 2) contributes to the reduction of the intrinsic linear birefringence.

![Glass surface](x, y)

**Fig. 2**: Near field pattern of an optical waveguide optimized for Faraday effect sensing.

**Experimental results**

The tests were conducted with a 0-1000A/50Hz electrical current generator. The current is measured with both a conventional current transformer (CT) and the IO current sensor. The small-signal output voltages of each sensor are sent to a digital oscilloscope for instantaneous measurements and to a multimeter for RMS measurements.
The instantaneous waveforms are compared in Fig. 3.a. The IO current sensor response is slightly noisy. We think this is due to mechanical vibrations of the input coupling since the sensing head has not been packaged yet.

In Fig. 3.b, we show that the IO sensor response is linear over a wide range of currents. This is in good agreement with our theoretical calculations - Faraday rotation is always much smaller than the accumulated linear birefringence. From 50A to 800A, the relative error between the two signals remains within ±2%, which is quite promising for a fully packaged sensor.

### Conclusion

We have presented an integrated optical current sensor. The optical waveguides, fabricated by a two-step ion-exchange, were optimized for Faraday effect sensing. The geometrical intrinsic linear birefringence has been lowered by burying deeply the waveguides and making them as circular as possible. Our first results can still be improved by a further lowering of the birefringence and the use of more turns. After packaging of the sensor head, environment tests (temperature and vibrations) will be the next step of our work. Unlike fiber optical current sensors, signal variations are expected to be small because of the low temperature sensitivity of the intrinsic birefringence of ion-exchanged waveguides, as it has already been shown [4,7].

### References


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INTEGRATED-OPTICAL BLUE LIGHT DISPLACEMENT SENSOR IN KTiOPO₄

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Abstract An integrated-optical Michelson-interferometer for the short visible wavelength region is demonstrated for application as optical displacement and position sensor. The integration of electrooptical phase-modulators allows the detection of the direction of movement and high resolution displacement detection for measuring distances in excess of 7 cm.

1. Introduction Interferometric methods for the measurement of optical path-lengths are high-sensitive and allow high-precision measurements over a wide measuring range with high linearity. Physical effects, which change the refractive index as well as direct changes of the measuring path can be detected. An integrated-optical Michelson-interferometer can be used to realize such a displacement sensor. Short wavelengths allow a higher resolution in comparison to the commonly used red or infrared light. An electro-optic phase modulator offers the possibility for the detection of movement direction and to make use of the more precise homo-dyne and heterodyne methods, respectively [1,2].

Because of its high linear electrooptic coefficients potassium titanyl phosphate (KTiOPO₄, KTP) is a promised substrate material for integrated-optical applications [3,4]. Fabrication processes using the ion exchange technology [5-8] were developed leading to low-loss optical waveguides with a high photorefractive threshold [3,5]. Contrary to the relatively isotropic diffusion in the case of proton exchange in the commonly used dielectric material LiNbO₃, for instance, the diffusion constant for the Rb+K ion exchange process in KTP is several orders of magnitude higher in the z-direction than in the x-y plane [6]. Devices requiring well-defined channels or barriers will be possible, such as channel waveguide modulators and singlemode interference devices in z-cut KTP at short visible wavelengths.

Here we describe the fabrication and optical characterization of an integrated-optical Michelson-interferometer for short visible wavelengths. Successful demonstration of electrooptic phase modulation will be shown.

2. Sample preparation The integrated-optical structure was fabricated in z-cut KTP substrate material (delivered by Crystal Technology, xyz dimensions: (5×25×1) mm³) in the y-propagating direction.

We performed a rubidium↔potassium ion exchange in a mixed melt of [65 mol% RbNO³/32 mol% KNO³/3 mol% Ba(NO₃)₂]. These mixed melts are the only possibility to obtain the small refractive index changes at the surface [7] necessary for singlemode operation at short visible wavelengths without a subsequent annealing procedure and reproducibility at the same time. The mixed melt also permitted us to carry out the ion exchange at the relatively low temperature 310 °C and, therefore, with relatively long exchange times from 0.3 up to 3 hours.

We defined the channel waveguides by using sputtered chromium/nickel or aluminium masks. The channel widths varied between 2.0 and 5.5 µm corresponding to the expected singlemode region from the blue up to the red. After exchange the samples were endface-polished. For the electrooptic phase modulation a 200 nm thick SiO₂ buffer layer and coplanar 200 nm thick gold electrodes were fabricated.
Figure 1 shows the schematic structure of the integrated-optical Michelson-interferometer-chip consisting of two Y-branches with an angle of 1°, S-bends and a separation distance of 300 µm for the waveguide geometry. The channel waveguide attenuation was approximately 2 dB/cm and the additional attenuation due to the interferometer geometry was about 4 dB, where 3 dB of it result from the asymmetric excitation of Y-branch 2. No polarization conversion occurred.

For the purpose of electrooptic phase modulation two pairs of electrodes with a length of L/2=5 mm and an electrode gap of g=6 µm were placed at both arms. To get a maximum overlap between the optical mode field and the applied electric field the waveguide had to be placed beneath one electrode because we had to use the linear electrooptic coefficient r_{33} for TM-light and r_{31} for TE-light, respectively [9]. The overlap integral was calculated with the Finite Element Method to \( \Gamma = 0.24 \). Assuming TM-polarization and nearly the same electrooptically induced index change for both the refractive index n_2 for TM-polarization and the effective channel waveguide index we obtain the switching voltage for a phase shift of \( \pi \) as

\[
V_s = \frac{\lambda g}{r_{33}n_2^2 L \Gamma}
\]  

with \( r_{33} = 36.3 \text{ pm/V} \) the linear electrooptic coefficient and \( \lambda \) the wavelength. For example we obtain \( V_s = 4.8 \text{ V} \) at \( \lambda = 488.0 \text{ nm} \). TE-polarization requires \( r_{31} = 9.5 \text{ pm/V} \) and \( n_2 \).

4. Experimental set-up Figure 2 shows the set-up for the measurement of the behavior of the interferometer due to displacements. A laserbeam which was focused by a lens was coupled into the interferometer by a microscope objective. This primary light is splitted up into a measurement beam and a reference beam with nearly equal amplitudes by the Y-branch 1. The outcoupled two beams were collimated by a second microscope objective and reflected back into the interferometer by two mirrors. A piezoelement, which could be modulated by an external voltage, moved one mirror in the direction of the outcoupled beam. Both beams interfere in Y-branch 1. Changes of the phase relation will cause an amplitude modulation of the detection signal, which is separated by Y-branch 2. The optical power of the focused outcoupled detection signal was measured by a photodiode. The distance between the outcoupling objective and the mirror was approximately 30 cm.
The electrooptic behavior was determined by a special interferometric set-up which is shown in Fig. 3. The two output beams were brought to an interference by a half wedged glass plate in the plane near the magnifying objective in front of the CCD-device. A special PC-program detected the phase shift due to the applied voltage across the electrodes.

5. Experimental results A displacement of the mirror of the half wavelength produces an intensity modulation of $2\pi$ of the output signal. That means, the shorter the wavelength the higher is the accuracy of measurement. We modulated the piezoelement periodically with a delta voltage as to be seen in the printout of a digital oscilloscope at $\lambda=488.0$ nm (Fig. 4).

The lower curve represents the periodical displacement over a range of a half wavelength while the upper curve shows the output power response of the modulator due to the displacement modulation. We see the typical shape of the power response if the operation point is adjusted to the slope of the sinusoidal modulator characteristic. The measured modulation depth of the output power is about 13 dB, the bandwidth is about 7 cm. Further we measured the function of the very same interferometer from the blue ($\lambda=476.5$ nm) up to red light ($\lambda=676.4$ nm). The difference between the ratios of the different wavelengths and the equivalent displacements was lower than 2%. The displacement resolution is about 120 nm by counting the extrema of modulation and lower than 10 nm by interpolation with the modulator characteristic.

For the determination of the electrooptic modulation we measured the half-wave voltage $V_x$ at the frequency of 100 Hz. If a square wave voltage is applied across the electrodes and the integration time of the CCD-device is high against the period of the voltage the interference pattern disappears if an odd multiple of $V_x$ is applied. The phase shifts electrooptically induced in the very same interferometer are shown in Fig. 5 for various wavelengths and TM polarization. At $\lambda=488.0$ nm the measured switching voltage is about 4.9 V in good accordance with the theoretical value above calculated. The $V_x$-voltage decreases with decreasing wavelength as it was to be expected from equation (1). For $\lambda=488.0$ nm and TE light we measured $V_x=18$ V.

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**Fig. 3** Interferometric setup for the determination of the electrooptical behavior.

**Fig. 4** Output signal and mirror displacement at $\lambda=488.0$ nm.
- upper curve: output signal
- lower curve: displacement

**Fig. 5** Dynamically measured phase shift versus switching voltage
The possibility of electrooptic modulation is the premise for the application of homodyne or heterodyne methods. With these principles high-precision measurements with resolutions about 1 nm should be possible. The chip can also be used for anemometer applications similar as shown in Fig. 3.

6. Conclusions We have successfully demonstrated the fabrication of an integrated-optical Michelson-interferometer for the short visible wavelength region by using the Rb→K ion exchange process. We demonstrated the properties of the interferometer as a distance sensor as well as the electrooptic effect. It is possible to use the advantages of KTP to fabricate single-mode channel waveguides for blue light to increase the resolution of interferometric devices. The function of the sensor chip as an anemometer was also demonstrated. Together with the low light-induced refractive index changes in KTP very compact and optical stable devices can be fabricated for applications to determine optical path length differences in the short visible wavelength region. Displacements as well as physical quantities that influence on the refractive index like pressure or composition of gases can be measured.

References

MMP ANALYSIS OF VERY SHORT DOUBLY PERTURBED WAVEGUIDE STRUCTURES

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Abstract

A rigorous analysis of very short doubly perturbed waveguide structures (DPS) will be presented. Using the semi-analytical MMP method for computational electromagnetics all unique properties of such a DPS including the evanescent field coupling within the structure and its influence on the far field have been investigated with great accuracy.

1. The MMP Approach

The multiple multipole (MMP) method [1] is a well-established tool for solving time-harmonic 2D and 3D scattering problems within piecewise linear, homogeneous and isotropic domains. It is based on the generalized multipole technique (GMT) [2]. With MMP the field $f_i$ within individual domains $i$ is approximated by a sum of $N$ cylindrical or spherical multipole expansion functions $f_{ij}$ which are themselves analytical solutions of the Helmholtz equation,

$$f_i = f_0 + \sum_{j=1}^{N} A_{ij} \cdot f_{ij} + \text{Error}$$  \hspace{1cm} (1)

where $f_0$ stands for the excitation. The origins for multipole expansions are usually set along the boundary of the domains in which the field is to be calculated. For the field around voluminous domains Hankel-type expansions are used whilst Bessel-type expansions are preferred inside. Other special functions are included as well, e.g. propagating and evanescent plane waves, etc. The coefficients $A_{ij}$ are obtained by enforcing the boundary conditions for the field components at discrete matching points on the boundary. Since more matching points are introduced than necessary, the MMP method leads to an over-determined system of equations. This system is solved in the least-square sense which is numerically equivalent to an error minimization technique.

2. Doubly perturbed waveguide structures (DPS)

The study of the propagation and scattering of waves in a dielectric waveguide structure sandwiched between two corrugated interfaces of the same period $\Lambda$ (Fig.1) offers a variety of new and unconventional applications in the field of integrated optics. In particular Avrutsky et al. [3],[4]
have demonstrated that for a certain ratio of the amplitudes and phases of the perturbations, highly efficient unidirectional radiation coupling occurs. Using such a DPS as the basis of a grating coupler design [5], it was possible to achieve a unidirectional coupling efficiency of 90 %. In the case of a second order Bragg resonance there are two main physical mechanisms which control the power radiating away from the DPS. First, the interference of the coherently coupled backwards propagating partial waves coming from each grating shape inevitably leads to different power reflections and to a different penetration depth along the DPS. This results in an variation of the total radiated power. Second, the interference between the outgoing first order diffraction beams coming from each grating surface results in a considerable variation of radiation loss. As a result, the input reflection coefficient and the radiation loss are therefore strong functions of the grating offset δ.

3. Numerical simulation of short DPS

Recently, the MMP method has been applied for the computation of infinite periodic structures. A technique based on Floquet-mode expansions was presented in [6] but suffers from convergence problems leading to a very inefficient computation. The most promising attempt was then made with the introduction of unit cells in the sense of periodic boundary conditions [7],[8]. In the case of short periodic structures none of the referenced symmetry decompositions are applicable. The problem has to be solved by extensive computation. The short DPS studied in this work consists of a perturbed Teflon slab (εr2 = 2.1) having a symmetrical triangular grating at each interface with the same period Λ and the same grating depth g (Fig. 1). The surrounding medium is air. On its left and right side there are unperturbed slab sections, carrying the incident, reflected and the transmitted mode fields. Each slab waveguide mode in the unperturbed section is constructed as a superposition of two propagating plane waves for the core domain and of two evanescent plane waves describing the field decay in the outer region. The propagation constant of the fundamental mode was chosen carefully to produce a second order Bragg resonance in DPS. The field within the grating region and the radiation field is completely approximated by multipole expansions of the Hankel-type. Their origins are set on both sides along the DPS boundaries.

As a first example, we have analysed a DPS with a length of 12 Λ and a grating depth of g = Λ/2. For this model the 6 field components of 261 multipole expansions have to be matched at 2226 matching points. This results in a strong over-determined equation system for the 1613 unknown parameters which is solvable in about 3 hours on a Sun SPARC+10 workstation. The average matching error was less than 0.4% compared to the excitation field. We have allowed the two
Fig. 2: Intensity plot of the time-averaged poynting field for TE-excitation from the left side.

Fig. 3: Reflectance and relative total radiated power as a function of the grating offset.

The calculation of the time-averaged poynting field is shown in Fig. 2 for TE-excitation (TE0-mode) and for two different grating offsets $\delta/\Lambda = 0.5$ and $\delta/\Lambda = 0.25$. For the latter case the unique unidirectional radiation behaviour can be clearly observed. Despite the fact that the input reflection of the DPS has its maximum at $\delta/\Lambda = 0.5$, the total relative power radiation also peaks at this location (Fig. 3). This is characteristic only for very short gratings where power radiation is governed mainly by the radiation coupling efficiency. The existence of a small amount of TE1-power contributes to a slight interference which is visible in Fig. 2 as well as in Fig. 3. In the second example we have reduced the length of the DPS to 4 $\Lambda$ while varying the grating depth. Here the grating offset was chosen to be $\delta/\Lambda = 0$. According to Fig. 3 this should lead to minimal up- and downward power radiation. As shown in Fig. 4 the poynting vector fields were calculated for two different grating depths ($g = \Lambda/2$ and $g = \Lambda$). Here the average matching error was less than 0.6%. Despite of the very short DPS, two slim outpropagating radiation beams can be identified in Fig. 4a. In Fig. 4b the situation has dramatically changed. Because of the resulting small separation between the two gratings, the evanescent fields diffracted from one grating does now interact with the other grating producing many unexpected higher-order beams which seem to be relatively insensitive to frequency changes. This unique behaviour was also measured by Gupta et al. [9].

4. Conclusion
The ability of the semi-analytical MMP code has been demonstrated by analysing very short DPS. The characteristic properties of the DPS such as unidirectional power radiation and the appearance
We have investigated unexpected higher-order radiation beams due to evanescent field coupling within the two gratings. Furthermore, the possibility of a proper error calculation permits a quantitative judgement of these results. To our knowledge such rigorous fully vectorial field computations on a DPS have not yet been reported. Since the electromagnetic field is calculated analytically by its multipole expansions, we are able to analyse every part of our problem at any time later on. Therefore far field calculations of the DPS may be performed as well as an analysis of its field within the structure. We demonstrated the flexibility of the MMP method as an attractive tool for integrated optics.

5. References


DESIGN OF ACHROMATIC LENSES FOR INTEGRATED OPTICS

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ABSTRACT

A novel design of a refractive-diffactive lens is presented. The suggested structure is corrected from third-order as well as from chromatic aberrations, within a field of view of a few degrees. The algorithm of BPM has been successfully used in order to simulate lens' operation and thus to achieve the optimization of the lens design.

1. INTRODUCTION

Since the very beginning of Integrated Optics the importance of high performance waveguide lenses has been well understood. A really attractive answer to this demand has been the geodesic lens, which joins flexibility of use to perfect aberration correction. The big drawback of geodesic lenses lies, unfortunately, in technology, since only expensive and complex techniques such as diamond-tooling make their fabrication sufficiently accurate. In view of today's technology only two types of waveguide lenses are truly suitable: the homogeneous mode-index and the diffractive ones. In both cases the fabrication methodology is fully planar and takes advantage of microlithographical techniques.

In a previous work we examined the problem of optimizing the design of a Fresnel lens with respect to spherical aberration and coma. The lens' behavior was analyzed by means of a numerical simulation based on the Beam Propagation Method (BPM). The basic point of our modelling was in the expression of the curve describing the lens' front diopter, which depended on a single shape parameter. The problem of optimization was found to be solved by a proper and univocal choice of this parameter.

In some applications, however, a serious limitation of Fresnel waveguide lenses is the strong dependence of focal distance on the operating wavelength, which may turn into a severe degradation of lens' performance. Achromatic lenses would then be quite useful, especially if they would allow not only to use relatively unstable (and low cost) laser diode sources, but even broadband and multiplexed ones.

It is well known that chromatic aberration can be corrected by cascading two optical components with opposite chromatic behavior. Spaulding and Morris have already demonstrated that a hybrid structure, made up by joining a mode-index and a diffusive lens, would achieve this goal; their hybrid lens, however, was optimized only for strictly paraxial operation. Since in some devices, especially for signal processing applications, a focusing lens is required to operate for incidence angles up to a few degrees, we have developed a design that combines both off-axis and chromatic corrections.

2. DESIGN OF AN ACHROMATIC HYBRID LENS

It is well known that a refracting boundary in integrated optics is constituted by the interface between two waveguide zones having different modal effective indices. An integrated optical lens intrinsically divides the propagation plane into an inner and an outer region, and the ideal border line constitutes the equivalent of a conventional diopter. The design of a chromatically-corrected lens starts from the analysis of the most general hybrid refractive-diffractive structure, as sketched in Fig. 1. We define the lens' front diopter $z_f(x)$ by the following expression:

$$z_f(x) = \left( \frac{1 + 1/\beta}{2} \right) f \left[ 1 - \sqrt{1 - \beta x^2/f^2} \right].$$

(1)
where $f$ is the design focal length and $\beta$ the conic parameter of the curve. Furthermore, we indicate as $z_2(x)$ the curve describing the lens' rear diopter and as $z_1(x)$ the support curve for the diffractive structure. One can now write $z_2(x) = g(x) + t_0$, and consider for the function $g(x)$ a dependence on a conic parameter $\beta_g$ similar to that of $z_1(x)$:

$$g(x) = \left(\frac{1 + 1/\beta_g}{2}\right) f_0 \left(1 - \sqrt{1 - \beta_g x^2/f_0^2}\right).$$

where $f_0 = f - t_0$. By imposing the identity (within integer multiples of $2\pi$) of optical paths for rays reaching the focus and taking into account the relationship between the entrance ordinate $x$ of a ray entering the lens and its exit ordinate $x'$, one finds the following expression for the $m$-th pad of the diffractive exit diopter:

$$z_{2_m}(x') = z_1(x) + \frac{f_1(x)}{J' + 1} - t_0 \frac{J' J - 1}{J'^2 - 1} + \frac{J'}{J'^2 - 1} m \lambda_0/n - \sqrt{\frac{x'^2}{J'^2 - 1} + \left[\frac{f_1(x)}{J' + 1} + t_0 \frac{J' - J}{J'^2 - 1} - \frac{m \lambda_0/n}{J'^2 - 1}\right]^2}, \quad m \geq 1;$$

where $J = (n + \delta n)/n$, $n + \delta n$ being the effective refractive index of the fundamental mode inside the lens region and $n$ that of the guided mode in the surrounding waveguide. $J'$ is defined as $J/\cos[\varphi(x)]$, where $\varphi(x)$ is the angle between the refracted ray and the optical axis, and $f_1(x) = f - z_1(x) - t_0$. Finally, $\lambda_0$ represents the design vacuum wavelength and $m$ a positive integer. By construction, the hybrid structure described by Eq. (3) is corrected from axial spherical aberration but, for an arbitrary choice of $\beta$, $\beta_g$ and $t_0$, not necessarily from off-axis and chromatic ones. In order to evaluate the chromatic behavior of the focal length, we fix the lens' geometrical characteristics and then invert Eq. (3). At the first order of approximation the focal length will not change if its derivative vanishes at the design wavelength $\lambda_0$. After some algebra one finds:

$$z_1(x_m) - z_1(x'_m) = \cos \varphi \left(-t_0 + \frac{m \lambda_0}{\delta n} \left(\frac{1}{\lambda_0} - \frac{dn/d\lambda}{n} - \frac{d(\delta n)/\delta n}{\delta n}\right)\right).$$

Here, the subscript $m$ indicates that all geometrical quantities are calculated at the border of the $m$-th pad. This condition corresponds to an implicit relationship between $\beta_g$, $\beta$ and $t_0$. Any hybrid structure satisfying Eq. (4) results automatically free from chromatic aberration. By putting (for example) $m = 1$ and by imposing a further limitation on geometry, $\beta_g$ can be made to depend univocally on the $\beta$ parameter of the input diopter. For instance, one can require that the front diopter and the curve supporting the diffractive structure intersect each other at lens' edge. The reduction to a single degree of freedom (the shape of the input diopter) allows us a straightforward analysis of lens' performance with the aim of its full optimization. Thus, we carried out an extensive analysis of a particular focusing hybrid structure by means of a BPM algorithm, developed on purpose.

3. BPM MODELLING OF THE HYBRID LENS

In order to introduce realistic chromatic dispersion values into the BPM simulation, we measured the TE$_0$ effective indices of a single-mode low-index waveguide (n$_{LIW}$) and of a multi-mode high-index waveguide (n$_{HIW}$), both produced in glass, as a function of wavelength. The waveguides were fabricated by ion exchange in soda-lime glass, the former by Na$^+$/K$^+$ and the latter by Na$^+$/Ag$^+$ ion-exchange. A tunable cw Ti-sapphire laser was used to measure the effective indices in the range 720 to 850 nm. A
quadratic best-fit of data gave a very good estimate of the values of $n$ (corresponding to $n_{LIW}$) and $n + \delta n$ (corresponding to $n_{HIW}$) to be used in the BPM calculations for any desired wavelength in the near infrared range.

The hybrid lens was designed to operate at 0.83 $\mu$m vacuum wavelength, with aperture $D = 1$ mm and focal length $f = 4.6$ mm. At the operational wavelength the effective indices outside and inside the lens were $n = 1.508$ and $n + \delta n = 1.553$, respectively. The optimum condition for lens' performance was derived from the analysis of the focal intensity distribution. In particular we compared the focal spot size and peak-to-sidelobe ratio (hereafter referred to as SNR) for different incidence angles and for different values of the conic parameter $\beta$.

Looking at off-axis aberrations, the best solution is considered to be achieved when all of the following conditions are verified: 1) the focal spot size is minimum; 2) the first side-lobes of the focal diffraction pattern are as low as possible; 3) the heights of the left-hand and of the right-hand side-lobes are as equal as possible. Satisfying the preceding conditions corresponds to minimizing both spherical and coma aberrations. In order to evaluate lens' off-axis performance as a function of the shape of its front dioptr, a rough scan has been first of all carried out on a wide range of $\beta$ values, for $0^\circ$, $1^\circ$, $2^\circ$ and $3^\circ$ off-axis incidence of a truncated gaussian beam. Optimization has then been refined in order to fulfill the above given rules. Figure 2 shows the SNR dependence on $\beta$ for the various incidence angles: one can observe that maximum SNR is reached at slightly different $\beta$ values for the different incidence angles, so that best off-axis performance occurs in the range $31.2 \leq \beta \leq 31.5$. The corresponding front dioptr is a prolate ellipsis, with eccentricity near to 0.94. The choice of $\beta = 31.3$ as a compromise solution proves to be a good one if one considers that for any incidence angle below $3^\circ$ the SNR remains greater than $21$ dB (the axial SNR for a perfectly corrected Fresnel with the same optical characteristics is $21.6$ dB). In this case, our 1 mm-aperture lens has a maximum thickness of 0.77 mm, while the conic parameter $\beta$, results equal to -18.5 (corresponding to a hyperbola).

As to chromatic behavior, Figure 3 summarizes the axial focal distance dependence on wavelength for three different types of waveguide lenses (purely refractive, purely diffractive and hybrid with $\beta = 31.3$). The comparison between theoretical behavior (dashed lines) and BPM results (symbols) is also shown. The superior performance of the optimum hybrid structure with respect to the diffractive one is clearly indicated in Figure 4, where the corresponding axial Strehl ratios as a function of wavelength, defined as HL $0^\circ$ and FL $0^\circ$, respectively, are compared; the hybrid lens' Strehl ratio for $3^\circ$ off-axis incidence is also shown (HL $3^\circ$). In the range $0.74$ $\mu$m $\leq \lambda \leq 0.94$ $\mu$m the hybrid lens' Strehl ratio is always greater than $80\%$, while for the Fresnel lens it falls down $15\%$.

As a further example, a comparison between the spot sizes in the two cases, shown in Fig. 5, makes even more evident the fact that the hybrid lens is an almost perfect achromatic optical system. It is clearly shown how critically the spot size given by a purely diffractive lens depends on the wavelength, while that of the hybrid structure is almost constant in the considered range (except for the obvious linear increase with wavelength).

4. CONCLUSIONS

A new design of a hybrid refractive-diffractive lens structure has been presented. By using a simulation algorithm based on the Beam Propagation Method, we have shown that this hybrid lens is corrected both from third-order aberrations and from chromatic aberration, for off-axis incidence angles up to 3 degrees. Such corrected field of view is suitable for most of the signal-processing integrated optical devices.

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Fig. 1: Geometry for the definition of the hybrid lens

Fig. 2: SNR in the focal point as a function of the conic parameter $\beta$, for different incidence angles

Fig. 3: Focal length as a function of wavelength (on axis incidence)

Fig. 4: Comparison between the Strehl ratios of the hybrid lens (HL) and the Fresnel lens with the same optical characteristics

Fig. 5: Comparison between the spot sizes of the hybrid lens (HL) and the Fresnel lens (FL). Values are calculated at the design focal distance

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REVERSE EXCHANGE IN THE ANNEALED PROTON EXCHANGED
LiNbO₃ STRUCTURES FOR BURIED WAVEGUIDES

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ABSTRACT

We describe the fabrication and properties of optical waveguides formed in annealed proton exchanged (APE) LiNbO₃ by reverse proton exchange Li⁺ → H⁺ in the LiNO₃-KNO₃-NaNO₃ and LiNO₃ melts at 300°C. Surface waveguides, supporting modes of ordinary polarization, as well as the buried waveguides for extraordinary polarization modes were produced. The relationship between extraordinary and ordinary index changes in APE LiNbO₃ waveguides was obtained.

INTRODUCTION

Proton exchanged lithium niobate waveguides fabricated by simple proton exchange (PE), as well as similar PE followed by annealing (APE waveguides) reported to have low optical losses, negligible decrease in the electro-optical coefficients, and high power handling capability.

Since the depth index profile for the conventional PE LiNbO₃ waveguides is asymmetric, the waveguide depth mode is also quite asymmetric. On the other hand, single-mode fibers have circular symmetric mode profiles. Thus, depth index profile symmetrizing is essential to reduce the fiber to waveguide coupling loss.

Earlier we reported about possibility of formation buried waveguides in LiNbO₃ by reverse proton exchange (RPE) in LiNO₃ melt. Results were achieved by Jackel and Johnson and Olivares et al used the LiNO₃ - NaNO₃ - KNO₃ melt. Recently we have extended the process to produce buried waveguides in LiTaO₃. However, all published results have been obtained only for PE LiNbO₃ waveguides with step-like index profiles. But for integrated optic applications the using of APE LiNbO₃ waveguides is more preferable. APE LiNbO₃ waveguides exhibit lower propagation losses than PE waveguides and the restoration of the electro-optic effect, and the nonlinear coefficients.

In this paper we report the fabrication and characterization of surface optical waveguides for ordinary polarization modes and buried guides, supporting the extraordinary polarization modes using a reverse exchange process in annealed proton exchanged LiNbO₃ waveguides.

PREPARATION OF PE SAMPLES AND THEIR INVESTIGATIONS

PE waveguides were fabricated in optical grade virgin LiNbO₃ substrates of X- and Z-cuts. As the sources of PE we used the solution of KHSO₄ in glycerin, pyrophosphoric acid and ammonium dihydrophosphate (NH₄H₂PO₄) and eutectic mixture of sulphate salts ZnSO₄, K₂SO₄ and Na₂SO₄ with a small amount of KHSO₄ added. RPE process was carried in LiNO₃ (37.5 mol.%) - KNO₃ (44.5 mol.%) - NaNO₃ (18.0 mol.%) melt (melting point of this eutectic mixture is 120°C) and pure LiNO₃ melt. The melts were heated in quartz crucibles to the set processing temperature T=300°C.
We measured the mode effective indices of the planar waveguides using a standard one-prism coupling setup at a wavelength of \( \lambda = 633 \text{ nm} \). The refractive indices profiles (RIP's) in the waveguides were reconstructed by the IWK method.

**RESULTS AND THEIR DISCUSSION**

SIMS analysis shows the absence of hydrogen at the surface of RPE structures. This indicates that practically pure LiNbO\(_3\) is formed at its surface. The surface ordinary refractive index \( n_o \) in RPE waveguides is close to that bulk lithium niobate value. This also points the formation of pure LiNbO\(_3\) at the RPE surface. Therefore, refractive index profiles in RPE waveguides were computed using constant value of \( n_o = 2.2960 \).

The deep PE layers were first obtained with a long treatment at high temperature. After that the samples were annealed at \( T = 320 \) to 400°C up to achieve the value \( \Delta n_e = 0.070 \), corresponding to an upper boundary of single crystal \( \alpha - H_xLi_{1-x}NbO_3 \) phase. Formed APE waveguides were immersed in the LiNO\(_3\)-KNO\(_3\)-NaN\(_2\)O\(_3\) or LiNO\(_3\) melt on 10 to 170 h.

Fig.1 shows the ordinary index profile in the reverse exchanged annealed proton exchanged (REAPE) waveguide. The extraordinary profile in satellite sample is represented also. Therefore, we can imagine the extraordinary profiles in REAPE sample (see fig 1).

![Graph](image.png)

**Fig.1.** Ordinary (1) and extraordinary (2) refractive index profiles in REAPE waveguide formed on Z-cut LiNbO\(_3\) under following conditions: PE in melt of NH\(_4\)H\(_2\)PO\(_4\) , \( T = 220°C \), \( t = 10 \) hours ; Annealing: \( T = 340°C \), \( t = 115 \) h; RPE: \( T = 300°C \), \( t = 100 \) h. Dashed line shows the extraordinary index profile in satellite PE LiNbO\(_3\) sample prepared under similar conditions and have been only annealed at the temperature of RPE (300°C) during 100 h.

We have performed a lot of similar experiments with PE LiNbO\(_3\) waveguides formed on X- and Z cuts. Fig.2 shows the dependence of ordinary index change for last ordinary polarization mode of surface REAPE waveguide on extraordinary index change at the same depth in satellite sample. So as both profiles are graded it would be not a large mistake to conclude that fig.2 shows a general
relationship between $\Delta n_e$ and $\Delta n_o$ for $\alpha$-phase $H_x \text{Li}_{1-x} \text{NbO}_3$ solid solution. One can see that this relationship differs substantially on that for $\rho$-phase $H_x \text{Li}_{1-x} \text{NbO}_3$ ($\Delta n_e=0.007 - 0.4\cdot \Delta n_e$).

Fig. 2. Relationship between extraordinary and ordinary index changes (comparatively to $\text{LiNbO}_3$) for well annealed PE $\text{LiNbO}_3$ waveguides. Open, semiopen and closed symbols correspond to APE waveguides annealed at $T_a=330, 355$ and 400°C, correspondingly.

One can see the discontinuity near $\Delta n_e=0.025$ for annealed at 330°C APE waveguides indicating on present of new $\alpha_0$ phase at $\Delta n_e$ smaller than 0.025. Such discontinuity was not observed for APE waveguides annealed at 400°C. This fact can explain why PE $\text{LiNbO}_3$ waveguides with all values of $\Delta n_e$ in the interval $0.01$ to $0.15$ can be produced by direct PE in $\text{ZnSO}_4$-$\text{K}_2\text{SO}_4$-$\text{Na}_2\text{SO}_4$-$\text{KHSO}_4$ melt at the temperatures above 400°C[H], whereas direct exchange in benzoic acid melts diluted with lithium benzoate at the temperatures 200 to 350°C allows to fabricate only the waveguides with $\Delta n_e<0.025$ or $\Delta n_e>0.08$[2]. The plot $\Delta n_e$ on $\Delta n_o$ for APE waveguides annealed at intermediate temperature 355°C shows a discontinuity around $\Delta n_e=0.04$.

The straight REAPE waveguides were also formed and characterized. The 8 $\mu$m wide channel PE $\text{LiNbO}_3$ waveguide was fabricated using respectively lithography on a Ti mask and the APE technique with 12 h exchange at 215°C in the solution of KHSO$_4$ in glycerin with concentration 1 g/l followed by 67 h of annealing at 320°C. The straight REAPE waveguide was fabricated by treatment of PE guide in $\text{LiNO}_3$-$\text{KNO}_3$-$\text{NaNO}_3$ melt at 300°C during 47 hours.

Fig. 3 shows the Near Field measurements of mode profile at the 1.55 $\mu$m wavelength for formed REAPE waveguide. One can see that mode profile is very close to circular that will leads to reduce the fiber to waveguide coupling loss.

CONCLUSION
We have reported the successful fabrication of surface and buried waveguides, supporting the modes of opposite polarizations by using reverse proton exchange technique in APE $\text{LiNbO}_3$ waveguides.
Fig. 3. Mode profile for REAPE waveguide.

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MODE EXPANSION SIMULATION OF VERTICAL TAPERS IN InP: COMPARISON WITH EXPERIMENTAL RESULTS AND OPTIMISATION

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Abstract

The mode expansion propagation method is used to calculate the beam divergence of vertical tapers. The simulations are successfully compared with experimental results. This is taken as a starting point for an optimisation where the adiabaticity and beam divergence of three different taper profiles are studied as a function of taper length.

Introduction

The development of low cost and performant laser to fibre coupling structures is one of the major issues in optoelectronics nowadays. The problem is conventionally solved by introducing complicated matching optics between laser and fibre [1]. A more attractive approach consists of integrating a spot size converter with the semiconductor laser diode. One can use a multimode coupler [2][3], GRIN lens [4] or a vertical taper [5]. Since growth of a vertical taper requires complex processing steps like shadow mask growth, it is very important to have a powerful and accurate numerical scheme to model these tapers. In this paper we will show that the mode expansion propagation method is such a scheme, by comparing simulated far field angles with experimentally obtained results on a double heterostructure laser diode with integrated taper. The influence of the taper profile on the far field and the adiabaticity will be compared for a linear taper, exponential taper and the experimentally obtained devices. The general statement that a well designed taper profile should vary slowly when the waveguide is near cut off will be illustrated numerically.

In this paper only the vertical dimension will be considered. The influence of the horizontal structure on the propagated field is not taken into account, thereby assuming that the horizontal waveguide structure (and spot size) is relatively broad over the entire taper length.

Theory

The propagative model used is the mode expansion propagation method [6][7]. The taper profile is discretised to a staircase approximation. In each section with uniform cross section modes are calculated, propagated and the coupling to the next section is evaluated. The simulations presented in this paper are done by taking into account non coherent reflections, meaning that the interference effects in the reflected light are neglected.

The mode expansion method is particularly useful for modelling tapers because it does not require a reference propagation constant as in conventional propagation methods. As the waveguide thickness diminishes the propagation constant of the local fundamental mode, which propagates most of the power in a well designed (adiabatic) taper, decreases too. Not adapting the reference propagation constant can therefore introduce significant errors in the calculation, especially when the index contrast is high (e.g. semiconductor/air). However, extending conventional beam
propagation with a longitudinally variable reference propagation constant requires a modal analysis anyway.

The point of comparison between theory and experiment will be the beam divergence angle, being the FWHM of the far field intensity profile $I(\theta)$. We used the approximate far field formula as derived in [8]

$$I(\theta) \propto |\cos \theta \cdot \hat{F}(E(x,z = L))(k_z)|^2$$

where $\hat{F}(\cdot)(k_z)$ denotes the spatial Fourier transformation, $E(x,z = L)$ the optical field at the output side, $L$ the taper length and $k_z = k_0 \cos \theta$ the spatial frequency with $k_0$ the wavenumber in vacuum.

**Taper description**

The device under study is the spot size transformer section of a double heterostructure laser diode with integrated taper. The taper is fabricated using the shadow mask growth technique. Details about the taper fabrication can be found in [9].

A vertical cross section of the taper is given in Fig. 1. The guiding region consists of InGaAsP ($\lambda_c = 1.55 \mu m$) material. The refractive index was estimated to be 3.506. The index of the InP cladding regions is 3.179. The taper profile was determined experimentally and can be fitted with a third order polynomial in $z$, the propagation coordinate. This function is shown in Fig. 2 (solid curve) for a unit input thickness. A linear and exponential taper profile having the same thickness reduction are also included in Fig. 2. The wavelength equals 1.55 $\mu m$ and the taper length of the experimentally grown devices is 200 $\mu m$. In the section Optimisation other taper lengths will be considered. The thickness reduction however remains the same, so that the taper profile in these cases is a scaled version of Fig. 2.

**Figure 1:** Schematic view of the taper structure. **Figure 2:** The three different taper profiles considered. The taper length was 200 $\mu m$. The profile for other lengths can be obtained by scaling the horizontal axis.

**Comparison between mode expansion results and experiment**

For the numerical calculation the taper was enclosed in a 16 $\mu m$ thick parallel plate waveguide to discretise the radiation mode spectrum. Window functions were used to simulate transparent boundary conditions [10]. All simulations were done with only 50 propagation steps and 39 radiation modes. Calculations with a higher number of steps proved that this choice gives sufficient accuracy. Only TE polarised light was considered.

In Fig. 3 the beam divergence angle as a function of the propagation distance through the taper is compared with experimentally obtained results. The beam divergence angle is defined as
the FWHM of the far field intensity profile. A very good agreement is observed. This is also illustrated in Fig. 4 where some calculated far field intensity profiles are compared with the measured ones. It should be noted that in the calculation only the vertical dimension was considered. Given the good agreement between theory and experiment it can also be concluded that the horizontal waveguide structure (which is described in [9]) has practically no influence on the vertical far field.

Figure 3: Comparison of calculated beam divergence angles with the measurements of [9].

Figure 4: Comparison of calculated far field intensity profiles with measurements at three vertical cross sections of the experimental taper profile of Fig. 2.

Optimisation

We will present some possible improvements on the experimental design [9]. The adiabaticity and the beam divergence will be compared for the three different taper profiles of Fig. 2. The results are summarised in Figs. 5 and 6.

Figure 5: Calculated power throughput of the fundamental mode as a function of the taper length for three different taper profiles. All tapers have a thickness reduction factor of 3.

Figure 6: Calculated beam divergence at the output of the taper as a function of total taper length for the cases considered in Fig. 6.

Fig. 5 shows the power content of the local fundamental mode at the output of the taper as a function of the total taper length. The butt-coupling efficiency from input to output section equals
0.79. It therefore follows that even a short taper of 20 µm length improves the power throughput in the fundamental mode by about 13%. However, Fig. 6 reveals that for short tapers the beam divergence angle increases rapidly, thereby decreasing the laser to fibre coupling efficiency. The beam divergence of the laser mode (±40°, see Fig. 3) can be used as a reference value here.

Fig. 6 also shows that the beam divergence angle for the exponential and experimental tapers is a relatively flat function of taper length over the range of about 65 µm to 200 µm. In this interval the fundamental mode power decreases by less than 2%. These results suggest that the fibre coupling efficiency will suffer only a small penalty when reducing the taper length down to 65 µm. For the linear taper the results are similar but slightly worse.

As a general conclusion it can be stated that the linear taper has the highest propagation losses and the highest beam divergence. This is in agreement with the property that tapering should happen very carefully for waveguides near cut off [10]. The slightly better performance of the experimental device compared to the exponential taper is therefore related to the somewhat steeper profile of the latter waveguide at small thicknesses.

Conclusions

The two dimensional mode expansion propagation method has proven to be a valuable analysis tool for semiconductor tapers. Calculated beam divergences and far field profiles were successfully compared with measured data on an experimentally realised double heterostructure laser diode with integrated taper. Furthermore the taper adiabaticity and beam divergence angle were both calculated for shorter taper structures. The results indicate that the tapers can be shortened by a factor of 2 to 3 with only a small penalty to the fibre coupling loss.

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References

THERMO-OPTICAL DIGITAL SWITCHES ON SILICON

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Abstract

Thermo-optically driven digital 2 x 2 switches on silicon are fabricated by plasma deposition of SiO$_2$ / SiON / SiO$_2$ waveguide layers and RIE delineation. The switches exhibit wavelength and polarization independent performance. Insertion losses of 2 dB and -27 dB cross talk are achieved. The switching power is strongly reduced by silica and silicon micromachining to 450 mW.

Introduction

Various types of optical switches have been proposed. On one hand, thermo-optic switches on glass [1], polymers [2] or silica on silicon [3] have been presented. They operate by the refractive index change caused by a local temperature increase. Because of the slow thermal constants of optical materials no fast switching times ($t_{rise} = 1$ ms) can be achieved. Mach-Zehnder-interferometers or directional couplers are employed for thermo-optical switches. A bias power is usually required to adjust the switching points. Moreover, the directional couplers are wavelength dependant. On the other hand, there are digital optical switches, e.g. on LiNbO$_3$, driven by the electro-optical effect [4,5]. ‘Digital’ means that they have two defined switching states if the driving signal is high enough. Our thermo-optical digital switch (TDS) is based on mode sorting as used for the digital optical switch, but it is driven thermo-optically. In contrast to the digital optical switch in [5] a completely unsymmetrical waveguide crossing as shown in Fig. 1 with small angles (less than 0.3°) is used. This type of switch shows a defined zero voltage state. By applying a driving voltage to a thin film heater, it can be switched.

Design

Digital optical switches are based on mode sorting in asymmetrical waveguide crossings with a two-moded intersection region [4]. Their zero voltage state is the ‘cross state’. By applying a driving signal to a thin film heater near the narrow waveguide its effective index is increased and can surpass the effective index of the broader waveguide. This causes a switching to the ‘bar state’. For silica, we have $dn/dT = 1.15 \times 10^{-5}$ K$^{-1}$ [6]. (In case of polymers with $dn/dT < 0$ the wider waveguide has to be heated.) A low cross-talk in the unswitched state demands a large effective index difference between both waveguides. On the other hand, for low switching powers the index difference has to be small. A compromise must be found by a proper design. The waveguides are fabricated by SiON plasma deposition and RIE delineation on oxidized silicon substrates. The waveguides with small cross sections are mode matched to standard 1.3 µm fibres. For an refractive index contrast of 3.5 % they are single mode up to 9 µm waveguide width. This allows a low loss design of the waveguide crossing with 4.5 / 5.5 µm or 4/6 µm wide waveguides as shown
in Fig. 1. A crossing angle 0.1° or 0.2° was chosen to ensure adiabatic coupling. Results of a FD-
beam propagation method simulation [7] of the passive waveguide crossing are given in Fig. 2 a/b.
A careful thermal analysis is necessary because of heat diffusion between the two waveguides.
Because silicon is a nearly perfect heat sink, short switching times can be achieved but the power
consumption is high. The switching effect is caused by the temperature difference between the two
waveguides. To achieve the maximum effect the position of the heating electrode has to be
optimised by calculations. Additionally, silica-on-silicon devices offer the ability to machine silica
and silicon independently to optimise the heat flow and to reduce the power consumption. Thermal
analysis was performed using the ANSYS - FEM-program taking into account the non-linear heat
diffusion coefficient of silica. The calculations exhibit a drastic reduction of the switching power by
underetching (see Fig. 1b): For planar devices, 2.5 W switching power is needed, but underetching
can reduce it below 0.5 W.

Device fabrication and experimental results

The thermo-optical digital switches are fabricated on thermally oxidised (8.5 μm) 100 mm
<100> silicon wafers. The waveguide SiON-core layer is deposited by plasma enhanced chemical
vapour deposition (PECVD) and delineated by reactive ion etching (RIE). The SiO2 superstrate
is also deposited by PECVD. The SiO2 / SiON / SiO2 - layers are structured with a resist masked
RIE-process using CHF3. The underetching of silicon can be achieved in two different ways:
Anisotropic wet chemical etching using ammonia based etchants [8] or dry plasma etching using
SF6. The thin film heaters are sputtered using aluminium (standard metallization in IC-fabrication,
low resistance, but poor thermal stability) or chromium (higher resistance, high thermal stability).
Low insertion losses (<2.5 dB) and a cross talk less than -27 dB (0.2 ° crossing angle, waveguide
width: 4 μm / 6 μm) or 15 dB (0.1° crossing angle, waveguide width 4.5 μm / 5.5 μm) were
obtained in the unswitched state. The switching power of a planar device is 2.5 W. A silica and
silicon micromachined switch needed a switching power of 450 mW, only (see Fig. 3). (The
switching power can drastically be reduced - without the requirement of the above underetching - if
the devices are fabricated on fused silica substrates.)

Conclusion

A thermo-optical digital 2 x 2 switch with silica-on-silicon waveguides is presented. The switch is
wavelength and polarization independent in a wide range and has a defined zero voltage state. The
cross talk in this cross state is below -27 dB. The power consumption can be reduced from 2.5 W
to 450 mW by micromachining the silicon substrate. The insertion loss is found to be 2.5 dB and is
not different from a straight waveguide of the same length. It should be mentioned that the
switching characteristic is almost independent of fabrication tolerances.

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**Fig. 1:** a) Waveguide layout of an unsymmetrical thermally driven digital switch (TDS) with SiON rib waveguides on silicon

b) Underetched waveguide structure (cross section AA’) for reduced driving power
Fig. 2: Beam propagation analysis
a) Analysis of the unswitched cross state, (0.1° crossing angle, waveguide width 4.5 μm / 5.5 μm)
b) Switched bar state of a) for 270 °C thin film heater temperature
   (temperature distribution calculated by the FEM-programm ANSYS)

Fig. 3: Transmission characteristic of an underetched TOS
(0.2° crossing angle, waveguide width 4.5 / 5.5 μm; 100 % reference: maximum output power)
SIMULATION OF SEMICONDUCTOR OPTICAL AMPLIFIERS

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ABSTRACT

Semiconductor optical amplifiers (SOAs) can perform the following functions: amplification, modulation, detection and wavelength conversion. This paper will describe an extensive numerical model for SOAs. It includes large-signal time dependent analysis, residual mirror reflection, amplified spontaneous emission (ASE) and multiple electrodes. Important parameters such as the bit-rate, amplification, noise figure, chirp, ASE-spectrum and polarisation-dependency can be obtained.

INTRODUCTION

A semiconductor optical amplifier (SOA) is an active electro-optical device. Its structure is similar to that of a laser, being that the difference is the anti-reflection coatings at the facets. In Figure 1 a schematic view of an SOA is shown. The main characteristic of SOAs is that an incoming optical signal can be modulated in amplitude and phase, depending on the applied current. SOAs have many applications in integrated optical circuits. They can be used as amplifiers, modulators, detectors, switches, wavelength convertors, optical demultiplexers and signal regenerators. The main advantage of SOAs over other components is the ease of integration with waveguides, lasers and other integrated optical devices. Another advantage is that SOAs can perform more than one function at a time. Multi-functional SOAs have been demonstrated which can simultaneously amplify, detect and transmit an optical signal [1]. We have developed a simulator, specially devoted to SOAs. This simulator includes large-signal time dependent analysis, residual mirror reflection,
amplified spontaneous emission (ASE) and multiple electrodes. Important parameters such as the bit-rate, amplification, noise figure, chirp, ASE-spectrum, polarisation-dependency and saturation behaviour can be obtained. It is also possible to use the simulator to investigate the influence of the accumulation of forward and backward propagating ASE in cascaded SOAs.

**SIMULATOR**

For the modelling of SOAs, standard semiconductor device equations are used:

1. **Poisson equation:**
   \[ \nabla \cdot (\varepsilon \nabla \varphi) = q (n - p - dop) \]  
   \( (1) \)

2. **Electron continuity equation:**
   \[ \frac{\partial n}{\partial t} - \frac{1}{q} \nabla \cdot (n \mu_n \nabla E_{fn}) = -U_{SHR} - U_{spon} - U_{Aug} \]  
   \( (2) \)

3. **Hole continuity equation:**
   \[ \frac{\partial p}{\partial t} + \frac{1}{q} \nabla \cdot (p \mu_p \nabla E_{fp}) = -U_{SHR} - U_{spon} - U_{Aug} \]  
   \( (3) \)

In these equations \( \varphi \) is the electro-static potential, \( E_{fn} \) is the electron Fermi-energy, \( E_{fp} \) is the hole Fermi-energy and all other variables have their usual meaning. The electron density \( n \) and hole density \( p \) can be calculated from the Fermi-Dirac integral \( \frac{1}{1 + \exp\left(\frac{\varepsilon - E_{fn}}{kT}\right)} \) and their respective Fermi-energies.

The equations describing the propagation of the light in the active layer, are added to the equation set:

1. **Light intensity propagation equation:**
   \[ \frac{1}{v_g} \frac{\partial I(z)}{\partial t} + \frac{\partial I(z)}{\partial z} = \left[ \frac{\Gamma g(z)}{1 + \varepsilon_{nl} \Gamma F(z)} - \alpha_s \right] F(z) \]  
   \( (4) \)

2. **Light phase propagation equation:**
   \[ \frac{1}{v_g} \frac{\partial \Phi(z)}{\partial t} + \frac{\partial \Phi(z)}{\partial z} = - \frac{1}{2} \frac{\alpha_H \Gamma g(z)}{1 + \varepsilon_{nl} \Gamma F(z)} \]  
   \( (5) \)

where \( z \) is the direction of propagation of the optical beam, \( v_g \) is the group velocity, \( \Gamma \) is the confinement factor of the active layer, \( \alpha_H \) is the linewidth enhancement factor and \( \varepsilon_{nl} \) is the non-linear gain compression term.

The optical gain of SOAs is due to stimulated recombinations of carriers in the active layer. This recombination term is added to the other recombination terms. The material gain \( g \) is derived from basic solid-state physical principles and is given by [2]:

\[ g(E) = \left( \frac{\pi q^2 h}{\varepsilon_0 n c m^2 E} \right) |M|^2 \rho_{red} (E) (f_e - f_h) \ast L (E, \Delta E) \]  
\( (6) \)

where \( M \) is the polarisation-dependent matrix element and \( \ast L (E, \Delta E) \) denotes a convolution with a Lorentzian lineshape function.

The spontaneous emission of photons is due to spontaneous band to band recombinations of electrons and holes. This spontaneous recombination of the carriers can be described by:

\[ U_{spon} = \int_{0}^{\infty} R_{sp}(\lambda) d\lambda \]  
\( (7) \)

where \( R_{sp}(\lambda) \) is the wavelength dependent spontaneous emission rate. A part of this spontaneous emission is coupled into the active layer waveguide and will be amplified. This amplified spontaneous emission (ASE) can be described by:

\[ \frac{1}{v_g(\lambda)} \frac{\partial \psi(z, \lambda)}{\partial t} + \frac{\partial \psi(z, \lambda)}{\partial z} = \left[ \sum \Gamma(\lambda) g(z, \lambda) - \alpha_s \right] \psi(z, \lambda) + \beta(\lambda) R_{sp}(z, \lambda) \]  
\( (8) \)
where $\beta(\lambda)$ is the part of the spontaneous emission that couples into the active layer waveguide. The stimulated emission of spontaneously generated photons is added to the recombination terms. The residual mirror reflections are taken into account by the boundary conditions.

In the active layer, an SOA has an almost uniform carrier distribution in the lateral direction. Therefore, the electrical equations can be solved in a two-dimensional domain along the transversal and longitudinal directions (see Figure 1). The light propagation equations are solved decoupled from the other equations, in a one-dimensional space. For their boundary conditions, the residual mirror reflections were taken into account. The numerical implementation is described in [3].

**APPLICATIONS**

**Bi-electrode wavelength convertor**

For the validation of our model, previously published measurements of Durhuus were used [4]. The measured SOA was a two-section double channel planar buried heterostructure (DCPBH) used as a wavelength convertor. The working principle of the wavelength convertor is schematically shown in Figure 2(a). The active layer was made of bulk material and had a cross-dimension of 0.32x0.70 $\mu$m$^2$. The first section was 100 $\mu$m long and the second section was 400 $\mu$m long. The applied currents were 37 mA and 27 mA respectively. The conversion took place from 1553 nm to 1548 nm. The continuous signal was TE-polarised with a power of -14 dBm at 1548 nm. The modulated signal was TE-polarised and modulated between -11.7 dBm and -21.7 dBm at 1553 nm with a bitrate of 1.5 Gb/s. The residual facet reflectivities were $5 \times 10^{-4}$.

The measurements, together with the simulation results, are shown in Figure 2(b).

**Inline modulator-detector SOA**

In a collaboration between CNET and CSELT (Italy), SOAs used as inline modulator-detector structures are studied. This device has two modes of operation. In listen-mode the SOA detects an incoming signal and transmits it, in the talk-mode the SOA modulates an incoming continuous wave (CW) signal. For a high detectivity, the SOA must operate under saturation-conditions. However, this will distort the extinction ratio of the transmitted signal. Hence, a compromise must be found between detectivity and signal distortion. A good compromise is to use a very short contact for the detector (less than 100 $\mu$m). However, to ensure a fibre to fibre gain of 1 dB, the chip gain should be...
around 13 dB and this cannot be attained with a short contact. Therefore, a bi-electrode structure is necessary. Our optimisations have shown that an SOA with two contacts of respectively 50 and 300 μm gives an acceptable performance. The first contact is used as a detector, while the second contact can modulate. Both contacts are biased with currents.

In listen-mode, the detectivity is 50 V/W, and the gain is 13.5 dB for a TE-mode and 11.6 for a TM-mode. The extinction ratio degradation of the optical output signal is 0.4 dB for a TE-mode and 0.2 dB for a TM-mode. The maximum bitrate is around 500 Mb/s.

In talk-mode, the extinction ratio of the optical output signal is above 30 dB due to very low off-state current. The modulation rate is limited to 400 Mb/s. The chip gain is 13.5 dB for a TE-mode and 11.6 for a TM-mode. The polarisation sensitivity is less than 2 dB, due to a nearly square active layer of 0.4x0.6 μm².

The output graphs for the TE-mode are shown in Figure 3(a) and 3(b), for respectively the listen-mode and talk-mode.

![Fig. 3(a) The time response of the detector for TE-mode.](image)

![Fig. 3(b) The time response of the modulator for TE-mode.](image)

**CONCLUSIONS**

We proposed an extensive numerical model for the simulation of SOAs. This model can accurately simulate SOAs, performing different functions, such as amplification, modulation, detection and wavelength conversion. The simulator is able to predict the optical gain, the bitrate, the extinction ratio, chirp, detectivity, noise figure, polarisation sensitivity and optical output spectrum at both facets. Comparison between measured data and simulation results shows a good agreement. Therefore, the simulator can be used for the design and optimisation of SOAs in integrated optical circuits.

**REFERENCES**

High-Concentration Erbium-Doped Silica-on-Silicon Grown by Plasma-Enhanced CVD


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Abstract
An investigation of PECVD-grown high-concentration erbium-doped silica-on-silicon is presented. The quantum efficiency is found to be strongly dependent on heat treatment of the erbium-glass. Co-doping with phosphor is found to have no significant effect on the quantum efficiency.

Introduction
Erbium-doped planar waveguides offer the attractive possibility of integrating amplification in structures such as wavelength division multiplexers [1] and power splitters. This may lead to the development of compact loss-less components to be used in for example optical communication systems. Because of the inherent length limitations of integrated waveguides practical devices require glass films with very high erbium-concentration. Studies on erbium-doped fibers [2] show that ion-ion interactions such as cross-relaxation and cooperative up-conversion [3,4], take place in highly doped glasses. Ion-ion interaction causes degraded quantum efficiency of the metastable level. This leads to poor laser-performance of erbium-doped waveguides as has been observed for both doped fibers [2,5] and planar waveguides [6]. Erbium-doped glass films have been produced by several techniques [6-8], however, very little information has been given to establish the extent of allowable erbium-concentration for the technology in use. Flame hydrolysis (FHD) has been shown to provide a maximum allowable erbium-concentration of ~0.5 wt% [6]. This level of concentration is somewhat low since it corresponds to a maximum gain of ~1 dB/cm, requiring waveguides with a length of 20 cm or more to produce amplifiers of practical interest. We are currently investigating PECVD as a candidate for a process that may allow higher erbium-concentrations. Compared to FHD, PECVD offers the possibility of reducing the deposition temperature to very low levels. The process temperature is believed to have a major influence on the allowable erbium-concentration as the solubility of erbium in glass is dependent on this parameter. In the following we will present investigations of the dependency of decay-time and quantum efficiency on erbium-concentration and heat-treatment of PECVD-grown active films.

Experimental
A conventional parallel-plate PECVD-apparatus was modified to include the possibility of erbium-doping. Silane, nitrus oxide, and phosphine are used to form the glass-film on 4-inch silicon wafers held at a deposition temperature of 300°C. The process gases are introduced into the chamber through the top-electrode which is formed as a shower head. Erbium-chelate is dissolved in butyl acetate and the liquid solvent is injected into a heated container in which it is vaporized and mixed with a nitrogen
carrier gas and led to the shower-head. The produced wafers are analysed by secondary ion mass spectroscopy (SIMS) to establish the composition of the glass film. The absolute concentration of erbium was calibrated against films analysed by Rutherford back scattering.

A fiber-based optical setup was established to provide the analysis of the spectroscopical behavior of the erbium-doped glass films. The films were optically excited using an Ar-ion laser pumped Ti:Sapphire laser yielding 200 mW of 980-nm light launched into a single-mode fiber. The fluorescence around 1550 nm is picked up by the same fiber used for excitation, and a fiber-fused 980/1550-nm wavelength division multiplexer is used to separate the fluorescence and the reflected excitation light. Also, a long-wavelength-pass filter with a cut-off wavelength of 1300 nm is used to suppress the luminescence from the silicon substrate and scattered pump light. The fluorescence spectra of the films are obtained using a monochromator equipped with an InGaAs-detector. The fluorescence decay is established through ON/OFF excitation using a fast InGaAs-detector followed by a transimpedance amplifier and a digital oscilloscope.

Results and discussion

Figure 1 displays the normalized fluorescence as a function of time for two erbium-doped silica-on-silicon samples with erbium-concentrations of 0.3 and 5.2 wt%, respectively. Both samples were heat-treated at 800 °C. The low erbium-concentration (upper curve) results in a purely exponential decay with a lifetime of 9.6 ms. The high erbium-concentration (lower curve) results in an inversion-concentration dependent decay, indicating ion-ion interaction.

![Figure 1](image)

**Figure 1** Measured decay of fluorescence for two erbium-doped silica-on-silicon samples. The excitation light is cut off at time = 0 s. The erbium-concentrations are 0.3 wt% (upper curve) and 5.2 wt% (lower curve), respectively.

Efficient planar waveguide lasers and amplifiers require erbium-doped films with both high concentration and high quantum efficiency. From fibers it is known that co-doping of the erbium-glass in some cases may improve the quantum efficiency and increase the allowable erbium-concentration...
We have attempted to use phosphor as co-doping, and figure 2 displays the fluorescence spectrum of (a) Er/P-silica and (b) Er-silica. It is seen that the use of phosphor has a broadening effect on the emission-spectrum, as is also known from fibers. The same behaviour has been observed for fibers co-doped with other elements.

The PECVD process operates at a relatively low-temperature. All of our samples are produced at 300°C. This gives us the possibility to investigate erbium-doped silica samples that have been exposed to temperatures much lower than that of FHD. In order to establish the impact of heat-treatment as well as co-doping, we produced two erbium-doped silica-on-silicon wafers with similar erbium-concentration, one with and one without phosphor co-doping. The two wafers were broken into samples which were annealed at different temperatures ranging from 300 - 1100°C. Decay-curves were obtained from all samples and used in the evaluation. We also measured the absolute fluorescence power launched back into the fiber from the samples. It was found that the fluorescence power is correlated to the shape of the decay-curve. Those samples that showed purely exponential decay also showed the highest fluorescence power per unit concentration. The higher concentration samples showed an increasingly non-exponential decay as well as a decrease in normalized fluorescence. This is believed to be due to ion-ion interactions. The observed correlation between decay behaviour and normalized absolute fluorescence allows us to use the latter in a relative comparison of quantum efficiency for samples of the same film thickness. Figure 3 displays absolute fluorescence power as a function of annealing temperature. The fluorescence power is normalized to the erbium-concentration of 0.54 and 0.66 wt% and the film-thickness of -4.0 and 4.4 micron for the P-silica and the pure silica, respectively. It is observed that the fluorescence power is strongly dependent on the annealing temperature. There may be several explanations for this. It is possible that part of the erbium is not active because it is not incorporated in the glass as Er$^{3+}$. Also, at higher temperatures, erbium ions agglomerate in clusters which causes co-operative upconversion degrading the fluorescence. It appears from the figure that the optimum annealing temperature is ~800°C. Figure 3 also indicates that co-doping with phosphor has a slightly improving effect on the quantum efficiency. However, the observed improvement is only marginal and within the uncertainty in the erbium concentration determined by SIMS.
Figure 3  Detected fluorescence normalized to erbium-concentration and film-thickness as function of anneal temperature. Curves are shown for erbium doped P-silica and pure silica.

Conclusion
Erbium-doped silica-on-silicon is produced by plasma-enhanced chemical vapor deposition. Decay-curves for the metastable $^4I_{13/2}$ energy level are measured for the produced samples with erbium-concentrations ranging from 0.3 to 5.2 wt%. Significant degradation of the quantum efficiency is found for the higher concentration levels, whereas purely exponential decay with a decay-time of ~10 ms is observed for the lowest concentration levels. Heat treatment of the samples shows that the quantum efficiency is strongly dependent on the annealing temperature of the erbium-glass. An optimum annealing temperature of 800°C is found. Co-doping with phosphor has a broadening effect on the emission spectrum, but no significant effect on the quantum efficiency.

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References
We study optical switching in an asymmetric Anti-Resonant Reflecting Optical Waveguide (ARROW) coupler with an optically induced grating in the spacing film. Comparing with conventional grating assisted couplers it exhibits a reduced switching power and permits remote coupling.

1. INTRODUCTION

Grating Assisted Couplers are asymmetric directional couplers with a diffraction grating formed by periodic changes of the refractive index along the propagation direction [1-6]. The efficient power exchange between different waveguides of the coupler is obtained when the grating constant $K=2\pi/\Lambda$ (where $\Lambda$ is the length of the grating period) is matched to the propagation constants difference ($K = \beta_2 - \beta_1$). The gratings in the traditional Grating Assisted Couplers are usually formed during the fabrication and have constant, immutable parameters, what limits the operation of the coupler to one, strictly defined frequency. The optically induced grating is formed by spatially periodic changes of the refractive index which results from the interference of two counter-propagating external fields in a nonlinear medium. The parameters of such a grating [7] depend on the external waves and can be varied when the device is in use. The grating constant can be tuned to the guided modes propagation constants difference by changing the external waves incidence angles. The coupling efficiency depends on the grating amplitude and can be modulated by changes of the external waves intensities. The sensitivity of optically induced grating assisted couplers is relatively low and high powers of the external waves or an extremely strong nonlinearity of the material are necessary. The evanescent nature of the mode coupling in directional couplers restricts the permitted guide separations to a few micrometers and lossy bend sections have to be incorporated. Anti-Resonant Reflecting Optical Waveguides (ARROWS) can represent the building blocks of another kind of grating assisted couplers. The waveguiding mechanism in ARROW relies on antiresonant Fabry-Perot reflection instead of a total internal reflection [8,9] and the field in the spacing region between two coupled ARROWS is oscillating instead of being evanescent. The potential of symmetric ARROW coupler for linear remote coupling [10] as well as for nonlinear power-dependent switching [11] was shown. Switching in a nonlinear ARROW coupler relies on both linear mode beating and nonlinear mode coupling [12] and can be obtained for lower power and larger waveguide separation then in a traditional coupler.

The aim of the paper is to show that it is useful to extend this scheme towards asymmetric grating assisted couplers. Due to remote coupling (wide spacing region, improved access of the external waves) one can expect a further reduction of the switching power.
2. THE ASYMMETRIC ARROW COUPLER

The coupler proposed consists of two film ARROWs, 'left' and 'right', with different core thicknesses ($d_3$ and $d_6$) separated by a spacing film of the thickness $d_0$ (Fig.1). The thicknesses of the outer reflecting layers obey the antiresonance condition to minimize the losses [8]. The inner reflector layers were slightly detuned from antiresonance to increase the field amplitude in the nonlinear spacing region in order to enhance the interaction with the induced grating.

![Fig. 1. Asymmetric ARROW coupler structure. The parameters fixed throughout the paper: wavelength 1.06 μm, low refractive index $n_1=1.53$, high refractive index $n_2=1.69$, thickness of the cores: $d_3=7$ μm, $d_6=5$ μm. Other layers thicknesses: $d_1=d_7=0.38$ μm, $d_2=3.5$ μm, $d_4=d_5=0.55$ μm and $d_B=2.5$ μm.](image)

The considerations are restricted to the TE polarized fields with a frequency $\omega$ propagating in $z$-direction. The total electric field in the coupler is expressed by a linear superposition of the leaky supermodes (modes of the whole system).

\[
E(x,z) = \sum_{\mu} A_{\mu}(z)E_{\mu}(x)e^{i(\beta_{\mu}z-\alpha z)} + \text{c.c.}
\]

where $k_0=\omega/c$ and $\beta_{\mu} = \beta_{\mu}' + i\beta_{\mu}''$ is the complex propagation constant of the $\mu$-th mode. The functions $A_{\mu}(z)$ denote the slowly varying amplitudes of the modes. The transfer matrix approach [13] was used to determine both the complex propagation constants and the field profiles of the supermodes.

![Fig. 2. Dispersion curves of the supermodes in dependence on the spacing distance $d_0$. The operation point of the coupler (for $d_0=17.5$ μm) is marked.](image)

The real part of the normalized propagation constant $\beta_{\mu}'/k_0$ of the first six modes as a function of the thickness of intermediate layer $d_0$ is presented in Fig.2. The real part of the propagation constants of the isolated ARROWs with thicknesses $d_3$ and $d_6$ ($\beta_{3}'/k_0$ and $\beta_{6}'/k_0$) are indicated by the dashed lines. When the propagation constant of a supermode is close to the propagation constant of one of the waveguides a main part of the mode energy is concentrated in this guide. Because the waveguides have different widths the field of the mode is almost located in one guide and vanishes in the other one, and the mode beating disappears. Due to the quasi-orthogonality of the ARROW
supermodes a power transfer to the other channel can only occur by a coupling of both modes, e.g. mediated by a grating. Thus, in order to implement a coupling device one has to tune the waveguide separation to such values that the supermodes are mainly located in different guides. Fig.2 tells us that one possible operation point is $d_0 = 17.5 \, \mu m$.

3. OPTICALLY INDUCED GRATING

The grating, necessary to obtain coupling between 'left' and 'right' mode, can be created by two control external waves at frequency $\omega_e$ propagating in different directions and overlapping in the nonlinear medium. Reflections of the external waves at the interfaces are neglected to simplify the calculations. The intensities of these waves are assumed to be much higher than the intensities of guided modes. The incidence angles of the control fields are chosen to obtain an interference pattern along the guided modes propagation direction. The nonlinear change of the dielectric constant is $\Delta \varepsilon_{NL} = 2\alpha_{NL} |A_{ex}|^2 [1+\cos(Kz)]$, where $\alpha_{NL}$ is the nonlinear Kerr coefficient and $A_{ex}$ are amplitudes of the external waves. The grating constant, $K$, depends on the frequency and the incidence angles of the external waves and can be varied when the coupler is in operation ($K = 2\beta_e$, where $\beta_e$ is a value of wave vectors z-component). The intensities of all interacting fields are assumed to be relatively low, so that the nonlinearity allows for generating small index changes in the nonlinear medium but does not change the properties of the modes. The coupled mode equations for the asymmetric ARROW coupler with optically induced grating are:

$$\frac{dA_{\mu}}{dz} = G_{\mu\nu} A_{\nu}(z) \exp[(\beta_{\mu} - \beta_{\nu})z] \exp(-ikz)$$

$$\frac{dA_{\nu}}{dz} = G_{\nu\mu} A_{\mu}(z) \exp[-i(\beta_{\mu} - \beta_{\nu})z] \exp(ikz)$$

where the functions $A_{\mu}(z)$ describe slowly varying amplitudes of forward running supermodes.

Coupling coefficients for TE modes are given by:

$$G_{\mu\nu} = \frac{\omega_e}{N} \int \Delta \varepsilon_{NL} E_{\mu}(x) E_{\nu}^*(x) \, dx$$

and

$$N_{\mu} = \frac{2\beta_{\mu}}{\omega_e} \int E_{\mu}(x) E_{\mu}^*(x) \, dx.$$

The grating amplitude $\Delta \varepsilon_0$ is variable and provides external power controlled coupling of two supermodes. The solution of the coupling equations for constant $K$ and only one guide initially excited $A_{\mu}(0) = A_0$, $A_{\nu}(0) = 0$ [14] are given by

$$A_{\mu}(z) = A_0[\cos(\kappa z) + i\delta \sin(\kappa z)/\kappa] \exp(i\delta z)$$

and

$$A_{\nu}(z) = -A_0[G_{\mu\nu} \sin(\kappa z)/\kappa] \exp(-i\delta z),$$

with $\kappa^2 = G_{\mu\nu}^2 + \delta^2$ and $2\delta = \beta_{\mu} - \beta_{\nu} - K$.

The above equations define a coupling length, $L_c = 2\pi/\kappa$, and the amount of energy which can be exchanged between interacting modes. The value of the coupling coefficient depends mainly on the grating amplitude, waveguide separation and amplitudes of modal fields in the nonlinear layer. The grating amplitude is a tunable parameter and the field amplitudes

![Fig.3. Coupling coefficient per unit $\Delta \varepsilon_0$ versus the spacing distance $d_0$. Thickness of inner reflector layers '4' and '5' tuned to obtain constant field amplitude in the central layer. Other parameters listed in Fig.1.](image-url)
can be controlled by changing the width of the reflecting layers $d_4$ and $d_5$. The dependence of the coupling coefficient on the ARROW separation $d_0$ is shown in Fig. 3. The calculations were only performed for these regions where two well located modes, one in the left ARROW and one in the right ARROW, could be identified. The thicknesses of the layers $d_4$ and $d_5$ were tuned for every $d_0$ to keep the amplitudes constant in the spacing region, $A_c = 0.25 A_m$, where $A_m$ is the amplitude of the field in the core. The periodic dependence of the coupling coefficient is due to the periodic behavior of the modal fields in the intermediate region. The amplitude of the grating necessary to obtain switching can be estimated from the relation $G_{pv} = \pi \sqrt{2} L$, where $L$ is the length of the coupler. For the coupler length of $L = 1$ cm and a spacing of $d_0 = 17.5 \mu m$ the amplitude of the refractive index grating has to be $\Delta n = 4.5 \times 10^{-4}$ being a few times less than in conventional grating assisted couplers which rely on evanescent coupling [1,4,5,7]. The grating period length, $\Lambda = 2 \pi / \Delta \beta$, is about $0.65 \times 10^{-3} m$.

4. CONCLUSIONS

It has been shown that an optically induced grating can provide coupling between different supermodes of the asymmetric ARROW coupler. Parameters of the grating, such as the grating constant and the grating amplitude, depend on the external waves intensities and directions of propagation. As a result the coupler can be tuned to a desired frequency and the efficiency of coupling can be varied when the coupler is in use. Comparing with previous couplers the ARROW coupler exhibits higher sensitivity to the external beams parameters and permits coupling between remote waveguides which is a clear advantage because there is a much better access of the external waves to the nonlinear region.

The additional advantage of the optically induced grating consists in the feasibility of all-optical switching or amplitude modulation in using the temporal and spatial variation of the external waves. A practical implementation of the device proposed would rely on the rib ARROW coupler concept the performance of which was demonstrated in [15].

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Waveguide grating coupling under normal incidence: 
a clarification

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Abstract

A complete analysis of a corrugated waveguide excitation by a normally incident light beam is presented. The conditions for optimum mode excitation are obtained in the presence of second order coupling between the two counterpropagating waveguide modes by the finite size grating. A new effect of dramatic coupling failure is revealed.

Introduction

Integrated coupling gratings are bound to play an important role in future integrated sensors and microsystems since they perform the important light access function to/from the waveguide in a configuration which is topologically and technologically compatible with the planar light circuit. The situation of normal incidence is interesting practically because it eases alignment operations and fits mechanical axes orthogonality. Normal incidence represents an interesting case of coupling degeneracy giving rise to some very specific properties which must be taken care of in practical applications. One of them is the known abnormal reflection\(^1\) which, under normal incidence exhibits a single peak only. Another property is the subject of the present contribution. It is associated with the inherent second order intraguide coupling between the 1st order-coupled counterpropagating modes in the situation of normal incidence. This new effect is shown to possibly cause a dramatic fall in the input coupling efficiency. It is the reciprocal case of the better known Distributed Bragg Reflection (DBR) configuration in a semiconductor laser using second order grating reflection. In such laser grating the period \(\Lambda\) is \(\Lambda = \lambda/n^*\) where \(n^*\) is the effective index of the corrugated waveguide and \(\lambda\) is the wavelength in vacuum. The feedback is achieved at the second diffraction order with simultaneous first order radiation normally to the waveguide plane. It is known that this normal radiation cancels when the DBR grating is sufficiently long to provide near to 100 % reflectivity. This is a result of destructive interference in the substrate and in the cover of the two first order radiated waves. One can therefore infer that such marked 1st order effect cancellation may somehow be present in the reciprocal situation which concerns us here of the first order normal excitation of a grating waveguide. In order to clarify this question we present here the analysis of the waveguide coupling structure, the efficiency results obtained in a practical example, and identify and describe the expected reciprocal cancellation effect.

Theoretical analysis

The specific feature of waveguide excitation under normal incidence is the presence of two counterpropagating excited modes, coupled to each other by the second diffraction order of the coupling grating. This excitation geometry will be called resonant due to the inherent intraguide power transfer to distinguish it from the common excitation geometry where one mode only is excited. The analysis makes use of the approach described elsewhere\(^2\). However, one must consider here a system of two coupled equations for the description of the excitation:

\[
\frac{d\alpha^+}{dx} = \beta^+ f \exp(i\Delta' x) - \alpha^+ a^+ + \kappa^- a^+ \exp\left[i(\Delta^+ + \Delta^-) x\right], \tag{1}
\]

\[
-\frac{d\alpha^-}{dx} = \beta^- f \exp(-i\Delta' x) - \alpha^- a^- + \kappa^+ a^- \exp\left[-i(\Delta^+ + \Delta^-) x\right]. \tag{2}
\]
where the incident beam of angle \( \theta_2 \) (figure 1), of smooth amplitude profile \( f(x) \) excites a waveguide mode of amplitude \( a^+(x) \) and \( a^-(x) \) in the positive (negative) \( x \) direction. This process is characterized by an amplitude coupling coefficient \( \beta^\pm(x) \) and a detuning \( \Delta^\pm \) between the incident and coupled waves. The excited mode has the net loss coefficient \( \alpha^\pm(x) \) which involves both radiation and dissipation losses. The coupling between the two guided modes is characterized by the coupling coefficients \( \kappa^\pm(x) \). The solution of system (1) - (2) gives the mode amplitude in the waveguide grating region \( 0 < x < d \). The boundary conditions for the mode amplitudes at the grating edges are:

\[
a^+(0) = a^-(d) = 0 \tag{3}
\]

Taking (3) into account yields the resulting amplitudes of the guided modes leaving the grating area. The excitation efficiency \( \nu \) of the waveguide is determined as the ratio of the power flow in a waveguide mode to the total power flow in the incident beam:

\[
\nu^+ = \frac{2n_2^4h^2|a^+(d)|^2}{\left[ \int n_2^2|f^+(\xi)|^2 \, d\xi \right]^2} \left( \frac{n_2}{n_0} \right)^\eta,
\nu^- = \frac{2n_2^4h^2|a^-(d)|^2}{\left[ \int n_2^2|f^-(\xi)|^2 \, d\xi \right]^2} \left( \frac{n_2}{n_0} \right)^\eta,
\]

where \( \eta = 0 \) in the TE case and \( \eta = 2 \) in the TM case.

**Numerical analysis**

Expression (1) - (5) were implemented on a PC for the calculation of the excitation efficiency dependence on the different structure parameters and on the conditions of excitation.

The results are presented in figure 2 showing the efficiency dependence on the incidence angle around the normal for different periods in the case of a concrete example involving a Gaussian incident beam of half-width \( w_0 \), a waveguide of Gaussian index profile with surface index 1.55 and substrate index 1.46. The waveguide thickness is \( h = 1.24271 \mu m \). The depth \( 2\alpha \) of the unity line/space ratio, rectangular groove grating is \( 2\alpha = 0.05 \mu m \). The excitation is from the cover side at 0.78 \( \mu m \) wavelength on the grating defined at the guide-cover interface. Unless specified otherwise, the beam and grating area centers coincide. The calculations based on the Rayleigh-Fourier method give the following results for the fundamental modes:
\[ \mathbf{h}_{\text{TE}} = 1.5112276; \quad \kappa_{\text{TE}} = (-3.937, -i1.759) \text{ cm}^{-1}; \quad \alpha_{\text{TE}} = 3.956 \text{ cm}^{-1}; \]
\[ \mathbf{h}_{\text{TM}} = 1.50816538; \quad \kappa_{\text{TM}} = (-2.189, -i7.612) \text{ cm}^{-1}; \quad \alpha_{\text{TM}} = 1.936 \text{ cm}^{-1}. \]

The optimum conditions on \( d \) and \( \omega_0 \) for maximum coupling efficiency under normal incidence have been found to be \( d = d_{\text{opt, TE}} = 2\omega_0 = 1\kappa^{-1} \) which in the present case gives \( d_{\text{opt, TE}} = 2.32 \text{ mm} \) and \( d_{\text{opt, TM}} = 1.26 \text{ mm} \). The angular dependence of the excitation efficiency around \( \theta_2 = 0 \) of the TE mode propagating contradirectionally was first studied for different grating periods and is shown in figure 2 from where one can see that there is a grating period \( \Lambda^* \) at which the angular dependences coincide; this period satisfies the condition:

\[ \Lambda^* = \frac{\lambda}{\mathbf{h}^* - \text{Im}(\kappa)\lambda/2\pi}. \tag{6} \]

This condition exactly corresponds to \( \theta_2 = 0 \) where both counterpropagating modes have equal excitation efficiency. The latter is however about 1.5 times smaller than in the non-resonant case. This decrease is a first result of waveguide mode interaction; this effect is however not very pronounced. In order to investigate it further, we shall now break the symmetry of the excitation geometry:

**Figure 3**

Excitation efficiency versus distance between beam and grating centers.

Another way of breaking the symmetry of the excitation geometry will lead us to the searched 2nd order DFB reciprocal case: starting with the optimized symmetrical configuration given by \( d = 2\omega_0 = 1\kappa^{-1} \), let us increase the grating length in one direction only:

This has been made step by step and is illustrated in figure 4 showing the efficiency versus the grating period at normal incidence. The optimized symmetrical case is represented by the dashed curve "2.2 mm". Enlarging the grating length in one direction, and calculating the coupling efficiency shows the appearance of the effect sought for; the solid line corresponding to a single-sided grating enlargement of 22 mm exhibits a sharp dip at the period \( \Lambda^* \) given by expression (6), meaning that the mode propagating in the direction of the enlarged grating part gets hardly excited. This effect is not surprising if one refers to the DBR reciprocal situation: physically it means that the mode coupled in the direction of the enlarged grating part gets strongly reflected at the 2nd order and interferes with the opposite coupled mode with a phase relationship that cancels the resulting amplitude of the coupled mode.
Such dramatic collapse of the efficiency is already present with an enlargement as small as $d_{opt}$ as illustrated by the dashed curve "4.4 mm".

This indicates that the dimensioning of a normal incidence coupling configuration as well as the relative beam - grating area positioning are quite critical if one wants to avoid a vanishing of the excitation efficiency.

**Figure 4**

Excitation efficiency dependence on the grating period at $\theta_2 = 0$ and $2\omega_0 = \hbar c^{-1}$ for different grating lengths.

### Conclusion

The Rayleigh-Fourier formalism was applied to the analysis of the three wave resonant coupling of a finite size beam into a waveguide grating of finite area under normal incidence. The opto-geometrical conditions for maximum coupling as well as the possible practical consequences of deviating from them are given. A configuration of possible catastrophic coupling failure is revealed. This peculiarity is the reciprocal effect of the known second order Distributed Bragg Reflection in some DBR semiconductor lasers.

The present analysis completes the investigations of the various resonance and interference effects taking place in waveguide gratings which were initiated by the authors. In their presentation, they will deliver a synthetic review of the features exhibited by resonant waveguide grating coupling under normal incidence.

### References

EXPERIMENTAL CHARACTERIZATION OF MAGNETOOPTIC WAVEGUIDES FOR INTEGRATED OPTICAL APPLICATIONS

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Abstract: Light propagation in magnetooptic waveguides shows some peculiarities which can not be observed in other materials. This implies applications for the realization of integrated optical isolators and sensors. We describe the production of waveguides in magnetooptic garnets and their experimental characterization by the help of unitary Jones matrices.

Because of their nonreciprocal properties, magnetooptic waveguides are the only components which can be used for a realization of integrated optical isolators and circulators. Moreover, the propagation of modes in these waveguides shows a strong magnetic field dependency. The latter effect can be used for the realization of sensors for magnetic fields and currents.

The interesting properties of the magnetooptic materials result from the special structure of their permittivity tensor. Depending on the direction of the magnetic field, it takes two typical forms

$$\epsilon_L(x) = \begin{pmatrix} \epsilon_x & i\xi & 0 \\ -i\xi & \epsilon_y & 0 \\ 0 & 0 & \epsilon_z \end{pmatrix} \quad \text{and} \quad \epsilon_T(x) = \begin{pmatrix} \epsilon_x & 0 & i\xi \\ 0 & \epsilon_y & 0 \\ -i\xi & 0 & \epsilon_z \end{pmatrix},$$

respectively. Here, we considered a propagation of light parallel (index L, longitudinal configuration) or perpendicular (index T, transversal configuration) with respect to the magnetization of the magnetooptic medium. The z axis always corresponds to the propagation direction of light. The nondiagonal elements $\xi$ are related to the specific Faraday rotation $\theta_F$ by $\xi = \theta_F \sqrt{\epsilon_z} \lambda / \pi$. They may couple different polarized modes of waveguides (longitudinal configuration) or modify the propagation constants of single modes (transversal configuration).
Magnetic garnets [1] are one of the most promising candidates for the realization of magnetooptic waveguides. Thin films of Lu$_{3-x}$Bi$_x$Fe$_{8-y}$Ga$_y$O$_{12}$ garnets on [111] oriented substrates of gadolinium gallium garnet have been grown by liquid phase epitaxy [2]. The optical properties of these films depend strongly on $x$, $y$, small contributions from impurities and on the growth parameters. This versatility of the garnet system allows for a "chemical design" of the materials. On the other hand, it complicates the controlled and reliable production of proper waveguides. The production of magnetooptic waveguides requires a good interplay between crystal growth and theoretical simulation. Figure 1 compares the results of theory and measurements for planar waveguides in the transversal configuration [2]. The double layer structure was proposed according to theoretical considerations with respect to the optimization of the nonreciprocal effect in the transversal geometry [3]. It shows a remarkable improvement with respect to the nonreciprocal properties of the waveguide.

![Figure 1: Difference of the propagation constants of forward and backward propagating modes in planar waveguides (transversal geometry). Solid line - theoretical values for a double layer which consists of two layers with opposite sign of the Faraday rotation, dashed line - theoretical values for a single layer using material parameters of the bottom layer, bullets - experimental data for the double layer.](image)

The performance of magnetooptic devices with respect to applications depends strongly on the superposition of magnetooptic tensor effects and other effects which influence the propagation constant and birefringence of waveguides. Established experimental procedures for the characterization of magnetooptic rib waveguides rely on the exact [4] or approximate [5] knowledge of the optical axis. The method which is used in this paper does not make any assumptions on a special geometry. The only assumption is, that all losses (absorption, scattering, conversion to radiation modes) concern the different polarized modes in the same way.
In this case the waveguide can be represented by a unitary 2×2 Jones matrix of the form

\[
\hat{M} = \begin{pmatrix}
  a_0 + i a_3 & a_2 + ia_1 \\
  a_2 + ia_1 & a_0 - i a_3 \\
\end{pmatrix}
\quad \text{with} \quad (a_0)^2 + (a_1)^2 + (a_2)^2 + (a_3)^2 = 1. \tag{1}
\]

The real parameters \( a_k \) (\( k=0,1,2,3 \)) are measured by the help of a combination of waveplates and polarizers. Figure 2 shows the experimental arrangement. The transmission of light from the left hand side waveplate to the detector is described by the Jones calculus. Measurement of the transmitted intensity for three independent rotation states of the polarizers and the right hand side waveplate gives the values of the \( a_k \). The left hand side waveplate is used to transform the linear polarized laser light to nearly circular polarized light. By this way, the intensity of the light behind the left hand polarizer becomes nearly independent of its polarization angle. The magnetic field is applied to the waveguide by the help of two coils. It can be adjusted parallel or perpendicular with respect to the propagation direction of light.

![Experimental setup](image)

**Figure 2:** Experimental setup for the determination of the Jones matrix of a magnetooptic waveguide. W-waveplate, P-polarizer, L-Lens

Finally, one has to interpret the obtained results. The \( a_k \) are the coefficients of a representation of \( \hat{M} \) on the basis of the Pauli spin matrices. The behaviour of these matrices in transformations and formal analogies to quantum mechanics imply conclusions with respect to the reciprocity of the system.

On the other hand, the \( a_k \) are related to known physical parameters. For example, the specific Faraday rotation \( \Theta_F \) of the waveguide under consideration is given by

\[
\Theta_F = \frac{a_3 \Gamma}{\sin \Gamma L} \quad \text{with} \quad \Gamma = \frac{1}{L} \arccos a_0 \tag{2}
\]

\( L \) is the length of the waveguide. Figure 3 shows the the specific Faraday rotation versus an external applied magnetic field (longitudinal configuration). Note, that waveguides with relatively high saturation fields have been used for this experiment.
Figure 3: Measured values of the specific Faraday rotation in the waveguide versus the external applied magnetic field (longitudinal configuration). The small deviation from a linear dependence is due to a hysteresis effect.

In conclusion, waveguides in Lu$_3$-$z$Bi$_z$Fe$_5-y$Ga$_y$O$_{12}$ show strong magneto-optical effects. A new method for the experimental characterization of such waveguides in arbitrary geometries has been proposed. It is based on the representation of the waveguide by an unitary Jones matrix.

References

SECOND HARMONIC GENERATION IN A RESONANTLY ABSORBING MEDIUM

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We suggest the use of the intensity depending losses associated with the resonant absorption of dopant centers in nonlinear materials. A suppression of parametric instability limiting the conversion efficiency of second harmonic generation is a quasi-phase matched structure is predicted.

Since its first observation by Franken et al. in 1961 [1], the efficiency of second harmonic generation in nonlinear materials has been severe limited by their coherence length. To obtain reasonable up-conversion efficiency one needs to use a scheme for quasi-phase matching (QPM) [2,3]. In such schemes, for imperfect phase matching, the process of frequency up-conversion evolves periodically in space because the residual pump wave is parametrically amplified in regions of high conversion efficiency. This results in frequency down-conversion. Even when perfect phase matching is met, any noise power at the fundamental frequency will be strongly amplified in regions of high harmonic power, causing down-conversion [4,5]. In practice, these effects limit the SHG efficiencies that can be achieved under stable conditions.

In this Report we suggest the use of the intensity depending losses to suppress these low-level noises and improve converter operation. We consider here the case of a nonlinear QPM structure that contains a saturable absorber, in the form of a dopant with a transition resonant to the fundamental wave, and whose saturation is relatively low. In this case, absorption does not play any essential role on the up-conversion process when the pump wave is strong enough to saturate the transition. It comes into action, however, at the point where the pump is depleted such that its intensity becomes lower than the saturation threshold. This means that deleterious instabilities, caused by parametric down-conversion in regions of high second harmonic efficiencies, are suppressed by elimination of the residual pump power. We examine the contribution of this technique to the conversion of near-IR radiation in QPM structures doped with rare-earth ions.
In the plane wave approximation the process of SHG in a QPM structure with saturable absorption obeys the following set of equations,

\[ \begin{align*}
\frac{dA_p}{d\xi} &= -A_p A_s \sin \Psi - \sigma A_p / (1 + \gamma_s A_p^2), \\
\frac{dA_s}{d\xi} &= A_p^2 \sin \Psi, \\
\frac{d\Psi}{d\xi} &= \Phi - (2A_p - A_s^2 / A_p) \cos \Psi, 
\end{align*} \] (1)

where \( A_p(\xi) \) and \( A_s(\xi) \) are the normalized amplitudes of the pump wave and second harmonic respectively, \( \Psi(\xi) = \Phi(\xi) - 2\Phi(\xi) \) is the relative phase between the second harmonic and the pump waves, and \( \Phi \) is the dimensionless parameter describing the dephasing from exact phase matching.

The dimensionless parameters \( \sigma \) and \( \gamma_s \) describe resonant absorption and its saturation respectively and can be written as,

\[ \sigma = \frac{\sigma_0 N}{\kappa(2)}, \quad \gamma_s = \frac{\sigma_0 c n_p T I_0}{4 \pi h \omega}, \]

where \( \sigma_0 \) is the absorption cross section, \( \tau \) is the lifetime of the upper excited level, \( N \) is the density of the resonant centers, \( \kappa(2) \) is the coupling constant of the nonlinear interaction, \( I_0 \) is the total input intensity, and \( n_0 \) is the non-resonant refraction index at the fundamental frequency.

This Report is basically centered on numerical solution of the system of coupled equations (1), but it is also possible to obtain some insight analytically. In the spatially homogeneous case, when \( DA_p / d\xi = 0 \) and \( d\Psi / d\xi = 0 \), the solution of the system (1) is,

\[ A_p(\infty) = 0, \quad A_s(\infty) = \text{const}, \quad \cos \Psi(\infty) = -\frac{\Phi}{2A_\infty(\infty)}, \] (2)

with \( A_i(\infty) \) being a function of the parameters \( \Phi, \sigma, \gamma, \) and of the boundary conditions \( A_i(0) (i=p,s), \Phi(0) \). From the form of the equation governing the evolution of \( A_p \) in the system (1) it follows that the homogeneous solution (2) remains stable at \( \sin \Psi(\infty) < 0 \) provided,

\[ A_p^2 \sin \Psi_{ch} = \frac{\sigma A_s^2}{\sqrt{A_p^2(\infty) - \Phi^2 / 4}}, \] (3)
where $S_0 = 1/\gamma_0$ is the saturation intensity for the pump wave.

\[ \begin{align*}
\sigma &= 0.1, \\
\gamma_0 &= 10.0 \\
\end{align*} \] (a)

\[ \begin{align*}
\sigma &= 0.5, \\
\gamma_0 &= 10.0 \\
\end{align*} \] (b)

\[ \begin{align*}
\sigma &= 1.0, \\
\gamma_0 &= 10.0 \\
\end{align*} \] (c)

\[ \begin{align*}
\sigma &= 0.75, \\
\gamma_0 &= 0.1 \\
\end{align*} \] (d)

Figure 1 Normalized pump and SH intensity vs length of resonantly-doped QPM for $A_0(0) = 0.3$, $\Delta_g(0)=0.1$, $\theta(0) = 0$ and $\phi = 0.1$

The numerical integration of Eqs.(1) which results are depicted on Fig.1 demonstrates interplay between parametric instability and saturating absorption. First, at small $\sigma$ [Fig.1a] the processes of frequency up- and down-conversion vary periodically in space, the only sequence of such absorption is gradual decreasing of limits of oscillations of the field amplitudes. Increasing of the absorption decreases the minimum value of $A_0$ attainable at every spatial cycle [Fig.1b] that eventually leads the condition of (3) to be satisfied. Then the fields $A_0$ and $A_1$ accept their homogeneous values, and the parametric instability is suppressed. It may be seen from Fig.1c
that around a certain optimum the non-reciprocal scenario of SHG can be provided in the very first cycle of spatial beating. In this regime, the output value of $A_2$ is pointed out to be sensitive to the saturation intensity, its increasing suppresses both parametric instability and up-conversion as well [Fig. 1d].

![Figure 2 Normalized intensities of the pump (a) and SH (b) at fixed value of the length of QPM structure vs phase mismatch.](image)

This is also explored by computer simulations which results are drawn in Fig. 2 that the maximum of efficiency of QPM converter can be achieved at non-zero values of the phase mismatch.

These results allow us to answer the question on whether this effect could be observed in experimental situation. Assuming silica fiber of 1.58 m long with nonlinear grating with quadratic nonlinearity of 10 pm/V, a refractive index of 1.45 and around 100 mW of incident pump, one needs $10^{13}$ cm$^{-3}$ the concentration of Er$^{3+}$ to observe the promising behavior predicted in Fig. 1c.

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DESIGN AND PERFORMANCE EVALUATION OF MULTI-MODE INTERFERENCE POWER SPLITTERS FOR OPTICAL COMMUNICATIONS

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Abstract
Fibre compatible multi-mode interference splitters are designed. All splitters show a loss of 0.8 dB and a uniformity below 0.6 dB. These devices are 10 - 15 % shorter than similar branching-type splitters but exhibit a narrow bandwidth. The reflection is below -55 dB while the polarisation sensitivity is below 0.01 dB.

Introduction
Optical power splitters are key components in optical communication networks; for instance for distribution of TV-channels. The power splitters may be manufactured as a fused bundle of optical fibers [1]. However, for large number of splittings (N>16) the integrated optical solutions become attractive [2]. The most straightforward design of an optical power splitter consist of a cascading of 1-by-2 branches (Y-branches) as indicated on Fig. 1a). This type of splitter has ideally a very low loss, an even distribution of power among the output waveguides and a very broad optical bandwidth. However the processing of the sharp branching points is technologically difficult and will lead to variations among the different Y-branches on a chip as well as among different samples. Also, as the device is an adiabatic design where the fundamental supermode should be maintained throughout the structure the branching-type splitters tend to be relatively long. Recently, the self and especially multi-imaging in multi-mode optical waveguides have been used in the design of 1-by-N splitters [3]. The structure of such a multi-mode interference (MMI) splitter is shown on Fig. 1b). Besides the potentially reduced length the MMI devices possess an improved fabrication tolerance as the sharp branching points and closely spaced waveguides are avoided in this design. The drawback of MMI splitters is a limited optical bandwidth [4].

Most of the attention concerning MMIs have been focused on relatively strong guidance waveguide structures such as those in many semiconductor technologies [3]. We have however concentrated on weakly guiding channel waveguides in glass. These structures are inherent in the silica-on-silicon technology which is a good candidate for the manufacturing of low-loss fiber compatible passive optical components [5].
We have designed a number of fiber compatible MMI power splitters with the number of splittings ranging from 4 to 64. Thereafter, we have calculated the process tolerances, the polarisation sensitivity, the reflection level and the optical bandwidth. Especially, we have made a comparison of the total length and of the bandwidth of MMI-type and branching-type power splitters.

**Design**

We choose as operating wavelength 1.55 μm corresponding to the lower loss minimum of silica fibers. The refractive index of the cladding is 1.445 at this wavelength. The single-mode input and output waveguides are chosen to have a square core cross section of 6x6 μm² and a refractive index difference of 0.005 to obtain low loss coupling to single-mode fibers. Calculations were performed both with a finite difference beam propagation method (BPM) and a propagating mode method. The length of the multi-mode section $L_{\text{MMI}}$ was adjusted for every value of the width $W$ to give minimum loss. The value of $W$ was chosen to obtain the lowest uniformity; defined as the ratio between the maximum power in an output waveguide and the minimum power in an output waveguide. As the waveguides in the output array are weakly guiding, evanescent coupling may occur for $N>2$. We performed BPM simulations on a full 1-by-4 power splitter and found that the smallest separation $W/N$ should be larger than 3 times the core width ($a$) to avoid this evanescent coupling.

The resulting designs are listed in Table 2 that also gives the length of the S-bend sections where the output waveguide separation is widened from $W/N$ to 250 μm to allow for fiber connection. The S-bends are designed requiring a maximum loss of 0.1 dB in each bend using the scaling laws for cosine shaped S-bends [6].

![Geometry of 1-by-4 power splitters. a) branching-type, b) MMI-type.](image)

**Fig. 1: Geometry of 1-by-4 power splitters. a) branching-type, b) MMI-type.**
<table>
<thead>
<tr>
<th>$N$</th>
<th>$W$ (µm)</th>
<th>$L_{\text{MMI}}$ (mm)</th>
<th>$L_{\text{q}}^{\text{MMI}}$ (mm)</th>
<th>Loss (dB)</th>
<th>Uniform. (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>90</td>
<td>2.084</td>
<td>6.661</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>8</td>
<td>195</td>
<td>4.686</td>
<td>10.134</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>16</td>
<td>405</td>
<td>9.820</td>
<td>14.804</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>32</td>
<td>760</td>
<td>17.095</td>
<td>21.356</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>64</td>
<td>1490</td>
<td>32.631</td>
<td>30.475</td>
<td>0.8</td>
<td>0.6</td>
</tr>
</tbody>
</table>

*Table 1: Design of MMI power splitters at 1.55 µm.*

In contrast to other MMI-devices the ones we consider are weakly guiding. Thus, the polarisation dependence must be expected to be small. We performed calculations on the designed 1-by-64 power splitter for both the TE and TM-mode and found a difference in the uniformity of less than 0.01 dB (less than 0.001 dB on the loss). The reflection level may be estimated to be below -55 dB since the difference in refractive index in the structure is 0.005. The process tolerances - when a loss penalty of 1 dB is accepted - are found to be ±0.1 mm on the length and ±3.5 µm on the width of the multimode section for the 1-by-64 power splitter.

**Comparison with branches**

We did also design a number of branching-type splitters with the same number of splittings as for the MMI-devices in Table 1. On Fig 2 we have shown the ratio of the total length of our MMI power splitters to the total length of branching-type splitters with comparable losses. As seen, the MMI-type splitters are all shorter than their branching-type counterparts. Finally Fig. 2 also shows the optical bandwidth of the MMI splitters in Table 1. For comparison we calculated the bandwidth of a 1-by-64 branching-type splitter to around 1000 nm.

**Conclusion**

In conclusion, we have designed a number of MMI-power splitters for use in fiber optical communications. The splitters show weak polarisation sensitivity, low reflections. Compared with branching-type power splitters the MMI-type is 10 - 15 % shorter but has a much lower bandwidth. However, the 20-30 nm amplification bandwidth of erbium-doped fiber amplifiers is still covered by a 1-by-64 MMI power splitter.
Fig 2: Length reduction of a MMI power splitter in comparison with a branching-type splitter and optical bandwidth of a MMI power splitter as a function of the number of splittings.

References

ANALYTICALLY OPTIMIZED APLANATIC HOMOGENEOUS WAVEGUIDE LENSES IN GLASS AND LiNbO₃

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Abstract

The homogeneous refracting waveguide lenses are optimized using third-order aberration theory and stigmatic contours. The mathematical expressions of the paraxial radii of curvature and the deformations parameters of the lens contours are given. The calculated characteristics of \( K^+ - Na^+/Ag^+ - Na^+ \) ion-exchanged waveguide lenses in glass and Ti-indiffused proton-exchanged lenses in \( LiNbO_3 \) are reported.

1 Introduction

The waveguide lenses are attractive basic components in integrated-optical devices for optical signal processing, computing systems and optical communications [1]. A variety of waveguide lenses including the geodesic, chirp-grating, Fresnel and Luneburg type have been investigated. Recently, great attention has been devoted to the so-called homogeneous refracting waveguide lenses (HRWL) because of success in the preparation of Ti-indiffused and \( H^+ \)-exchanged waveguides in \( LiNbO_3 \), as well as of complementary \( K^+ - Na^+ \) and \( Ag^+ - Na^+ \) ion-exchanged waveguides in a common glass substrate [2]. As shown in Fig. 1 HRWL is an

![Figure 1: Schematic view of homogeneous refracting waveguide lens: SA-stop aperture, D-linear aperture ("lens diameter"), d-lens thickness, \( n_l \) and \( n_w \) - mode effective refractive indices.](image-url)
appropriately shaped planar waveguide region, immersed in another planar waveguide with a different refractive index, i.e., it is a two-dimensional analog of the conventional lenses. The lens contours are photolithographically defined, which makes possible to produce the acircular refracting boundaries with high degree of precision as easy as circular ones. Therefore, the geometric-optical optimization of such a lens is actually valuable. A simple analytical optimization procedure based on the third-order aberration theory and stigmatic contours is described in [3]. Here we give the mathematical expressions of the paraxial radii of curvature and the deformation parameters of analytically optimized aplanatic lenses. The lens performances are studied using combination of ray-tracing and Huygens-Fresnel construction [4].

2 Optimization procedure.

It is well known that, in general, any lens can be made aplanatic using two aspheric contours [5]. The proposed optimization procedure is based on the satisfying the conditions for realization of aplanatism of single HRWL using stigmatic contours with appropriate parameters. Briefly, the method consists in the following.

Let us assume that the distance of the pole of the first contour from the source, lens thickness \( d \) and the distance \( a' \) of the pole of the second contour from the image formed by the lens (or in the case of the parallel input beam \( a = -\infty \), \( d \) and the back focal length \( f' \) are given. The lens contours are chosen to be stigmatic.

Employing the Fermat's principle for such contours one obtains an equation for Cartesian oval (in particular ellipse or hyperbola)

\[
-s n_1 + v n_2 = -n_1 \sqrt{(s-x)^2 + y^2} + n_2 \sqrt{(v-x)^2 + y^2}
\]

where distances \( s \) and \( v \) are measured from the pole \( O \) and can be positive or negative (Fig. 2), \( n_1 \) and \( n_2 \) are the mode effective refractive indices (MERI) of the two waveguide regions. It is supposed, that the lens is formed by single mode waveguides. If the waveguides support several modes, \( n_2 \) and \( n_1 \) are MERI of the working mode pair.

The realization of aplanatism by the employment of the results of the third-order aberration theory is connected with the requirement for the first and second Seidel's sums to go to zero. The fulfilling of these requirements for the single lens formed by two stigmatic contours leads to the relation:

\[
-\alpha_1 - \alpha_2 = \frac{N}{N+1} (a + a')
\]

where \( \alpha_1, \alpha_2 \) and \( \alpha_3 \) are the angles between the optical axis and the first paraxial ray in the regions in front of the lens, inside the lens and behind the lens, respectively. \( N \) is the relative refractive index of HRWL and is in fact the ratio between MERI inside and outside the lens. The distance \( s_1 \) between the first contour pole and the image, formed by the same contour is obtained using eq.(2):

\[
s_1 = \frac{a}{a + a'} \left( \frac{N+1}{N} a' + d \right)
\]
The lens contours are completely defined by eqs (1) and (3). In this way the conditions for aplanatism are fulfilled and the primary and higher order spherical aberrations are removed.

3 Contour parameters.

In two dimensional case the Cartesian oval is expressed in an explicit form by the equation:

\[ x = \frac{y^2}{2r} + \frac{y^4}{8r^3(1 + b)} + \ldots \]  

(4)

where \( r \) is the paraxial radii of curvature and \( b \) is a deformation parameter [5]. Here the paraxial radii of curvature \( r_i \) and the deformation parameters \( b_i \) of the contours \( i = 1, 2 \) for a single lens) are not explicitly used because the optimization procedure ensures by itself such \( r_i \) and \( b_i \), which satisfy the corresponding relations of the third-order aberrations theory. But they are necessary for the characterization of the aspheric lenses. In our case \( r_i \) and \( b_i \) can be obtained taking into account that each term in the first Seidel's sum goes to zero due to the stigmatism of the lens contours. This leads to the following expressions for \( r_i \) and \( b_i \):

\[ \frac{1}{r_1} = \frac{1}{(N-1)a} \left[ \frac{N^2(a + a')}{(N + 1)a' + Nd} - 1 \right] \]  

(5)

\[ \frac{1}{r_2} = \frac{1}{(N-1)a'} \left[ \frac{N^2(a + a')}{(N + 1)a - Nd} - 1 \right] \]  

(6)

\[ b_1 = \frac{N^2[(a - d)N - a]^2[a - (a' + d)N]}{a[N^2 + a'(N^2 - N - 1) - Nd]^3} \]  

(7)

\[ b_2 = \frac{N^2[(a - (a' + d)N)^2[(a - d)N - a']}{a[N^2 - N - 1] + a'N^2 + Nd]^3} \]  

(8)

In the case of parallel input beam, which is important from the practical point of view, taking a limit \( a \to -\infty \), and introducing the back focal length \( f' \) one can transform the equations (5)-(8) into:

\[ r_1 = \frac{(N - 1)[(N + 1)a' + Nd]}{N^2} = \frac{N^2 - 1}{N^2} f' \]  

(9)

\[ r_2 = \frac{(N^2 - 1)a'}{N^2 - N - 1} = \frac{(N + 1)f' - Nd(N - 1)}{N^2 - N - 1} \]  

(10)

\[ s'_1 = \frac{N + 1}{N} a' + d = \frac{N + 1}{N} f' \]  

(11)

\[ b_1 = -\frac{1}{N^2} \]  

(12)

\[ b_2 = \left( \frac{N}{N^2 - N - 1} \right)^3 \]  

(13)

\[ a' = f' - \frac{N}{N + 1} d \]  

(14)

4 Lens performance.

The field distribution in the locality of the paraxial focal line and the field curvature of the optimized aplanatic lenses are studied using the hybrid approach, based on combination of ray tracing and Huygens-Fresnel construction [4]. The results show that for the HRWL in glass
with typical values of $N$ in the range $1.020 - 1.030$ (at wavelength $632.8 \text{nm}$) the focal curve tends to the paraxial focal line with decreasing axial lens thickness $d$ so that the field curvature becomes minimal at the lowest $d$. Increasing the angle of incidence, the intensity in the best focus decreases most slowly for the lens with the lowest $d$. But the relatively low value of $N$ requires low paraxial radii of the lens contours, which limits the possibility of further reducing of $d$.

In the case of HRWL in $\text{LiNbO}_3$ the higher $N$ permits to design thinner lenses. It appears that there is a thickness, at which the focal curve of the lens oscillates about its paraxial focal line with little deviations. In this way, varying $d$, one can obtain an aplanatic lens practically without field curvature [6]. We have numerically analyzed the analytically optimized $Ti$-indiffused $H^+$-exchanged HRWL in $\text{LiNbO}_3$ with parameters: $f = 10 \text{ mm}$, $D = 2.5 \text{ mm}$, $N = 1.050$ ($n_r = 2.2000$ at wavelength $632.8 \text{nm}$), $d = 2.05 \text{ mm}$, $r_1 = 0.929705 \text{ mm}$, $r_2 = -0.968206 \text{ mm}$, $b_1 = -0.907029$ and $b_2 = -1.360913$. For on-axis parallel homogeneous input beam the spot size of this lens, defined as FWHM of the focal spot, is equal to the theoretical diffraction minimum of $1.0 \mu m$. Its focal curve oscillates around the paraxial focal line with deviations less than $4 \pm 5 \mu m$, for the angle of incidence in the range of $(-4^\circ \pm 4^\circ)$, i.e. the field curvature is practically absent.

5 Conclusion.

The paraxial radii of curvature and the deformation parameters of the optimized HRWL are derived on the base of the third-order aberration theory. The study of the aplanatic lenses with the wave theory shows that they can be additionally optimized concerning the field curvature.

Acknowledgment.

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References

IO BIOCHEMICAL SENSORS

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Abstract
In recent years, various optical probes have been devised for sensitive measurement of the changes in refractive index that result from the binding of molecules to the surface of a sensor chip. These optical affinity sensors commonly rely on the detection of the change in the phase velocity of a guided optical surface-wave as induced by the change in the optical properties determined by the surface-attached mass. The availability of these sensor devices has stimulated the development of a novel analytical methodology based on real-time detection of molecular interactions and binding processes at the surface of a sensor chip. This paper reviews the design and the operating principle of optical probes for biochemical affinity sensing. We present a newly developed optical probe for highly sensitive biomolecular interaction analysis. We describe the fabrication of the sensor device and outline its applications in pharmaceutical research.

Introduction
The analysis of molecular recognition and binding processes at the surface of a solid-supported phase is a widely used technique in biological assays. In the past decade, optical engineers have devised a variety of probes to detect the changes in refractive index that result from adsorption, desorption or binding of molecules at the surface of a sensor chip. These optical affinity sensors commonly rely on the following principle for signal transduction: The binding of molecules at the sensor surface is detected by measuring the change in the phase velocity of an optical surface-wave as induced by the change in the optical properties determined by the surface-attached mass. The optical surface-wave can be a surface plasmon propagating at the surface of a gold film [1], or a waveguide mode propagating in a thin dielectric waveguide of high refractive index [2]. In this way, the molecular interaction process at the interface between the sensor surface and a liquid (or gaseous) sample medium can be monitored by measuring the interfacial mass loading as a function of time. The availability of these sensor devices has stimulated the development of a novel analytical methodology based on real-time detection of molecular interactions and binding processes at the surface of a sensor chip. An application of this analytical method is the functional characterization of biomolecules using an optical sensor chip with a chemically modified surface [3,4].

Sensor design and operating principle
The formation of a molecular layer on the sensor chip is accompanied by a change of the refractive index in the immediate vicinity of the solid surface. To obtain
high detection sensitivity, the penetration depth of the evanescent field of the optical surface-wave into the sample medium has to be as small as possible, typically 100 nm or smaller. A small penetration depth implies a very high "effective refractive index N" of the surface-wave, this is achieved by using a waveguide film with a very high refractive index n. To obtain optimum detection sensitivity, the thickness of the waveguide film has to be properly chosen [2]. The TiO₂ waveguide film described in this paper consists of amorphous TiO₂ and has a refractive index n=2.4, its optimum thickness is about 140 nm at the operation wavelength of 633 nm (HeNe laser). The 140 nm thick TiO₂ waveguide supports only the two fundamental modes of different polarization. For an aqueous cover medium, the two modes have the effective refractive indices N_{TE0}=2.04 and N_{TM0}=1.81. The penetration depth of the evanescent field into an aqueous (or gaseous) cover medium is 65 (57) nm for the TE0 mode and 82 (70) nm for the TM0 mode. For comparison, sensors based on surface plasmon waves on a gold film have a penetration depth into the cover medium which is distinctly larger. At \( \lambda = 633 \text{ nm} \), the penetration depth of the TM polarized surface plasmon is 180 nm for an aqueous cover medium and 240 nm for a gaseous cover medium, cf. Ref. [5].

A cross-sectional view of our newly developed sensor device is shown in Fig. 1. The sensor consists of a chip with a surface structured with a submicron grating relief coated by an extremely thin waveguide film of amorphous TiO₂. The optical microstructure incorporated in the waveguide is composed of two superimposed uniform diffraction gratings with different periodicities. This so-called "bidiffractive grating coupler" [6] serves as both an input port and an output port for coupling and decoupling light beams to and from the planar waveguide.

The required high refractive index of the waveguide film implies that the modes have to be coupled by a diffraction grating with a submicron grating constant. The two alternatives for grating coupling, namely prism coupling and butt-face coupling, are not feasible: Prism coupling through the chip substrate would require a substrate material having a refractive index which is distinctly higher than the effective refractive index of the excited mode. Butt-face coupling [7] is very delicate and has turned out to be not practicable for routine analytical applications because of stability reasons and packaging issues.

The surface of the sensor chip is sensitized with an immobilized molecular layer. The sensitized surface is covered with a micro cell contacted to the edges of the chip. The cell defines a 1-mm-wide and 5-mm-long flow chamber for the sample medium.
above the chip surface. The chamber has a thickness of only 40 μm and contains a volume of 0.2 μl. The sample medium is injected into the flow chamber through an inlet port and an outlet port in the upper wall of the cell. Typical flow rates are on the order of 2 to 20 μl min⁻¹.

Optical read-out of the sensor chip

The optical read-out function of the bidiffractive grating coupler is explained with reference to Fig. 2. Coupling of the incident laser beam occurs only for certain incident angles where coupling resonance is met for one of the two superimposed gratings. In Fig. 2 the incident beam couples via grating Ga. The coupled waveguide mode propagates in the waveguide, interacting along its path with the molecular layer on the surface of the chip. Due to continuous decoupling via the two superimposed gratings, the excited mode fades out after a few millimeters of propagation. The mean propagation length of the coupled mode depends on the modulation amplitudes of the two superimposed gratings and is typically 1.5 mm. Two beams, decoupled via the two gratings, are generated on both sides of the sensor chip. The two beams decoupled via grating Ga propagate parallel to the reflected and transmitted portions of the incident beam. The important feature is that the two beams decoupled via the second grating Gb propagate in different directions well separated from the reflected and transmitted portions of the incident beam. This angular separation of the beams decoupled via the second grating from non-coupled background radiation enables sensitive and accurate analysis of the decoupled light to be made.

A second important feature of the bidiffractive coupler is that the coupling angles of the two modes can be set to selected, adjacent angular positions by adjustment of the two grating constants of the two superimposed gratings. A suitable coupling configuration is shown in Fig. 3. The incident beam on the left couples to the TEO mode via the coarser grating, the incident beam on the right couples to the TM0 mode via the finer grating. The TEO mode is decoupled via the finer grating, and the TM0
mode is decoupled via the coarser grating, the decoupling angles lie close to the normal. The two incident beams are slightly focused and impinge at a common point on the chip surface. The beam diameter is about 0.3 mm in the plane of the chip, this has the advantage that the input coupling angles are less sharply defined, so that tuning of these angles can be avoided during the measurement of the molecular binding process at the sensor surface.

The response of the sensor is obtained by measuring the small difference angle between the beams decoupled from the two modes as a function of time [8]. This differential detection scheme relaxes the requirements on the positioning stability of the sensor device with respect to the read-out system. Because the difference is measured between the sine of two coupling angles located near to the normal, a common angular shift of the decoupled beams caused by a small tilt of the sensor chip does not influence, to first order, the sensor response. Figure 4 demonstrates the sharpness of the coupling resonance curves of the bidiffractive grating. The two inner coupling angles lie at 0.70° for the TEO mode and 1.03° for the TM0 mode, giving an angular difference of only 0.33°. The width (FWHM) of the coupling resonance curves is $5 \times 10^{-2}$°. The two outer coupling angles lie at 16.4° for the TEO mode and at -14.4° for the TM0 mode. The measurement of the difference angle between the beams decoupled from the two modes is performed using Fourier transform optics. The two decoupled beams are focused onto a diode array or onto position sensitive detectors, and the distance between the two foci in the focal plane is measured. The sensor response is proportional to this distance.

Fabrication of the sensor device

The TiO$_2$ waveguide film is fabricated using a low-temperature microwave plasma-impulse chemical vapor deposition technique (PICVD) [9]. The substrate to be coated is inserted into a chamber in which the precursor gases TiCl$_4$ and O$_2$ are
brought to reaction by a series of short microwave pulses. The resulting TiO$_2$ film is amorphous, has a very high refractive index of 2.4 and has excellent waveguiding properties. The PICVD coating process is used because it enables the fabrication of very dense and stable amorphous optical films having a refractive index close to the value of the corresponding bulk material [10]. An important property of the PICVD process is its capability to deposit the TiO$_2$ waveguide film onto polymer substrates.

The superposition of the two uniform gratings with different periodicities is achieved by double exposure of a resist-coated glass blank to two laser interference patterns adjusted to the two grating constants of the bidiffractive coupler. Using electroplating of Ni onto the resist surface an embossing master (Ni shim) is fabricated. The bidiffractive grating is then transferred from the embossing master to a polymer surface using hot embossing or injection moulding. These replication processes are potentially of very low cost and are well suited for the fabrication of the required microstructure on the surface of a polymer substrate. The two superimposed gratings have grating constants of 314 nm and 362 nm and equal amplitudes, the modulation amplitude of the bidiffractive grating is in the 5-10 nm range. The PICVD TiO$_2$ waveguide film is deposited onto the polymer substrate carrying the bidiffractive microrelief on its surface. This fabrication process is well suited for mass production of the sensor chip.

The translational invariant symmetry of the bidiffractive grating provides practical and position independent input and output coupling. This feature considerably facilitates the fabrication of the sensor device. Large polymer plates carrying the bidiffractive grating and the waveguide film on their entire surface can be fabricated. On the plate surface the molecular monolayer coatings required for recognition and selective binding of a specific substance of interest can be prepared. The plates with the sensitized surface are then cut into chips which can be packaged into the sensor device. Applications of this sensor technique in pharmaceutical research include the analysis of macromolecular interactions in biological assays, the determination of the affinity constant and the kinetic binding parameters for different biochemical...
compounds without the use of labeled auxiliary reagents, and the measurement of the inhibition constant of a chemical compound of interest intervening in a given biomolecular recognition process.

References


A HIGH-PRECISION, COMPACT, HYBRID OPTICAL EVANESCENT WAVE SENSOR FOR CHEMICAL AND BIOLOGICAL APPLICATIONS.

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A hybrid evanescent wave sensor component is fabricated using an integrated optical interferometer and a specially designed photodetector array. The design of the interferometer is based on the use of tapered waveguides to obtain two intersecting collimated beams. Phase shifts can be measured with an angular precision of $10^{-3}$ radians, corresponding to a superstrate index change of $10^{-4}$ with our structure.

Introduction.

Integrated optical circuits made by glass ion exchange is a flexible low-cost technology today particularly adapted for detector applications like displacement detection¹ and chemical² and biological³ sensors. Our aim is to measure the optical phase shift resulting from a small refractive index change in the waveguide superstrate, and the two-wave interferometer represents the evident solution as it transforms optical phase into light intensity. In its classical version, the Mach-Zehnder interferometer, the output signal is a light-spot of varying intensity, and its cosine response curve represents in itself a problem for the detection of small phase shifts. The intensity signal is furthermore susceptible to different noise sources in the experimental set-up (variation in the light intensity coupled into the integrated optical circuit) or in the active material used as

Figure 1. Hybrid sensor device including integrated optical circuit on glass, photodetector array and chamber for test-gases. A 2 μm thick SiO₂ layer protects the waveguides except for an interaction window on the measurement arm and a compensation window on the reference arm, the latter not indicated on the figure.
waveguide superstrate (light absorption). These limitations reduce the capability of the sensor to measure and even sometimes to detect phase shifts inferior to π radians. Phase shifts that are multiples of 2π radians can of course be readily measured using amplitude-level triggered counters.

The small phase shifts often involved in optical evanescent wave sensors for biological and chemical applications create a need to cope with these limitations. This was the reason to develop a sensor based on the two-wave interferometer presented by Schanen et al. 

**Principle of operation.**

Like the Mach-Zehnder interferometer the source beam is first coupled to a single-mode waveguide and then divided into two beams at the Y junction. Each beam propagates in a curved single-mode waveguide and then in a tapered waveguide that transforms the confined beam into a collimated beam. One beam constitutes the measurement arm of the interferometer, while the other beam serves as a reference. The waveguides are confined waveguides fabricated by sodium-potassium ion-exchange in a glass substrate. They are covered by a 2 μm thick layer of SiO₂, except for a 26 mm long interaction window on the measurement arm and a 1 mm compensation zone on the reference arm. The compensation zone ensures equal transition losses between the two arms.

The active material, for example a polysiloxane being able to absorb different hydrocarbons and thus change its optical index, is spin-coated or deposited by other technological means on the optical substrate. This material acts as the waveguide superstrate in the non-protected zones. Its optical index will therefore modify the effective index of the waveguide.

![Figure 2](image-url)  
*Figure 2. Calculated image of the interference pattern in the intersection zone of the beams from the two tapers. (Units in microns.)*

Figure 2 is a calculated image of two coherent Gaussian beams crossing at an angle of 1°. White represents light intensity above a certain level. The 40 μm beam waist and the divergence angle of 1° correspond to the output signal of the tapers. We notice the extension in x and z-direction of the interference pattern occurring in the intersection zone of the two beams. The photodetector array will be placed in this zone in a plane perpendicular to the z-axis as shown in figure 3.

The interference pattern in the photodetector plane is given by

\[
I(x, t) = 2|A(x)|^2 \left[ 1 + \cos(2k\sin \gamma x + \varphi(t)) \right] \tag{1}
\]

where \(|A(x)|^2\) is the envelope function depending on the position of the photodetectors in the z direction and the intensity-profiles of the beams, \(k\) the wavenumber, \(\gamma\) the semiangle between the interfering waves, and \(\varphi(t)\) the phase difference between the two beams. A variation in \(\varphi(t)\) causes the interference peaks to move left or right while the
envelope function \( |A(x)|^2 \) remains stationary.

We wish to monitor the interference pattern by the use of a photodetector array to determine the temporal change in \( \varphi(t) \). Our aim is to choose the \( x \) position of each photodetector so that the \( x \)-dependent phase-term in (1), \( 2k \sin \gamma x \), from now on called \( \alpha_k \), equals \( -\pi, 0, \frac{\pi}{4} \) and \( \frac{3\pi}{4} \). The normalised signals can then be written
\[
I_{\alpha_k}(t) = \frac{1}{2} \left[ 1 + \cos(\varphi(t) + \alpha_k) \right] 
\]
where
\[
\alpha_k = 2k \sin \gamma x = -\pi, 0, \frac{\pi}{4}, \frac{3\pi}{4} \tag{3}
\]
This choice lets us calculate the phase difference using
\[
\varphi(t) = \arctan \left( \frac{I_{\alpha_k}(t) - I_{\alpha_0}(t)}{I_{\alpha_0}(t) - I_{\alpha_k}(t)} \right) \tag{4}
\]
During the measurement, consecutive values are compared and the difference is integrated to obtain the total phase shift.

The photodetector array.
Although the principle cited above seems simple, the small dimensions of the interference pattern create an experimental problem. For reasons inherent to technology and interferometer design, the semiangle \( \gamma \) in our integrated optical component was 0.9° and the tapers' output waist about 40 \( \mu \)m. The wavelength was 0.83 \( \mu \)m. This gives a distance between interference maxima (\( \alpha = 2\pi \)) of 16.8 \( \mu \)m, which is a small value taken into account that the pixel size of commercially available CCD cameras is about 10 \( \mu \)m.

We monitored the interference pattern by two methods: a commercially available CCD-camera combined with optical magnification of the interference fringes, and a special photodetector array designed to match the optical signal without magnification. The results from the first method will be reported elsewhere.

The silicone photodetector array contains four 125 \( \mu \)m long PN-junctions with an active area width of 1.5 \( \mu \)m. The distances between the zones are 8.4, 4.2 and 8.4 \( \mu \)m, which correspond to the values chosen in equation 3. The photodetector responsivity was measured to 0.15 A/W. The photodetector currents, in the range 0 - 1 \( \mu \)A, were converted to tensions in the range 0 - 10 V by low-cost operational amplifier circuits. These circuits were placed close to the detector array and shielded in a metallic housing. Each signal was sampled by a 12-bit analogue to digital converter and the data were processed in real-time by a personal computer. After digitalisation several samples were averaged to suppress noise. The signals were then normalised with respect to calibration data.

Experimental set-up and results.
In addition to the elements of figure 1, the experimental set-up contained a light-source and the signal-processing equipment mentioned above. The light-source was a pigtailed laser diode (\( \lambda = 0.83 \) \( \mu \)m) with a stabilised current source. The ion-exchange technology permits good coupling\(^1\) between the monomode optical fibre and the confined waveguide. Direct butt-coupling of the diode laser has also been reported for similar devices\(^6\) and represents an interesting alternative for industrialisation as it yields a compact result at a reasonable cost. The photodetector array was positioned in the interference zone outside the optical component or attached to its end-face. Its position should be within a range of about \( \Delta x = 40 \) \( \mu \)m and \( \Delta z = 500 \) \( \mu \)m. The \( y \) direction range depends on the length of the detector zones, and could be several hundred microns.
Finally a test cell was fixed to the component surface. Input and output tubes were attached to the cell, and permitted the transport of vapours as well as liquids for sensor testing. The small volume of the test cell (about 0.5 cm$^3$) made possible the testing of explosive gases without important safety precautions.

The sensor system was tested using synthetic air saturated with hexane vapour. The active material was the dimethylphenylmethyl-siloxane copolymer deposited in a thin layer on the waveguide substrate. The graphic in figure 3 shows the continuous phase shift measure performed by the algorithm described above. The phase shift was measured with a precision of 5·10$^{-3}$ radians, while the theoretical limit due to the quantisation error in the 12-bit A/D converter was 10$^{-3}$ radians. Higher precision operational amplifier circuits and A/D converters should further improve these results.

**Conclusion.**

We have fabricated a compact, hybrid sensor system including an integrated optical circuit and specially adapted electronics for photodetection. One application, detection of hexane vapour, has demonstrated the sensor performance. More complete results concerning applications in the chemical and biological domains will be presented elsewhere.

The sensor elements are well suited for serial production. Optical phase shifts can be measured with a precision of 5·10$^{-3}$ radians using 12-bit A/D converters and low-cost operational amplifiers. We are now working on the transfer of the signal processing algorithm from the personal computer to a microcontroller in order to obtain a complete, independent sensor system.

**Bibliography.**


WAVEGUIDE SURFACE PLASMON RESONANCE BIOSENSOR FOR THE AQUEOUS ENVIRONMENT

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We report the fabrication and performance of gold coated waveguide surface plasmon resonance biosensors. Biotin-avidin binding reactions at the sensor surface were observed. The output power of the sensor showed a decrease of 32% on binding a dual layer of biotin-avidin.

1. Introduction

The use of guided-wave optical biosensors, and their market possibilities, is well documented. Many optical transducer mechanisms are possible and they are currently generating a great deal of excitement as the potential of such devices is realised in the laboratory and, increasingly, commercially. Optical biosensors are generally small, light, and rugged, offering the portability required for a field monitoring system. Integrated optical sensors maybe connected by optical fibres and allow for the fabrication of multiple sensors in a single substrate using photolithographic techniques.

The exploitation of a surface plasmon resonance (SPR) to form the basic transduction mechanism of a chemical sensor has been known for some years. A surface plasmon is usually a transverse magnetic (TM) electromagnetic mode guided by the interface between two media whose dielectric constants have real parts of opposite sign. For visible light this requirement can be fulfilled by a dielectric and a metal. The formation of a surface plasmon can be achieved by using a 'bulk' optical component such as a prism, and equipment employing this approach is now commercially available. Another option is to employ the distributed coupling between a planar waveguide and a surface plasmon in a metal-coated waveguide. The use of SPR transduction in an optical sensor allows for the use of the metal film as an electrode for electrochemical control of sensing reactions.

In this paper we demonstrate the use of a simple waveguide SPR sensor to measure the binding of several layers of a biotin-avidin system onto the surface of the sensor. This device represents a portable sensor realisation of the otherwise laboratory-based 'bulk' SPR technique.

2. Waveguide SPR Sensor Design and Operation

The general configuration of the sensor whose operation can be described in terms of coupled modes is detailed in figure 1. A single TM mode is excited in the waveguide and this mode then couples to the surface plasmon mode, guided by the interface between the metal layer and the dielectric superstrate, if the two modes are closely phase matched. If a thin dielectric film is adsorbed to the metal surface then the effective index of the surface plasmon mode will be altered, changing the coupling condition between the waveguide and surface plasmon modes. This change can then be monitored, for example, as a function of wavelength or a change in the output intensity of the sensor.

A rigorous model has been used to evaluate the performance of the type of sensor shown in figure 1 when monitoring the adsorption of a thin dielectric film to the surface of the metal layer. A typical SPR curve is given in figure 2, for a waveguide SPR sensor based on a low refractive index glass substrate, a potassium ion-exchanged waveguide, and a thin gold film. The figure shows that the SPR is located at an analyte index close to that of water, indicating that it is not strictly necessary to employ a buffer layer in the sensor design to enable operation in an aqueous
environment. However extensive design work\(^4\), has revealed that the use of a buffer layer in the sensor design should lead to the greater sensitivity for the device in an aqueous environment. Modelling also shows that the transverse electric (TE) polarisation is not significantly affected by the adsorption of thin films and may be used as a reference.

3. Experimental Measurement of Biotin-Avidin Binding Reactions

The waveguides were fabricated by potassium ion-exchange in low index glass \((n=1.471)\) substrates at a temperature of 385 °C for 18 hours. A thin gold film was deposited on top of the waveguides by thermal evaporation. The length of the gold film varied from 1.5 mm to 3.4 mm, in 100 μm steps, over a total of 40 waveguides each with a nominal width of 2 μm. Two samples were fabricated with identical ion-exchange parameters but with gold thicknesses of 64 and 36 nm. The variation in the thickness of the gold films was determined to be ±10% of the quoted thicknesses over the area of both of the films. Light from a 10 mW linearly polarised, intensity stabilised, He-Ne laser, operating at a wavelength of 632.8 nm was end-fire coupled into the waveguide under test so that both TM and TE modes were excited in the device. The ratio of the TM output power to the reference TE output power was taken, to correct for instrumental drift, and recorded on a chart recorder.

The first experiment, employing the device with a 64 nm thick gold film, was performed by measuring the ratio of the TM/TE output signals from the sensor as a function of the analyte refractive index before and after adsorbing a combined layer of thermally denatured biotinylated bovine serum albumin (BSA) and polystreptavidin. The analyte index was varied by attaching a flow cell on the sensor and using a peristaltic pump to flow sucrose solutions over the gold film. By dissolving increasing weights of sucrose in de-ionised water, solutions of varying refractive index could be readily produced. The refractive index of each sucrose solution used was measured using an Abbé refractometer at \(\lambda = 589.3\) nm. The sensor surface was then washed with phosphate buffered saline (PBS), \((0.1\) mol/l \(KH_2PO_4, 0.15\) mol/l \(NaCl, pH 7.5)\), and incubated for 10 minutes with a solution of 40 μg/ml BSA in PBS. The surface was then washed again with PBS before being incubated with a solution of 40 μg/ml polystreptavidin in PBS. Finally the sensor surface was washed with PBS solution. The measurements of the ratio of the TM/TE output signals of the sensor were then repeated using sucrose solutions with the same index as used previously.

The second experiment used the sensor with a 36 nm thick gold film. The ratio of the TM and TE output signals from the sensor was measured as a series of biotin-avidin films were adsorbed on the gold layer of the sensor. The peristaltic pump was replaced by a flow injection analyser pump and six way valve. The sensor was initially washed with PBS \((n=1.337\) at \(\lambda=589.3\) nm) at a flow rate of 0.186 ml/min (used for all solutions) to provide a system baseline. Subsequently 40 μg/ml BSA in PBS solution was passed over the sensor surface for approximately 10 minutes. Following this, a solution of 40 μg/ml polystreptavidin in PBS was passed over the sensor surface for the same period of time. The biotin-avidin solutions were alternately passed over the sensor surface to build up several complete biotin-avidin layers. Finally PBS was passed through the flow cell to ensure that the biotin-avidin layers were firmly attached to the sensor.

4. Results and Discussion

Plots of the TM/TE ratio as a function of superstrate index, before and after adsorbing a combined biotin-avidin layer are shown in figure 3 for the sensor with a gold thickness of 64 nm and an interaction length of 3.3 mm. The SPR in the absence of biotin-avidin is centred at a superstrate index of 1.355. At superstrate indices below this, the curve has its greatest slope at an index of 1.348, representing the most sensitive operating point of the sensor. However the slope of the SPR curve at the refractive index of water is substantial and indicates that the device will operate as a sensor, while not fully optimised.

The second plot in figure 3 shows the SPR curve for the sensor after a biotin and an avidin layer have been adsorbed to the gold surface. It is believed that the biotin and polystreptavidin layers have thicknesses of approximately 3 nm and 6 nm respectively\(^5\). The centre of the resonance has now
shifted to an index of 1.351, leading to a decrease in the TM/TE ratio at a superstrate index of 1.333 of approximately 16.5%, showing that the sensor adequately detects the adsorbing of biotin and then avidin to the sensor surface in an aqueous environment.

Figure 4 shows the variation in the TM/TE ratio as a series of biotin and then avidin layers are adsorbed to the surface of the sensor having a 36 nm thick gold film and an interaction length of 4 mm. The change caused by the adsorption of the first biotin layer to the sensor surface is 14%. However the slope is greatest when the second biotin layer is bound to the sensor, with a decrease in the TM/TE ratio of 35%. The location of this maximum at a point other than on the attachment of the first molecular layer also indicates that the sensor is not fully optimised for water. A similar biotin-avidin protocol has also been applied to an integrated optical Mach-Zehnder interferometer which has also been interrogated by measuring the change in the output power of the sensor as the biotin-avidin layers adsorb to the surface of the device. It is clear that both types of sensor are capable of monitoring a binding sequence of biotin-avidin layers and exhibit similar performance, although neither device is fully optimised.

The curve plotted in figure 4 was extracted from the chart recorder trace displayed in figure 5, which details the real-time variation in the output of the SPR waveguide sensor as the biotin and avidin solutions were pumped over the sensor surface. The plot shows the first 3 biotin, and 2 avidin, layers attached to the device. The gap in the trace was caused by an air bubble which was visually observed to enter the flow cell at that time.

5. Conclusions

Gold coated waveguide SPR sensors have been fabricated and used to monitor the attachment of biotin-avidin layers to the surface of the sensors in the aqueous environment. Fabrication was kept as simple as possible, leading to reliable devices which are not, however, fully optimised for operation in water. It is expected that the incorporation of a low refractive index buffer layer into the sensor design will lead to devices with a greater sensitivity, if required.

Further studies are also being carried out into the experimental optimisation of the gold film parameters and the form of the detection system. Utilising the gold film as an electrode to allow the possibility of performing electrochemical experiments also remains to be investigated and is a potential advantage over other, dielectric based, integrated optical biosensors. It is intended that this type of waveguide SPR biosensor will be employed to monitor low concentrations of organic pollutants in ground water.

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References

Figure 1. Schematic representation of a waveguide SPR biosensor.

Figure 2. Theoretical plot of the normalised output power of a gold coated waveguide SPR sensor.

Figure 3. Shift in the SPR curve of a gold coated surface plasmon sensor on adsorbing a monolayer of biotin and avidin.

Figure 4. Variation in the ratio of the TM and TE output signals of the sensor as a series of biotin and avidin layers are adsorbed to the gold surface.

Figure 5. Chart recorder plot of the sensing of a sequence of biotin-avidin layers.
LOW COST POLYMER-OPTICAL AMMONIA SENSOR

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ABSTRACT

An integrated optical ammonia gas sensor based on evanescent field absorption is developed. The sensitive element is a low cost polymer multimode waveguide, fabricated by replication from a V-shaped mould and coated with an immobilised indicator dye. The moulds are prepared by silicon micromachining. The sensor measures ammonia concentrations lower than 5 ppmv, and shows a short response time.

INTRODUCTION

Sensors for chemical and biological substances are important for process control, environmental control and pollution detection. Most of the disadvantages that exist with electrochemical devices (e.g. short lifetime, difficulties in miniaturisation, need for suitable reference electrodes) can be avoided using a fibre coupled optical sensor. Optical sensors fabricated using an integrated optic technique allow the construction of optical sensor systems for parallel detection of several chemical substances, provide the generation of reference signals and reduce the problems of cross sensitivities. In [1] an optical ammonia sensor on the bases of glass waveguides is described which is fabricated by field assisted ion exchange. The production of this sensor is very cost intensive and therefore not well suited for mass applications. In this paper a new technology for the fabrication of low cost optical sensors is presented. It is based on replication techniques using high quality optical polymers and silicon micromachining for the preparation of the precise micro moulds. This process we called SIGA: Silizium, Mikrostrukturierung, Galvanik und Abformung[2].

PRINCIPLE OF OPERATION

The principle of operation of the evanescent field optical sensor is shown schematically in Fig. 1. The basic element of the sensor is the polymeric multimode waveguide coated with the immobilised indicator dye Bromcresolpurpur. Depending on the concentration of ammonia, the indicator dye reversibly changes its colour from yellow to blue. The change in colour leads to an attenuation of the evanescent field of the guided light, especially at 600 nm wavelength.
SENSOR FABRICATION

For the fabrication of the sensor waveguide a triangular cross section has been chosen (see Fig. 2), because this configuration is simple to prepare by silicon V-groove etching, it provides smooth sidewalls (111-crystal planes) and therefore low light scattering, and offers a large waveguide surface to enhance the sensor sensitivity.
The waveguide fabrication starts with the preform preparation by V-groove etching into silicon. These silicon structures are electroplated in Nickel to create solid metal moulds. In order to create waveguides like that shown in Fig. 2, the moulds are passivated on the surface and electroplated again to obtain Nickel V-grooves. These V-grooves are filled by our liquid waveguide core monomer mixture and covered by a PMMA plate. This procedure is carried out in a pneumatic press in which the monomers is hardened by UV-light. The monomer mixture consists of different acrylates to be well suited for processing [3]: 50% ethylenglycoldimethacrylate (viscosity, stability), 27% butylmethacrylate (flexibility), 10% tetrafluoropropylmethacrylate (refractive index tuning), 10% methylmethacrylate (adhesion on the PMMA-substrate), 3% photoinitiator. An attenuation of 0.6 dB/cm (wavelength: 600 nm) of the V-shaped multimode waveguides (width: 75 μm) was measured without an indicator coating using the cut-back method.

Now, the evanescent field ammonia sensor is prepared by coating the surface of the waveguide by the indicator dye (Bromcresolpurpur) which is solved in sol-gel or in polymers in order to be immobilised [4]. Here the sol-gel layers are spin coated onto the substrates with typical thickness around 0.5 μm. The adhesion of the sol-gel layers to the polymer waveguides was found to be excellent under normal environmental conditions (humidity not greater than 60%).

EXPERIMENTAL RESULTS

Realised sensors have been coupled with a standard multimode fibres (core diameter: 50 μm) and spectrally characterised by using a tuneable withlight source. The exposure of the sensor to defined ammonia test gases has been achieved by fixing the sensitive chip surface upside down as a cover on a small chamber which is flowed by diluted ammonia. Figure 3 shows the reversible response of a high sensitive (10 ppm,) ammonia sensor. The highest sensitivities obtained were less than 5 ppm,. The time response of the sensor depends on the thickness and the porosity of the sensitive layer and the ammonia concentration. Sol-gel layers have shown faster response times than polymeric ones. In Fig 3 (sol-gel coating) the response time (t90) is 55 seconds. For polymer layer the response time is increased to a few minutes. The sensors show a humidity and temperature dependence of the signal which is, however, reversible and therefore calibratable. Limitations of the sensors are defined by the temperature stability of the polymeric materials (85° for PMMA based systems) and by the stability of the sensitive layers against humidity. For sol-gel layers the maximum allowable humidity is 60 %, whereas polymer layers may be used even for applications in hydrous solutions.
CONCLUSION

Low cost replication techniques have been utilised to fabricate polymeric evanescent field ammonia sensors. High sensitivity (< 5ppm) and fast response times (55s for 10 ppm) have been achieved for sol-gel coatings. Polymer coatings are especially suited for applications in high humidity or hydrous environments showing, however, slower response times. Besides the mass production capability, the replication technology in polymers offers the potential of cost effective integration of coupling elements (e.g. gratings) and passive alignment structures (e.g. for fibre alignment).

REFERENCES

1 Introduction.

Integrated optics (IO) is now older than a quarter of a century. Nevertheless, electromagnetic modelling of IO devices is still a widely open, and, at least from time to time, fashionable subject of research. The basic reasons why, in sharp contrast with microwave waveguides and with step-index optical fibers, analytical solutions of Maxwell's equations in IO structures can be found very seldom, are well known:

- geometrical shapes of IO waveguides give troubles from the very beginning; in fact, in most cases they do not even allow separation of variables;
- index distributions are, first, difficult to describe analytically, and second, often they do not allow to pass rigorously from Maxwell's equations to the wave equation;
- approximations that work very well in neighbouring fields (e.g., slowly-varying media, or weak guidance) are often unacceptable in IO, where some index differences (typically, between guide cores and air) are large.

Since the very beginning [1], these constraints have triggered an extremely deep, and still restless, interest in modelling techniques based on numerical methods. But none of these, so far, has been proved to be a panacea. Given the impressive improvements that took place, during these 25 years, not only in computers themselves, but also in the familiarity of those who work in IO with computers and with numerical methods, there is no doubt that the lack of a complete success on this front has been caused by the same fundamental reasons that hinder analytical approaches.

In recent years, it became necessary, in IO, to open a new frontier, that of nonlinear guided-wave propagation. Problems of this kind may range from simple ones, where extensions of very well-known linear methods (e.g., the FFT-BPM) are almost trivial, to extremely complicated ones, where one does not get any meaningful result unless physical models of the medium itself are intimately mixed with electromagnetic wave propagation models.

In this scenario, an effort to list all the existing methods, within the space and time limits of a conference presentation, would lead inevitably to grossly incomplete results. It is more advisable to recommend to our audience to consult exhaustive reviews that either have been recently published (e.g., [2]), or are in the process of being published [3].

It is self-explanatory that different numerical methods, being based on different simplifying assumptions, do not necessarily lead to the same results, when applied to the same structure. For this reason, detailed comparisons among various methods, on the ground of "problem sets" that were previously agreed upon, have become very popular. Also for these, examples can easily be found in the literature [4, 5]. However, let us warn the audience that, even when using the same principles, different groups may reach different results because of different programming approaches, or for other similar reasons. In spite of this, we believe that these comparative tests should be encouraged, provided that participants are willing to explain details on their programming approaches. Further comments on this point will follow in the next Section.

Rather than offering another example of "round robin tests", we prefer to devote the core of our presentation to the following questions:
how advanced are we now in the field, with respect to where we should be by the time IO becomes a fully mature technology;

• in which directions is the IO-modelling community making progress;

• which directions appear to be suitable for future exploration and exploitation.

 Needless to say, answers on such issues are strongly dependent on personal opinions and biases.

Methods and approaches to modelling can be classified following various criteria, like: analytical vs. numerical methods; purely functional models vs. physical models; linear vs. nonlinear models. All of them will be useful in organizing our presentation. The last one is unambiguous only for passive devices; but active device models can not be covered sufficiently in depth within the limits of this paper, so they will be omitted completely.

There is still another classification criterion, which we propose and use: divide into classes according to the purpose of the model. In fact, a model can be made for better understanding experimental data; or for predicting new phenomena; or for CAD of devices and systems. The relative weights of these purposes are a measure of the maturity of a technology. On this point, compare today's situations in three fields: microelectronics, classical optics (lens design), and IO. In the mature fields, chances of predicting something new without a suitable CAD package are negligible. In IO, the situation is almost reversed. The following Sections will be devoted to more specific comments and opinions on the categories of linear and nonlinear devices.

2 Linear devices

As known, most of the modelling work in IO has dealt, so far, with this class of devices, which in turn lends itself to a further subdivision: longitudinally invariant structures, and structures which vary along the direction of propagation, z.

This distinction has indeed strong implications on modelling, particularly on numerical approaches. Additional mathematical complication introduced by the z-dependence can force one to make rougher simplifying assumptions, compared to z-independent cases, in order to maintain processing times and memory occupation within reasonable limits. A typical example is the choice between vector and scalar methods. If we concentrate, for instance, on the finite-element method, it is well known that its full vectorial version predicts, in longitudinally invariant structures, polarization-related effects that are disregarded by scalar versions. It is very demanding to preserve these capabilities for a z-dependent structure. Notice, on the other hand, that analytical techniques have lead, in the recent past, to theoretical breakthroughs on z-dependent structures [7] and to important results on vector effects in longitudinally-invariant ones [8]. Hence, we identify analytical [9] and semi-analytical [10] techniques in apparently complicated structures and/or in z-dependent ones, as one of the areas where research is still in fast progress.

Coming back to numerical methods, abundance of competing techniques made it easy and useful to draw comparisons, on the basis of preslected tests. These tests encompass methods which can, by now, be called classical (like the FFT-BPM, the FD-BPM, the FEM, the FDM) as well as methods which are still rather new, at least in IO. Some of the latter ones (like FD implementations of eigenmode expansion techniques) had been successfully used for years in microwaves. As mentioned in the Introduction, the state of the art is well represented by examples like [2, 3, 4], where pluses and minuses of each method are well described. Let us stress here that, in some of these reports, all the methods which are compared share some fundamental assumption, or some crucial preliminary step - typically, the use of the effective-index method (EIM) - for passing from a 3-D to a 2-D numerical problem. We believe that critical evaluation of the influence of these assumptions is one of the guidelines for urgent future work. Indeed, it has been pointed out several times that passing from 3 to 2 dimensions when using a BPM technique may yield puzzling results; for example, Fig. 1 (from [11]) refers to a right-angle intersection between SiO2-on-Si waveguides. So, the importance of round-robin tests grows rapidly as a function of severity and criticism in the attitude of all participants.

Efforts are being made to move from device simulation to CAD. Just as an example, we quote a procedure for minimizing bend losses in LiNbO3 waveguides [12], where BPM and semi-vectorial FD methods have been interfaced with a standard optimization procedure, the so-called symplex method. However, there are still at least two big hurdles on the way to CAD in IO. One is because some of the IO
technological processes are not yet completely mastered, as their results depend on many experimental parameters [13]. The other one is because of insufficient accuracy in some of the measurements that are necessary in order to feed a CAD package with all the numbers it requires. As long as experimentalists do not remove these causes of uncertainty, there is no incentive to develop CAD procedures whose sophistication is beyond what can actually be exploited.

3 Nonlinear devices

Forces that drive IO towards "photonic switching" have been known for quite a few years, are very well grounded, and are heavily advertised too. Theory and modelling of IO devices which operate in nonlinear regime is now slightly older than 10 years [14]. Leaving aside the early experiments on self-focusing and self-trapping that go back to the 60's, before the birth of IO, we may say that the first experimental demonstration of modes guided by a self-induced index change were made in 1986 [15]. Interest in theory and modelling of such devices is growing at a high rate, but the distance from the final target, CAD, is still much larger than in the linear case. Most of the approaches are still physics-oriented, rather than engineering-oriented. With reference to the scheme of classification that we mentioned in the Introduction, we estimate that the amount of theoretical work that has been invested so far in better understanding experimental data, and to predicting new phenomena, are comparable in size.

One of the basic reasons why there is a strong physics-oriented content in these studies is because, very often, the physical model of the phenomenon which gives rise to the nonlinearity is not yet satisfactory. Some of the main reasons why this occurs are: the time scale of nonlinear response can be comparable to the length of the propagating pulses; or there may be strong resonances (sometimes, two-photon ones [16]) in the vicinity of the carrier frequency. Notice how complication grows exactly under those circumstances where application interest grows (fast devices, with strong nonlinearities). For very important details, like, e.g., saturation of nonlinear coefficients, quantum-mechanical models are strictly necessary. The same is true in order to explain fast nonlinear phenomena in guided-wave active devices (e.g., [17]). It is impossible to cover here subjects that are so broad. Being very schematic for the sake of clarity, we may state that there is only one class of nonlinear propagation problems, of interest to IO, where several well-established models, both analytical and numerical, are available and developed to a stage where one can draw comparisons. It is the class of phenomena that are modelled by the well-known NL Schrödinger Equation, which, in normalized units, reads:

\[
\frac{\partial u}{\partial z} + \frac{\partial^2 u}{\partial t^2} + 2|u|^2 u = 0
\]  

(1)

or by variations on this theme. Many techniques that have been applied, or suitable modified, in IO, were already available, or at least had been proposed, in fluid dynamics, or in the theory of optical fibers. Problems in IO which can be modelled solving the NLSE range from propagation of very short (femtosecond) temporal solitons, to NL directional couplers and/or self-switching devices (spatial solitons). An essential feature in all of them is a Kerr-type nonlinearity; variations on this are still at a much more primitive stage. Just for this class of phenomena, the subject is mature enough to allow a fairly systematic classification of approaches, and some comparison. Analytical methods (as well as semi-analytical ones) appear to share the feature that, at a suitable stage, the original infinite-dimensional problem is approximated by a finite-dimensional one. The most commonly used, and most advanced, among them, are:

- variational methods [18, 19, 20]. Essentially borrowed from fluid dynamics, they proceed by identifying a suitable Lagrangian and/or Hamiltonian density, such that Eq. (1), or others derived from this, can be looked at as Euler's canonical equations. Normally, the next steps are to introduce trial functions, with a finite number of parameters (i.e., the pass to the reduced Lagrangian and/or Hamiltonian) and then solve a finite set of ordinary differential equations. In this way, the original infinite-dimensional problem is approximated with a finite-dimensional one. Among the typical results of this approach, when the number of dimensions is reduced to two, let us quote "phase portraits" (see an example in Fig. 2, from [21]), which are powerful helps in intuitive understanding of problems like stability, bifurcation, etc.

- The so-called Soliton Perturbation Theory [22], where, assuming small deviations from a soliton solution of a similar equation, one derives a set of linear differential equations for the parameters
of the perturbation.

- The Inverse Scattering Method [23], [24] which is very elegant and powerful, but, unfortunately, is applicable only to some narrow classes of partial differential equations, not to all those of interest in NL IO.

Coming back to the NLSE, the unknown $u$, representing a slowly-varying envelope, affects the refractive index. Consequently, the distinction between $z$-dependent and $z$-independent structures is blurred, in the nonlinear case. Among numerical methods, the BPM, in both the FFT and the FD versions, dominates over all the others. However, a few warnings may be useful to those who used it only in the linear case. The first one is that, in the NL case, results are strongly dependent on the integration steps along both coordinates, $\Delta z$ and $\Delta \xi$. To get reliable outputs, their size must be orders of magnitude smaller than in linear BPM. A second reason for being cautious is what is behind the NLSE, or similar equations. Very often, one arrives from Maxwell's equations to such a 2-D equation giving for granted that the field dependence on other coordinates remains the same as in a similar linear problem. This "weak nonlinearity" assumption has been demonstrated experimentally to be well grounded in SiO$_2$ fibers. But numerical models of some IO structures, where multidimensional BPM simulations offer an alternative to simplifying assumptions like coupled-mode theory, proved that differences due to introducing or omitting this assumption can be impressive (see an example in Fig. 3).

For time-harmonic cw fields in longitudinally-invariant structures, the fundamental interest is in finding the profiles of nonlinear guided modes, and their propagation constants, as functions of beam power. Compared to the previous class of problems, it appears that this one has attracted much less interest, until now. To the best of our knowledge, the only techniques which have been used rather systematically, yielding well consistent results, are suitably modified versions of the Finite-Element Method (FEM) [25, 26], where the NL index distribution was calculated iteratively, using at each step the field profile at the previous step. The front of NL FEM is a hot one. For example, we have been - and still are - working [27] on a totally different iterative technique, where a converging sequence of corrections is calculated using the so-called polarization currents. In principle, this approach is very appealing, but in practice it runs into problems that are typical of numerical analysis, as it requires inversion of matrices that, on some occasions, are not well conditioned.

Another question, on the front of NL modelling in IO, which is now neglected almost always, but may become very hot soon, comes from the fact that, for some kinds of strong nonlinearities, the scalar approximation in Maxwell's equations is no longer well grounded. If one rejects it, then one does not arrive to the NLSE any more. A critical evaluation of many NLSE-based results that appeared recently in the literature may be expected for the near future, provided one develops suitable vectorial numerical methods. The fully vectorial FEM is a very good candidate, but further improvements are necessary in terms of processing time and memory occupation. When this goal is achieved, or, alternatively, if the exponential growth in processing power continues over the next few years, then this method would become very useful for $z$-dependent structures as well.

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![Figure 1:](image)
Abstract - A CAD-tool for simulation and design of integrated optical circuits, based on a professional microwave design system is reported. An example describing the complete design and simulation of a MZI switch is given.

Introduction

Computer aided design tools for integrated optical circuits are far less developed than their microwave counterparts. In general commercially available tools initiate the design and simulation based on a physical description of the circuit and use BPM based computational techniques to carry out the simulation. Computer aided design tools for microwave integrated circuits use a more abstract approach initiating the design on a symbolic level. From this level the simulation is performed and the layout is generated (see Fig. 1). The advantage of this approach is that the circuit can be better structured and that one can choose both BPM and other simulation methods for different components or subcircuits. Realizing that integrated optical circuits are conceptually quite similar to microwave integrated circuits, we have chosen to adapt a professional microwave design system, Hewlett Packard's MDS, for the CAD of optical chips [1].

General features

HP's MDS provides a graphical interface for building circuits with standard or user-defined components. MDS performs (multi-) parameter sweeps and automatic (multi-) parameter optimizations. The simulation results can be processed and presented on screen, or exported to other applications. Mask layout can be (automatically) generated, manipulated and viewed on screen. Subcircuits can be grouped into new circuit components facilitating hierarchical designs. User supplied models written in C, C++ or FORTRAN can be used to calculate the component's scattering matrix $S$. These models are linked with the standard MDS component library and can be used in an identical fashion. We have implemented a series of user-compiled models to realize the optical simulator.

Description of optical components

The coupling between optical components may take place via guided modes and radiation fields. If coupling through radiation fields can be neglected, optical components may be seen as individual units connected to each other at well defined ports. In this concept, the response of an $N$-port component can be described by its $N \times N$ $S$-matrix. For each guided mode one port is used. An ideal monomode waveguide is a 2-port component described by a $2 \times 2$ scattering matrix with $S_{11} = S_{22} = 0$. The junction between two monomode waveguides is described by a $2 \times 2$ scattering
straight curved waveguide
waveguide waveguide junction

\[ \begin{pmatrix} 0 & e^{-j\beta l} \\ e^{j\beta l} & 0 \end{pmatrix} \]

\[ \begin{pmatrix} 0 & e^{-j\beta\phi} \\ e^{j\beta\phi} & 0 \end{pmatrix} \]

\[ \begin{pmatrix} 0 & \sum U_1 U_2^* \\ \sum U_1^* U_2 \end{pmatrix} \]

Table 1: Graphical representation and S-matrix description of monomode waveguide components.

Figure 2: (a) Multimode waveguide and junction connecting to two curved waveguides. (b) Component used for specifying the waveguide structure.

matrix. The matrix elements are given by the overlap integral of the modal fields, \( U_1 \) and \( U_2 \), in each of the waveguides: \( S_{12} = S_{21} = \sum U_1 U_2^* \). As reflections in optical chips are usually small, we assumed that \( S_{11} = S_{22} = 0 \) for the junctions as well, although inclusion of reflections is straightforward. The basic elements are summarized in Table 1. The parameter list attached to each component specifies the geometry. Figure 2(a) shows an example of a multimode waveguide attached to a junction connecting it to two curved monomode waveguides. The scattering matrices for the multimode waveguides and junctions can be determined based on calculations of the modal propagation constants \( \beta \) and the corresponding modal field distributions \( U_\nu \).

As a first step we implemented the Effective Index Method [2] in combination with the Transfer Matrix Method [3] for determining the propagation constants and modal fields in straight waveguides. For curved waveguides we use a conformal transformation as proposed by Heiblum and Harris [4]. This method has the advantage of high computational speed and is well suited for parameter sweeps. It can, however, not be used for simulating continuous junctions (e.g., Y-junctions, directional couplers or tapers), where the BPM would be more suited. The University of Twente in the Netherlands has successfully implemented a 2D BPM [5] for simulating tapers in MDS.

A special component specifies the layer structure of the waveguides. An example representative of the layer structure of a strip-loaded rib waveguide is shown in Figure 2(b). For each layer the user specifies the thickness and the material used. Each of these parameters can be entered directly, as with for example the film thickness (\( d_O = 600 \) nm), or through a variable (\( d_e = \text{etch} \)).

To enter the material parameters the user can specify the (complex) refractive indices or, in the case of InP/InGaAsP, specify the bandgap wavelength and doping level. The refractive indices of InP/InGaAsP at a given wavelength are calculated using the model of Fiedler and Schlachetzki [6] and take into account the material dispersion.

Design of a Mach-Zehnder interferometer switch

The design of a Mach-Zehnder interferometer (MZI) switch is useful in illustrating the potential of the present approach. The circuit is represented symbolically in Figure 3 and consists of about 50 separate components: straight and curved monomode and multimode waveguides and junctions.
The incoming light is equally distributed into the two arms of the interferometer by the first 2 x 2 multimode interference (MMI) coupler. The second MMI coupler recombines the light into a single output waveguide. If both arms of the MZI are identical, the switch is in the cross state. Introducing a phase shift of $\pi$ in one of the arms causes a switch to the bar state. The radius of curvature of the waveguide bends and the optimum offsets between the straight and curved waveguides [7] are first determined. Next the multimode interference (MMI) couplers are designed and finally we simulate the overall switch behavior and generate the mask. Based on experience a waveguide width of 2 $\mu$m is chosen. In order to determine the optimum bending radius, we use a circuit consisting of a curved waveguide and plot the loss as a function of the radius. Figure 4(a) shows the result as it appears on the MDS screen. We choose a conservative value for the radius, 700 $\mu$m. We now optimize the offset between a straight and a curved waveguide and between two curved waveguides, and find 0.14 $\mu$m and 0.29 $\mu$m, respectively (see Fig. 4(b)). In order to guide a sufficient number of modes we choose the width of the MMI section to be 6.5 $\mu$m. The access waveguides are positioned such that the gap between them is 2.5 $\mu$m. We varied the length of the MMI around an estimated value of 240 $\mu$m and plotted in Figure 4(c) the excess loss ($-10 \log(P_1 + P_2)$) and the splitting ratio ($10 \log(P_1 / P_2)$), where $P_1$ and $P_2$ are the normalized optical power at either output. Since we are mostly concerned with a symmetrical operation, we choose $L_{\text{MMI}} = 234$ $\mu$m, where $P_1 = P_2$. All important design parameters having been determined we can now simulate the behavior of the full design. The simulation results\footnote{The simulations were done on a (low end) Hewlett Packard HP9000/710 workstation and all simulations shown take less than one minute to perform.} as shown in Figure 5, take into account the losses at junctions and radiation losses in curves. Figure 5(a) shows $P_1$ and $P_2$ as a function of $\Delta w$, the deviation from the design width for all waveguide structures. It is therefore a simulation of the sensitivity for the width...
Figure 5: (a) Output power (in dB) for the MZI outputs as a function of the structure widths. (b) Normalized power at the MZI output ports versus a variation in refractive index in one of the MZI arms. (c) Normalized power at the MZI output ports versus the etch depth.

Figure 6: Automatically generated mask.

variations due to lithographic or processing tolerances. For one of the two waveguides arms in the MZI, shown hatched, the refractive index for the film layer may be varied slightly (for instance by applying an external electric field). Figure 5(b) shows the simulated behavior of the switch as a function of this difference in refractive index. A critical parameter is the waveguide etch depth which was nominally set to 350 nm. Figure 5(c) shows the normalized power at the output ports as a function of the etch depth, from which the tolerance is directly read.

Mask generation modules have been appended to the optical component models. Figure 6 shows the mask layout directly generated from the symbolically defined circuit.

Conclusion

A powerful CAD-tool for simulation and design of integrated optical circuits based on Hewlett Packard’s microwave design system has been developed. It provides a fast and flexible system in which the circuit is described on a symbolic level. The optical behavior of the circuit can be accurately simulated and photolithographic masks can be automatically generated. Work is continuing on the implementation of additional components as well as numerical methods such as 2D BPM and 3D mode solvers.

References

ACCELERATED ALGORITHM FOR VECTORIAL BEAM PROPAGATION

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Abstract
Acceleration of a vectorial finite difference beam propagation method is investigated. Several steps, including use of a modified Crank-Nicholson scheme, a decreased initial error, a reduced iteration parameter and a transparent boundary condition, are discussed. The resulting program has a speed fast enough for calculations at intricate structures on a conventional workstation.

1 Introduction
The beam propagation method (BPM) is a powerful means for simulating the wave propagation in waveguiding structures. Scalar versions of the BPM have widely been used because of their high speed. Since the vectorial properties of the electromagnetic wave are not taken into account, however, scalar versions of the BPM are not adequate for polarization-sensitive waveguides. Vectorial versions of the BPM have been developed to overcome this a problem [1-5]. These require intensive computations, especially for three-dimensional waveguide structures. In this paper, we investigate the acceleration of the vectorial finite difference BPM (FD-BPM) by use of the relaxation method based upon the slowly varying envelope approximation. The resulting program is fast enough for field calculations at tapered structures on a conventional workstation.

2 Vectorial BPM
Assuming a harmonic time dependence, the starting point is the vectorial wave equation for the complex electric field $E(x,y,z)$ in an inhomogeneous dielectric medium which is source free and isotropic:

$$\nabla^2 E(x,y,z) + k_0^2 n^2(x,y,z) E(x,y,z) = \nabla (\nabla \cdot E(x,y,z)),$$

where $k_0$ is the wave number in vacuum and $n(x,y,z)$ is the local refractive index. Considering wave propagation through a guide along the $z$-axis, we further assume $E(x,y,z) = F(x,y,z) \exp(i\beta z)$ where $F(x,y,z)$ is the complex wave amplitude. $\beta$ is a reference propagation constant chosen such that $F(x,y,z)$ becomes a slowly varying function of $z$, its actual choice depends on the structure. Based upon the slowly varying envelope approximation, the vectorial formulation [1]:

$$\begin{bmatrix}
\frac{\partial F_x}{\partial z} \\
\frac{\partial F_y}{\partial z} \\
\frac{\partial F_z}{\partial z}
\end{bmatrix} =
\begin{bmatrix}
H_{xx} & H_{xy} & H_{xz} \\
H_{yx} & H_{yy} & H_{yz} \\
H_{zx} & H_{zy} & H_{zz}
\end{bmatrix}
\begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix},$$

(2)
can be derived, where

$$H_{qr} F_r = \frac{i}{2\beta} \frac{\partial}{\partial q} \left( \frac{2 \partial n}{\partial r} F_r \right) \quad (q, r = x, y, z; q \neq r),$$

$q, r = x, y, z$; $q \neq r$,
The waveguide structure is discretized by a grid division with grid sizes $\Delta x$, $\Delta y$ and $\Delta z$, sampling the function values at the intersection points. A new matrix equation

$$A \cdot X = b,$$  

(3)

can be obtained by use of the standard Crank-Nicholson finite difference scheme [6], where $A$ denotes a square matrix of known coefficients, $X$ is the solution column vector ($F_x$, $F_y$ and $F_z$) and $b$ is a known column vector. Eq. (3) can be solved following the simultaneous relaxation algorithm [6].

3 Acceleration of the vectorial BPM

Compared with the known scalar methods, the vectorial method has numerical complications originating mainly from the coupling among field components. Based upon the standard Crank-Nicholson finite difference scheme, the matrix $A$ in Eq. (3) for a three-dimensional waveguide structure will be dimensioned as $[(HX-2)(JY-2)]$ in a scalar method, while it has the size of $[2(HX-2)(JY-2)]$ in the vectorial method for a structure with a constant cross section ($HX$ and $JY$ are total numbers of grids in $x$- and $y$- directions, respectively). Since the simulation speed of the relaxation method is inversely proportional to $HX^3$ (if $HX = JY$), a speed difference of a factor of 8 between a scalar method and the vectorial method can be expected. Similarly, for a tapered three-dimensional waveguide structure, the speeds differ by a factor of 27.

It should be pointed out that there exist techniques to speed up the scalar BPM, such as the split-step procedure [7], leading to an even bigger speed difference between a scalar method and the vectorial method. Therefore, special steps for speeding up the vectorial BPM are required to arrive at a useful method. This is carried out by introducing the following:

(1). Modified Crank-Nicholson scheme: An explicit finite difference scheme means that field components in step $l+1$ can be calculated explicitly from the known quantities in the last step $l$, while an implicit scheme means that implicit equations containing field components in step $l+1$ have to be solved. An explicit scheme is unstable, in the sense that it yields exponentially growing answers after many propagation steps, while an implicit scheme is stable but leads to a dissipation in the calculated wave propagation resulting from the numerical method [6]. A standard Crank-Nicholson scheme, which is stable and is the least dissipative, uses the average of the unknowns from the explicit and implicit schemes. To decrease the dimensions of the matrix $A$, we apply a modified Crank-Nicholson scheme [4] to Eq. (2), using only the explicit scheme to the coupling items, while ensuring the stability by introducing a finite difference scheme parameter $\alpha$ ($\alpha > 0.5$). Thus:

$$\frac{F_x^{(l+1)}(h,j) - F_x^l(h,j)}{\Delta z} = \alpha \cdot F D[H_{xx} F_x^{(l+1)}(h,j)] + (1 - \alpha) F D[H_{xx} F_x^l(h,j)]$$  

(4a)

$$\frac{F_y^{(l+1)}(h,j) - F_y^l(h,j)}{\Delta z} = \alpha \cdot F D[H_{yy} F_y^{(l+1)}(h,j)] + (1 - \alpha) F D[H_{yy} F_y^l(h,j)]$$  

(4b)
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\[
\frac{F_{i+1}^l(h,j) - F_i^l(h,j)}{\Delta z} = \alpha FD \left[ H_{xz}F_{i+1}^l(h,j) \right] + (1 - \alpha) FD \left[ H_{xz}F_i^l(h,j) \right] + FD \left[ H_{zx}F_{i+1}^l(h,j) \right] + FD \left[ H_{zy}F_{i+1}^l(h,j) \right]
\]

(4c)

where \( h = 2, 3, \ldots, HX-1 \); \( j = 2, 3, \ldots, JY-1 \); \( l = 0, 1, 2, \ldots \). \( FD \) stands for the finite difference operation. Each of the above three equations can be rewritten as \( AX = b \) where the coefficient matrices are sparse having a tridiagonal form with fringes. Thus, the vectorial BPM is converted to three mutually related scalar BPM schemes, resulting in a higher simulation speed. The validity of this modified Crank-Nicholson scheme has been confirmed previously by the simulation of a polarization converter on InP [8].

The choice of the finite difference scheme parameter \( \alpha \) is important [5]. We used the von Neumann method [6] to analyze the stability of the modified Crank-Nicholson scheme. It can be shown that, there exists a critical value \( \alpha_0 \) (\( \alpha_0 > 0.5 \)), if \( \alpha < \alpha_0 \), the scheme is unstable, leading to an unrealistic increase of the field power. If \( \alpha > \alpha_0 \), however, there is an extra numerical power dissipation. The optimal choice is \( \alpha = \alpha_0 \). Actually, for a longitudinally varying waveguide structure, the exact value of \( \alpha_0 \) is difficult to calculate and could slightly change along the propagation direction. We usually look for the best value obtained from numerical simulation. To ensure the stability, a slightly bigger value should be used, leading to an inevitable but small spurious power dissipation.

(2). Decreased initial error: An initial estimate of the solution vector for each propagation step is necessary for the iteration in the relaxation method, which usually is chosen as the zero vector. An error defined as

\[
\sum_h \sum_j \left| A_{h,j} X_j - b_j \right|
\]

will be introduced by this initial guess. The criterion for terminating the iteration is the reduction of error by a factor of \( 10^{-P} \) with respect to the initial one, where \( P \) is a prescribed integer. A bigger initial error will correspond to a bigger number of iteration steps to obtain the same absolute accuracy, leading to a lower speed. Therefore, an appropriate initial guess is important to speed up the simulation. Based upon the local continuity of the optical field, we expect that the calculated field in the previous propagation step is a suitable initial estimate for the field in the next step.

As an example, we simulated a rib waveguide structure as described in [5] with a \( 61 \times 61 \) grid division (\( \Delta x = \Delta y = \Delta z = 50 \) nm) at a wavelength of 1500 nm we have chosen. \( \beta = 14.205 \mu m^{-1} \) and \( \alpha = 0.7 \). The HE00 guided mode field is launched as the input at \( z = 0 \) \( \mu m \). To reach a given accuracy, the zero initial guess of the propagating field requires 90 iterations for one propagation step, while the calculated field of the previous step as an initial guess needs 58 iterations only. Thus, a 55% speed increase is obtained.

(3). Reduced iteration parameter: Usually, the iteration parameter \( P \) is chosen as \( P \geq 5 \). A bigger \( P \) will lead to a higher accuracy, but the simulation speed will decrease simultaneously. Therefore, \( P \) should be chosen as small as possible within the accuracy limits required for the results.

Since the field in the previous propagation step has been used as the initial estimate for the field in the following propagation step and the propagation step size is usually smaller than 100 nm, the initial error is quite small. Our results show that \( P = 3 \) is enough for an accurate simulation, which means that the relative error between the calculated results (field amplitudes) with \( P = 3 \) and \( P = 5 \) is less than \( 10^{-4} \). Still using the same waveguide structure mentioned above, 99 iterations are needed for \( P = 5 \), while only 58 iterations are needed for \( P = 3 \), leading to a 70% speed increase.
(4). **Transparent boundary condition:** Several different boundary conditions can be posed [9], of which the Dirichlet and the Neumann boundary conditions are widely used. A widespread problem is the reflection of outgoing radiation back into the computational window from the boundaries, which causes an unphysical interference. To prevent this boundary reflection, the most common way is the insertion of artificial absorption regions adjacent to the boundaries [9]. The thickness of these regions, their maximum absorption coefficient, and their functional shape must all be carefully chosen for the method to work properly. In addition, such extra absorption regions result in runtime penalties and extra storage requirements.

A new transparent boundary condition [9] has been developed, which allows radiation escaping out through the boundaries without appreciable reflection, such that a radiation flux back into the computational window is prevented. Therefore, a smaller widow size can be used. Since the simulation speed is inversely proportional to $J^3$ for a $J \times J$ grid division, the speed has been effectively increased. As an example, a $61 \times 61$ grid division of the rib waveguide structure corresponds to a simulation time of 3.3 seconds for a single propagation step on a workstation (SUN Sparc 10/40), while 6.6 seconds for a $81 \times 81$ grid division. Consequently, the transparent boundary condition is preferred.

We have used the accelerated algorithm for our vectorial FD-BPM to simulate many waveguide structures. Its validity and accuracy have been confirmed [5, 8]. For a three-dimensional waveguide structure with a $61 \times 61$ grid division ($\Delta x = \Delta y = 50$ nm), the simulation time for a single propagation step (50 nm) is about 3.3 seconds on the workstation.

4 Conclusion

The acceleration of a vectorial finite difference beam propagation method based upon the slowly varying envelope approximation, solved by using the relaxation method, has been investigated. We have accelerated the numerical simulation in four effective ways: applying a modified Crank-Nicholson scheme, introducing a decreased initial error, using a reduced iteration parameter and applying a transparent boundary condition. The resulting vectorial beam propagation algorithm has shown a high simulation speed, fast enough for use in complicated structures.

References

MODAL ANALYSIS OF CIRCULARLY CURVED RIDGE WAVEGUIDES;
A FULL-VECTORIAL SOURCE-TYPE INTEGRAL EQUATION APPROACH

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Abstract

The source-type integral equation method has already proven to be a powerful method for determining the guided modes of a straight channel waveguide configuration. The method is full-vectorial and mathematically rigorous. In this paper, the method is extended to the circularly curved ridge waveguides, as encountered in integrated-optical and opto-electronic devices.

Introduction

Optical waveguides interconnect various devices present on an integrated optical circuit. They frequently consist of straight and curved ridge waveguide sections, see Figure 1.

Figure 1: Coherent receiver

The inaccuracies in approximate methods like the Effective Index Method (EIM) [1] show that there is need for a rigorous method to determine the guided modes in the curved ridge
waveguide such as the source-type integral equation method (STIM), which has formerly been applied for the guided wave propagation in straight channel waveguide configurations [2]. In this paper we outline the method for curved ridge waveguides as shown in Figure 2. No 2π-periodicity of the electromagnetic fields is assumed. The waveguiding structure supports guided modes of the form

\[ \{E, H\}(x, \rho, \varphi; t) = \{E, H\}(x, \rho) \exp[j(\omega t - k_\rho \rho)]. \]  

The propagation constants \( k_\rho \) are complex valued, the imaginary part accounting for the radiation loss.

**The homogeneous background**

In [1],[3] a full-vectorial source-type integral equation is derived for the guided modes when the background is homogeneous with permittivity \( \varepsilon_b \) and wave number \( k_b = \omega \sqrt{\varepsilon_b \mu} \):

\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & \frac{\varepsilon_w}{\varepsilon_b} & 0 \\
0 & 0 & 1
\end{bmatrix}
\cdot \mathbf{E}(x, \rho) = -\frac{j(\varepsilon_w - \varepsilon_b)}{4\varepsilon_b} \int_{-\infty}^{\infty} k_\rho^2 \mathbf{H}_\rho \int_{D_w} \mathbf{E}_w(k_\rho \rho) \mathbf{J}_w(k_\rho \rho') \cdot \mathbf{E}(x', \rho') d\rho' d\rho,
\]

with the electric Green's tensor \( \mathbf{G}(x, x'; \rho, \rho'; k_\rho, k_\rho) \) equal to

\[
\mathbf{G} = \begin{bmatrix}
-k_\rho^2 & -jS_z k_\rho^2 \partial_\rho & \frac{S_z k_\rho^2 k_\rho}{\rho} \\
-jS_z k_\rho^2 \partial_\rho & -\frac{(k_\rho^2)^2 \partial_\rho}{k_\rho^2} - \frac{j(k_\rho^2)^3 k_\rho \partial_\rho}{k_\rho^2} & 0 \\
\frac{S_z k_\rho^2 k_\rho}{\rho} & 0 & -\frac{k_\rho^2 k_\rho^2}{k_\rho^2 \rho^2} \partial_\rho
\end{bmatrix}
+ \begin{bmatrix}
0 & 0 & 0 \\
0 & \frac{-k_\rho^2 k_\rho^2}{k_\rho^2 \rho^2} & -\frac{j k_\rho^2 k_\rho \partial_\rho}{k_\rho^2} \\
0 & \frac{j k_\rho^2 k_\rho \partial_\rho}{k_\rho^2} & \frac{-k_\rho^2 k_\rho^2}{k_\rho^2 \rho^2} \partial_\rho
\end{bmatrix} e^{j k_\rho^2 |x' - x|},
\]

and \( k_\rho^2 = \sqrt{k_\rho^2 - k_\rho^2} \), \( \text{Im}(k_\rho^2) \geq 0 \), \( S_z = \text{sign}(x' - x) \). The p-column, \( p = x, \rho, \varphi \), of the Green's tensor \( \mathbf{G} \) represents the electric field in the spectral \( k_\rho \)-domain at the point \( (x, \rho) \) as generated by a point-source situated at \( (x', \rho') \) and pointing in the direction of the p-th unit vector. For observation points \( (x, \rho) \) inside the ridge \( D_w \), (2) constitutes a homogeneous Fredholm integral equation of the second kind. A non-trivial solution exists only for the values \( k_\rho \) that are propagation constant of a guided mode.

**Green's tensor for the multi-layered background**

For ridge waveguides, the electric Green's tensor \( \mathbf{G} \) for the multi-layered background will be constructed by means of a scattering matrix formalism. Its p-column, \( p = x, \rho, \varphi \), equals
the solution of the point-source problem. For \( x \neq x' \), it satisfies the homogeneous Maxwell equations, having for \((x, \rho) \in D^n\) the general solution

\[
\begin{align*}
\{\mathbf{E}, \mathbf{H}\}(x, \rho; k_p) &= \{\mathbf{E}, \mathbf{H}\}(k_p, k^n) e^{jk^n(x^n - z)} f^+, f^- + \{\mathbf{E}, \mathbf{H}\}(k_p, -k^n) e^{-jk^n(x^n - z)} f^-, f^-,
\end{align*}
\]

with \( k_p \) and \( k^n \) related through \( k^n = \sqrt{(k^n)^2 - k_p^2}, \Im(k^n) \geq 0, k^n = \omega \sqrt{\varepsilon n \mu_0}, \) and

\[
\begin{align*}
\mathcal{E}_e(k_p) &= 
\begin{bmatrix} 
1 & 0 \\
-\frac{-jk^n}{k_p^2} \partial_\rho & \frac{\omega \mu_0 k_p k^n}{k_p^2} \\
-\frac{-k_p k^n}{k_p^2} & \frac{-i \omega \mu_0 k^n}{k_p^2} \partial_\rho 
\end{bmatrix} J_{k_p}(k_p \rho), \\
\mathcal{H}_e(k_p) &= 
\begin{bmatrix} 
0 & -k^n \\
\frac{-\omega n k_p}{k_p^2} & \frac{i (k^n)^2}{k_p^2} \partial_\rho \\
\frac{-i \omega n k_p}{k_p^2} & \frac{-k_p (k^n)^2}{k_p^2} \partial_\rho 
\end{bmatrix} J_{k_p}(k_p \rho).
\end{align*}
\]

The reference vectors \( f^+ = (f_E^+, f_H^+) \) and \( f^- = (f_E^-, f_H^-) \) can be determined by matching the continuous tangential field-components across the interfaces between adjacent subdomains of the background. The relations for "E" and "H" components of the reference vectors decouple. The \( E \)-components of the reference vectors are interrelated through the transmission and reflection coefficient \( t_{E} \) and \( r_{E} \) defined as \( f_E^+ = t_{E} f_E^-, f_E^- = r_{E} f_E^- \). The coefficients \( t_{E} \) and \( r_{E} \) are evaluated recursively

\[
\begin{align*}
t_{E} &= t_{E}^{-1} \exp\{jk^n h^n\} \{p^n_E + q^n_E r_{E}^{n-1}\}^{-1}, \\
r_{E} &= \exp\{2jk^n h^n\} \{q^n_E + p^n_E r_{E}^{n-1}\} \{p^n_E + q^n_E r_{E}^{n-1}\}^{-1},
\end{align*}
\]

with initialisation \( r_{E}^0 = 0 \). Similar relations hold for the \( H \)-components. The Green's tensor for the homogeneous background directly yields the components \( f_i^{n-1} \). Subsequently, the reflection coefficients together with (3) give the \( p \)-column of the Green's tensor. For observation points \( x \) situated in the cover \( D^N \), the Green's tensor for the source-type integral equation (2) of the multi-layered background becomes

\[
\begin{align*}
\begin{bmatrix} 
-a k_p^2 & -b j S_z k^n \partial_\rho & b S_z k^n k_p \\
aj S_z k^n \partial_\rho & -b j (k^n)^2 k_p \partial_\rho & b -j (k^n)^3 k_p \partial_\rho \\
aj S_z k^n \partial_\rho & b (k^n)^2 k_p \partial_\rho & b -j (k^n)^3 k_p \partial_\rho
\end{bmatrix} + 
\begin{bmatrix} 
0 & 0 & 0 \\
0 & c -j (k^n)^2 k_p \partial_\rho & c -j (k^n)^3 k_p \partial_\rho \\
0 & c j (k^n)^2 k_p \partial_\rho & c -j (k^n)^3 k_p \partial_\rho 
\end{bmatrix}
\end{align*}
\]

\[
a = \exp[jk^n(x-x')] + r^N_E \exp[jk^n(x-x')], \\
b = \exp[jk^n(x-x')] + S_z r^N_E \exp[jk^n(x-x')], \\
c = \exp[jk^n(x-x')] + S_z r^N_E \exp[jk^n(x-x')] .
\]
The numerical implementation of (2) is based on the method of moments, and is extensively described in [1].

The results of the STIM are compared with those of the well-known Effective Index Method (EIM) and those of the Method of Lines (MoL). The structure considered is the GaAs/AlGaAs optical rib waveguide configuration of Deri et al. [4], Figure 3. The radiation loss \( L_{\text{rad}} = -10 \pi \Im \{k_p\} / \ln(10) \) [dB/90°] for the TE\( \infty \)-mode is graphically represented in Figure 3. The STIM yields field-plots of all components. Figure 4 shows the field-components of the fundamental TE\( \infty \)-mode for \( \rho_H = 3000.0 \mu m \). The outward shift of the field-distribution due to the waveguide curvature is clearly visible.

If one compares the results of the STIM with those of the EIM and the MoL, the differences seem to be marginal and the extra effort in deriving the STIM seems to be superfluous. In [1] however, a number of examples are given with very large differences (in excess of a factor 10 in dB radiation loss), together with a multitude of additional numerical results.


TECHNOLOGY AND APPLICATIONS OF COMMERCIAL LiNbO₃ INTEGRATED OPTIC DEVICES

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Abstract - Commercial applications of lithium niobate integrated optic devices in broadband and telecommunication systems, RF analog fiber optic links, navigation systems, and instrumentation are reviewed.

I Introduction

Lithium integrated optic (IO) devices have become key components in a variety of commercial applications within the past several years and are available from about ten sources worldwide [1]. Modulators and more complex IO devices are enabling components in CATV distribution systems, long haul telecommunication links, RF analog transmission systems, and navigation systems using fiber optic gyroscopes. Unique IO devices are important in several instrumentation applications. As the volume of components being manufactured has increased, process improvements have resulted in improved reliability, reproducibility, and stability. Module level products including the IO components and electronic interface circuitry have been developed for specific applications.

II Integrated optic devices for cable television

Integrated optic modulators have been used in 1320 nm CATV transmitters for several years. These transmitters include diode pumped YAG laser sources operating at power levels in excess of 100 mW. Many nodes can be fed from a single transmitter in a densely populated area. Alternatively, the maximum transmission distance for a point-to-point link using this technology may be more than twice that possible with a transmitter using directly modulated DFB lasers. In these cases, the externally modulated solution offers an economic advantage. By using balanced bridge modulators rather than Mach Zehnder devices, two optical outputs are available from the modulator instead of one. Optical power normally dissipated in a Mach Zehnder device is available at the second output, resulting in a doubling of the optical power available to the user.

Long distance transmission of high power optical signals is limited by the onset of stimulated Brillouin scattering (SBS). At power levels well below the onset of the saturation of transmitted optical power, the nonlinearities associated with SBS result in the generation of intermodulation products and increased noise in the detected signal. Because SBS is a coherent effect, it can be minimized by broadening the linewidth of the source. One means for achieving line broadening is to phase modulate the optical signal. A phase modulator is included on some modulator chips for CATV applications to allow line broadening to be accomplished without increasing the number of optical components or the insertion loss of the optical path. An IO chip designed specifically for cable television transmitters is shown in Fig. 1.
Fig 1. IO chip for CATV transmitter includes phase modulator for SBS suppression, flat response intensity modulator, and complementary optical outputs.

CATV applications require operation with 40 to 80 or more signals at composite modulation indices greater than 25%. Slight deviations from linearity result in the generation of intermodulation products which are discernible in the television picture. Bias control circuitry is used to maintain the operating point of the modulator at exactly the half intensity point to minimize even order distortion products, while odd order products are minimized using either electronic predistortion or optical linearization. Second and third order products are maintained at levels less than -65 dBc using these techniques. In the real time control loops normally used to maintain the correct operating point of the modulator, a low level, low frequency tone is added to the RF input signal. The signal and its harmonics are monitored and processed to generate an error signal which is used to adjust the operating point. Modules including the modulator, bias control circuitry, and a photodiode for detecting the control signal are supplied to customers.

In order to meet CATV transmission requirements, the RF and optical components must provide a flat frequency response over the band of interest. Many installations in the US. currently operate over 550 MHz, while European frequency plans generally cover 860 MHz. As additional services become available, it is expected that the bandwidth of systems will increase to one gigahertz.

III Integrated optic devices for telecommunications

External modulation was first deployed in telecommunications on submarine routes. Systems currently being deployed transmit data at rates to 5 Gbit/s, operate at 1550 nm, and utilize optical amplifier technology. Integrated optic modulators are key to meeting the system level specifications on long distance routes. The key feature of external modulators important to long distance transmission is the chirpless encoding of the data stream. Next generation 10 Gbit/s systems may utilize dispersion compensating properties which may be incorporated into designs for integrated optic modulators. External modulators have been incorporated in wavelength division multiplexed (WDM) systems, where frequency control and chirpless transmission are intimately related to system performance and product value. Acousto optic tunable filters (AOTFs) combine optical waveguide and surface acoustic wave technology on LiNbO₃. These devices are commercially available. High performance products are being developed for wavelength switching applications in telecommunications networks.

Large numbers of terrestrial 2.4 Gbit/s SONET/SDH systems have been deployed worldwide over the past several years. While early hardware used directly modulated 1320 nm sources, the latest transmission products operate at 1550 nm and use LiNbO₃ modulators. Operation at the longer wavelength results in a reduction of fiber loss (from 0.4 dB/km at 1300 nm to 0.2 dB/km at...
1550 nm) and allows the use of optical amplifiers. The result is an increase in repeater spacing from approximately 40 km to several hundred kilometers. However, the fiber used in many installations is not dispersion shifted for 1550 nm operation. Further, erbium doped fiber amplifiers (EDFAs) are incompatible with chirped signals. External modulators allow existing fiber networks to support transmission at 1550 nm. Savings to the long haul carriers result from a manyfold reduction in the number of repeaters required along a route and reduced maintenance expense.

As LiNbO$_3$ devices have been considered for deployment in telecommunication systems, long term device reliability and stability, and device packaging have improved. In addition to being driven to meet the reliability specifications set forth by organizations such as Bellcore, long term bias point stability is required. Early approaches utilized electronic bias point control; however, an alternate approach, in which devices are passively biased to the correct operating point during manufacture, eliminate the need for this circuit [2]. On/off extinction ratios in excess of 20 dB are maintained over 0 to 50 C in static temperature environments and during thermal cycling at rates to 5°/min. as shown in Fig. 2.

![Fig. 2. On/off extinction ratio greater than 20 dB (upper) is maintained as passively biased 2.4 Gbit/s modulator is cycled over 0 to 50 C at 5 degrees per minute (lower).](image)

**IV Lithium Niobate Modulators in Microwave Transmission Systems**

Lithium niobate modulators are used in transmission systems at frequencies to 20 GHz and have been demonstrated to operate over optical bandwidths to 75 GHz [3]. One advantage associated with external modulators in microwave frequency systems is high dynamic range. In addition, by using external modulation, it is possible to physically separate the laser source from the modulator. This feature can be used to reduce heat dissipation at the modulator location or to allow a single laser source to power multiple modulators.

**V Applications in Fiber Optic Gyroscope Navigation Systems**

Multi function LiNbO$_3$ IO circuits are key to achieving the performance required in closed loop fiber optic gyroscopes (FOGs) with 0.1 to 1 deg/hr drift specifications. FOGs are used in navigation systems because they offer compactness, high dynamic range, and have no moving parts. To date, commercial FOG deployment has been in low accuracy applications where open loop, all fiber architectures offer adequate, and cost effective performance in avionic and automobile applications. Significant numbers of integrated optic FOG chips have been delivered to systems integrators and
hundreds of closed loop FOGs have been built for extensive flight and field testing. Major efforts are underway to reduce the costs associated with the IO component, the pigtails, and assembly techniques. If successful, the optical hardware will be cost competitive with the mechanical assemblies currently in use. Environmental studies which have been completed on pigtailed IO chips show the devices offer excellent performance over -65 to 125 C, and minimal sensitivity to mechanical shock and vibration.

VI Custom Devices for Instrumentation

Custom design services are available from lithium niobate IO vendors, giving optical instrumentation engineers access to parts which have been designed to meet their specific requirements. Devices operating at nonstandard wavelengths, modulators designed of offer high performance over frequency bands specified by the user, and multifunction chips designed to minimize overall system cost have been delivered to customers. By using an approach based upon design rules and standard cells, custom devices can be designed with a high degree of confidence. An example of a multifunction chip designed for shaping pulses for laser fusion experiments is shown in Fig. 3 [5].

Fig. 3 Use of a custom IO chip with three modulators in a pulse shaping application [5].

VII Summary

Lithium niobate integrated optic devices are critical components in several commercial products, most notably cable television transmitters and multigigabit telecommunication systems. Navigation systems using fiber optic gyroscopes, new products for antenna remoting, and custom devices for instrumentation applications provide additional market opportunities for the technology.

References
System Requirements and Opportunities for Lossless Integrated Active Splitters

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C. Lerminiaux - Corning Europe Inc.

Abstract
Lossless optical splitters, integrated on a partially erbium-doped glass substrate, enable cost-effective extension of today's optical customer access networks. The requirements for performance and costs, derived for application in analog CATV distribution networks and in interactive POTS/N-ISDN environments, are achievable for devices with splitting factors up to 1:16.

1. Introduction
Passive optical local access networks (PONs), as being installed today, are mostly limited in their extent by the losses in the optical power splitters. By compensating the splitting losses with a preceding amplifying stage, the Lossless Integrated Active Splitter for Optical Networks (LIASON) device is expected to enable a cost-effective extension of these networks. It increases the number of optical network units (ONUs) served via one fibre from the head-end station, and it brings the fibre from the curb into or close to the customer premises. The ultimate size of the network is limited by the noise contributions of the amplifying stage. Planar optical integration of an amplifier section with the splitting section will yield a robust and sufficiently cheap device. The signal transparency of optical amplifiers makes them suitable for applications in digital as well as analog communication systems. Erbium-doped fibre amplifiers (EDFAs) already have reached high performance levels; they can deliver high gains and high output powers, together with a low noise figure. However, their bulk realization is expensive, and they are not suited for further optical integration with other optical functions.

In the RACE project R2109 "LIASON - Lossless Integrated Active Splitter for Optical Networks", we have studied the required specifications for application of such a splitter in two optical subscriber access networks: one for optical distribution of analog CATV signals, and one for interactive POTS/Narrowband-ISDN signals. The basic scheme for a LIASON splitter, based on a partly erbium-doped glass substrate, is shown in Fig. 1.

2. Optical customer access network for analog CATV distribution
2.1. Network Model
Four typical scenarios for optical CATV distribution networks have been studied, as shown in Fig. 2. All scenarios comprise a head-end station from which the CATV signal via an optical transmitter and a power-boosting EDFA is launched into a feeder link (L1). The transmitter is supposed to use a directly-modulated low-chirp highly-linear laser diode. Fig. 2.A and Fig. 2.B show typical FTTH and FTTC scenarios without in-field optical amplification. With currently available booster EDFAs, a splitting factor $N$ up to 16 is feasible. With the LIASON device an extra optical splitting level can be added, thus realizing a considerable extension of these networks, yielding the extended FTTC and FTTH scenarios depicted in Fig. 2.C and Fig. 2.D, respectively.

2.2. Performance analysis
For the FTTC and FTTH scenarios of Fig 2.C and 2.D, the impact of the LIASON device on the resulting total carrier-to-noise ratio $\text{CNR}_{\text{out}}$ and on the intermodulation products at the outlet of the ONU has been calculated. To the noise contributions of the other system components, the LIASON

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device adds signal-spontaneous beat noise (heterodyning of the CATV signal with the spontaneous emission noise of the gain section). Intermodulation distortion is generated by the LIASON device by three different mechanisms. Firstly, multiple reflections in a short cavity including the gain section cause coherent interference of the signal with (multiple) delayed versions of it [1]. Secondly, polarization-dependent loss or gain in the device, together with fibre polarization mode dispersion and laser chirp, causes conversion of optical frequency- to intensity-fluctuations [2]. Thirdly, also a non-flat gain-versus-wavelength characteristic of the device induces conversion of optical frequency- to intensity-fluctuations [3]. To calculate these noise and intermodulation distortion contributions of the LIASON device and their impact on the system performance, typical system data have been used. Typical signal quality requirements at the ONU outlet are a weighted $SNR_{out}>46$ dB (corresponding to a $CNR_{out}>45.4$ dB), and for the intermodulation products a composite second order distortion $CSO<-70$ dBc and a composite triple beat distortion $CTB<-70$ dBc [3]. The gain $G$ and noise figure $NF$ required to meet this CNR value for a 1:16 splitting device can be read from Fig. 3; e.g., for a lossless device a $NF<5.3$ dB is needed. Based on the CNR and intermod requirements and on the data of the other system components, the target specifications for the device listed in Table 1 have been derived.

2.3. Cost analysis

For each of the 4 system scenarios of Fig. 2, an estimate has been calculated of the system costs per connected ONU. The starting points for the calculations are price data and system layout data based on studies done within the RACE projects R2024 BAF and R2062 COMFORT.

The fibre cable and installation costs are a considerable part of the cost per ONU. Depending on the local conditions and the opportunities for duct sharing, the fibre cable and installation costs may vary considerably. In addition, when studying upgrading scenarios, the fibre infrastructure will be for a large part already in place. Therefore in the calculations the fibre infrastructure costs have been excluded, and the 4 different scenarios have been compared on basis of the equipment costs per connection.

The LIASON device can be either locally or remotely pumped. Local pumping, i.e. a pump laser (with a wavelength of 1.48 or 0.98 $\mu$m) included in the device, implies that the device has to be electrically fed, and for maintenance purposes should be easily accessible. Therefore it must be located in a (rather expensive) outdoor curb housing. The second option is remote pumping, i.e., locating the pump laser at one of the ONUs and feeding the pump power to the LIASON device upstream via a separate fibre. The pump wavelength will then have to be 1.48 $\mu$m. In this case the LIASON device does not need any specific maintenance, and can be placed in a box buried in the ground. This box is significantly cheaper than the curb housing. Thus remote pumping, although an extra fibre is needed, tends to lead to lower per-connection costs than local pumping. The cost differences are even larger if the reduced maintenance costs are taken into account.

Fig. 4 shows the cost calculation results for a 1:16 LIASON splitter. Extension of the FTTC scenario of Fig. 2.B to FTTC scenario 2.C (e.g., in urban renovation plans) leads to lower costs per ONU when the splitting device including pump laser costs less than 5000 ECU in case of remote pumping, or less than 4200 ECU in case of local pumping. The same break-even prices hold for extension of the FTTH scenario of Fig. 2.A to FTTH scenario 2.D.

3. Optical customer access network for digital interactive narrowband services

For the transport of narrowband interactive ISDN and POTS signals in passive optical networks, a typical German OPAL system has been taken as a reference (see Fig. 5). Up- and downstream traffic is on two separate optical networks. The optical line termination (OLT) establishes the connection to the central exchange via 16 separate 2.048 Mbit/s channels. This corresponds to a net capacity of 480 channels with 64 kbit/s. For customer services a variety of options exist: telephony
(POTS), basic and primary ISDN lines, synchronous 2 Mbit/s lines and channels with an integer multiple of 64 kbit/s. The OLT can serve up to three different PONs which connect the ONUs to the OLT. Per PON a single star configuration is preferred above a double star one, because of easier planning and maintenance.

For less densely populated areas with fibre feeder lengths up to 10 km the power budget allows a maximum passive split factor of 1:16. As each ONU can realize 8 telephone lines (64 kbit/s each), the number of telephone lines which the OLT can serve is power-limited to 384. The full 480-telephone-lines capacity of the OLT can be achieved by inserting an only 1:2 splitting LIASON device. More recent systems have OLTs which can serve nearly 1000 lines, and the LIASON splitting ratio may easily be increased to implement these. Thus the advantage which can be gained by applying a LIASON device will increase correspondingly.

For these digital applications, the required specifications on the LIASON device are quite relaxed: for a 1:2 split only a gain of >5 dB, output power of the gain section 0 dBm, noise figure <10 dB, and internal reflection levels <-23 dB.

The typical cost per telephone line, including operation and maintenance, has been calculated. Comparing the situation with 1:2 LIASON splitter to the situation without it, the device should cost less than 2624 ECU to obtain lower costs per telephone line.

4. Production cost estimates for a 1:16 splitting LIASON device
An analysis has been made of the production costs of a 1:16 splitting LIASON device. Compared to passive planar glass-based splitters, additional costs are involved with the larger substrate size (about one order of magnitude larger to accommodate the waveguide gain section), the pump laser and testing. First estimates for 1:16 splitting devices point at typical prices of around 8000 ECU for volumes of thousands. Volume production (in the 100000s range) may lead to prices around 2500 ECU, including a pump laser of 1500 ECU as predicted by the R2062 COMFORT project. In addition size reduction (by improved waveguide design) to a size comparable to the one of a passive splitter may yield prices around 1500 ECU.

These production cost estimates are in line with the target costs as derived in the analyses of the distributive CATV system and of the interactive POTS/N-ISDN system.

5. Conclusions
The LIASON device, a lossless splitter integrated in a planar partly erbium-doped glass substrate, offers the opportunity to bring fibre cost-effectively closer to the customer premises than in today’s passive optical access networks. Theoretical analysis of CATV distribution networks shows that both technical and cost targets for a 1:16 splitting device are ambitious but achievable; for interactive POTS/N-ISDN networks the targets are more relaxed.

This work has been done under the contract of RACE project 2109, and financial support from the European Commission is gratefully acknowledged.

References
Fig. 1  Schematic layout of lossless integrated splitter

Fig. 2  Application scenarios of the LIASON device in an analog CATV distribution network

Fig. 3  Relation between LIASON noise figure $NF$ and gain $G$, with $CNR_{\text{req}}$ as a parameter (split factor $P=16$; lossless operation requires $G=13$ dB)

Table 1. Target specifications for the LIASON device, intended for application in an analog CATV distribution network

<table>
<thead>
<tr>
<th></th>
<th>1:8 split</th>
<th>1:16 split</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>10</td>
<td>13</td>
<td>dB</td>
</tr>
<tr>
<td>Maximum output power of the gain section (typ.)</td>
<td>$&gt;6.1$</td>
<td>$&gt;9.1$</td>
<td>dBm</td>
</tr>
<tr>
<td>Noise figure</td>
<td>$&lt;5.6$</td>
<td>$&lt;5.3$</td>
<td>dB</td>
</tr>
<tr>
<td>Internal reflection levels</td>
<td>$&lt;-46$</td>
<td>$&lt;-49$</td>
<td>dB</td>
</tr>
<tr>
<td>Polariisation dependent loss</td>
<td>$&lt;0.05$</td>
<td>$&lt;0.05$</td>
<td>dB</td>
</tr>
<tr>
<td>Gain slope</td>
<td>$&lt;0.1$</td>
<td>$&lt;0.1$</td>
<td>dB/nm</td>
</tr>
</tbody>
</table>

Fig. 4  Costs per connection with 16-split LIASON device, excluding cable infrastructure costs (for scenarios A through D; lp=locally pumped, rp=remotely pumped)

Fig. 5  Application of the LIASON device in an interactive PON for POTS/N-ISDN
ENVIRONMENTAL RELIABILITY OF POLYMER WAVEGUIDE DEVICES

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Abstract
Polymer multimode waveguide devices have been tested in respect to their temperature and climatic resistivity. The result is a sufficient short- and long-term stability between temperatures of -40 °C and +85 °C and a humidity of 90% with additional losses of less than 0.2 dB in average. This qualifies these components for industrial application even in a rough environment.

1. Introduction
Integrated-optical waveguide devices based on polymer materials have been reported since several years as a low-cost alternative for mass applications [1-3]. While earlier products mainly relate to multimode waveguides, newer developments also show the possibility of realizing singlemode waveguides with the additional advantage of integrating fiber alignment grooves [4,5]. One main question and also one main challenge is the environmental and especially the temperature stability of these components. To demonstrate the high resistance of polymeric waveguides, a test programme with various temperature and climatic procedures has been applied to a number of devices.

2. Passive components for plastic optical fibers
The components chosen for the test are 1x2-splitters for plastic optical fiber (POF) of 1 mm diameter. These waveguides are fabricated by injection moulding of a PMMA-substrate with 1 mm grooves and casting of a higher refractive index epoxy resin core [6]. Using this process, up to now several thousand splitters have been fabricated. A similar fabrication process can be used for singlemode waveguides [4]. Typical parameters of the 1x2-splitters are an excess loss of 1.5 dB, a uniformity of 0.3 dB and a near end crosstalk of 30 dB.

3. Test procedures
Because plastic optical fibers are used for a variety of applications, e.g. inter-office links, automotive networks, or sensors, it is difficult to find general specifications for all these applications. A frame for the temperature range is given by the stability of the PMMA-based POF itself. Most commercial fibers give a range between -40 °C and +85 °C. Typical test results for long-term tests on POF are given e.g. in [7]. For the actual test routine the Bellcore Technical Reference for Fiber Optic Branching Components [8] was chosen as a good compromise for all applications. Slight modifications in parameters or test procedures have been done in respect of the POF transmission system. In detail, the following tests have been applied in the given sequence (details see [8]):
- Thermal aging at 85 °C for 336 hours (14 days)
- Temperature cycling between -40 °C and +75 °C for a total of 42 cycles
- Humidity Resistance with a relative humidity of 90 % and a temperature of 60 °C for 336 hours
- Water immersion in water of pH 5,5 at 43 °C for 7 days
- Low temperature storage at -40 °C for 1000 hours
- High temperature storage at +85 °C for 1000 hours

All tests except the water immersion test have been performed in a climatic test chamber on 10 devices of 1x2-splitter. The components were fully packaged with 1 meter pigtail on each side and ST connectors. As light source, a LED of 660 nm wavelength has been used. To define the changes in attenuation caused by the waveguides and not by the fiber pigtails or changes in the setup, two reference fibers of 2 meter length, one inside the test chamber and one outside, have been used. The insertion loss was measured before and after the test, partially also during the test. The accuracy of the total measurement setup is 0,1 dB.

4. Test results

Fig. 1 to 6 give the changes in attenuation caused by the different environmental stress conditions as given above for 10 devices. The two bars for each device represent the two output ports.
Fig. 5: Low temperature storage

Fig. 6: High temperature storage

Fig. 7: Total change of insertion loss after all tests

Fig. 7 gives in addition the total change of insertion loss after all of the tests. This gives an idea of maximum possible changes under real live conditions. The absolute attenuation of the pigtailed devices increased by additional 0.4 dB caused by changes of the fiber loss as could be seen at the internal reference fiber. This effect occurred mainly in the humidity and the high temperature storage test.

5. Interpretation of results

The very positive result of all tests is, that no drastic change of attenuation or failure of devices can be observed even at a temperature of +85 °C. So the most critical points as the adhesion of the core resin to the substrate and the fibers and the mechanical stability of the PMMA at these temperatures seem to be solved sufficiently.

Because all average changes are in the order of the measurement accuracy of 0.1 dB it is very difficult to interpret the observed effects. The effect of high temperatures is negligible in the short-term test (fig. 1). During the long-term test (fig. 6) a slight increase of 0.1 dB in average can be observed. Also during the temperature cycling, an average increase of 0.1 dB can be seen. An earlier temperature cycle measurement with a higher cycle number (500 cycles from -40 °C to +65 °C) has shown a mean increase of 0.05 dB and a maximum increase of 0.3 dB and demonstrates that also the
long-term behaviour under temperature cycling is quite stable. The improvement of the attenuation during the low temperature storage test (fig. 5) cannot be understood immediately and should be seen in context with the water immersion test (fig. 4). Either it is a systematic error of the measurement or it is caused by an additional drying effect of the devices after the water immersion test done before. The humidity test (fig. 3) gives no real changes in contrary to the results observed for the pure fiber (increase of 0.2 dB). This can be understood quite well, because the water permeability of the 0.6 mm polyethylene coating is much lower than that of the waveguide package. The waveguides are shielded by 1 mm polycarbonate housing, 1 mm epoxy casting resin between housing and device and 1 mm PMMA of the substrate and waveguide cover plate.

The total change of insertion loss over all tests (fig. 7) varies between -0.2 dB and +0.4 dB with an average value of 0.12 dB. This is acceptable for most of the applications of such kind of devices. Especially the water based effects can be reduced further if desired by an adequate metal housing.

6. Conclusion and outlook

The demonstration of the temperature stability of passive devices for POF networks is an important step for a lot of applications of these kind of devices. Especially for automotive networks with a very rough environment, 85 °C temperature stability (except the engine compartment) is requested by the customers. For higher resistivity other substrate materials like polycarbonate with a resistivity up to 125 °C have to be used. Due to the different refractive index also new core polymers have to be identified in this case.

In addition, the results show, that PMMA-based polymeric waveguides fabricated by injection moulding and casting have no problems with temperature, temperature cycling and humidity. The fulfillment of Bellcore requirements is an important step for the application of low-cost polymeric waveguide devices in communication networks. The test of corresponding low-cost polymeric singlemode waveguides for glass fibers will be the next important milestone in the way of polymeric waveguides to the market.

7. References

FULLY PACKAGED, INTEGRATED OPTICAL, ACOUSTICALLY TUNABLE ADD-DROP-MULTIPLEXERS IN LiNbO₃

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Abstract: Integrated add-drop multiplexers have been developed consisting of passive polarization splitters and acousto-optical TE-TM converters with weighted coupling. The packaged four port devices have a filter bandwidth of 2 nm and a tuning range of 120 nm. Fiber-to-fiber insertion loss of 5 dB and a residual polarization dependence of 3 dB for bar-state and of 1 dB for cross-state routing has been achieved.

Introduction

Integrated acousto-optical circuits in LiNbO₃ have a large potential for applications especially in WDM communication systems [1][2]. Acousto-optical filters and wavelength selective switches have been developed offering narrowband filtering (~ 2 nm halfwidth), broad tuning ranges (> 100 nm) and fast tuning (< 10 μs). Moreover, the simultaneous filtering capability of several wavelengths is a unique and particularly attractive feature of these devices.

For WDM communication systems tunable add-drop multiplexers are key components. They are used to add optical channels at distinct wavelengths and to drop other channels from a transmission line or to operate as wavelength selective space switches in WDM-network nodes. We have developed add-drop multiplexers in LiNbO₃ with special regard to low insertion loss and polarization insensitivity by combining polarization splitters [3] and acousto-optical mode converters with weighted coupling [4] (see Fig. 1). Moreover, the devices have been packaged allowing an easy handling and a reliable operation. The multiplexers are dedicated for applications within simplified switching nodes similar to that described in [5] being developed within the EU-RACE project “MWTN” and in test beds of the Research Institute of the German Telekom.

Multiplexer design

The basic structure of the integrated optical add-drop multiplexer is shown in Fig. 1. It consists of two polarization splitters and two acousto-optical mode converters. Optical waves entering into one input port are separated according to their polarization components by the first polarization splitter and routed towards the mode converters. Via the interaction with a surface acoustic wave (SAW) the state of polarization of the optical wave can be converted. This requires a phase-matched acousto-optical interaction, i.e. the difference of the wavenumbers of the fundamental TE- and TM-modes must be equal to the wavenumber of the SAW. As result a strong wavelength selectivity of the multiplexer is obtained; tuning is accomplished by varying the SAW frequency. Two separate mode converters with acoustical waves propagating into opposite directions are
necessary to get a SAW-induced frequency shift of the optical waves in the same direction.

Behind the mode converters the two branches are recombined within a second polarization splitter. It separates the converted and unconverted waves and routes them to the cross- and bar-states, respectively.

Component design and technology

Waveguides and bendings: Optical waveguides have been fabricated by indiffusion of 7 µm wide, 100 nm thick Ti-stripes into X-cut, Y-propagating LiNbO₃. The diffusion has been performed at T₀ = 1060 °C for 9 h. This process yields single mode waveguides in both polarizations in the spectral range around λ = 1550 nm. Propagation losses are typically 0.1-0.2 dB/cm.

For fiber-chip coupling the two input and output branches are separated by 165 µm; in the converter sections the two optical waveguides are separated by 270 µm. Therefore, waveguide bendings are required. We use S-shaped bending structures consisting of circular arcs (R = 160 mm) with 8.5 µm wide waveguides. The guides are asymmetrically connected with a 0.75 µm lateral offset at curved-straight and 1.5 µm at curved-curved interfaces.

Polarization splitters: Truely passive polarization splitters [3] are based on two mode interference in a directional coupler structure. They consist of a double moded central section of 14 µm width and an opening angle of 0.55°. With central section lengths around 220 µm splitting ratios of more than 20 dB and excess losses around 0.7 dB have been obtained.

Acousto-optical mode converters: The interaction of surface acoustic waves and the optical fields is performed within a tapered acoustical directional coupler [4]. In one of its arms the optical waveguide is embedded, in the other arm the SAW is excited via an rf-signal (f ~ 170 MHz) applied to the interdigital transducer electrode. The acoustical directional coupler has been designed to yield a complete coupling cycle for the SAW, i.e. the acoustical power is coupled to the adjacent acoustical guide and back again. This results in a weighted acousto-optical interaction with a soft increase and cutoff of the acoustical intensity at the location of the optical waveguide. With such structures a sidelobe suppression down to about -20 dB has been achieved.

The acoustical directional coupler has been fabricated by Ti-indiffusion into the cladding region of the waveguiding structure. The diffusion of 160 nm thick Titanium has been performed at 1060 °C for 24 h before the fabrication of the optical waveguide. The directional coupler is formed by 110 µm wide acoustical waveguides. One of these guides is straight whereas the other one is inclined in the outer sections by an angle of 0.59° resulting in a linear change of the gap between 0 and 70 µm (see Fig. 1). The overall length of the coupler structure is 19 mm. The two couplers are laterally separated by a 170 µm wide Ti-diffused area to guarantee acoustical isolation.

SAWs are excited via interdigital transducer electrodes (500 nm thick aluminum) consisting of 14 finger pairs with a period of 20.8 µm. To absorb the acoustical power behind the transducer and at the end of the interaction length absorbers of UV-curing glue have been deposited.

Fiber-chip coupling: To reduce coupling losses between standard single mode fibers and the optical waveguides the mode field distributions should be well matched. The depth profile of 7 µm wide optical waveguide modes is stronger localized (FWHM of intensity distribution 4.3 µm for TM and 3.5 µm for TE) than that of the fiber (6.0 µm) resulting in coupling losses typically larger than 1 dB. To increase the waveguide mode sizes we use a linear taper of the width which is reduced to 5 µm. Theoretical coupling losses are below 0.5 dB; practically, the losses have been kept below 1 dB.

To avoid reflection losses at the waveguide-fiber interfaces, λ/4-layers made of Y₂O₃ (n ~ 1.7) have been deposited on the endfaces of the LiNbO₃-substrate as anti-reflective coating. Before attaching the fibers have been embedded in V-grooves made of silicon.

Packaging: The 65 mm long sample has been mounted on a copper block, which can be temperature stabilized using thermoelectric coolers. The multiplexer is enclosed in an aluminum housing (80 × 120 × 40 mm³) which also contains the electronic circuit to match the impedance of the transducer electrodes. The housing is fixed on a printed circuit board containing the electronics of the temperature stabilization. The overall system has been designed as a cassette to be mounted into a 19” enclosure. In this way the multiplexers can...
be connected with a computer controlled four channel synthesizer [6]. Fig. 2 shows a photograph of the packaged multiplexer unit. On the front panel there are connectors for the optical input and output ports and control knobs for the temperature stabilization.

**Device performance**

The devices have been investigated measuring the transmission of the broadband amplified spontaneous emission of an erbium doped fiber amplifier with an optical spectrum analyzer with 0.1 nm resolution. In Fig. 3 examples of such measurements are given. It shows the transmission versus optical wavelength into the cross- and bar-states for both input ports. The SAW frequency has been adjusted to yield polarization conversion and thereby switching at $\lambda = 1556$ nm. The transmission spectra into the cross-states are shown in the right diagrams; their 3-dB width is 2 nm. At longer wavelengths sidelobes about $-15$ dB below the maximum level occur which are mainly due to inhomogeneities of the optical waveguides [7]. The left diagrams show the transmission into the bar-state, i.e. the notch filter operation. A rejection of more than $-17$ dB is achieved at $\lambda = 1556$ nm.

From the diagrams in Fig. 3 the losses of the multiplexers can be deduced. For the (nearly) unpolarized light the fiber-to-fiber losses are around 5 dB. Detailed investigations show that there is a residual polarization dependence. For routing into the bar-state the losses are 5.5–6.5 dB for TE and 3–4 dB for TM polarized waves. A smaller polarization dependence occurs for routing into the cross-state; the losses vary between 4 and 5.5 dB for both polarizations. The losses are mainly due to the bendings in the structure. For TE the waveguides become double moded in the broader waveguide bends resulting in excess losses of about 3 dB by passing the whole multiplexer, whereas this figure is kept below 1 dB for TM polarization. The result is a polarization dependence of the multiplexer transmission which is larger for bar-state routing. The state of polarization is not changed in this mode of operation, whereas for cross-state routing the state of polarization changes; half of the bending structures is passed in TE polarization and the other half in TM.

Tuning of the multiplexer is achieved by varying the acoustic frequency; the tuning slope is given by $\approx -8$ nm/MHz. The tuning range is mainly determined by the bandwidth of the transducers. In Fig. 4 the electrical RF-power to drive the multiplexer versus the optical wavelength is shown. Minimum drive...
power is required at $\lambda = 1540$ nm. This minimum drive power is for the present devices around 100 mW. The power is split to drive the two mode converters. Each converter requires about 30 mW for complete mode conversion; the remaining power is lost in the electronic power splitter and an adjustable attenuator required for balancing the power levels for both converters. The tuning range of 120 nm extends from 1480 nm to 1600 nm, defined by the wavelength range in which the drive power is below twice the minimum value.

To demonstrate the multi-wavelength capability of the multiplexers they have been driven with two rf-signals simultaneously with a frequency difference of 1 MHz. In Fig. 5 the spectral dependence of the transmission into the cross- and bar-states is shown. Conversion occurred at $\lambda = 1558$ nm and $\lambda = 1566$ nm, respectively.

**Conclusions**

We have developed and investigated integrated acousto-optical add-drop multiplexers in LiNbO$_3$. The fully packaged, fiber pigtailed devices have an average fiber-to-fiber insertion loss of 5 dB with a maximum polarization dependence of 3 dB. These figures can be further improved using an optimized design of the bendings.

The multiplexers are ideal devices for applications in WDM communication systems. For example, they can be used within ring networks [8] or in wavelength selective building blocks [5][9].

**Acknowledgement**

We gratefully acknowledge the financial support of parts of this work by the Research Institute of the German Telekom and by the European Union within the RACE II project R2028 ("MWTN").

**References**


[6] The driving electronics has been developed in the Optical Communication group of the Department of Electrical Engineering (Prof. Noé).


Microspectrometersystem Based on Integrated Optic Components in Polymers as Spectral Detection System for the VIS- and NIR Range

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Abstract
A microspectrometersystem based on a polymeric multimode waveguide with blazed reflection grating, adjusted fibre fixing grooves and an inclined focus line to easily adapt a photodiode array and a tailored electronic circuit board has been fabricated. The reflection grating which is patterned into the integrated waveguide works in the spectral range from 400 nm to 1100 nm with a maximum transmission of 25% at the blaze wavelength of 760 nm. The spectral resolution of the whole system is 7 nm and the dynamic ranges from 10,000 to 20,000. The performance of the system has been demonstrated for different applications like transmission, reflection and fluorescence measurements.

Introduction
In many optical sensor applications like colour detection or analysis of chemicals and chemical processes small, compact and stable spectral analysis systems are needed. By these systems process quality is characterised continuously and the quality of the products can be fully controlled. For this purpose spectral detection systems small in size, simple to handle and specially adapted to the application are needed, which furthermore can be directly integrated in the fabrication line [1]. In addition, the system components have to be build in large scale manufacture with constant performance.

Such a compact and stable optical sensor set-up is achieved by fabricating a grating in a light guiding polymeric multimode waveguide together with a fibre fixing groove and a detecting photodiode array placed on the focal line of the grating. The complete optical set-up is structured in one process sequence taking advantage of the LIGA-technique [2]. By this, all components are adjusted with respect to each other and no further alignment is required. Furthermore, a tailored electronic circuit on a multilayer board with memory, a µ-controller and a standard interface to a PC to evaluate the spectral information complete the detection system.

Microspectrometer device
The optical set-up is fabricated by deep-etch X-ray lithography or by moulding, esp. stamping. Using a lithographic technique arbitrary lateral shapes, precise alignment of all optical elements as well as submicrometer accuracy in structural details can be used to fabricated optimised detection systems for the VIS and NIR region. The spectral bandwidth and spectral resolution of such a system can easily be optimised with respect to the applications [3].

The scheme of the optical set-up is shown in Fig. 1. The waveguide consists of a polymethylmethacrylate (PMMA) or fully deuterated PMMA-d8 core and a cladding from copolymers of PMMA and tetrafluoropropyl methacrylate (TFPMA). The material attenuation in the visible and NIR spectral range up to 1100 nm for a PMMA core and up to 1300 nm for a PMMA-d8 core is in the order of 0.3 dB/cm which is small enough with regard to the optical path length of 2 cm to 3 cm.
The thickness of the different layers is matched to the fibre parameters (50/125 μm multimode fibre, N.A. = 0.2) by which the light is launched into the waveguide. The position of the fibre end face is given by the fibre fixing groove and is adjusted to the grating on a Rowland circle. The blazed reflection grating is structured with optimised individual positions of each single grating tooth. Thus, imaging losses on the linearised focal line can be neglected [4]. A high reflectivity is achieved by coating the grating with a 100 nm thick silver layer.

The dispersed light is totally reflected at the inclined sidewall of the focal line (angle of inclination is 45°) and can be analysed with a photodiode which is adjusted on top of the waveguide. The photodiode used is a HAMAMATSU type S5464-512F with 512 pixels and a pixel size of 25 μm x 500 μm. The length of each pixel of 500 μm makes the positioning of the photodiode with respect to the focal line very simple. The dispersed light is focused on the photodiode surface and guided via a fibre window to the individual diode pixels.

**Evaluation board**

An electronic board made in SMD multilayer technique has been developed for the readout of the photodiode array. By this the total size of the system is only 60 mm x 70 mm. The evaluation board includes the LIGA microspectrometer, the photodiode array and the complete electronic circuit for data acquisition and evaluation. The system is powered by 5 V and consumes only 800 mW.

The diode output signal is processed analytically and fitted to the input level of the A/D-converter. The drive of the diode array is generated by a μ-controller which also controls the A/D-converter, the read in of the spectral data, the pre-processing and evaluation of the data as well as the communication with the host computer.

In Fig. 2 the block diagram of the evaluation board is described. The communication with the host computer is performed by serial ports (RS232, RS485). The input parameters, e.g. integration time, amplification factor and number of the averaged spectra are inquired by the PC and transferred to the system. The pre-processed readout data are transmitted to the PC and are displayed on a monitor.
Microspectrometersystem

Fig. 3 shows a photograph of the mounted microspectrometersystem in a housing. The features are listed in Tab. 1.

Fig. 3: Photograph of a mounted microspectrometersystem in an Al housing

<table>
<thead>
<tr>
<th>feature</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>spectral range</td>
<td>400 nm - 1100 nm</td>
</tr>
<tr>
<td>transmission at $\lambda_{	ext{max}}$</td>
<td>25%</td>
</tr>
<tr>
<td>spectral resolution</td>
<td>7 nm</td>
</tr>
<tr>
<td>attenuation to scattered light</td>
<td>25 dB</td>
</tr>
<tr>
<td>optical fibre</td>
<td>50/125 µm, gradient index</td>
</tr>
<tr>
<td>photodiode array</td>
<td>Hamamatsu S5464-512F</td>
</tr>
<tr>
<td>16 Bit A/D-converter</td>
<td>Siemens SAW 80 C166</td>
</tr>
<tr>
<td>dynamic range</td>
<td>10.000 - 20.000</td>
</tr>
<tr>
<td>measuring time</td>
<td>40 ms - 2560 ms</td>
</tr>
</tbody>
</table>

Tab. 1: Features of the microspectrometersystem.

The spectral range from 400 nm to 1100 nm is covered with one grating. Other spectral regions or spectral bandwidths can be obtained by varying the grating parameters [5]. The dynamic of the system is a function of the spectral distributions of the lightsource, the waveguide, the grating and the photodiode array. A typical spectrum for white light launched into the waveguide is presented in Fig. 4. This spectrum is used as a reference spectrum in the application.

Fig. 4: Spectral intensity distribution of the microspectrometersystem.
The lower limit of the dynamic range for shorter wavelengths is a consequence of the low intensity of the tungsten lamp whereas for longer wavelengths the sensitivity of the photodiode array decreases dramatically.

**Applications**

The performance of the microspectrometersystem has been tested for different applications. In Fig. 5a the oxygen content in arteriole and vein blood is measured. The difference spectrum clearly proofs the capability of the system in measuring strong absorbing materials. On the other side even hardly absorbing materials can be detected as is shown in Fig. 5b. Here, the absorption spectrum of an optochemical material indicated by the straight line is changed while NH$_3$ gas flows across it.

![Fig. 5a: Absorption spectra of blood to detect the oxygen content.](chart1)

![Fig. 5b: Absorption spectrum of NH$_3$.](chart2)

These two examples are related to transmission measurements using an adapted micro-machined cuvette. Other experimental set-ups, e.g. for reflection or fluorescence measurements have also been tested and lead to similar results. Thus, the well defined and simple to handle optical interface of the spectrometer - the optical fibre end face or a fibre connector - opens up a variety of applications.

**Conclusions**

Our results demonstrate that the performance of a micro machined spectrometer is sufficient for the envisaged applications in on-line process control and colour detection. The integrated optical set-up has the potential of cost effective fabrication by moulding techniques. There is a further potential of miniaturisation and cost reduction by fabrication of well adopted photoasics including the whole electronic evaluation board. In this case the moulding step can be performed directly on top of the photoasic which both decreases the size of the system and the assembling efforts. With these fully integrated optoelectronic system completely new applications can be expected even in the consumer market.

**Literature**


LOW VOLTAGE, POLARIZATION-INDEPENDENT LiNbO3 MODULATORS

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Abstract

We report on the development of low-voltage, polarization independent modulators. The devices, based on long, shaped Y-branch switches in LiNbO3 offer complementary outputs and require no DC bias voltage. These devices operate with a differential drive voltage of +/- 8 V, a bit rate of 100 Mbit/sec, and an extinction ratio of 13 dB.

Introduction

Y-shaped electro-optic switches in lithium niobate have been studied recently as a means of providing polarization independent optical switching [1]. Several groups have taken advantage of their polarization independence and their voltage-insensitive switch states to fabricate large switch matrices [2]. However, their use at higher speeds for data modulation has not been previously reported. In this paper we investigate the behavior of long, shaped Y-based switches for low-voltage, polarization-independent modulator applications. In addition to polarization independence, Y-shaped switches provide several advantages over other switch elements. Their broad optical bandwidth extends over several hundred nanometers. Their saturating (or "digital") transfer characteristic minimizes the effects of ringing of the drive signal (from low cost electronics), drive voltage variations (from process variations), and voltage drift. Finally, the Y structure provides complementary outputs and allows operation with no DC drive voltage.

We have designed, fabricated, packaged and tested several devices. The devices function at 1.3 and 1.55 microns and provide low voltage operation and reasonable extinction ratios. The modulators are lumped-electrode capacitive devices capable of speeds up to at least 100 Mbits/second.
Externally modulated laser sources are required in a variety of communication systems in which direct laser modulation is not possible. For instance, in fiber-in-the-loop applications, external modulators eliminate the need for remote lasers and provide a means for generating modulated data at the customer premise (far end) and transmitting the data back to the central office (head end) [3,4]. In this application, polarization independent operation is essential because the state of polarization generally is not known and will vary with time. Other requirements for such a modulator are low power consumption, low loss and moderate modulation rates and depths.

Design, Fabrication and Packaging

The device adopts the double angle, two section design of Okayama et al [2]. In the first section, the waveguides branch at an angle of 10 mrad until reaching an inner waveguide edge to edge separation of 2 microns. For the second section, we use the shaping function suggested by Burns [1] to obtain a shape intermediate between a linear and logarithmic curve. The shape is calculated using a shaping parameter of 1.5 and coupling constants which are intermediate between measured TE and TM values. The shaping function determines the Y structure until the waveguides reach a center to center spacing of 19 microns at a length of 40 mm. (For these devices, the length of the switching element is extended to 40 mm to achieve lower voltage operation.) Finally, 35 mm radius of curvature S-bends are used to separate the waveguides for fiber attachment. The waveguide width, chosen for optimum performance at 1.55 µm, is 7 microns. The electrodes are a simple lumped capacitor design.

The devices were fabricated on z-cut lithium niobate using standard processes. The titanium thickness was 1150 Angstroms, the diffusion temperature was 1035 C and the diffusion time was 12 hours. A 3000 Angstrom thick buffer layer was used under the gold electrodes. The endfaces of the device were angled at 6° to reduce reflections. The device was packaged with standard single mode fiber. The two output fibers were held at 250 micron separation by a silicon v-groove chip. Electrical contact was made by ribbon bonds between the center conductor of two SMA connectors mounted in the package wall and the two electrode bond pads.
Characterization

Two devices, one from each of two different wafers, were packaged and tested. Figure 1 is a photograph of a packaged device. Testing was performed at 1.3 and 1.55 microns. The switching characteristics of the devices were measured in single ended and differential drive configurations using 100 Mbit/sec square wave pulses. Switching results are shown in figures 2 and 3.

Figure 2 shows the drive signal (a), the TM output (b) and the TE output (c) for a 1.55 micron signal driven differentially with a +/- 8V source. Figure 3 shows the TM output (a) and the TE output (b) for a 1.3 micron input and a +/- 5V source. In all cases, extinction ratios greater than or equal to -13 dB were obtained. The devices were also operated at 1.55 microns with a +/- 8V single sided drive (the second electrode is held at ground) and a differential drive at +/- 4V. In these cases, 10 dB extinction ratios were measured. The broad optical bandwidth of the device is shown in figure 4. An optical spectrum analyzer was used to measure the extinction ratio as a function of wavelength with 10 V applied to one of the electrodes and an unpolarized white light source coupled into the device. The spectrum shows extinction ratios below -12.5 dB over a 350 nm bandwidth.
Figure 4. Extinction ratio spectrum

The insertion loss at 1.55 microns was -2.5 dB for TE and -3.6 dB for TM. At 1.3 microns, the corresponding numbers are -2.0 dB and -4.7 dB. The higher TM loss is associated with scattering at the Y junction. The waveguides were designed for 1.55 microns so it is likely that a higher order mode(s) propagates and scatters in the wide branching region at 1.3 microns. Tapering of the waveguides in the Y junction region should reduce the TM loss.

Discussion

We have demonstrated a low voltage, polarization independent modulator. The device operates up to 100 Mbits/second at 1.3 and 1.55 microns with voltages of less than or equal to 8 volts and extinction ratios in the -10 to -15 dB range. For this work, no attempt was made to optimize the electrode or package design for high speed operation. The use of travelling wave electrodes should improve the modulation rate by at least a factor of ten. Additional measurements on other devices indicate that there is some waveguide coupling at the end of our 40 mm long devices and that improved voltage and crosstalk performance is possible by increasing the waveguide separation.

References


WDM devices in InP/InGaAsP

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Abstract:
This paper reviews the state-of-the-art of monolithic integration on InP of components for wavelength multiplexed networks. Key components such as multiwavelength lasers and wavelength demultiplexers are reviewed in terms of their performance and ease of fabrication. In addition, the crucial issue of the wavelength precision of these devices is addressed.

Introduction:
Multiwavelength optical networks are gaining interest due to their potential of creating all-optical routed, rearrangeable, scaleable and transparent networks [1]. Essential ingredients for such networks are wavelength division multiplexing, the use of wavelength for routing purposes, and wavelength translation at network nodes. Multiwavelength transmitter and WDM-receiver arrays are key components for the realization of these functions. Monolithic integration of these devices increases reliability and reduces packaging costs. The present paper reviews the state-of-the-art of integration of these devices.

Multiwavelength lasers:
Starting with a DFB (or DBR) conventional single wavelength laser, the most straightforward way to realize a multiwavelength laser is by fabrication of an array of DFB lasers with variable grating period. Twenty-wavelength DFB laser arrays with 3 and 7 nm channel spacing have been demonstrated [2,3]. Typically a wavelength accuracy of 0.3 nm (relative deviation) can be achieved with this approach. In order to reduce packaging costs the individual laser signals should be recombined on-chip into one output. Planar star coupler recombiners have been integrated with 16-channel DBR [4] and 21-channel DFB laser arrays [5]. The inherent power splitting loss incurred by the recombiner may be reduced by integration with a semiconductor amplifier or, in the future, by replacing it with a wavelength multiplexer.

Fig. 1: Schematic representation of the MAGIC laser [6].
An alternative approach for the realization of multiwavelength lasers is to integrate an array of gain blocks with a cavity incorporating a wavelength demultiplexer. Bellcore’s MAGIC (multistripe array grating integrated cavity laser) was the first example of such a device [6].

More recently a similar device was reported by AT&T using a phased-array demultiplexer (see below) as the wavelength selective element [7]. Due to the precisely defined wavelength spacing of the demultiplexer, the relative wavelength position can be accurately controlled. Relative wavelength variations of 0.023 nm have been reported for the MAGIC laser.

The long cavity length however limits the direct modulation speed. Therefore external modulation will be required to achieve high bit rates. In addition, the threshold current of these lasers has been relatively high due to the loss of the wavelength demultiplexer.

WDM receiver arrays:

Monolithic wavelength demultiplexers employing a curved reflection grating as the dispersive element have proven accurate demultiplexing of a high number of closely-spaced wavelength channels [8,9,10] and have also been integrated with photodetector arrays [11,12] (see table 1). However, due to the critical vertical mirror etching required, the insertion loss of these devices was relatively high.

<table>
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<tr>
<th>Reference</th>
<th>year</th>
<th>channels</th>
<th>(\Delta\lambda_{\text{ref}}) [nm]</th>
<th>loss [dB]</th>
<th>crosstalk [dB]</th>
<th>size ([\text{mm}^2])</th>
<th>(\Delta\lambda_{\text{pol}}) [nm]</th>
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<td>[8]</td>
<td>91</td>
<td>35</td>
<td>4</td>
<td>10-17</td>
<td>&lt; -25</td>
<td>2.5 x 3.2</td>
<td>0.4</td>
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<td>[11]*</td>
<td>92</td>
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<td>[9]</td>
<td>91</td>
<td>78</td>
<td>1</td>
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<td>&lt; -19</td>
<td>12 x 2</td>
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<tr>
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<td>65</td>
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<td>13-20</td>
<td>&lt; -7</td>
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<td>1.7</td>
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<td>9.7</td>
<td>&lt; -30</td>
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<td>[24]</td>
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<td>8</td>
</tr>
</tbody>
</table>

Table 1: Comparison of wavelength demultiplexers on InP-substrate. The * indicates that the device has been integrated with photodetectors.

As an alternative, wavelength demultiplexers employing a phased array of curved waveguides [13,14] as the dispersive element have become increasingly popular [15,16]. Due to the elimination of the reflective mirror these devices can be fabricated with simple and tolerant technology. Experimental results appear to be close to the theoretical limits. Figure 2b shows the spectral response of a 4-channel demultiplexer integrated with a photodetector array [17,18]. The device combines excellent spectral resolution with low-loss operation.

Due to the birefringence of conventional InGaAsP/InP waveguides, these demultiplexers may exhibit a significant TE/TM-shift (see table 1). Different approaches have been used to eliminate this effect. By reducing the refractive index contrast between waveguide core and cladding this shift can be reduced significantly. However, this occurs at the expense of higher loss or increased device size [19].
An alternative approach has been to design the demultiplexer free spectral range equal to the TE/TM shift of the waveguide [14,20,21,22]. This limits, however, the operation range of the demultiplexer to only a few nanometers. A λ/2 waveplate inserted in the middle of the glass waveguides demultiplexers [23] yields a fundamentally polarization independent performance through 90° polarization rotation halfway the symmetrical design. The application of this concept to monolithic demultiplexers is, however, not straightforward. So far, the only broadband polarization insensitive demultiplexer on InP has been realized by employing non-birefringent raised stripe waveguides. A first prototype of such a device [24] has shown polarization independent demultiplexing of 8 wavelength channels at 2 nm spacing, with 5 dB on-chip loss and less than 1 dB coupling loss to a lensed fiber.

Recently an electronically tunable wavelength demultiplexer has been reported [25]. Tuning over more than 2 nm was obtained by injecting current into the arms of the phased-array through electrodes with a linearly increasing length, thus causing a current-dependent phase front tilting at the end of the array.

Another novel development is the realization of a phased-array demultiplexer based on MMI-couplers [26], as shown in Figure 3. These demultiplexers apply Multi Mode Interference (MMI) couplers instead of star couplers at both sides of the waveguide array. The demultiplexers tend to be more compact than conventional phased-arrays and have potentially lower insertion loss for waveguides with a high lateral refractive index contrast. A disadvantage is the reduced low-crosstalk bandwidth as compared to the classical design. The width of the passband is comparable. Although we do not expect this novel demultiplexer to replace the classical phased-array, it may be advantageous in applications where compactness is very important.
Wavelength accuracy:
An important issue for WDM components that, until recently, received little attention is the wavelength precision and stability that can be realized for individual components. Especially if a number of WDM components are to be cascaded both the absolute wavelength and the channel spacing have to be controlled accurately. Soole et al. measured a run to run reproducibility of about +/- 0.5 nm (see Figure 4) for reflection grating demultiplexers [27]. This would require a temperature tuning < 6°C (~0.11 nm/°C) to line up the wavelengths of the individual devices. Channel spacing deviations were found to be less than 0.03 nm and may therefore be neglected.

**Fig. 4:** Wavelengths of 8 demultiplexer devices formed from two 2" MOCVD-grown wafers [27].

Since the absolute wavelength of InP-based devices is fundamentally temperature dependent, temperature control will be necessary to keep the device operating at the right wavelength. In addition, it may be desirable to provide passband flattening of the demultiplexer to correct for potential deviation of the laser source wavelength from the design value. A 4-channel spectrally flattened arrayed waveguide demultiplexer has been realized on InP by using relatively wide multimode output waveguides [28]. This device shows a 1-dB passband of 1.0 nm at 2.0 nm wavelength spacing (see Figure 5). Owing to the multimode excitation of the output waveguides, the demultiplexer outputs cannot be coupled efficiently to monomode fibers. If they are coupled to photodetectors, however, the advantage of the passband flattening can be fully exploited.

**Fig. 5a:** Schematic representation of the focused spot in the image plane of a spectrally flattened demultiplexer.

**Fig. 5b:** Spectral response of a passband flattened phasar demultiplexer on InP [18].
Conclusion:
In the last few years significant progress has been made on the monolithic integration of multiwavelength sources and detectors for WDM systems. Developments in the field of passband flattening and polarization independent operation are promising but still need further elaboration. The channel spacings of the WDM-devices recently reported are sufficiently accurate for many applications. Temperature control will be necessary to stabilize the absolute wavelength of InP-based devices. The results obtained so far are sufficiently promising to support development of novel network concepts based on WDM.

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Optical Phased Array in SiO$_2$/Si with Adaptable Center Wavelength

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An optical phased array in the SiO$_2$/Si material system with 8 nm channel spacing in the 1.5 µm wavelength region exhibiting quasi polarization independent operation with insertion losses of 2.5-3 dB and crosstalk attenuations of > 20 dB is reported. It can be adapted to the specified center wavelength simultaneously with the adjustment of the input fiber.

Introduction: During the last years, integrated optical demultiplexers for dense WDM – in particular planar reflection gratings and optical phased arrays – have been significantly improved [1]-[4]. In particular, the insertion losses have been substantially reduced so that integrated optical filters have attained now the figures of their high-end hybrid equivalents. The wavelength allocation, i.e. the fabrication of DWDM transmitters and filters for a specified set of wavelength channels, represents a problem which is currently subject to further developments.

We present here a 4-channel optical phased array in the SiO$_2$/Si material system for a channel spacing of 8 nm. It can be adapted to the specified center wavelength during the alignment process.

Design and Fabrication: Figure 1 shows the layout of the optical phased array. In contrast to previous layouts, the input signal is coupled directly into the slab waveguide in front of the phase shifter. Since the center wavelength of the filter depends on the relative position of the input fiber, the filter may be adapted to the specified wavelengths simultaneously with the alignment of the input fiber. By the way, fabrication tolerances may be compensated. The phased array itself represents, as usual, a Rowland mounting. This means that the grating line, which is formed by the waveguide endfaces at the output side of the phase shifter are located on a circle and both the light-path function on the input side and the groove function describing the chirp of the phased array are linear functions [5, 6]. The focal line of such a phased array, i.e. the curve formed by the images of the input fiber, is given by the Rowland circle. This circle is tangential to the grating line and has half its radius.

The device was designed for four DWDM-channels at $\lambda = 1.55$ µm with a channel spacing of $\Delta \lambda = 8$ nm. Four additional output ports were realized in order to provide its more flexible use. The phased array reported...
here operates in the \(-31\)th diffraction order. The phase shifter consists of 20 waveguides. The spacing of the waveguides at the end of the phase shifter, which corresponds to the pitch of a conventional grating, was 20 \(\mu m\). The ports at the end of the output slab waveguides are 20 \(\mu m\) apart from each other, as well. At the chip endface, the waveguides are separated by 125 \(\mu m\) according to the minimum spacing of single-mode fibers. The overall length of the device shown in Figure 1 is about 30 mm.

The silica waveguide layers [7] were fabricated on a silicon substrate by flame hydrolysis deposition (FHD). The layer system consists of three layers, a 17 \(\mu m\) SiO\(_2\)-B\(_2\)O\(_3\) buffer layer, a 7 \(\mu m\) SiO\(_2\)-B\(_2\)O\(_3\)-TiO\(_2\)-GeO\(_2\) core layer and a 20 \(\mu m\) SiO\(_2\)-B\(_2\)O\(_3\) cover layer, respectively. The strip waveguides with a width of 7.5 \(\mu m\) were formed by projection lithography and CHF\(_3\) reactive ion etching (RIE). The refractive index contrast between core and buffer/cladding was \(\Delta n \approx 10^{-2}\). As a result of the rather strong guidance, we did not observe significant extra losses for strip waveguides with radii of curvature >15 mm. In order to achieve polarization independent devices, we have reduced the stress, which is the source of birefringence, by matching the thermal expansion coefficients of the waveguide layers to those of the silicon substrate.

**Results:** The spectral response of the phased array, i.e. the fiber-to-fiber insertion loss as a function of the wavelength, was measured for both TE and TM polarization. For the measurements, the light of a tunable external cavity laser was butt coupled into the device via a standard single-mode fiber. The polarization was controlled by a fiber-loop polarization controller. On the output side of the device the light was fed into a PIN photodiode via a graded index fiber.

Figure 2 shows the spectral TE response for all the output ports. The four output ports marked in Figure 2 show insertion losses of 2.5-3.1 dB. The crosstalk attenuation between adjacent wavelength channels was > 20 dB, the crosstalk between non-adjacent channels was even smaller.

The tuning characteristics of the phased arrays are shown in Figure 3 which presents the detuning, i.e. the shift of the center wavelength at the output ports, as a function of the lateral shift of the input fiber. All devices showed the expected tuning characteristics, \(d\lambda/dx = 0.4 \text{nm}/\mu\text{m}\). Due to the increasing insertion losses (see Figure 2), the useful tuning range of the device was limited to about \(\pm 8 \text{nm}\).

Figure 4 shows the spectral response of a single output port over an extended spectral range. The center wavelength of the filter curves for TE and TM polarization are shifted 0.1 - 0.2 nm against each other, i.e. the devices provide a quasi polarization independent operation. The side lobes of the filter curves of this early sample are caused by the spatial filtering, i.e. too little waveguides within the phase shifter, and by the optical coupling between the output waveguides.
Conclusions: An optical phased array in the SiO$_2$/Si material system, which allows to adapt the center wavelength during the alignment process, was successfully demonstrated. The tuning curve of the adaptation scheme was completely linear. In addition, the device reported here exhibits excellent figures (insertion loss: 2.5-3 dB, crosstalk attenuation: $>20$ dB, polarization-independent operation).

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**Figure 1:** Adaptable optical phased array: layout.
Figure 2: Spectral response of the phased array for the eight output ports (TE-polarisation).

Figure 3: Detuning of the optical phased array.

Figure 4: Spectral response of the phased array for one output port and both polarizations.
Passband Collisions and Multi-Channel Crosstalk in Acousto-Optic Filters and Switches

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Abstract. The integrated acousto-optic filter/switch exhibits strong interchannel coupling during multichannel operation, including the deleterious effects of passband attraction, and degraded switching extinction and channel intermodulation. A rigorous analysis of these "passband collisions" is made, supporting experimental data is provided, and implications for WDM systems and EDFA gain equalization are discussed.

Summary. Recent experiments have shown that the interchannel coupling between AOTF-switched WDM channels is strong even at separations large compared to the filter passband width [1]. It is important to observe that the filter resonance for single-wavelength filtering is pulled toward a suddenly-injected neighboring resonance, and the originally-excellent polarization conversion (switch extinction) is degraded. Understanding and controlling these severe passband "collisions" is the purpose of this paper. In this work, we apply an exact model of the mechanism of AOTF polarization-flip filtering which takes into account the frequency shifts imposed by the acoustic grating and which also includes time-dependent effects due to the composite multi-channel acoustic grating. This analysis shows that there is modulation imposed on a filtered spectrum, which exacerbates interchannel crosstalk, as has been observed in acousto-optic switch experiments for WDM systems. Pass band attraction and notch degradation is seen as a consequence of the time-dependent model. Experimental results are provided which confirm the predicted intermodulation effects at low frequencies.

Background. Figure 1 shows an AO filter/switch routing wavelength channel \( \lambda_2 \) to the filtered (or cross-state) port by causing a TE-TM interconversion of the chosen wavelength band, while leaving wavelengths \( \lambda_1 \) and \( \lambda_3 \) unaltered. The bar-state (or unfiltered spectrum) has a notch burnt into it, centered at \( \lambda_2 \), the complement of which is a bandpass or cross-state spectrum located at the cross-state port. In the AOTF, a single passband is generated by a moving uniform-intensity grating of frequency \( F_1 \) (angular frequency \( \Omega_1 \)) which selects out and flips the polarization state of a specific phase-matched wavelength band centered about a frequency \( \Omega_1 = \Omega_2 / (v \Delta n) \) where \( c \) is the speed of light, \( v \) is the speed of sound and \( \Delta n \) is the effective waveguide birefringence.

Multi-channel AOTF operation. In early work on passband interactions, only the weak-coupling or widely-spaced channel limit was considered [2]. In that model, two SAW gratings were present but separated far enough that each was a minor perturbation of the other with regard to polarization flip: i.e. the relative sidelobe intensities of one passband at the other's center were low and of relative intensity \( n_{12} \approx 1 \). The resulting intermodulation was referred to as coherent crosstalk, and it was insidious because it was magnified to an intensity of \( \sqrt{n_{12}} \), a factor which is generally not small for nearest neighbors in dense WDM systems, perhaps of order 10%.

The small-signal argument obviously breaks down for close channel spacings, or during passband "collisions", when two gratings strongly compete to polarization-flip the same spectral components. What has been observed, however, but not explained well, is that these collisions have a larger than expected crossection, i.e. that passbands suffer significant intermodulation at distances large compared to their nominal filter width, and other unexpected coupling effects have been observed [1].

A powerful technique of examining passband collision effects is to use a single-wavelength probe and generate a pair of acoustic signals which are swept in time so that the average acoustic frequency slides through resonance with the probe laser wavelength, and then to plot the intensity as a function of time. This technique also provides information about the depth of modulation of the optical signal. In order to create a pair of notches, a filter was run in the notch mode (parallel input and output...
polarizers) and driven by a pair of closely-spaced acoustic frequencies. The details of the setup are shown in Fig. 2, in which a mixer was used to cause the pair of frequencies to sweep repetitively past a 1531-nm laser resonance. Note that the filter notch with only one passband active is deepest (most complete polarization conversion). The notches are attracted by a small amount which is hard to see in the available traces. Notches burnt into EDFA white-light spectra by one or more SAW gratings show these effects clearly [1]. Calculated filter spectra, based on the theory presented here, yield similar behavior.

Fig.1. (a) An AO filter routes wavelength channel \( \lambda_2 \) to the filtered port, leaving wavelengths \( \lambda_1 \) and \( \lambda_3 \) unaltered; (b) action of the filter on a "white light" spectrum is superimposed.

A simple explanation. The weak-collision model had to be replaced by a rigorous analysis in order to include the strong or close collision case. To start with, consider a simple time-dependent model of two equal-strength gratings at arbitrary separations. When two or more passbands are active, as would be the case in a WDM switch, there are two or more moving gratings with different periods. The composite function has both position and time dependence. Consider two gratings at frequencies \( \Omega_1 \) and \( \Omega_2 \) and, for simplicity, having equal amplitudes \( A \), designed to create passbands (notches) at optical frequencies \( \Omega_1 \) and \( \Omega_2 \). The composite grating can be exactly described as
\[
\Omega(t) = 2A\cos(\Omega't)\cos(\Delta\Omega t)\]
where \( \Omega' \) is the average frequency and \( \Delta\Omega \) is half the difference frequency. Note that \( \Omega(t) \) can be written as a function of position \( z \) along the device from the acoustic transducer, because time is retarded by an amount \( z/v \).

Strong-collision limit. For a near-uniform grating which changes very slowly in time compared to the device acoustic transit time, the filtered power is simply
\[
P_x = \frac{\sin^2(\alpha t)}{2(\alpha/\Delta\Omega)^2},
\]
where \( \Delta\Omega \) is the amplitude for 100% polarization conversion if only one grating is present, and \( \gamma=4\cos^2(\Delta\Omega) \). The close-collision values for cross power \( P_x \) and bar (notch) power \( P_n \), are
\[
P_x = \sin^2(2\pi\alpha\cos^2(\Delta\Omega t)) \quad \text{and} \quad P_n = \cos^2(2\pi\alpha\cos^2(\Delta\Omega t))
\]
and can be compared to experiment as we will show. The two-passband device can be thought of as an over-driven single-frequency filter centered at the mean resonant wavelength. The time dependent effects arise with multiple acoustic gratings because, although each photon sees a quasistatic grating, the envelope shape seen by that photon is determined by the instant at which it passed through the device, according to Eqn. 1. The transmitted light intensity has Fourier components at many multiples of \( 2\Delta\Omega \) because the output intensity is not linearly proportional to grating strength. An experiment was performed using an integrated AOTF of about 20 mm active length, similar to the design of Ref. 3, but without integral polarizers, placed between crossed polarizers and probed with a...
stable, single-frequency 1531 nm DFB laser signal. Figure 3(a) shows the RF drive amplitude (voltage) for two signals with a mean frequency 176.44 MHz, differing by about 300 Hz (1 ms/div). In this case, the applied RF power was 15.5 dBm, exactly that required for 100% polarization conversion when only one SAW signal was present. Of course, the filter was therefore overdriven (as discussed above) and reached maximum throughput (100% conversion) at half the peak RF amplitude, as is clear in Fig. 3(b). When the two waves were in-phase, as seen in Figs. 3(c) and 3(d), only 9.5 dBm power was required in each signal component to obtain 100% conversion at peak power.

![Diagram](image)

Fig. 2. Details of the weak-collision experiment, in which a mixer was used to generate a pair of frequencies which swept repetitively past the 1531-nm laser resonance.

![Diagram](image)

Fig. 3. (a) RF drive amplitude (voltage) and (b) filter transmission for two signals differing by about 300 Hz (strong collision). In (c) and (d) the RF drive is reduced by 6 dB in order to achieve 100% switching at the maximum RF drive power.
The close-collision case. The weak-collision criterion can be written \( t \omega < 1 \) where \( t \) is the device acoustic transit time. If the envelope changes appreciably over a device length \( L \), i.e. unless \( L \Delta \omega / v < 1 \), where \( v \) is the speed of sound, we must analyze the collision not as a uniform grating of time-varying strength, but as a grating whose strength varies with position along the device as well as with time. The critical difference frequency where this occurs is when the RF beat length for the acoustic grating \( L_{\text{beat}} = v / \Delta F = 2 \pi v / \Delta \Omega \) becomes of order the length of the total acousto-optic interaction length \( L \). We can restate this condition as \( \Delta \omega_{\text{crit}} = \Delta \omega_{\text{FWHM}} \) where \( \Delta \omega_{\text{FWHM}} = 0.8 \lambda^2 / \Delta n L \) is the classical AOTF passbandwidth.

Direct calculation of passband collisions in the close-collision case, of importance to WDM switching, is possible if one breaks up the device into many segments which are much smaller than the distance over which the interaction strength envelope changes appreciably. One then applies the coupled-mode theoretic polarization change calculation to each segment as if it were a uniform grating of period \( \Omega \), using the complex output Jones vector of stage \( k \) as the input to stage \( k+1 \). This method of analysis is exactly what has been used to calculate apodized filter transmission profiles [4], [5] and to understand passband asymmetry in AOTFs with nonuniform waveguide birefringence [6]. Even as many cycles of the envelope function occupy a single device length, the mathematics of Eqn. 1 remains correct.

The weak-collision limit. When the difference frequency between the perturbing passbands is large enough that several cycles of the RF power are encompassed within the device interaction length, then we expect that the intermodulation amplitude decreases significantly, since time evolution doesn't drastically alter the intricate grating structure encountered by light passing through the device. A full study of beat effects across the full range from strong to weak passband collisions is underway. An entirely different treatment based on assuming a multi-component beat spectrum and using coupled mode theory self-consistently to evaluate the coupling, followed by BER studies of interchannel beating, has been presented by another group [7].

Discussion. It is certainly possible to reduce coupling between passbands by suppressing the off-resonant polarization conversion (sidelobe reduction). Current WDM demonstration systems in the US employ AOTF switches which have sinusoidal apodization in order to keep interchannel coupling to a minimum for 4-nm-spaced WDM transmission [8].

In addition to deep sidelobe suppression, one technique to reduce interchannel coupling, called wavelength dilation [9], involves separating the WDM spectrum into two interlaced subspectra, where even- and odd-numbered channels are driven by different two AOTFs in series, perhaps on the same integrated substrate, in order to space the polarization-converter gratings by twice the nominal WDM channel spacing. This technique has been very successful in reducing interchannel interference [1].

The consequences of "colliding passbands" are also encountered in EDFA gain equalization [10], since signals amplified by AOTF-equalized EDFAs will also be modulated. The intermodulation effects in this important potential application are now under study.

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Asymmetric Y-junction wavelength demultiplexer in \textit{Ti : LiNbO}_3, using a segmented waveguide branch

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Abstract
An asymmetric Y-junction wavelength demultiplexer, with a segmented branch, was realized in \textit{Ti : LiNbO}_3. The device was fabricated in a single-step lithographical process. WDM operation in the range 633nm < \lambda < 834nm is demonstrated, with extinction ratios up to 30dB. Insertion losses vary between a negligible value (away from cutoff) up to 6dB (near cutoff).

Wavelength division multiplexing (WDM) is an important function in fiber optics communication. One possible integrated optics configuration is the adiabatic, asymmetric Y-junction, in which two wavelengths \lambda_1, \lambda_2, can be routed individually through the branches, typically for passive 1.3 - 1.55/-L channel separation [1]. The advantage of this configuration is its noncritical behaviour, in contrast to other waveguide devices, such as a directional coupler and Mach-Zehnder - which are based on interferometric principles and depend on a critical length. For the purpose of WDM, the wavelength dispersion curves of the two branches must intersect at a phase-matching wavelength \lambda_0, where \lambda_1 < \lambda_0 < \lambda_2. That requires that the branches would differ in both width and index difference. Whereas width difference is simple to realize, varying the index difference typically requires a multi-step fabrication process (e.g. double diffusion) [2, 3, 4], which complicates fabrication. Recently we suggested to circumvent this difficulty by using a periodically segmented waveguide (PSW) as the wider, lower index branch [5]. In this case, the index averaging property of the PSW - which has already been demonstrated experimentally [6, 7] - is utilized to obtain the required phase-matching condition. In this letter we report the realization of such device in \textit{Ti : LiNbO}_3 waveguide.

The device (see Fig. 1) consisted of an input section \(w_i = 5\mu m, l_i = 2mm\) wide, adiabatically widened in a taper section \(l_i = 2mm\) and then splitted into two branches: a segmented branch \(w_s = 10\mu m, A = 15\mu m, \eta = \frac{A}{2}\) - which directly continues the input waveguide, and a continuous branch - tilted at \(\theta = 2mrad\) from the segmented branch. The length of the branches was \(l_s \approx 2cm\). The continuous branch width varied in the range 3 \(\leq w_c \leq 4.8\mu m\) (altogether ten variants of the device, with \(\Delta w_c = 0.2\mu m\)). At the output, the waveguides were 40\mu m apart.

The waveguides were coated with 215\AA\ Ti layer, indiffused at 1015°C for six hours (in wet O\textsubscript{2} atmosphere), and polished. The waveguides were excited by a HeNe laser and later by a tunable Ti:Al\textsubscript{2}O\textsubscript{3} laser via a butt-coupled single mode fiber. The fiber was positioned for maximum power at the output (i.e. the sum of the two branches), to obtain pure excitation of the fundamental mode. The output near-fields were observed with a CCD camera (having \(\gamma = 1\), i.e. a linear response) and recorded by an 8-bit image grabber. Alongside the Y-junctions, the optical chip contained a reference continuous channel (similar to the input waveguide section) which was used to estimate the relative transmissions of the Y-junction branches.

The transmissions of the two branches were measured, relative to that of the reference waveguide. This way, only the excess loss related to the specific configuration is taken into account, while the
absolute guiding losses of the chip, which are assumed to be the same for all waveguides, are discounted. The branch transmissions were first measured for HeNe laser (λ = 633nm), for all ten variants of \( w_c \), for both TE and TM polarizations. This measurement was then repeated at a longer wavelength, \( \lambda = 751nm \), for the TE mode (the TM mode was cut-off at that wavelength) by using the TiAlO_3 laser. Finally, a more direct demonstration of wavelength demultiplexing was obtained by measuring the transmissions of the junction with \( w_c = 4.8 \), as a function of wavelength, (in the range 750nm < \( \lambda < 835nm \)) by using the TiAlO_3 tunable laser.

Some of the recorded near-fields are given in Fig. 2, for the junction with \( w_c = 4.8\mu \). At \( \lambda = 633nm \) the light exits at the continuous branch. At \( \lambda = 760nm \) phase matching is achieved, and the light is split equally between the two branches. At \( \lambda = 795\mu \) the light exits from the segmented branch. As the wavelength increases further, however (to \( \lambda = 832nm \)), the mode of the segmented branch approaches cutoff and widely spreads out. This leaves some amount of coupling between the branches (even though their outputs are 40µ apart) and results in an incomplete routing through the device.

Detailed results of the branch transmission measurements are given in Fig. 3. Consider first the cases of \( \lambda = 633nm \). Clearly, as the continuous branch narrows, the light tends to exit the junction at the segmented side, due to a higher effective index of that branch. The extinction ratio (\( 10 \log \frac{I_1}{I_2} \)) generally increases with the deviation from phase-matching. For the TE polarization, the extinction ratio is quite high away from the phase-matching - up to about 30dB. Note that about 10% width deviation is sufficient for a useful extinction ratio of 15 - 20dB. Recalling that the V-number varies as \( \frac{\lambda^2}{\lambda^2 - \omega_c^2} \), note that this width deviation is roughly equivalent to a 10% deviation in wavelength.

The phase-matching (equal outputs) values of \( w_c \) were slightly different for the two polarizations (\( w_c = 4.3\mu \) for TE, \( w_c = 4.2\mu \) for TM). This difference is very small (by the above argument, it corresponds to \( \approx 12nm \) wavelength deviation) and does not have much functional effect. It is somewhat surprising, however, that the TM mode has a lower phase-matching value than TE: one would expect that since the TM mode is more weakly guided, the phase matching value of \( w_c \) would increase for TM, rather than decrease. This is due to the fact that lower effective index means (referring to Fig. 2) dispersion lines which are lower than for TE. Since the lowering of the lines of the continuous branches is larger than for the segmented branch line (roughly in proportion to the duty cycle of the segmentation), the phase matching value of \( w_c \) is expected to increase for TM. This effect is indeed evident for the measurements taken at the longer wavelength of \( \lambda = 751nm \) (see Fig. 3), where guiding is also weak. With respect to the TM case, the lower phase-matching width of TM - as deduced in our case, may be related to the different branch transmissions rather than to the phase-matching itself.

The lower extinction ratios and higher insertion losses observed for TM can also be related to its weaker guidance. Extinction ratios are reduced in the weak guiding region because in that region the slopes of the intersecting dispersion lines are reduced. Thus, for a given deviation from phase matching (in wavelength or width), the difference \( |n_{eff}^T - n_{eff}^M| \) is lower, which results in a lower discrimination between the two modes.

The insertion loss of the device is attributable to three mechanisms, related to the pre-junction tapering, branching and segmentation of the wider channel. In all sets of measurements (see Fig. 3), the insertion loss is highest when the light exits at the continuous branch. For example, with \( \lambda = 633nm \) TE excitation, there is practically no loss for \( w_c = 3\mu \) (light exits at the segmented branch) but about 1.5dB loss for \( w_c = 4.8\mu \) (light exits at the continuous branch). Furthermore, as guiding becomes weaker, insertion loss increases for both switching conditions. Segmentation loss is low here due to the short period, low \( \Delta n \) and large width of the segmented branch. Furthermore, this loss is expected to decrease for longer wavelengths, as the mode becomes less confined. In view of that, the measured results seem to indicate that branching (and perhaps also tapering) losses are dominant, in spite of the small branching angle. It is well known that in a Y-branch, mode that approaches the cutoff wavelength suffers from relatively large insertion loss [8]. Note that in the present design the segmented branch is almost a collinear extension of the input waveguide, whereas the continuous branch is tilted and shifted from the input axis. Improving this design, as well as operating the device away from cutoff, can thus be expected to lower the losses. In that context, note that the junction with \( w_c = 4.3\mu \) can be used as an efficient low loss demultiplexer around a phase matching wavelength \( \lambda = 633nm \).
The extinction ratios described above are comparable to, and in some cases exceed, previously reported results - obtained with more complicated fabrication methods. The insertion losses are low away from cutoff - where the device would typically be operated. This good performance, combined with the simple fabrication process involved in this device, can be applied for several purposes: first, by a proper change of design parameters, the device may be utilized for passive 1.3 – 1.55µ channel separation. Second, it may be readily extended to multi-channel demultiplexing, retaining the same single-step fabrication process. In comparison, any of the other multi-step methods would require the addition of fabrication steps (according to the number of channels). Third, the device may be useful as a calibration device, to estimate fabrication parameters. In this device, phase-matching can be easily identified (though some care should be taken to the effect of branch transmissions). This is to be contrasted with other types of calibration devices, notably directional couplers and Mach-Zehnder interferometers, which are simultaneously affected by the effective indices and the device length. Knowing the phase-matching wavelength of a junction (or perhaps even few such wavelengths - for a set of junctions) the parameters of the (single-step) fabrication process can be well fitted by trial and error algorithm, using a mode solver. For example, in the case of Ti : LiNbO3 the values of the diffusion coefficients and the index gradient $\frac{dn}{dx}$, all of which vary significantly between specific processes, may be obtained by using a set of such junctions.

Acknowledgement: We thank Irina Finkelstein for her skillfull technical help. This work was partially supported by a grant from the Israel Academy of Arts and Sciences.

References

Figure 1: The layout of the asymmetrical Y-junction wavelength demultiplexer.

Figure 2: Near field patterns at the output of the branches, at various wavelength, for the junction with \( w_c = 4.8 \mu \text{m} \). In all these cases a TE polarization is used.

Figure 3: Measured branch transmissions (normalized by the transmission of the reference waveguide): Solid lines - continuous branch. Dashed lines - segmented branch.
FLATTENED RESPONSE ENSURES POLARIZATION INDEPENDENCE OF InGaAsP/InP PHASED ARRAY WAVELENGTH DEMULTIPLEXER

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Abstract - A four channel polarization independent phased-array wavelength demultiplexer has been made by using different array orders for TE and TM. The insertion loss is 3.5 dB and the crosstalk is -16 dB. TE/TM peak position difference is only 0.2 nm. The response is flattened over 0.5 of the 1 nm channel spacing, yielding 0.3 nm of polarization independent flattened response for each channel.

Introduction

Wavelength Division Multiplexing (WDM) is a simple and effective way of exploiting the large bandwidth of optical fibres. The Phased Array wavelength demultiplexer has been shown to be the superior WDM demultiplexer for systems with a small number of channels [1].

Because of the undefined polarization state of the signal from an optical fibre, this demultiplexer must be polarization independent. For Phased Arrays (PA), this has been achieved in a number of different ways, i.e. by insertion of a half wave plate in the middle of the array waveguides [2], by use of non-birefringent waveguides composed of Q(0.97) material [3], or by a PA design in which the Free Spectral Range (FSR) equals the waveguide TE-TM shift, thus overlapping different orders of the TE and TM response [4].

The latter approach, which is adopted in our present work, is appealing because it requires no new technology. It will be shown, however, that the TE-TM shift depends heavily on the waveguide geometry. This imposes tight requirements on process control in order to make TE and TM response overlap, unless this response is flattened, as proposed earlier [5].

Design issues

A Phased Array consists of a dispersive waveguide array connected to input and output waveguides through two radiative couplers. Its operation is based on the imaging of the input field at the output plane. Due to the dispersion, the phase front at the output plane will tilt with varying wavelength, thus projecting the light onto different output waveguides. (See figure 1.)

Because of the slightly different effective indices for TE and TM, the wavelength response for TE polarized light will be slightly shifted with respect to the response for the TM polarization. The TE-TM shift $\Delta \lambda_{TE-TM}$ is defined as the shift between these two response patterns. It can be shown that

$$\Delta \lambda_{TE-TM} = \lambda \left(1 - \frac{N_{TM}}{N_{TE}}\right)/(1 - \frac{\lambda}{N_{TE}} \frac{dN_{TM}}{d\lambda}),$$

taking the material dispersion into account [1]. Figure 2 shows the dependence of this waveguide property on different waveguide parameters. It is seen that practical fabrication tolerances can induce a change in the TE-TM shift of about 0.2 nm in either direction, and thus affect the polarization
independence of the PA, unless the response can be flattened over a region of at least 0.2 nm. This is
done by using multimode output waveguides [6].

In a previous design a conservative configuration of the receiver plane was used, i.e. wide multi­
mode waveguides for a large flatness region and wide gaps for low crosstalk between channels [5].
This, in combination with the small channel spacing necessary to fit 4 channels in one FSR results in
large devices, (i.e. 2.2x3.4 mm$^2$ excluding input/output waveguides) in which layer and lithographic
nonuniformity pose difficulties for proper phase transfer through the array.

In the present design, an optimal balance was sought between device size and crosstalk/flatness
region. This resulted in a device working in 327th order for TE and 326th order for TM, with 30 array
waveguides, and 4.5 $\mu$m wide multimode output waveguides separated by 2.5 $\mu$m gaps. The device
size is 2x2.7 mm$^2$.

Fabrication

The device was fabricated in a simple one step masking/etching process on a SI-InP substrate on which
600 nm of InGaAsP(1.3) and 300 nm of InP were grown with MOVPE [7]. It was first patterned
in a 140 nm thick RF-sputtered SiO$_2$ masking layer and then etched 350 nm with an optimized RIE
etching/descumming process [8]. Finally it was cleaved.

Measurement

The chip was measured by launching linearly polarized light from a single-mode source into the
waveguides with an AR-coated microscope objective. The output light was picked up with a similar
microscope objective and projected onto a Ge-detector.

First, Fabry-Perot measurements were done to establish the propagation loss in straight waveguides.
This was 2.0±0.2 dB/cm for both polarizations.

Then, the demultiplexer response was measured by exciting the PA in the central input channel.
The results are plotted in figure 3. The TM peaks are shifted 0.2 nm to longer wavelengths relative to
the TE peaks, indicating a TE-TM shift 0.2 nm smaller than the theoretical 4.7 nm. Disregarding the
Fabry-Perot ripple due to multiple reflections at the (not yet AR-coated) cleaving faces, the response is
flattened over 0.5 nm, yielding 0.3 nm of polarization independent flattened response for each channel.
The insertion loss and the crosstalk are 3.5 dB and -16 to -18 dB, respectively.

Figure 4 (left) compares the response of one channel with what is theoretically expected, i.e. the
field of a monomode input waveguide sweeping over a multimode output waveguide. Agreement is
excellent, indicating that phase transfer through the array and the focus in the receiver plane are good.

Discussion

In figure 4 the response of the presently considered device is compared with that of a previous one [5],
that suffered from the problems discussed under "design issues". It is seen that the new optimized
device considerably improves the flatness of the response. Furthermore, the insertion loss is reduced
from 5 to 3.5 dB for the complete range of flatness.

It has been shown that, notwithstanding various sources of uncertainty regarding TE-TM matching,
fabrication of polarization independent Phased Arrays is feasible by using a flattened response. This
has been done without requiring new technology and with very simple one step waveguide processing.

References


Figure 1 Operating principle of a phased array: The input field, coupled into the array, is projected onto the receiver plane. Tuning the wavelength tilts the phase front, and thus addresses different outputs.
Figure 2 Dependence of TE-TM shift on several waveguide parameters. The unperturbed waveguide is 2 μm wide, and is etched 350 nm in a layerstack of 300 nm InP and 600 nm Q(1.3) on InP substrate.

Figure 3 Response of each of the four output channels for TE (solid) and TM (dashed). Insertion loss is 3.5 dB, crosstalk is -16 dB (worst case). There is 0.3 nm of polarization independent flattened response per channel. The next higher order can just be discerned at the left. The cleaving faces have not yet been AR-coated, hence the Fabry-Perot ripple.

Figure 4 Left Simulated (dotted) and measured (solid) response for one channel (#3, TE). Excellent agreement indicates good focus and phase transfer through the array. Right Response of previous device [5] compared to its simulation.
Bandwidth Optimization of Add/Drop Filters Using a Cascaded Coupler Mach-Zehnder Configuration

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Abstract

A new synthesis method for channel add/drop filters consisting of cascaded directional couplers and equal Mach-Zehnder sections is presented. The optimum distribution of the coupling coefficients with respect to sidelobe suppression and filter bandwidth is found.

1 Introduction

Wavelength-division-multiplexed (WDM) communication systems require optical filters to multiplex or demultiplex channels operating at different wavelengths. Those filters are supposed to have a high skirt selectivity and a transmission characteristic that stays below a maximum allowable channel crosstalk (CT) in the entire stopband. One filter that might be important for practical applications in future WDM systems is the "resonant coupler" (RC) (see figure 1). It consists of \( N \) directional couplers that are connected by waveguides of unequal arm lengths (Mach-Zehnder sections). An experimental and a theoretical study was performed by H. Yaffe, et. al. [1] and M. Kuznetsov [2] respectively, concerning a tapered coupling strength distribution to reduce the CT. In this paper we present a new synthesis method for the RC which yields the minimum possible bandwidth for a given CT and stage number \( N \). The major advantage of the RC is that it is easy to fabricate since it only requires one lithographical step. Furthermore it consists of basic optical components like waveguide bends and couplers, so that each stage of the filter can be optimized separately. The principle of operation of the RC is similar to the one of transversal filters (FIR), known from digital signal processing. The uniform delay time difference \( \Delta t \) of the two MZ arms determines the free spectral range (FSR) of the optical filter. With respect to a generalized mathematical description we will use the phaseshift difference \( \Delta \phi \) of the optical waves rather than \( \Delta t \).

2 Mathematical Description

The transmission characteristic of the RC can easily be calculated by describing each coupler with the coupled wave equations

\[
\frac{dA}{dz} = -j\kappa B \quad \text{and} \quad \frac{dB}{dz} = -j\kappa A
\]

where \( A \) and \( B \) are the normalized electric fields in the upper and the lower waveguides and \( \kappa \) is the coupling coefficient between them (see e.g. [3]). In this equation we have already assumed that the waveguides are symmetric. An analytical solution to (1) for each individual coupler of the length \( L_k \) \((k = 0, 1, \ldots, N)\) is given by the following matrix formulation

\[
\begin{bmatrix}
A(L_k) \\
B(L_k)
\end{bmatrix} = S_{ck} \begin{bmatrix}
A(0) \\
B(0)
\end{bmatrix} = \begin{bmatrix}
c_k & -j\sqrt{1-c_k^2} \\
-j\sqrt{1-c_k^2} & c_k
\end{bmatrix} \begin{bmatrix}
A(0) \\
B(0)
\end{bmatrix}
\]

(2)
with \( c_k = \cos(\kappa L_k) \). The MZ-sections are simple phaseshifters which can be described by the transmission matrix
\[
S_{MZ} = \exp(-j\phi) \begin{bmatrix} \exp(-j\Delta\phi) & 0 \\ 0 & \exp(j\Delta\phi) \end{bmatrix}
\] (3)

with \( \phi = \frac{\beta_A L_A + \beta_B L_B}{2} \) and \( \Delta\phi = \frac{\beta_A L_A - \beta_B L_B}{2} \). In these expressions \( \beta_A, \beta_B \) refer to the propagation constants and \( L_A, L_B \) to the lengths per MZ section of the upper and the lower waveguides respectively. Considering the fact that the device is lossless and reciprocal the transfer matrix of the cascaded configuration can be written as
\[
S_g = \left( \prod_{k=1}^{N} S_{ck}S_{MZ} \right) S_{c0} = \begin{bmatrix} s_{31} & -s_{41}^* \\ s_{41} & s_{31}^* \end{bmatrix} \exp(-jN\phi)
\] (4)

with the relation \(|s_{31}|^2 + |s_{41}|^2 = 1\). The absolute square value of the scattering element \( s_{41} \) denotes the power transfer function of the device. It can easily be shown from equation (4) that this element can always be written in the form
\[
s_{41} = j \sum_{k=0}^{N} a_k \exp\left[ j\frac{\Delta\phi}{2} (N-2k) \right]
\] (5)

where the coefficients \( a_k \) are determined by the coupling coefficients \( c_k \) via a nonlinear set of \( N+1 \) equations. This means on the other hand that the coupling coefficients \( c_k \) can be calculated numerically once the coefficients \( a_k \) are given by a synthesis of the transmission function \( s_{41} \).

### 3 Weighted Coupling Coefficients

The filter transmission \( s_{41} \) is supposed to be symmetric around the points where \( \Delta\phi \) is a multiple of \( 2\pi \) (i.e. the filter frequency). Hence the coefficients \( a_k \) have to satisfy the equation \( a_k = a_{N-k} \) (see (5)), resulting in a purely imaginary \( s_{41} \) and an overall phaseshift that is given by the exponential term \( \exp(-jN\phi) \). The symmetry of the coefficients \( a_k \) simplifies the nonlinear equation system, because a simple solution can always be obtained by choosing the coefficients \( c_k \) symmetric (\( c_k = c_{N-k} \)) as well. The number of equations reduces to \( (N+1)/2 \) for an odd number \( N \) or to \( N/2 + 1 \) for an even number \( N \). For most coupling distributions the magnitude of the minor lobes occurring in the stop band decreases continuously in both directions from the pass band. This means that the channel crosstalk (CT in dB) is determined by the largest minor lobe which is adjacent to the pass band. An equal magnitude of all occurring subresonances in the stop band would be the optimum, resulting in a narrower pass band. This can be achieved by setting the polynomial \( s_{41} \) equal to
\[
s_{41} = -j \frac{T_N(z_0 \cos(\Delta\phi/2))}{T_N(z_0)}
\] (6)

where \( T_N \) is the Chebyshev polynomial of the first kind and of the order \( N \). The constant \( z_0 \) (\( z_0 > 1 \)) is a design parameter that can be calculated by the desired CT. The Chebyshev characteristic is well known from the design of dipole arrays, where the mathematical formulations are equivalent to equation (5). It is shown in [4], that the so called Dolph-Chebyshev radiation pattern produces a minimum beamwidth for a given sidelobe level, or applied to our case the desired minimum bandwidth for a given CT. The Chebyshev polynomials have the following properties: 1. \( T_N(x) \) stays in between \(-1\) and \( 1 \) for \(|x| < 1 \) and \( 2. T_N(1) = 1 \). The minimum attenuation in the stop band is therefore given by \( 1/T_N(z_0) = 10^{CT/20\text{dB}} \). With the relation \( T_N(\cosh(x)) = \cosh(Nx) \) for \( x > 1 \) the constant \( z_0 \) can be calculated by
\[
z_0 = \cosh\left( \frac{\arccosh(10^{-CT/20\text{dB}})}{N} \right).
\] (7)
The coupling coefficients $c_k$ are now given by the equations (4), (5) and (6), since each exponent of the Chebyshev polynomial has a corresponding exponential term in the transmission function $s_{41}$ in equation (5). Figure 2 shows an example of a solution for a five stage filter. The total coupling strength of all couplers is $\sum \kappa L_k = \pi/2$. This is obvious, since in resonance the device is supposed to route the light into the lower waveguide. Except for high crosstalks a stronger tapering of the coupling distribution yields a higher sidelobe suppression and a wider filter bandwidth. This for example can be seen in figure 3, where the transmission function $s_{41}$ of a five stage filter is plotted.

4 Maximum Number of Channels

If we define the filter bandwidth to be the bandwidth at which the magnitude stays below the CT we can write

$$z_0 \cos \left( \frac{\Delta \phi_{FW}}{4} \right) = 1,$$

where $\Delta \phi_{FW}$ corresponds to the full bandwidth. Let us further suppose that the bandwidth of the optical signal is much smaller than the bandwidth of the filter. The channel spacing is then given by $\Delta \phi_{FW}/2$ which results in a number of selectable channels $N_c$ that can be determined by

$$N_c = \frac{2\pi}{\Delta \phi_{FW}/2}$$

Combining equations (8) and (9) yields

$$N_c = \frac{\pi}{\arccos(1/z_0)},$$

with $z_0$ given from equation (7). The dependence between $N_c$ and $N$ is almost a linear function for a large number of stages and a low CT so that it can be further simplified with the approximations $\cos(\pi/N_c) \approx 1 - 1/2(\pi/N_c)^2$ and $1 - 1/\cosh(x) \approx (1/2)x^2$ for $x \ll 1$ to

$$\frac{N_c}{N} \approx \frac{\pi}{\arccosh(10^{-CT/20dB})}.$$

Figure 4 compares equation (10) and (11). It is worth noticing that a crosstalk of 20dB results in a number of selectable channels that is approximately equal to the number of filter stages. This result is better than the results for other coupling distributions (see e.g. [2] for the given cosine and binomial distributions). As shown before it is the best coupling distribution that can be achieved for this kind of filter, and it therefore yields the ultimate lower limit for the filter bandwidth.

5 Conclusion

We have shown that the coupling distribution of a resonant coupler acting as an add/drop multiplexer can be tapered in that way that it produces a minimum possible bandwidth for a given channel crosstalk. The number of selectable channels in that case is found to vary linearly with the number of filter stages. One advantage of this filter is that it consists of basic well known optical elements like directional couplers and curved waveguides. Each element can be optimized separately, resulting in easier device design and fabrication.

Acknowledgment

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References


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![Fig. 1 Resonant coupler with N stages](image1)

![Fig. 2 Coupling strength $\kappa L_k/(\pi/2)$ with $N = 5$ stages](image2)

![Fig. 3 Transmission function $s_{41}$ for a $N = 5$ stage filter. The channel crosstalks are CT = $-15$dB and CT = $-30$dB](image3)

![Fig. 4 Maximum number of selectable channels $N_c$ per number of filter stage $N$ versus desired CT](image4)
Advanced Optical Switching Devices

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*This invited paper has not been received in time.*
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Selective Area Growth of Q/Q-MQW Structures for Active/Passive 2x2 Space Switch Matrices


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Abstract:
We report on the selective area growth (SAG) of compressively strained all quaternary (InGaAsP/InGaAsP) MQW structures by LP-MOVPE resulting in a bandgap shift of 138 nm. This technique is well suited for the integration of active and passive regions in one epitaxial step as demonstrated here for 2x2 space switch matrices. First results of these devices show on-off ratios of >35 dB in all 4 gates.

Introduction:
Optical space switch matrices are of great importance for optical routing. An interesting concept to realize blocking free space switch matrices is the use of active segments for on-off switching via carrier injection in combination with passive waveguides. Based on bulk structures and double core technology 2x2 /1/ and even 4x4 /2/ matrices have been reported previously.

A new approach to integrate active gates with passive waveguides is the combination of our MQW structure based Y-laser technology /3/,/4/ with selective area growth (SAG) on patterned substrates /5/, /6/. SAG is a powerful technique to control the local bandgap energy in MQW structures. The use of ternary/quaternary (InGaAs/InGaAsP) MQW structures was reported until now to realize laser/modulator devices with bandgap differences up to 60 nm /7/.

Experimental:
In our space switch the longitudinal integration of active and passive sections is realized for the first time by SAG of 5 compressively strained (0.7% strain) InGaAsP wells separated by 7 nm thick lattice matched InGaAsP barriers (λ=1200 nm) as described in /8/. Growth is performed on SiO2 masked n-InP substrates with low pressure MOVPE. To adjust a photoluminescence wavelength of 1440 nm in the passive sections a well thickness of 4nm is necessary. The SiO2 patterns are designed to result in a photoluminescence wavelength shift of around 140 nm in the active sections (see fig.1) due to increased well thickness and strain. A schematic cross section of the active-passive coupled region is given in fig.2.

The space switch matrix is fabricated using a dry etched buried ridge lateral structure (BRS). The regrowth with p-doped InP cladding and InGaAs contact layers is performed by LP-MOVPE. Electrical separation of the segments is done by etching the ternary contact layer followed by ion implantation. The wafer processing is completed by conventional thinning and metallization. After cleaving a standard antireflective (AR) coating is applied to both facets. The 3 mm long devices are mounted on copper submounts and each active segment is bonded separately for characterization. A schematic view of the structure is given in fig.3. The monolithic
integration of 4 passive Y junctions (including 1 crossing), 4 amplifiers and 4 gates using the SAG technology allows us to restrict the chip size to 0.5 x 3 mm².

For standard characterization transmission experiments on all possible optical paths through the space switch matrix were performed. The 2 input and 2 output amplifiers are driven in parallel with a constant current of 55 mA and the gates are switched between 0 and 50 mA for the off and on state, respectively. CW light of an external cavity laser is coupled into the input amplifier of the chip with lensed fibres in TE polarisation. The output light is coupled into a lensed fibre and analyzed using an optical spectrum analyzer.

Experimental results of transmission experiments of one of the four paths of our 2x2 matrix are depicted as an example in figure 4. An on-off ratio of the switch of >35 dB is found at 1540 nm for all 4 gates with best value of 45 dB. Crosstalk between different optical output ports is found to be equivalent with the on-off ratio of the space switch.

Summary:
In conclusion, a compact (0.5 x 3 mm²) InP based 2x2 space switch matrix with integrated active and passive sections was realized using a one step selective area growth technique (SAG). On-off ratios up to 45 dB were measured.

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References:
Figures:

Fig.1: Room temperature photoluminescence spectra of passive (1440 nm) and active (1578 nm) sections

Fig.2: Schematic cross-section of the active-passive coupling region
Fig. 3: Scheme of active/passive 2x2 space switch matrix with 2 input amplifiers (I1, I2), 4 active gates (G1 - G4), 2 output amplifiers (O1, O2) and 4 passive Y-junctions (including 1 crossing).

Fig. 4: Measurement of the transmission of one path (e.g. cross: I2-O1) with a gate current of 0/50 mA: on-off ratio: 45 dB.
1:8 OPTICAL MATRIX SWITCH ON InP/InGaAsP WITH INTEGRATED MODE TRANSFORMERS

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Abstract

A 1:8 optical switch based on three waveguide directional couplers in InGaAsP/InP has been monolithically integrated with adiabatic mode transformers. The switch operates polarization independent at currents as low as 5mA in a 100 nm wide wavelength range. The average insertion loss is 9.8dB. Fiber coupling tolerances are ±3µm horizontally and ±2µm vertically for 1 dB penalty.

Introduction

Optical switching modules with polarization independent operation and low insertion loss are key components for optical telecommunication networks.

During the past year especially thermooptic silica based switches have reached a notable state of maturity. On the other hand, III-V semiconductor based switches offer the advantage of lower power consumption, typically a few milliwatts, and faster switching times, typically in the nanosecond range and below. Nevertheless, for a long time, the considerable mode mismatch between the chip waveguide and the singlemode fiber prevented these advantages from really coming to fruition.

The invention of monolithic integrated mode transformers was the decisive step to overcome this disadvantage. Optical switches based on III-V semiconductors with integrated mode transformers are beginning to challenge the transmission values of silica, LiNbO	extsubscript{3}, and polymer based switches.

In the present paper we report on a 1:8 optical matrix switch monolithically integrated with adiabatic optical mode transformers.
1400 μm, respectively. The complete MOST has a length of 2 mm, including 200 μm of fiber matched waveguide.

The 1:8 matrix switch is prepared for self-aligned module assembly /10/ by means of special assembly ridges which are formed in the same process steps as the fiber matched waveguides. The spacing of the waveguides at the cleavage plane is 250 μm in order to allow for fiber ribbon coupling. The complete matrix switch has a length of 10.4 mm and a width of about 2 mm.

The chip was not antireflection coated.

Objective. Lock-in technique was used in order to increase the dynamic range. Polarization control was performed by use of a polarization beam splitter in the output light path. To measure the fiber-fiber transmission, the microscope objective was replaced by a butt coupled single mode fiber. In that case polarization control was performed by fiber squeezers. For wavelength selective measurements we used the EDFA light source together with an HP 70004 optical spectrum analyzer.

Experimental Results

Experimental Setup

The spontaneous emission of an EDFA was fed to the input waveguide of the 1:8 matrix switch via a butt coupled single mode fiber. The output waveguides were imaged, one after the other, on a photodiode by an infra-red microscope objective. To measure the transmission of a desired path through the matrix, the three corresponding TIC switches were activated by current injection. In the present measurement all switching currents were set to 5 mA. No individual optimization of
the switching current was performed. The remaining four switches were currentless, thus operating as passive splitters. Fig. 4 shows the measured fiber-fiber transmission of each of the eight outputs at all the eight switch states. The 1:8 matrix exhibits a very homogenous signal and crosstalk level. The measured average insertion loss is of the uncoated device is 12.8 dB, corresponding to a loss of only 9.8 dB for a device with AR coating. The variation of the transmission for any light path and any polarization was only ±0.75 dB. The crosstalk suppression is 17 dB at average and better than 10 dB in the worst case.

![Fig. 4 Transmission (fiber-fiber) of the 1:8 matrix switch with integrated mode transformers.](image)

Fig. 4 shows the measured wavelength dependence of the light intensity at two output waveguides, one carrying the signal and the other the highest crosstalk level. Currents were kept constant during the measurement. The spontaneous emission spectrum of the EDFA is shown for comparison purposes. In the wavelength range of 1500 nm to 1600 nm the signal intensity varies by less than 2 dB, the crosstalk by about 5 dB. We suppose that the biggest part of this is due to Fabry-Pérot reflections between the uncoated cleaved fibers and the uncoated chip facets, both at the input and output side.

Aiming at a better understanding of the matrix's transmission characteristics we additionally performed measurements on subcomponents, as described in the following.

### Waveguides and Bendings

Fabry-Pérot measurements of straight waveguides gave polarization independent losses of typically 1.4 dB/cm. Straight waveguides with integrated MOSTs showed transmission losses of 7 dB, independent of polarization. Again, this includes 3 dB Fresnel losses due to the uncoated endfaces. No extra losses for bendings were found.

### MOST

The MOST-components, integrated next to the cleaved facets, transform the small modes used in the matrix switch to the mode of a single mode fiber. Fig. 6 shows, on the left side, the measured optical mode at the fiber matched side of the MOST and, on the right side, the measured optical mode of a single mode fiber. The intensity overlap is as high as 93% (−0.3 dB). The alignment tolerances are ±2 μm vertically and ±3 μm horizontally for 1 dB excess loss.

### TIC Switch

Fig. 7 shows the measured switch characteristic of one of the seven TIC switches within the 1:8 matrix switch. As expected the TIC switch...
shows a symmetric and rather digital characteristic. For unpolarized light (solid lines) the maximum transmission is -12.7 dB at a current of only 4 mA. As theoretically expected the best crosstalk suppression occurs at somewhat higher current values. Selecting 5 mA as the switching current gives a crosstalk suppression of better than 13 dB at a transmission of -13 dB for both switching states. These values still include 3 dB Fresnel reflections. As can be seen from the dotted lines, a weak polarization dependence is observed.

![Fig. 7 Transmission (fiber-fiber) characteristic of one of the seven TIC switches of the matrix.](image)

**Summary and Discussion**

A 1:8 switching matrix in InP/InGaAsP with integrated mode transformers was realized. The fiber-fiber losses are less than 10 dB for the anti-reflection coated device. To our knowledge this is the best value published for passive InP matrix switches so far.

A detailed analysis of the loss mechanisms gives 1.4 dB waveguide losses, 1.3 dB loss per MOST due to mode transformation and mode mismatch at the fiber-chip interface, and 1.9 dB loss per TIC switch. Theory and measurements show that the loss per TIC switch can be reduced below 1 dB.

The crosstalk suppression of 17 dB at average and 10 dB in the worst case qualifies this matrix as a building block for 8:8 matrix switches.

The usable wavelength range of more than 100 nm exceeds by far the range of fiber amplifiers. Consequently, these optical switches are well suited for the application in optical network systems that use EDFAs because they do not cause any additional wavelength restrictions.

Wide fiber coupling tolerances of ±3 μm horizontally and ±2 μm vertically for 1 dB penalty make this chip predestinated for low loss selfaligned module assembly.

**Acknowledgement**

The authors are very grateful to Dr. G. Ebbinghaus for MOVPE processing, to Mr. W. Kunkel and Ms. G. Baumeister for CVD and RTP processing and to Dr. E. Knapek and his group for the prompt fabrication of the reticles.

**References**


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A Mach-Zehnder interferometric switch with a 0.2 V.mm voltage length product.

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Abstract.

We have developed a 2x2 Mach Zehnder interferometric switch employing laterally contacted hetero n-i-p-i quantum wells for providing refractive index changes. We observe switching over a 4\pi range with an on/off ratio of 17:1. A differential switching voltage as low as 0.2 V.mm is observed in the push-pull configuration.

It is the objective of the present paper to reduce the switching voltage-length product of a Mach-Zehnder interferometric switch1 by exploiting the advantages of a hetero n-i-p-i quantum well structure2,3 for providing refractive index changes in the arms of a Mach Zehnder interferometer switch.

A schematic of a hetero n-i-p-i structure is shown in fig. 1. The intrinsic layers of the hetero n-i-p-i structure contain a 10 period GaAs/AlAs multiple quantum well providing the required refractive index change at 850 nm due to the Quantum Confined Stark Effect. A 2 \mu m waveguide has been selectively etched in the 0.5 \mu m AlGaAs cladding layer. The voltage is applied to the n-doped and p-doped layers using selective lateral contacts2 which are evaporated on the side edges of a 16 \mu m wide mesa which is as also shown in fig. 1. Ideally, the n-type Ge/Ni/Au ohmic contact only establishes contact with the n-doped layers and the p-type Zn/Au metal contacts the p-doped layers. A lateral voltage applied between both contacts results in an applied electric field along the growth direction of the quantum wells.

Fig. 1 Schematic cross section of the hetero n-i-p-i modulator showing the selective lateral contacts to the n-doped and p-doped layers and the multiple quantum wells within the intrinsic layers.

One of the advantages of a hetero n-i-p-i structure is the possibility for independent optimization of the operating voltage and the magnitude of the refractive index.
change. The operating voltage can be reduced since the thickness of each of the intrinsic regions can easily be as thin as 1000 Å. The achievable magnitude of the electrorefractive effect can be optimized by increasing the number of n-i-p-i periods and thereby the number of active quantum wells inside the waveguide core.

An important aspect of the hetero n-i-p-i quantum well material is the reduced amount of free carrier absorption as compared to a conventional p-i-n structure. In a switching network, the total length of the switches including the connecting waveguides is easily a few centimeters, leading to very large free carrier absorption losses when the waveguide mode overlaps with doped layers. A p-i-n structure with the same intrinsic layer thickness as our hetero n-i-p-i (1000 Å) and doping levels of $2.8 \times 10^{17} / \text{cm}^3$ still suffers from a 20 dB/cm absorption loss. In our hetero n-i-p-i structure, the doping atoms are confined within doped layers of 300 Å thickness with a doping level of $2.8 \times 10^{18} / \text{cm}^3$. The overlap of the waveguide mode with the conducting parts of the doped layers has been calculated to be approximately 3% for each doped layer in our hetero n-i-p-i structure, leading to 6.5 dB/cm free carrier absorption loss for a hetero n-i-p-i with only two doped layers. Experimentally, a waveguide loss of 6.4 dB/cm was measured which can be further reduced by a factor of two by further reducing the width of the doped layers.

The basic layout of the switch is shown in Fig. 2. The incoming light is equally distributed into the two arms of the interferometer by the first 2x2 multimode interference (MMI) coupler. The second MMI coupler recombines the light into a single output waveguide. If no voltage is applied to the tuning section, the switch is in the cross-state. The MMI couplers operate in restricted paired interference mode by accurate positioning of the input waveguides. This allows three times shorter couplers for the same MMI width. Two different couplers have been used, measuring 9.6x277 μm² and 13.2x504 μm², respectively.

![Fig. 2 Schematic of the Mach Zehnder Interferometric switch with 3 dB Multi Mode Interference (MMI) couplers and electrorefractive tuning sections using laterally contacted hetero n-i-p-i quantum wells.](image)

Both arms of the Mach Zehnder Interferometer (MZI) have electrodes on either side of the second etched mesa which contains the doped layers (see fig. 1). The electrode
lengths are 400, 600 and 800 μm, which, in combination with the two type of MMI couplers yield compact switches with a total device length of 1.4 to 2.2 mm.

An advantage of the hetero n-i-p-i material is that electrical isolation between the two arms of the MZI is not necessary since the sheet resistance of the very thin conducting layers is high enough for establishing electrical isolation.

We have processed 8 different MZI's with different contact lengths and MMI sections. The switching behavior of all switches could be scaled according to the \( V^2L \) product required for switching from the cross-state to the bar-state in which \( L \) is the length of the contact region to the hetero n-i-p-i quantum wells. Scaling with the internal electric field \( E^2 \) is expected due to the quadratic nature of the quantum confined Stark effect. We observed scaling with the externally applied \( V^2 \).

The switching behavior of a switch with 600 μm contact length is shown in fig. 3 for four different operating wavelengths. It can be seen that the switch can be operated over four half periods from the cross state to the bar state at 852 nm. The operating range reduces to two half periods further away from the bandgap at 864 nm. It can be seen that a maximum on/off switching ratio of 16:1 (852 nm), 17:1 (855 nm) and 10:1 (864 nm) has been achieved for our MZI switch. The absorption loss due to the quantum well interband absorption at zero bias varies between 0.06 and 12 dB as shown in table I. Here it should be emphasized that this excess absorption loss is measured in a device cleaved to a total length of 7 mm in which the major part of the excess absorption loss occurs in the passive waveguides.

Fig. 3 Switching behavior for a Mach Zehnder Interferometric switch containing hetero n-i-p-i quantum wells for different operating wavelengths, \((+) = 849 \text{ nm}, (a) = 852 \text{ nm}, (o) = 855 \text{ nm} \) and \((\times) = 864 \text{ nm}\). The lines are only a guide to the eye.

Finally it can be seen from fig. 3 that the average transmission decreases for increasing voltage due to electroabsorption, especially for the shorter operating wavelengths.
The figures of merit and the voltage length product of our hetero n-i-p-i MZI switch are shown in Table I for several operating wavelengths. The figures of merit are average values for 8 different devices with different contact lengths. The voltage length products are calculated from the averaged V²L values for a switch with a 400 μm contact length. The voltage length products are most frequently quoted in literature, although they are not representing the V² dependence of the quantum confined Stark effect correctly. Anyway our observed voltage length products are to our knowledge the lowest ever reported for a 2x2 switch.

The figures of merit reported above have all been measured by applying a bias voltage to only one arm of the Mach Zehnder Interferometer and keeping the contacts to the second arm floating. We have also applied a bias voltage to both arms of the MZI. The switch can be tuned exactly in the cross-state for each applied bias voltage with a bias voltage difference of less than 0.1 V. When a bias voltage of 1.8 V is applied to both arms, a differential voltage of only 0.5 V is enough for complete switching of a device with a 800 μm contact length, corresponding to a voltage-length product of only 0.4 V.mm at 859 nm. This very low differential voltage-length product again exploits the V² dependence of the quantum confined Stark effect and allows an electronic driver circuit in the push-pull configuration. In the push-pull configuration, switching is already obtained at ΔV_L = -ΔV²L = 0.2 V.mm. This voltage-length product provides nearly an order of magnitude improvement with respect to previously published results.

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References:
A 1.3μm LiNbO₃:Ti reflective modulator, hybridised with a photoreceiver, for bidirectional full-duplex transmission.

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Abstract

An optimized reflective LiNbO₃:Ti modulator, packaged with a photoreceiver, has successfully employed as a subscriber terminal in a full-duplex bidirectional transmission on a single fibre at 1.3μm. The component exhibits a 12 dB modulation figure for reflected light with a 4.5V swing, the polarization dependence being inferior to 0.5dB.

1. Introduction

Optical fibre distribution networks are still facing the problem of the optical sources at the subscriber terminal [1-3]. An interesting solution could be brought by bidirectional transmission techniques on a single fibre using external modulators. However, the introduction of such components in the optical single-mode fibre network requires polarization-independent devices. A simultaneous point-to-point bidirectional transmission with double light intensity modulation has been previously demonstrated using a 1.5μm LiNbO₃ modulating/reflecting device (mounted with input and output pigtails) in the subscriber terminal [4].

In this letter, we describe the experimental results for a hybrid device designed for 1.3μm operation. This packaged device is composed of a folded electro-optic Mach-Zehnder modulator for the upstream transmission and a hybridised photoreceiver for the downstream transmission (Figure 1). The modulator has been optimized to exhibit a driving voltage as low as 4.5V, low losses and a good polarization independence. The device has been successfully tested in a full duplex transmission with dissymmetrical bit rates (50Mbit/s for the downstream signal and 2 Mbit/s for the upstream one) over a 15km optical link using a -12dBm launched optical power.

2. Device Structure

The device is composed of a folded electro-optic Mach Zehnder modulator with a partially-reflecting end facet for the upstream transmission (using Fresnel reflection). Both output waveguides are coupled to a single photoreceiver for the downstream transmission (Figure 2).

Specific technological processes have been developed to come up with system expectations. In particular, a localized dielectric deposition has been used to compensate for the static phase mismatch between TE and TM guided modes. Furthermore, an anti-reflective coating process has been designed and realized to reduce the reflectance of the LiNbO₃ guided-wave device/fibre interface using a SiO₂/TiO₂ bilayer. This process significantly improves the modulation extinction ratio on the upstream signal [5].

In this device, light propagates along the crystallographic Z-axis to ensure polarization independent operation both for the TE and TM guided waves.
2.a. Optical waveguide technology.

The LiNbO₃ X-cut Z-propagating devices are fabricated using well-known and simple technologies. Thin titanium stripes are sputtered, photolithographically patterned, and diffused on a 3” lithium niobate wafer.

Electrodes 38mm in length and 3000 Å thick are formed by RF sputtering. A silica layer is deposited between the LiNbO₃ substrate and the electrodes to avoid optical absorption on the TM guided mode. This layer can also be used to compensate for the static phase difference between TE and TM modes [6]. Some other devices have been processed using a silicon nitride (Si₃N₄) compensation layer (4000 Å film thickness).

2.b. Compensation technique for the parasitic phase difference.

The use of the Z-propagation configuration reduces the effective index difference between TE and TM guided waves. Furthermore, in our device configuration, the application of an electrical field along the Y-axis results in opposite phase shifts for TE and TM waves propagating in the same arm \((r_{12} = -r_{22})\). Due to the push-pull electrode structure, the phase shifts \(\phi\) induced between the TE (resp. TM) waves propagating in one arm and in the other one are also opposite.

If the optical paths of the two arms are perfectly balanced, the TE and TM modulation curves plotted as a function of the applied voltage would be superimposed. However, for practical devices, the Mach-Zehnder being folded, the optical paths in the Y-branch are slightly different. Thus, a polarisation independent phase shift, \(\phi_0\), is introduced between the two arms by technological imperfections. This phase shift, which is quite identical for both TE and TM modes, induces a translation of TE and TM modulation curves in opposite directions as shown in Figure 3.a for a 9V modulator.

Consequently, it is essential to control this parasitic phase difference to realise polarisation independent devices (Fig. 3.b). One method used to compensate for the optical path difference is to deposit a dielectric layer of calibrated length on one of the arms (Fig.4). This layer locally induces a slight variation of the effective indices of the guided waves. Figure 5 shows the calibration of the induced phase \(\Delta\phi_0\) versus compensation layer length respectively with silica and silicon nitride as a dielectric layer.

2.c. Module packaging.

After the compensation process, an antireflection coating using sputtered SiO₂/TiO₂ bilayer was deposited on the device input facet to reduce the reflectance of the lithium niobate/fibre interface. Typical reflectance values around -30dB were obtained by this technique [5].

Finally, a single mode fibre pigtail is attached to the input waveguide and the device is packaged with a photoreceiver consisting of an InGaAs photodiode and an hybridised preamplifier.

3. Device characterisation.

The components have been characterised at the 1.3μm wavelength with a Fabry-Pérot laser diode. The upstream signal measurement was performed using a 3dB coupler. Figure 6 shows the modulation characteristics of an optimized modulator. The driving voltage is reduced to 4.5V for both TE and TM modes. The losses amount to 12dB for the upstream signal and to 3dB for the downstream signal, the polarisation dependence being inferior to 0.5dB.
Using the device described above, a full duplex transmission with dissymmetrical bit rates has been experimented using the separation of the two signal spectra [7]. We transmitted a 50Mbit/s downstream signal over a 15km link simultaneously with a 2Mbit/s upstream signal using a launched light power of -12dBm (for a BER better than $10^{-9}$).

Conclusion

In this paper, we report the performance of a reflective modulator hybridised with a photoreceiver. This device was successfully tested at 50Mbit/s on a full-duplex transmission experiment with dissymmetrical bit rates.

Another reflective modulator hybridised with a photoreceiver, using a partially reflecting mirror deposited on the end facet (losses for the reflected light and for the transmitted light are respectively around 5dB and 11dB), has been also tested in a full-duplex transmission experiment with identical bit rates (20 Mbit/s) over a 11km long fibre with -12dBm optical power.

All these solutions based on LiNbO$_3$:Ti reflective modulators are very attractive for optical access networks.

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References.


Figures:

Fig.1 : System configuration

Fig.2 : Device structure
\[ I_{TE} = I_0 \cos^2 \left( -\phi + \frac{\phi_0}{2} \right), \quad I_{TM} = I_0 \cos^2 \left( +\phi + \frac{\phi_0}{2} \right) \]

3.a : before compensation

3.b : after compensation

Fig. 3 : Reflected light modulation versus driving voltage for both TE and TM polarisations

Fig. 4 : Compensation method

Fig. 5 : Compensation calibration

Fig. 6 : Reflected light versus driving voltage for both TE and TM polarisations.
FROM MICROCAVITIES TO PHOTONIC BANG GAPS:
Control of spontaneous emission

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Abstract
We provide a short overview of how microcavities and photonic band gap structures can be used to control spontaneous emission. The direction, linewidth and rate of spontaneous emission can all be changed in such structures and this will play an important role in the next generation of luminescent devices.

Introduction:
It is becoming increasingly clear that two roads exist towards high efficiency light emitting diodes (LED's) and ultra-low threshold lasers\textsuperscript{1}. One is that of band gap engineering where the electronic properties are tailored by reducing the dimensionality of the structure, e.g., from bulk semiconductors through quantum wells to quantum wires and boxes. Significant improvements in the performance of lasers have been achieved using this approach and further refinements in this type of technology will continue to improve device characteristics.

A second more recently highlighted route is through photonic engineering. The underlying principle is that spontaneous emission can be controlled by changing the optical environment\textsuperscript{2}. Through photonic engineering it is possible to control the direction, wavelength, linewidth and even the rate of spontaneous emission. Two related problems can be solved using this approach; lasers show a threshold because below threshold almost all the spontaneous emission is going either in the wrong direction or being emitted at the wrong wavelength. Only a fraction, $\beta$, is captured by the lasing mode. For edge emitting semiconductor lasers $\beta$ is in the order of $10^{-4}$ to $10^{-5}$. By controlling the spontaneous emission it is possible to increase $\beta$, with the goal of having $\beta=1$, in which case the structure would show no threshold in its intensity output. The second related problem is that only 2% of light emitted from an LED escapes through the top surface. The remaining light undergoes total internal reflection at the semiconductor-air interface and is lost in the substrate. By controlling the directionality of spontaneous emission, this problem can be overcome.

Changing $\beta$:
Evidently it is of great technical advantage to change $\beta$, so how can this be achieved? If we look at Fermi's golden rule, which gives the transition rate for a two level system, we see that the rate depends explicitly on the density of photon states, i.e.,
\[ A = \frac{2\pi}{\hbar} \langle i | H_p | f \rangle \rho(v) \]  

where \( \rho(v) \) is the density of photon states into which emission can occur. This term depends on the environment and holds the key to most microcavity and photonic band gap effects. In free space \( \rho(v) \) is isotropic so that spontaneous emission is equally probable in all directions. However even a single mirror can change the photon density of states both spatially and spectrally; a dipole placed one wavelength from a highly reflecting mirror will emit preferentially in certain directions. The interference between the dipole and its mirror image leads to directions of constructive and destructive interference, or directions of enhanced and inhibited spontaneous emission. In total there is just as much constructive as destructive interference, i.e., the radiation has been merely redistributed while the total emitted power has remained constant. This geometrical effect accounts for the majority of microcavity effects and can be useful for shaping the emission pattern.

Microcavities:
The basic building block of solid state microcavities is an active medium embedded in a Fabry-Pérot (FP) cavity. The mirrors can be either metal, dielectric or some hybrid of the two depending on the application. The emission pattern from a FP microcavity typically shows enhanced emission normal to the cavity, and reduced emission at large angles. For a high \( Q \) microcavity the following relationship holds:

\[ \beta = \frac{Q \lambda^3}{8\pi V_{\text{cav}}} \]  

where \( V_{\text{cav}} \) is the volume of the cavity. A significant change in both \( \beta \) and the spontaneous emission rate can be achieved if the dimensions of the cavity are similar to the wavelength of light. Although this is more difficult than simply redirecting the spontaneous emission, significant changes in the spontaneous emission rate have been observed for atoms in high \( Q \) cavities. A drawback with planar devices is that there is no lateral mode confinement. Despite the semi-infinite extent of a planar cavity there is a definite lateral mode size which is determined by diffraction. The mode size increases with mirror reflectivity in such a way that both the cavity volume and \( Q \) increase at the same rate. A second drawback with planar structures is that there is an equivalent enhancement of emission in the plane of the
cavity into guided modes which play a significant role in determining the efficiency of microcavity LED's. Despite these shortcomings, planar FP devices remain an essential testing ground for microcavity physics.

Lateral mode confinement can be achieved in several ways. One is to fabricate a hemispherical curved mirror on one side on the cavity leading to a confocal arrangement, increased $\beta$ and a lower threshold\(^7\). A more obvious method is to etch a pillar or a post and the difference in refractive index between the pillar and the surrounding air is sufficient to control the lateral mode size. For such structures, surface passivation is required to achieve high efficiencies and low lasing thresholds\(^8\). The microdisc or "thumb-tack" laser\(^9\), uses total internal reflection around its edge to define a lasing mode while the refractive index change at the air above and below the disc confines the optical mode tightly into the plane of the disc. The circulating light follows a whispering gallery mode and is not specifically directional.

![Figure 2: A Fabry-Pérot microcavity showing the important emission directions](image)

Table I list various microcavity structures along with there calculated and measured $\beta$'s. It should be noted that $\beta$ can be improved by either redirecting the spontaneous emission into the lasing mode or by making the lasing mode much broader spatially. This latter effect accounts for the high $\beta$ reported for microdisc lasers. The failure of the micropost and hemispherical lasers to achieve their calculated $\beta$ arises because the linewidth of the emission is larger than the cavity linewidth. Band gap engineering may play a role in reducing this problem in future structures.

Spontaneous emission control is critical for high efficiency LED's, where only 2% of the emitted light escapes out of the device. Already many manufactures use a mirror on the bottom side to double this output. By using mirrors on both sides, microcavity LED's have achieved efficiencies up to 10\%\(^10\). The main problems for these kinds of structures are again the losses into guided modes in the plane of the structure, which can be overcome using hybrid dielectric/metal mirrors.
Organic materials possess broad absorption and emission bands. Unlike with semiconductors, quantum size effects cannot be exploited in order to overcome this limitation. Instead, microcavities have been used to selectively enhance emission from different spectral regions, leading to electroluminescent diodes that can emit red, green and blue light, by using the same organic polymer in cavities of different widths.\(^{11,12}\)

Inside a high Q cavity the vacuum electric field, \(\rho(v)\), is greatly modified; normally one cavity mode is greatly enhanced while other modes are suppressed. The enhanced cavity mode can then affect a two-level system (e.g. atom) in the cavity. The light-matter interaction can no longer be considered a perturbation, so that Fermi's golden rule breaks down. Instead the atom and the cavity exchange energy in a cyclic fashion at a rate known as the Rabi frequency and the system eventually decays at a rate which is an average of the atom and photon lifetimes.\(^{13}\) This unusual regime is not restricted to atomic physics but has also been observed for excitons in semiconductor microcavities.\(^{14,15}\) The resulting coupled exciton-photon state has become known as a cavity-polariton because of its similarity to coupled photon-exciton states (polaritons) which exist in bulk semiconductors. A variety of experiments have probed the absorption, reflection\(^{16}\), and photoluminescence\(^{17,18}\) characteristics of these structures both under cw and time-resolved\(^{19}\) conditions. The bearing of strong-coupling on future novel devices has not yet been established although the observation of cavity-polaritons at room temperature is promising.\(^{16}\)

**Photonic band gaps\(^{20}\)**

The simplest monolithic microcavity is made from two quarter-wave dielectric stacks with a cavity layer in between. Quarter-wave dielectric stacks or DBR mirrors, have high reflectivities because all the backward reflections are in phase with each other. Alternatively, one can view such a stack as a dielectric with a periodic refractive index. As in a crystal lattice, the periodic structure leads to allowed and forbidden bands, in this case for photons. The forbidden band corresponds to the high reflectivity stopband of the DBR mirror. A DBR mirror is thus a one-dimensional photonic band gap (PBG) structure. By using periodic dielectric structures\(^{21,22}\), it is possible to make photonic band gaps in both 2-D and 3-D, i.e., structures where light, at certain wavelengths, is not free to propagate in any direction. In
such a structure the vacuum photon density of states is reduced to zero and the spontaneous emission is completely inhibited.

For a PBG structure an impurity introduced is made by locally breaking the periodicity. In practice this can be done by adding extra material of a high or low refractive index. This is easiest seen in the one dimensional case of a Bragg mirror. If one of the layers is made thicker than normally, then for certain wavelengths, light starts to be localised near this layer. The build up of light around the impurity is greatest when the optical path length of the impurity becomes a multiple of $\lambda/2$. However this is exactly the condition necessary to form a Fabry-Pérot cavity; For the one-dimensional case an impurity in a PBG structure and a microcavity are identical.

By analogy, an impurity in a 3-D PBG material creates a high Q-cavity with confinement in all directions. This can have a major effect on the spontaneous emission of any emitter placed at the impurity site. In general, PBG materials are not very easy to make, as a high contrast in refractive index is usually required, and the periodicity should be on the same order as the wavelength of light. This requires, for example, the formation of small accurately made holes in a high refractive index material. While a full 3-D PBG has been observed in the microwave region, there has been no similar demonstration yet in the optical region of the electromagnetic spectrum. The field is moving away from the original FCC 'Yablonovite', and other structures inspired by naturally occurring crystals. For example, a layered structure of Si and SiO$_2$ with cylindrical air holes has been recently proposed, with ease of fabrication in mind.

Similar to an ordered PBG material, a random dielectric medium can also localise light. An emitter placed anywhere in the material will experience light localisation and a sharp increase in the local density of photon modes. This occurs because there is always a back-scattered component, and with a sufficiently large refractive index contrast the back-scattered wave can destroy the forward going wave leading to localisation of light. A colloidal suspension of dielectric spheres serves as an excellent light localisation medium, and such colloids...
impregnated with dye have been made to lase without any cavity. This leads to the interesting prospect of laser paint.

Conclusion.
Spontaneous emission control is passing, from the fundamental physics explored using atoms in microwave cavities, to solid state structures with a view to future high efficient emitters and detectors. As there is no clear advantage between the microcavity and PBG approach, hybrid structures seem promising, where a two dimensional PBG provides the guided and leaky mode suppression in a standard planar microcavity. The different approaches of microcavity, photonic band gap, and randomly oriented dielectrics, each shows great promise for exploring fundamental physics and should be relevant to future integrated optical design.

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OPTICAL FILTERS FROM PHOTONIC
BAND GAP AIR–BRIDGES
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Abstract:
Photonic band gap materials can produce compact, optical filters with large stop bands, sharp
transmission resonances, and low cross talk. The transmission and reflection spectrum of these
novel filters are described using a modified finite difference time domain program.

1 Introduction
Wavelength division multiplexing uses the large bandwidth of optical fibers by transmitting
data through many different frequency channels. In order to distinguish between adjacent
channels, telecommunication systems need filters. Quarter-wave shifted distributed feedback
gratings can provide such a transmission filter. Such a filter would transmit one frequency
channel but reflect the other channels that fall in the filter's stop band. Only the large index
contrasts of photonic band gap materials can provide both large stop bands to cover the gain
bandwidth of erbium and narrow transmission resonances to pack many channels close together.
Here we present optical filters whose stop bands exceed the 40 nm bandwidth of erbium. One
has a 70 nm stop band while the other a 600 nm stop band.

2 Results
These filters are to be constructed from photonic band gap air-bridges. First we will describe
the bridge with the wider stop band (figure 1a). The index of refraction is \( n = \sqrt{13} \). This air-
bridge has only six circular air holes. In particular, the hole-to-hole spacing is 0.232 free-space
wavelengths or (for \( \lambda = 1.55 \) μm) 0.360 μm. The center two holes are spaced 0.325 \( \lambda \) or 0.503
μm. The air holes have a 0.167 \( \lambda \) or 0.258 μm diameter, while the air-bridge is 0.151 \( \lambda \) or 0.234
μm wide. A longer version of this structure — one with more air holes — can act as a high Q
microcavity.\(^1,2\)

Our calculations are based on a vectorial finite difference time domain code.\(^3\) We find the
quality factor \( Q \) of the structure to be 387. This is obtained by monitoring the the decay rate of
the eigenmode with the largest \( Q \). This is a surprisingly large \( Q \) for a structure that has only 6 air
holes. The total structure is less than 1.5 wavelengths long! This small size allows for a compact
integration of many wavelength filters on a small chip. Resonators with high \( Q \) resonator give
narrow transmission resonances. Figure 2 shows the transmission as a function of frequency.
Here the transmission coefficient is the fraction of power that remains in the fundamental transverse mode of the waveguide after propagating through the air holes. The transmission resonance occurs at $\lambda = 1550$ nm or 194 THz. In figure 3, a monochromatic source (TM magnetic) is incident from the left side of the filter. The source is at the resonance frequency of the cavity, so light is coupled into the resonance mode, creating strong field localization about the phase slip or dielectric defect. At this frequency, the transmission is nearly perfect; 85% is transmitted. The size of the stop band is 600 nm. This is over one third of the carrier frequency!

If one reduces the index contrasts or grating strengths by omitting the holes and by notching the sides of the air-bridge instead (figure 1b), one can achieve larger Q's, because the losses due to radiation are reduced. The stop band width also drops. In this case, the stop band width falls to 70 nm while quality factor increases to $Q = 10,350$. The notches are 0.0356 free-space wavelengths deep and 0.0888 wavelengths long. Notches are separated from each other by 0.178 wavelengths. The bridge has index $n = 3.4$. It is 0.195 wavelengths wide and 11.812 wavelengths long. There are 33 notch pairs on each side of the phase slip, which measures 0.178 wavelengths long. Figure 4 shows the TE electric field propagating through the center section of the air-bridge. The forward and back propagating waves were separated by examining the fields at different points in space and time,[4] giving the transmission and reflection coefficients (figure 5). Note the sharpness of the transmission peak at resonance. Moving off resonance, the transmission falls by 60 dB. As a result, adjacent channels see very little crosstalk.

3 Conclusion

We have presented two compact, optical filters. The larger index contrasts of the photonic band gap air-bridge lead to a 600 nm stop band. Quality factors of over 10,000 are achieved with notched air-bridges, giving sharp transmission resonances and very little crosstalk. A modified finite difference time domain program calculates transmission and reflection spectrum for these novel, air-bridge filters.

4 Acknowledgements

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References


Figure 1:
A. Air-bridge with six circular holes.
B. Air-bridge with 33 notches.

Figure 2: Fraction of power transmitted through filter as a function of frequency.

Figure 3: TM Magnetic field at transmission resonance.
Figure 4:
TE Electric field at transmission resonance.

Figure 5:
Fraction of power transmitted and reflected by notched filter as a function of frequency.
CIRCULAR GRATING SURFACE-EMITTING LASERS WITH COMBINED FIRST AND SECOND ORDER GRATINGS

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Abstract

We propose and demonstrate, for the first time, the use of combined first and second order gratings in grating-coupled surface emitters of circular geometry. Combined grating orders facilitates the realization of highly functional integrated optical emitters through separate optimization of coherent light generation and outcoupling.

Introduction

Integrated optics and optoelectronics are key technologies for future developments in photonics. Integration enables a higher level of functionality, providing photonic integrated circuits that will enhance the competitiveness of photonic technologies.

Integration requires the use of integration compatible materials and device structures. The natural choice for on-chip light sources is therefore surface emitters. The grating-coupled surface-emitting lasers (GCSELs) are suitable for integration since gratings, rather than cleaved facets, are used for feedback and outcoupling. In addition, the horizontal cavity enables light to be transmitted to other components in the plane of the wafer. The performance of GCSELs is set by the chosen combination of gain sections and gratings. The use of both first and second order gratings increases functionality and enhances performance by the separation of feedback and outcoupling functions.

Fig. 1. Different types of CCGSE lasers.
Using second order gratings as feedback elements give simultaneous outcoupling which is not always desirable. By using first order gratings as feedback elements the emitted light is propagating in the plane of the wafer and can then be transmitted to other passive or active elements such as waveguides, outcoupling elements, amplifiers, modulators, and detectors. We have earlier studied the combination of first and second order gratings in linear configurations [1], now we extend the study to circular geometries. To evaluate the circular gratings we have fabricated concentric-circle-grating surface-emitting (CCGSE) lasers with combined grating orders.

CCGSE lasers operate with inward and outward propagating circular waves coupled by a periodic perturbation of the dielectric constant in the radial direction induced by concentric circular gratings. Combined with a relatively large emitting aperture, the CCGSE laser can produce high power output beams of circular symmetry which is preferable in many applications. The CCGSE laser has been studied theoretically [2-4] and investigated experimentally under both optical [5] and electrical excitation [6-7]. In previous work on electrically pumped CCGSE lasers the devices have been based on a design with a central gain section and an outer second order grating (see Fig. 1(a)). The second order grating then acts as both feedback and outcoupling element. In order to separate the functions we propose two different designs shown in Fig. 1(b-c). Fig. 1(b) shows a laser where feedback is provided by a circular first order grating surrounding an inner circular gain section. Light transmitted through the feedback element is then outcoupled by a detuned and chirped second order grating. If the second order grating is detuned it provides no feedback, and by using a chirped grating the emitted beam can be focused at a given distance above the surface. In Fig. 1(c) the oscillation occurs between the central resonant second order grating, which provides both feedback and outcoupling, and the outer first order grating. We have fabricated and evaluated lasers of this type. This is, to the best of our knowledge, the first time a circular first order gratings and combined grating orders have been incorporated in a GCSEL.

![Diagram](image)

Fig. 2. Schematic drawing, including composition profile of the epitaxial structure, of the laser used in this work.
Fabrication

The epitaxial structure and the fabrication method used is outlined in reference [8]. The InGaAs/AlGaAs lasers were fabricated from an MOVPE grown SQW-GRINSCH structure, supplied by Epitaxial Products International, with an etch-stop layer to enable precise positioning of the grating relative the GRINSCH (Fig. 2). After depositing metals for p-contacts the cladding layer above the etch-stop layer was removed with a selective wet chemical etch, and first and second order concentric circular gratings, with periodicities of 147.5 nm and 295 nm respectively, were patterned in resist using electron beam lithography (EBL).

The JEOL JBX-5DII EBL machine used in this work uses a cartesian grid with a spacing of 2.5 nm and a field of 80x80 μm² in its highest resolution. Due to different pixel densities for different angles of a circular arc, the dose has to vary with angle in order to obtain an uniform exposure. The present software makes this compensation too course resulting in gratings with angle dependent duty cycles. This effect has been discussed in reference [2]. As a consequence, the optical mode experience an angle dependent reflectivity and the laser therefore shows an angle dependent threshold. In addition, when exposing grating areas larger than 80x80 μm² the fields have to be stitched together, resulting in stitching errors.

The gratings were etched to a depth of 100 nm using chemically assisted ion beam etching. Finally, the wafer was thinned, an n-contact were formed on the backside, and the gain section was connected to an electrical terminal.

Evaluation

The characterization of the lasers included pulsed measurements of emission spectra, light-current characteristics and near/far field. The lasing wavelength was 980 nm. The lowest measured threshold current was 302 mA, corresponding to a threshold current density of 63 A/cm², and the external differential efficiency was 5%. The remarkably low threshold current density is misleading since only one narrow sector oscillates at threshold. We believe that the poor efficiency is a result of optical loss in the feedback section and poor outcoupling efficiency due to relatively shallow grating grooves.

![Fig. 3. Contour plots of the near fields at different injection currents.](image)

![Fig. 4. 3-D plot of the far field at I=2.4·I_{th}.](image)
The near fields were recorded by imaging the emitting surface on a CCD matrix using a camera lens. Fig. 3(a-d) show contour plots of near fields at different injection currents. At threshold only one narrow sector oscillates. With increasing current, other sectors reach threshold and at the highest drive current used the lasing sector is 65°. This behavior is due to the azimuthal inhomogeneities in the grating. When one sector reaches threshold the carrier density is clamped in that region and excessive current is funneled into this sector. One way to overcome this problem could be to divide the gain section into sectors that can be pumped individually. Another possibility is to improve the grating fabrication process by using an optimized dose correction method and a high contrast electron resist. In Fig 4, a 3-D plot of the far field at an injection current corresponding to Fig 3d is shown. As a reference we have also fabricated conventional CCGSE lasers with a central gain section and an outer second order grating (Fig. 1(a)). These lasers do not show the same pronounced tendency to oscillate in a narrow sector at high injection currents. In this case the threshold current density is 179 A/cm², the external differential efficiency is 16%, and the circular symmetric far-field divergence is less than 1°.

Conclusion

The feasibility of combined first and second order gratings in CCGSE lasers has been demonstrated experimentally. Combined grating orders allow higher functionality. Initial results show pronounced angular inhomogeneities which is expected to be reduced with further improvements in fabrication and device design.

Acknowledgement

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References


DFB LASER ARRAYS REALIZED IN ONE HOLOGRAPHIC EXPOSURE

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Abstract:
In order to extend the high throughput of holographic exposure to multiwavelength DFB arrays, we have designed a mask with novel aperture edges that allows fringe-free localized insolations. This mask has been successfully used for the realization of six wavelength MQW DFB arrays.

Introduction:
DFB laser arrays are key components for wavelength division multiplexing systems (WDM) in order to exploit the broad bandwidth of optical fibers. They can also be used in switching systems. In the case of conventional monolithic DFB laser arrays, the lasing wavelength is controlled by adjusting the pitch corrugation transcribed in identical optical waveguides. This is usually realized by e-beam lithography, which is an expensive and low throughput fabrication technique [1],[2],[3]. Use of successive holographic lithographies has also been successfully realized [4], but still remains awkward for a large number of different wavelengths.

Going to a single lithography step requires proper localized holographic exposure. This letter describes the realization and use of a novel window mask that allows proper localized insolation, i.e. without the fringe pattern which is the unavoidable consequence of the use of coherent light. The diffraction perturbation is inconvenient for closely spaced lasers (< 500µm). In order to realize a different grating pitch for each laser, both the holographic set-up (for the period) and the wafer (for the ridge spacing) should be moved. Up to 6 different grating periods 100µm apart have been realized in a single holographic lithography step.

I- Localized holographic exposure
For grating realization, we use an S-polarized two-divergent beam interferometer. The laser line is the 363.8nm Argon line (λ). An aperture with sharp edges placed against the
wafer results in fringe diffraction superimposed to the grating lines (for our purpose, the window direction is perpendicular to the grating lines). This varying intensity distribution gives a variation in the grating shape that will result in a spurious variation in the coupling efficiency along the laser cavity.

In order to extend the high throughput of holographic technique to multiwavelength arrays, we have designed windows with fuzzy shape edges spread on a characteristic width w. When w is chosen as \( w \gg \lambda \) (in our case \( w=2\mu m \)), the wavelets diffracted by each elementary part of the aperture do not interfere nor constructively neither destructively. The intensity distribution is averaged and oscillations are washed out as soon as one is located at a distance from the edge larger than its characteristic width \( w \). Windows 40\( \mu m \) wide with such edges are designed in a mask by electronic lithography. Insolation with coherent light through such fuzzy edge apertures yields a very uniform intensity distribution. Six different insulations have been realized in areas 100\( \mu m \) apart. The grating shape after etching is uniform, and is the same in each area. Hence, using our method a 2\( \mu m \) wide laser strip can be properly defined in each grating area with uniform coupling all along the laser cavity.

II-Device realization and performance:

The wafer used for array realization consists of four 9nm thick strained quaternary wells with quaternary barriers sandwiched between 130nm thick optical confinement layers. A 30nm thick grating layer is buried into InP layers. Six different grating pitches have been realized. The different pitches are obtained by moving the interferometer mirrors with 1/100 degree accuracy. There is no limitation in reaching any pitches difference. In our case, the expected emitted wavelength spacing \( \delta \lambda \) is 2.31nm. All the gratings are developed and etched at the same time. Then, a quarter-wave shifted structure is realized by widening the stripe, which ensures monomode oscillation [4]. The stripes are 1.5\( \mu m \) wide. RIBE etching of the ridges has been chosen to minimize the geometrical variations. Then the ridges are buried with 1.5\( \mu m \) thick p-InP layer and a thin highly doped InGaAs contact layer. Proton implantation is carried out to create highly resistive regions on each side of the buried stripes. On the p-contact side, the contact layer is etched down to the p-InP buffer layer to insure electrical insulation between the lasers of an array.

Lasers are 400\( \mu m \) long, and 100\( \mu m \) apart. Both facets are cleaved. Fig. 1 shows typical I-L curves -under pulse injection- for an array with 6 different emitted wavelengths. The threshold currents range from 7 to 12mA. 10mW can be reached for all the lasers at injection lower than 100 mA. Wavelengths have been measured at 5mW output -under continuous injection- for each laser. The SMSR is always greater than 35dB (Fig.5). The spacing between
the emitted wavelengths is $\delta \lambda = 2.16 \pm 0.2 \text{nm}$. This value is in reasonable agreement with the expected one.

Dynamic characterizations have been made on the laser array. Each laser exhibits a 4GHz bandwidth limited by RC constant. Electrical crosstalk lower than -36dB for +10dBm modulation at 3GHz and 75mA bias has been measured for two adjacent lasers. Such closely spaced lasers can be used for multiplexed transmission, and can be monolithically integrated with a coupler.

**Conclusion:**

We have designed novel aperture edges that allow fringe-free localized holographic insolation. A mask with such apertures has been successfully used for the realization of a six wavelength DFB laser array. We demonstrate that the high throughput of holographic lithography is extended to high packing density multiwavelength DFB array fabrication.

**Acknowledgment:** The authors are grateful to S.Grosmaire and P.Boulet for their technical assistance.

**References:**


**Figure captions:**

Fig. 1: I-L curves (under pulse injection) and lasing spectra (under continuous injection) at 5mW output power of a six DFB laser array.
Fig. 1
A SURFACE GRATING DISTRIBUTED FEEDBACK GaAs/AlGaAs LASER WITH VARIABLE WIDTH WAVEGUIDE FOR SINGLE MODE OPERATION

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Abstract:
Single mode distributed feedback laser operation has been achieved by varying the stripe width, in conjunction with a surface grating structure of uniform periodicity. Only postgrowth processing was used. A phase change was introduced and allowed to accumulate over a sufficient length of waveguide to realise a $\lambda/4$ shift.

Introduction:
Holographic interference is an ideal method for producing gratings, with an accurate and constant period over large areas, for use as Bragg-type reflectors. However, for distributed feedback (DFB) lasers a single period continuous grating leads to two possible longitudinal lasing modes, one on either side of the stopband [1]. Single mode operation at the Bragg wavelength can be achieved by introducing a $\lambda/4$ phase jump in the grating at the centre of the laser, but this is relatively difficult to realise by holography [2]. Alternatively, if the middle portion of the grating has a slightly different period [3], a $\lambda/4$ phase difference can accumulate along the length of this perturbed section. This approach would normally require two stages of holography. An equivalent effect can be achieved using a grating having a single period, by changing the width of the stripe waveguide [4], thereby altering the effective periodicity of the grating. This approach ensures a perfect phase transition at the change over of the grating sections. Because the phase shift accumulates slowly there is less concentration of the optical field at the centre of the laser, thus reducing the spatial hole burning problems associated with conventional $\lambda/4$ shifted DFB lasers [3].

In this paper we describe a surface grating DFB laser, Fig. 1 [5], fabricated entirely by planar processing and involving a single, postgrowth reactive ion etch (RIE) stage with a patterned, holographically generated mask to define the grating structure. The use of entirely postgrowth processing allows full wafer characterisation before processing and avoids regrowth problems associated, in particular, with AlGaAs [6].

Theory:
For any order of grating the wave propagation constant, $\beta_{Bragg}$, is

$$\beta_{Bragg} = \frac{m\pi}{\Lambda_g}$$  \hspace{1cm} (1)

where $\Lambda_g$ is the grating period and $m$ is the order of the grating. If the effective index of a stripe waveguide is perturbed by altering its width, there is a corresponding change in the propagation
coefficient. In that section of the laser the propagating light will dephase from the Bragg grating by a phase difference \( \theta \)

\[
\theta = L(\beta_{Bragg} - \beta) = L \cdot 2\pi \frac{(n_0 - n_1)}{\lambda}
\]

(2)

where \( L \) is the length propagated and \( n_0 \) and \( n_1 \) are the effective refractive indices for the two waveguide sections. The length of the perturbed waveguide section \( (L_p) \) to achieve a \( \lambda/4 \) shift is

\[
L_p = \frac{\lambda}{4(n_0 - n_1)}.
\]

(3)

In our devices physically realistic dimensions of 2.5 and 4.5 \( \mu \)m were chosen for the two waveguide widths using a third order grating (380 nm). The refractive indices for the different stripe widths were calculated at 860 nm, assuming an etch depth of 0.5 \( \mu \)m. The corresponding length for the 4.5 \( \mu \)m wide central section was calculated to be approximately 210 \( \mu \)m. A photolithographic mask was designed having lasers with central perturbed section lengths of 60 \( \mu \)m (10%), 180 \( \mu \)m (30%), 300 \( \mu \)m (50%) and 420 \( \mu \)m (70%) (for a total device length of 600 \( \mu \)m). Some control devices with no width change were included on the mask to confirm the effectiveness of the perturbation.

![Fig 1 Surface grating DFB laser with a variable width waveguide of length \( L_p \), included to introduce a \( \lambda/4 \) phase jump for single longitudinal mode operation. The grating is entirely of one period \( \Lambda_g \).](image)

**Fabrication:**

The lasers were fabricated from a previously characterised wafer grown by metal-organic chemical vapour deposition (the structure is shown in Fig 2.) The as-grown wafer was coated with 2000 \( \AA \) of SiO\(_2\) for protection. To suppress standing wave patterns in the photoresist, a commercial anti-reflection polyamide layer (ARC) was applied [7]. Thinned photoresist was spun onto the ARC, giving a photoresist thickness of approximately half the period of the third order grating (200 nm). The photoresist was pre-exposed through a mask to activate the photoresist in those areas where a grating was not required. The sample was then exposed to the holographic pattern and developed. The photoresist was developed fully in the pre-exposed areas, exposing the ARC layer. In the masked areas a sinusoidal resist grating was formed on top of the ARC. The grating was shadow masked with NiCr at an angle of 60° calculated to give a 1:1 mark space ratio. RIE in O\(_2\) was used to remove the ARC in the shadowed areas of the grating, while the pre-exposed areas were protected by a continuous layer of NiCr. RIE with C\(_2\)F\(_6\) and SiCl\(_4\) was then used to etch the SiO\(_2\) and the epitaxial GaAs/AlGaAs respectively. The ARC/photoresist/SiO\(_2\) mask was removed and the GaAs contact layer was etched away from the top of the grating regions to reduce current spreading through the grating. A new layer of SiO\(_2\) was deposited and a window was opened over the centre of the waveguide for current injection. The lasers were thinned, contacted, cleaved and
the facets were AR coated with a single film of sputtered Al\textsubscript{2}O\textsubscript{3}. The devices were mounted p-side down on heat sinks for CW operation and tested for mode stability over an 80 °C temperature range.

0.1 \textmu m GaAs Contact layer \(p^+=5 \times 10^{18}\) cm\(^{-3}\)

0.7 \textmu m Al\textsubscript{0.4}Ga\textsubscript{0.6}As Upper cladding layer \(p=5 \times 10^{17}\) cm\(^{-3}\)

0.1 \textmu m Al\textsubscript{0.7}Ga\textsubscript{0.3}As

0.1 \textmu m Al\textsubscript{0.7}Ga\textsubscript{0.3}As

0.9 \textmu m Al\textsubscript{0.4}Ga\textsubscript{0.6}As Lower cladding layer \(n=5 \times 10^{17}\) cm\(^{-3}\)

GaAs Substrate \(n^+=10^{19}\) cm\(^{-3}\)

**Results:**

2.5 and 4.5 \textmu m wide oxide-stripe waveguide lasers with constant widths and the same grating period (380 nm) lased at wavelengths of 862.8 and 863.0 nm respectively (±0.05 nm). From the difference in the wavelengths, the change in effective refractive index was calculated to be 8 x 10\(^{-4}\). However, the change due to the increased waveguide width has been reduced by the simultaneous move to a longer wavelength. We calculated that increasing the wavelength by 0.2 nm reduces the effective refractive index by 1.5 x 10\(^{-4}\) so the true change in refractive index at 862.8 nm would be 9.5 x 10\(^{-4}\), very close to the 1.03 x 10\(^{-3}\) predicted. This experimental value gives a perturbed section length of approximately 230 \textmu m, agreeing with the theoretically predicted result within the experimental error of the wavelength measurements. From CW measurements using a scanning Fabry-Perot interferometer, Fig 3, it was found that only the lasers fabricated with central perturbed sections of 180 \textmu m (30 %) and 300 \textmu m (50 %) operated in a single longitudinal mode. This single mode operation occurred over the temperature range from 10 to 75 °C. Threshold currents for these devices were 43 and 47 mA respectively, with quantum efficiencies of about 0.28 and output power of 7 mW per facet at 2x\textsubscript{ILh}. From measurements of the stop-bandwidth on the uniform width lasers, the coupling coefficient of the gratings was found to be 14 and 5.5 cm\(^{-1}\) respectively for the 2.5 and 4.5 \textmu m waveguides, in agreement with a simple analysis based on multi-layer reflectors [8].

**Conclusions:**

Holographic production of gratings for DFB lasers is desirable because of the accuracy of the grating pitch and the ability to define large areas very quickly. We have demonstrated a patterned holographic mask layer suitable for RIE processing. Single longitudinal mode operation of the resulting DFB lasers has been achieved by the introduction of a progressive phase shift brought about by changing the waveguide width Surface grating technology is a useful post-growth process that could offer higher yields than regrowth techniques for GaAs/AlGaAs based DFB lasers.
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Fig 3. Schematic representations of typical oscilloscope traces observed with the scanning Fabry-Perot interferometer. The mirror separation was 0.44 mm giving a free spectral range of $3.4 \times 10^{11}$ Hz (0.84 nm @ 860 nm). (a) shows the multi-mode pattern characteristic of oxide-stripe Fabry-Perot lasers. (b) shows the double-moded operation of the single-width surface grating DFB lasers reported here, while lasing on either side of the stop-band of the grating. (c) shows the single mode operation of the perturbed-width surface grating lasers.

References
Erbium-Doped Integrated Lasers and Amplifiers

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Abstract: The recent developments in the field of Er-doped integrated optical amplifiers and lasers is reviewed. Material systems and fabrication technologies for Er-doped waveguides are discussed and - as far as possible - are compared in terms of waveguide quality, specific gain and potential for devices of higher complexity. Results of broadband and narrow band (tunable) amplifiers, of tunable lasers, narrow linewidth DBR-lasers, and modelocked lasers are presented. Prospects for devices of even higher functionality are discussed.

I. Introduction:
In recent years the success of the Er-doped fiber amplifier EDFA has stimulated a growing interest in Er-doped integrated optical amplifiers and lasers. A variety of different vitreous (phosphate-, soda-lime-, and borosilicate glasses [6, 11, 16, 8]) and crystalline hosts (LiNbO$_3$, Si, Al$_2$O$_3$, CaF$_2$, and TiO$_2$ [1, 3, 4, 7, 10, 9]) has been investigated as potential substrates for Er-doped integrated optical devices. Besides homogeneous (bulk-) Er-doping a number of surface-near or even local doping techniques have been applied like indiffusion of evaporated Er- (or Er$_2$O$_3$-) layers or stripes [1], Er-implantation and annealing [2-3], doping during epitaxy [10], flame hydrolysis deposition (FHD)[13], plasma enhanced chemical vapour deposition (PECVD) [6], sol-gel process [9], or sputter deposition [16]. Several of these techniques have just been applied to fabricate doped waveguides but practical devices of higher complexity still need to be demonstrated. An exception are Er-doped silica on silicon planar light guide circuits (PLC) [6, 13, 14-15, 19] and Er-diffusion doped LiNbO$_3$-waveguide amplifiers and lasers with already very promising characteristics [17, 18, 20-26]. Especially the latter material system promises very attractive device concepts like modelocked lasers [22-23], Q-switched lasers, tunable lasers [24], and even monolithic integrations with other active and passive components taking advantage of the excellent electrooptic, acoustooptic and nonlinearoptic properties of LiNbO$_3$. This paper gives an overview of the fabrication techniques and of the devices already demonstrated in Er-doped LiNbO$_3$ and silica on silicon.

II. Fabrication Techniques:

a) Er-doped silica on silicon
The interest in PLCs on Si is probable due to the fact that Si is frequently used as an optical mother-board allowing self aligned fiber-to-chip coupling methods by utilizing selectively etched V-grooves. Using flame hydrolysis deposition (FHD) of Er-doped silica, subsequent reactive ion etching (RIE) for the definition of the doped channels, and overcoating with an undoped silica layer, embedded waveguides with scattering losses below 0.1 dB/cm have been fabricated [13]. FHD is a method in fiber preform fabrication which has already been developed to maturity. The main issue in the fabrication of Er-doped silica waveguides for PLCs is the very high doping level (several thousand ppm of Er, see e. g. [13]) necessary for such short (a few centimeter long) waveguide structures. Fluorescence quenching due to clustering and associated Er-Er-cross relaxation as known from Er-doped silica fibers [27] has to be avoided. Phosphorus-codoped silica seems to be a promising candidate to meet these requirements. PECVD-deposition of Er-doped, phosphorus-codoped silica allows the incorporation of higher amounts of phosphorus than FHD.

b) Er-doped LiNbO$_3$
Er:LiNbO$_3$ allows to combine the low noise gain properties of the dopant, erbium, with the excellent electrooptic and acoustooptic properties of the host, LiNbO$_3$. In single crystalline LiNbO$_3$ erbium is incorporated on regular lattice sites [28] in contrast to vitreous silica. Thus, very high concentrations of erbium up to the solid solubility in LiNbO$_3$ can be used without fluorescence quenching [3].
For surface-near Er-doping of LiNbO$_3$ two approaches have been studied: Er-indiffusion of evaporated Er-(Er$_2$O$_3$)-layers [1] and Er-implantation and annealing [2-3]. The latter method requires an extended annealing at temperatures above 1000°C to remove the radiation damage and the columnar structure after onset of solid phase epitaxial regrowth and to restore the single crystalline structure necessary for the fabrication of low loss waveguides [29]. The doping profiles after extended annealing are close to a Gaussian similar to the Er-indiffusion after the Er-reservoir has been exhausted.

The indiffusion technique, on the other hand, is simple but ideally suited for local doping as the doped regions can easily be defined by photolithography. It completely avoids amorphization and retains the single domain ferroelectric phase necessary for efficient active electrooptic and acoustooptic devices. For the waveguides in principle two alternative fabrication technologies exist: Ti-indiffusion or proton-exchange and annealing (APE). TE- and TM-guiding is possible only in Ti-indiffused channels whereas APE-channels are guiding only one polarization. Up to now, by far the best Er-doped LiNbO$_3$-waveguides have been fabricated using the Ti-indiffusion technique [1]. Scattering loss figures below 0.1 dB/cm in both polarizations have been achieved, comparable to undoped channels. This is a prerequisite for the realization of high net-gain figures and a low threshold pump power for lasers. As the Ti-diffused guides have a larger mode size than APE-guides the highest possible temperature close to the Curie-point of LiNbO$_3$ is used for the Er-diffusion doping. Typical parameters are 1130°C, 100h leading to a 1/e-penetration depth of the Er-profile of about 7 μm in Z-cut and 5.3 μm in X-cut LiNbO$_3$. Channel waveguides are subsequently fabricated by standard Ti-indiffusion (1030°C, 9h).

**Waveguide amplifiers:**

The highest net signal gain (up to 27 dB at 1533nm wavelength) has been achieved to date in an Er-doped silica on silicon-PLC [14]. In Fig. 1 the structure and the measured net gain as function of launched pump power are shown. Signal and pump have been superimposed using a monolithically integrated WDM-coupler. The total length of the amplifier is 47.7 cm leading to a specific gain of $2.1 \times 10^{-3}$ dBcm$^{-1}$mW$^{-1}$.

![Fig. 1](image)

Fig. 1 Left: design of amplifier with integrated WDM for pump and signal superposition. Right: Net signal gain at 1533nm versus pump power launched into the pump input port of the integrated WDM-coupler; after [14].

Significantly higher specific net gain figures have been achieved in Er:LiNbO$_3$-waveguide amplifiers at 1531 nm [17]. In a 4.8 cm long double pass pumped waveguide amplifier up to 14.7 dB net gain or $3.4 \times 10^{-2}$ dBcm$^{-1}$mW$^{-1}$ specific gain have been demonstrated. In Fig. 2 very recent results for a 7 cm long single pass amplifier are shown. Up to 13.8 dB have been obtained. As can be seen the low waveguide losses lead to an onset of net gain at very low pump power levels.

Besides broadband amplification acoustooptical filtering in LiNbO$_3$ can be utilized to achieve tunable narrow band amplification. A tunable filter with up to 4.8 dB net gain at the filter peak
has been demonstrated [18]. Amplification can also be utilized to compensate losses in other integrated optical LiNbO$_3$-devices.

Lasers:
A number of different laser devices have already been demonstrated in Er-doped silica and Er:LiNbO$_3$. Silica is essentially a passive material and does not allow a fast control of the lasing wavelength or mode of emission. However, slow tuning of the wavelength over 2 nm has already been shown by Oguma et al. [30] using a Y-branch laser with thermooptic phase shifter in one branch.

In LiNbO$_3$ acoustooptic tuning over a broad wavelength range is possible. Such acoustically tunable wavelength filters can also be applied inside a laser cavity. Using a double stage filter [31] the frequency shift during the first acoustooptic polarization conversion is compensated by an equal but opposite shift in the second stage leaving the circulating wave in a cavity with no net frequency shift per round trip. By applying this concept we have realized the first acoustically tunable Er:LiNbO$_3$-waveguide laser [24]. Its structure and its tuning properties are shown in Fig. 3. A total tuning range of 12 nm has been achieved.

Another important feature of lasers especially for applications in WDM-systems is a stable
narrow linewidth emission. Recently the first Er-doped single-longitudinal-mode DBR-laser in phosphorus codoped silica with photo-imprinted Bragg-gratings has been demonstrated by Kitagawa et al.[19]. The structure of the laser and its measured output spectrum are shown in Fig. 4.

![Fig. 4](image)

**Fig. 4** Left: design of a DBR-laser with photo-imprinted Bragg-gratings. Right: single frequency spectrum of the DBR-laser, shown in two orders of a spectrum analyzer of 25 GHz free spectral range; after [19].

Also in LiNbO\(_3\) a first DBR-laser has been realized (for details see separate paper at this conference [25]). Surface relief gratings as Bragg-reflectors have been defined by holographic exposure and subsequent reactive ion etching. The structure of the laser, its power characteristics and output spectrum are shown in Fig. 5.

![Fig. 5](image)

**Fig. 5** Left: schematical diagram of the structure of the Er:LiNbO\(_3\)-DBR-laser; right: DBR-laser power characteristics and spectrum (inset).

Very recently, even single frequency emission at power levels in excess of 3 mW has been achieved.

The excellent electrooptic properties of LiNbO\(_3\), moreover, allow the realization of fast phase- and amplitude modulators. Such a modulator can be used intracavity as modelocker for the generation of short laser pulses with multi-GHz-repetition rates. Using an intracavity travelling wave phase modulator FM-type modelocked laser operation at the fundamental [22] and at harmonics [23] of the axial mode frequency spacing has already been demonstrated. In Fig. 6 the structure of such a laser is shown together with an autocorrelation trace and a spectrum of the pulses for 3rd harmonic modelocking. Transform-limited Gaussian pulses have been achieved. Recently, locking up to the 8th harmonic (10.4 GHz pulse repetition rate) has been shown.

Such a device can also be used as a fast optical spectrum analyzer with significantly improved resolution and sensitivity if operated slightly below the lasing threshold [26].
Fig. 6 Left: schematic diagram of the design of the modelocked Er:LiNbO$_3$-waveguide-laser. Right: autocorrelation trace and spectrum of the laser pulses for 3rd harmonic modelocking.

**Conclusion:**

The technology for integrated optical Er-doped amplifiers and lasers and a number of state of the art devices have been reviewed. By monolithic integration of further components devices of even higher complexity and functionality can be envisaged for the near future.

**References:**


INTEGRATED DBR LASER IN ERBIUM-DIFFUSION-DOPED LiNbO₃

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Abstract

Optically pumped (λₚ=1484 nm) DBR waveguide lasers with dry-etched Bragg-gratings (345.5 nm period) have been demonstrated in erbium-diffusion-doped Z-cut LiNbO₃ with titanium-diffused waveguides. A resonator configuration with a dichroic input mirror and Bragg-gratings of different lengths has been investigated. Laser emission at λₑ=1531 nm was achieved with threshold values of 40 mW and cw output powers of 3.6 mW at 185 mW coupled pump power. The typical emission bandwidth is 3.6 GHz.

Introduction: One of the key components for applications in optical communication is an integrable, narrow band, fixed frequency light source. In semiconductors, distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers have already been developed. In LiNbO₃ however, up to now free running lasers [1], mode-locked lasers [2] and tunable lasers [3] with erbium-doped Ti:LiNbO₃ waveguides have been reported with dielectric end face mirrors only. Despite the attractive properties of these lasers, narrow bandwidth operation and integration with further components on the same chip is difficult. Therefore, we developed a DBR waveguide laser in erbium-diffusion-doped LiNbO₃. First results have just been submitted for publication [4]. We report fabrication and operation of this device with further results for DBR gratings of different length.

Sample configuration: A schematic diagram of the laser chip of 60 mm overall length is shown in Fig. 1. It consists of titanium-indiffused monomode waveguides in Z-cut, Y-
\( \approx 85\% \) transmittivity for the pump. The latter is a first order Bragg-grating of 345.5 nm period and of 16 mm or 30 mm length, etched into the surface of the undoped waveguide. The resulting narrow band reflection for \( \sigma \)-polarized optical modes (TE) matches the gain peak of Er:LiNbO\(_3\) at \( \lambda = 1531 \) nm. The right end face of the sample is anti-reflection (AR) coated.

**Laser fabrication:** The fabrication of the laser essentially consists of four steps: planar erbium-diffusion-doping of the gain section, waveguide definition, DBR grating fabrication, and dielectric coating deposition.

1.) A vacuum deposited \( \text{Er}_2\text{O}_3 \) film of 28 nm thickness was indiffused at a temperature of 1130\(^\circ\)C for 100 h resulting in a Gaussian-like doping profile of 5.5 \( \mu \)m depth and an erbium surface concentration of \( 1.45 \times 10^{20} \) cm\(^{-3}\) [5].

2.) \( 7 \mu \)m wide, 95 nm thick titanium-stripes were photolithographically defined on the LiNbO\(_3\) surface and subsequently indiffused at 1030\(^\circ\)C for 9 h.

3.) First order DBR gratings of 345.5 nm period were fabricated using dry etching techniques. A protective Cr layer was sputtered onto the sample surface and photolithographically patterned to define openings for the grating areas. A layered structure of heat resistant polyimide, sputtered Cr etch-stop, dyed polyimide AR coating, and photore sist was then deposited. The grating was holographically exposed in the resist utilizing a conventional setup with a large distance of 70 cm between the spatial filters and the sample. Good quality of the developed resist grating was only achieved by using the AR coating to suppress backreflections and greatly reduce standing wave effects. Rectangular grating mask line profiles were obtained by Cr shadow evaporation onto the resist relief, \( \text{O}_2 \) gas reactive ion etching (RIE) down to the Cr stop layer, opening of this layer by SF\(_6\) gas RIE and a final \( \text{O}_2 \) gas RIE down to the crystal surface. The polyimide/metal mask obtained was then transferred into the LiNbO\(_3\) to a depth of about 240 nm using an SF\(_6\) gas RIE process. (A more detailed description of the grating processing can be found in [6].) The grating profile in the waveguide surface was of trapezoidal cross section due to redeposition effects. An SEM top view of the etched grating is shown in Fig. 2.

4.) The end faces of the sample were coated using an ion beam assisted evaporation technique. The dichroic mirror, a stack of 18 layers of \( \text{TiO}_2 \) and \( \text{SiO}_2 \), was vacuum deposited onto the left end face. The AR coating on the right end face was formed by a single quarter-wave \( \text{SiO}_2 \) layer.

**Passive device properties:** The titanium diffused optical channel waveguides are single mode in the wavelength regime around 1.5 \( \mu \)m. \( \sigma \)-polarized modes with 5.7 \( \mu \)m \( \times \) 4.0 \( \mu \)m extension (horizontal half width \( \times \) vertical half width) are guided with scattering losses as low as 0.07 dB/cm. The indiffused erbium doping is responsible for absorption coefficients of \( \alpha(1484 \text{ nm}) = 1.8 \) dB/cm at the pump wavelength and of \( \alpha(1531 \text{ nm}) = 6.7 \) dB/cm at the signal wavelength. The reflection characteristics of the grating structures were measured using the broad band fluorescence of an erbium-doped fiber pumped by a 1480 nm laser diode. A linear state of polarization (\( \sigma = \text{TE} \)) was selected by a fiber polarizer butt-coupled to the AR coated sample end face. The reflected signal was extracted via a 3 dB coupler and analyzed with a conventional monochromator of 0.04 nm wavelength resolution. Fig. 2 shows the reflectivity spectra of the Bragg-gratings of 16 mm and 30 mm length with halfwidths of 0.8 nm and 1.2 nm, respectively. This is much broader than expected theoretically and measured with other samples [6]. An ideal, chirp free grating of 30 mm length should give a narrow band reflectivity of less than 0.1 nm width. This discrepancy is due to the holographic grating definition with spherical wavefronts of small curvature inducing a weak chirp of the grating periodicity. The Bragg-gratings were fabricated symmetrically with smallest periodicity in the center and growing periodicity
Fig. 2: Center: SEM top view of a DBR grating of 345.5 nm periodicity etched into the surface of a Ti:Er:LiNbO₃ waveguide. Left and right: σ (TE) reflectivity of the 16 mm long (left) and 30 mm long (right) Bragg-grating as function of the wavelength.

to the edges of the gratings. Therefore, the length of the grating determines the maximum periodicity and thus the total width of the reflection spectrum. So the chirp broadens the overall response and reduces the peak reflectivity, but cannot completely explain the unusual wavelength dependence in Fig. 2. This might be caused by inhomogeneities of the grating depth and/or the waveguide effective index.

Laser operation: A color center laser with an output power of up to 220 mW at $\lambda_p=1484$ nm was used as pump source. The polarization of the pump was chosen $\sigma$ (TE) because maximum gain is achieved with both pump and signal $\sigma$ polarized. The pump light was launched via a single mode fiber by butt-coupling to the laser resonator. In this way a Fabry-Perot cavity is formed by the end face of the fiber and one of the resonator mirrors leading to an effective pump (and/or signal) reflectivity which depends on the fiber-chip distance. This results in an uncertainty in the absolute values of coupled pump power given below. These values can be taken as upper limits because they were not corrected to take the effective endface/mirror reflectivities into account. The DBR laser emission was filtered by two WDM-couplers with a total pump suppression of more than 50 dB. In the following results from the two different optical waveguides with grating lengths of 16 mm and 30 mm are presented.

Even without the end face mirror coating the sample could be operated as DBR laser. The small reflectivity of the uncoated LiNbO₃ end face (R=14.3%) together with e.g. the 30 mm long grating was sufficient to allow lasing ($\lambda_l=1531$ nm) above 135 mW coupled pump power and to yield a maximum output power of 1.8 mW in backward direction at 180 mW coupled pump power.

With the dichroic, dielectric mirror the laser output was monitored in forward direction through the grating (see Fig. 1). The laser performance of both devices is presented in Fig. 3. The device with the longer grating had a threshold of only 40 mW; 2.0 mW of output power could be generated with a coupled pump power of 185 mW. The slope efficiency was 1.5%. The waveguide with the short Bragg-grating showed a slightly higher lasing threshold of 53 mW. Due to a slope efficiency of 3.0% an output power of 3.6 mW was achieved. The differences of the laser performance can be qualitatively understood from the reflection characteristics in Fig. 2. Compared to the 30 mm long grating the 16 mm long grating has a lower reflectivity which leads to an increased threshold, but a higher slope efficiency.

The bandwidth of the laser emission was measured with a bulk scanning Fabry-Perot spectrum analyzer of 15 GHz free spectral range. The DBR lasers oscillate with a few (1–4) longitudinal modes. The mode spacing of the device with 30 mm long grating is
1.8 GHz. Frequently, every second mode is suppressed, leading to a typical output spectrum as presented in the inset of Fig. 3. The emission wavelength of the DBR laser can be fine-tuned via an adjustment of the temperature with a tuning coefficient of 0.02 nm/K.

**Conclusions:** We have demonstrated integrated optical DBR lasers of different grating lengths in erbium-diffusion-doped LiNbO₃. Threshold values of 40 mW coupled pump power and maximum output powers of 3.6 mW have been obtained. The laser emission has a small bandwidth; sometimes even single-frequency operation is observed. Further improvement of the Bragg-grating (chirp free, reduced excess loss) will allow stable single mode operation, even lower threshold values and higher output power levels. DBR lasers of this type can be designed with different emission wavelengths within the gain spectrum of Er:LiNbO₃. Further samples with Bragg-gratings of longer periodicity and reflection at 1561 nm have been fabricated and will be investigated. The results will be communicated to the conference.

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**References**

MULTIPLE FUNCTION WAVEGUIDE LASER IN Nd-DIFFUSED Ti:LiNbO₃.

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A multifunctional, low threshold waveguide laser is demonstrated in Nd:Ti:LiNbO₃. Tuning over 2.3nm has been observed using on-chip electro-optic modulators. Applying a sinusoidal modulation to the electrodes results in the formation of a train of 20ns pulses at rates of 1MHz and 120mW peak output power.

Introduction

Rare-earth-doped channel waveguides in glass and LiNbO₃ are the basis for the construction of active devices in these material systems, and are becoming increasingly attractive for optical communications and sensor applications. In addition, the integration techniques used in the manufacture and processing of waveguide structures permit a degree of robustness and dense packing that is difficult to achieve with rare-earth-doped fibres. In particular, rare-earth doping of LiNbO₃ significantly increases the potential of this material, and attractive device concepts can be realised by taking advantage of the electro-optic and acousto-optic properties of the substrate. Moreover, the localisation of the rare-earth ions by indiffusion techniques enables passive waveguide components to be developed on the same substrate as those with gain. The recent demonstration of periodic poling in Nd-diffused LiNbO₃ also implies the possibility of the integration of domain reversed sections in rare-earth-doped laser cavities in LiNbO₃ for intracavity second harmonic generation.

Monolithically integrated multiple-cavity resonators have recently been the scope of study for several researchers, and more robustness and flexibility towards photonic integration can be achieved with complex interferometric resonator configurations than is possible with fibre devices. The suitability of rare-earth-doped lithium niobate for advanced laser applications has been established with the realisation of Q-switched², mode-locked³,⁴ and tuneable⁵,⁶ sources. We have recently demonstrated an electro-optically tuned Nd:Ti:LiNbO₃ waveguide laser at room temperature in a Y-branch geometry⁵, and report in this contribution the observation of Q-switched pulses using this structure, demonstrating the versatility of this simple coupled-cavity configuration.

Laser fabrication and characterisation

Details of the waveguide fabrication and cw laser characterisation have been described previously⁵ and will be reiterated here only briefly. An X-cut, 1mm x 50mm x 50mm lithium niobate substrate was doped near the surface by indiffusion of a 13±2nm thick layer of thermally evaporated neodymium. The diffusion was carried out at 1090°C over 240 hours in a dry oxygen atmosphere, resulting in an estimated 1/e depth of 5μm. Five parallel Y-branch waveguide structures were then defined along the Y-axis by conventional lift-off of
a 95nm thick layer of titanium, and the waveguides were subsequently fabricated by indiffusing the titanium at 1005°C for 9 hours in an oxygen atmosphere. A typical device is shown in Fig. 1. The coupled cavities were in general designed to be asymmetric, with the widths of guides 1 and 2 being 3µm in all the devices and the width of guide 3 incrementing by 1µm between adjacent devices so that the first device has a guide 3 width of 3µm and the last of 6µm. The asymmetry ensures an intrinsic optical path length difference between the two arms of the Y-cavity. Finally, aluminium electrodes were defined alongside guide 2, as shown in Fig. 1. The electrodes were 50µm wide, 10mm long and spaced apart by 10µm. The waveguide endfaces were polished to yield devices ~45mm long.

Dielectric mirrors with a reflectivity of 95% at 1060nm and a reflection bandwidth of 200nm were attached to the endfaces. The mirrors were index-matched to the substrate using a fluorinated liquid. A Ti:Al₂O₃ laser tuned to 816nm was used as the pump source and a x10 microscope objective was used to couple light into the Y-branches via guide 1, with a coupling efficiency of 26±3%. CW lasing was observed at 1092.7nm from all of the devices, and the results presented here are for the device with guide 3 width of 6µm. With no bias voltage applied to the electrodes, lasing set in with ~4.2±0.5mW of launched pump power, and a slope efficiency of 2.6±0.3% was obtained. The laser emission was σ-polarised, with a linewidth of 0.2nm, as measured on an ANDO spectrum analyser. We have recently also achieved diode pumping of this laser device, and this will be reported elsewhere. Application of a dc voltage in the range -25V to 25V caused the lasing signal to be observed.

The modulators were then driven by a sinusoidal wave in the MHz regime, with a peak-to-peak magnitude of 20V, using a 5MHz Wavetek waveform generator. The laser output was fed into a Tektronix Optical Converter (7GHz bandwidth) connected to a 1 GHz oscilloscope. As the driving frequency was varied between 200kHz and 5MHz a periodic train of Q-switched pulses was observed, as shown in Fig. 2. At a driving frequency of 2.2MHz, we observed pulses with an average power of 2.5mW, for coupled pump powers of ~165mW. A typical pulse is shown in Fig. 3. The minimum pulse duration was 20ns and the peak output power was ~120mW. The symmetric nature of the pulses, with rise times and decay times approximately equal, implies that the inversion level at the time of switching was low8. This is not entirely surprising as the pulse separation of 0.9µs is considerably shorter than the 100µs metastable state lifetime, the characteristic time scale for inversion to build up at low pump levels. We note also that the period of the Q-switched pulses was approximately twice that of the modulation period, indicating that each pulse depleted the inversion such that it required two modulation periods for the gain to recover to its prepulse level. Under different conditions, pulse periods of between two and six times the driving period were seen. The pulses showed good amplitude stability and low jitter. Modulation of the Q-factor of a Y-branch waveguide laser can be explained by the shifting of the resonant frequency of the coupled cavity within and out of the gain band9. However, in this device it was not possible to suppress the lasing indefinitely, implying that the Q of the laser cavity is always maintained at a high enough level to allow cw oscillation. As a result, optical pulse generation by conventional Q-switching, where the Q-factor of the laser cavity is deliberately kept low for long periods, typically of the order of the lifetime of the excited ions, before
being rapidly switched back to the high state, is difficult to implement here. By applying a sinusoidal modulation to the electrodes we are nonetheless able to see Q-switched pulses forming in the slow switching regime. Further investigations are underway to determine precisely the dynamics of formation of these pulses in our device. We believe we can increase the peak power of the Q-switched pulses by at least an order of magnitude by optimising the output coupling of the cavity, and experiments are being carried out to demonstrate this.

Conclusions

We have demonstrated a versatile waveguide laser in Nd:Ti:LiNbO₃. The waveguide laser, which consists of a Y-branch cavity, has a threshold of ~4.2mW of launched pump power and a slope efficiency of ~2.6% with 95% reflectivity mirrors butt to its endfaces. On-chip modulation of the optical path length of one arm of the Y-branch has been used to demonstrate tuning over a range of 2.3nm. Q-switching has been observed by applying a sinusoidal modulation to the electrodes, and peak pulse powers of 120mW with pulse widths of 20ns have been observed with a repetition rate of 0.9kHz. We are at present working on improving the quality of the pulses.

We believe that multifunctional devices in LiNbO₃, for which electro-optic switching can be used to provide intracavity modulation and in which the gain may be localised to specific areas, may find applications in many areas of optics.

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References

Fig. 1. Schematic of a Y-branch waveguide laser device.

Fig. 2. Q-switched pulse train, observed on a 1 GHz oscilloscope. The time base is 200ns per division. The pulse repetition rate is 0.9$\mu$s.

Fig. 3. Oscilloscope trace of one Q-switched pulse. The time base is 20ns per division. The peak power is 120mW and the pulse width is 20ns.
DISTRIBUTED FEEDBACK LASERS IN RARE-EARTH-DOPED PHOSPHATE GLASS

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ABSTRACT

We have successfully demonstrated waveguide lasers operating at 1056.1, 1058.2, and 1062.6 nm in Nd-doped phosphate glass. The waveguides were fabricated by potassium ion exchange from a nitrate melt. Distributed feedback grating patterns were holographically written at 458 nm in photoresist spun on the sample surfaces. The gratings were developed, coated with chromium at a 60-degree evaporation angle, and were then transferred into the glass by argon ion sputtering. Typical laser threshold was 32 mW of absorbed pump power at 805 nm with a corresponding slope efficiency of 2 %.

In this report we describe the first operation of distributed feedback lasers fabricated in rare-earth-doped phosphate glass. Distributed feedback lasers with Bragg gratings have previously been demonstrated in Nd-doped silicate glass. The phosphate host, however, has a significantly larger emission cross section ($\sigma_e = 3.62 \times 10^{-20}$ cm$^2$) than typical silicates ($\sigma_e = 1.7 \times 10^{-20}$ cm$^2$), and thus is far more attractive as a laser host. The glass composition has been reported previously. For the present work, the Nd doping level was 1 mol %, corresponding to a calculated Nd ion density of $2.7 \times 10^{20}$ ions/cm$^3$. Single-transverse-mode waveguides were formed by sodium-potassium ion exchange in a melt of KN0, through a series of apertures opened in a 150-nm thick Al masking film. The apertures ranged in width from 3 to 8 μm. The exchange time was 6 h at a temperature of 375°C. After the exchange process, the sample was cut so that the end flat was normal to the waveguides to ensure accurate alignment in the grating exposure apparatus. The Al mask was removed, and the sample was cleaned thoroughly.

The grating formation process was begun by spinning Shipley S-1805 Photoresist at a speed of 7000 rpm. This yielded a photoresist film thickness of approximately 340 nm. The sample was

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prebaked at 105°C on a vacuum hotplate for 2 minutes. The sample was then holographically exposed using a 90° corner mounted on a rotation stage to split collimated light into two beams. Light from a 458 nm Ar ion laser was spatially filtered by focusing through a pinhole using a 10x objective lens. The resulting beam was collimated using a 76-mm diameter lens with a 350-mm focal length. One face of the corner was a mirror, and the other was a vacuum chuck for holding the sample. Four 8-mm long gratings were exposed on the same sample substrate at angles of 40.9°, 41°, 41.1°, and 41.2° through windows cut in opaque masks. These angles correspond to grating pitches of 349.76, 349.05, 348.35, and 347.66 nm, which should provide laser operation at wavelengths of 1060.5, 1058.3, 1056.2, and 1054.1 nm. These numbers are based on effective index estimates for the lasing mode of 1.516 ± 0.004. The uncertainty in index corresponds to possible center wavelength variation of ± 2.8 nm. The exposure time for the resist for this work was 24 s, which gives an exposure energy density over a 5.5 cm circular aperture of 54.7 mJ/cm².

Representative test gratings with a period of 500 nm were also fabricated by the same process for examination by atomic force microscopy (AFM). The gratings were developed in undiluted Shipley CD-30 developer.

Diffraction of light from a HeNe laser at 632.8 nm was monitored during the developing process step. The diffracted power increased during developing as the photoresist grating was etched. When the diffracted power began to decrease, the sample was removed from the developer bath and rinsed in deionized water. After the developing, the sample was mounted at a 60°-incline in an electron-beam evaporator and 50 nm of Cr was deposited. At this deposition angle, the Cr accumulates only on the tops of the gratings and not in the grooves. This provides a durable etch mask for the photoresist and allows the grating to be transferred into the glass. The grating is transferred into the glass using a reactive ion etching system with 4 Pa (30 mTorr) Ar ion plasma as the etching agent. The low pressure plasma created a large self bias voltage of 1600 V when running at 375 W of coupled power which accelerated Ar ions into the substrate. The etch time was 25 min. After etching was complete the sample was ultrasonically cleaned in 85°C photoresist stripper. The sample end facets were then polished to facilitate end-fire coupling of pump light into the waveguides.

Figure 1 shows micrographs of the 500 nm test grating which were taken using an AFM. This grating had a normally incident diffraction efficiency of 60% at 632.8 nm wavelength which is the best diffraction efficiency yielded in our process thus far. The maximum etch depth is indicated by the section analysis to be 153.7 nm. The AFM also revealed a nearly sinusoidal etch profile. This follows directly from the photoresist profile created by a holographic exposure.

To operate the distributed feedback laser, a mirror with a reflectance of 99.9% at 1060 nm was placed on the input facet of the waveguide using a spring clip. The waveguide was end-fire
pumped through the mirror using a Ti:Al$_2$O$_3$ laser tuned to 805 nm. The laser spectrum and slope efficiency data are shown in Figure 2. The threshold for this sample was 32 mW of absorbed pump power with a slope efficiency of 2.08%. Other samples displayed similar laser characteristics at wavelengths of 1062.6 and 1056.1 nm. The full width half maximum linewidth as measured with a 0.2 nm resolution automatic spectrum analyzer was 0.26 nm on the 4 µm waveguide. On other waveguides we have seen widths below the resolution limit of the spectrum analyzer. We think that the linewidth may be narrower or could be reduced. We are currently working to determine if the excessive width is due to end facet reflections introducing feedback in multiple longitudinal modes. Linewidth measurements using a scanning Fabry-Perot etalon will be presented at the conference.

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Disclaimer

Specific materials and process chemicals are reported only to make the process reproducible and are not endorsed by the U.S. Government. Other materials and chemicals may work as well or better.

References


Figure 1. AFM micrographs of a 500 nm pitch grating. Top view and cross sectional trace. Vertical scale is in nanometers for section view.

Figure 2. Slope efficiency data and spectrum for distributed feedback laser. Threshold is at 32 mW. Slope efficiency is 2%.
Packaging and Reliability of IO in Glass

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Due to delay in delivery this invited paper will appear in Proceedings for Post-deadline Papers.
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PACKAGING AND RELIABILITY OF ACTIVE INTEGRATED OPTICAL COMPONENTS

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Introduction

The rapid penetration of optical transmission technology into all types of telecommunications systems has been a major driving force behind the development of high performance opto-electronic and optical components. Whilst in recent years we have seen considerable advances in the development of key devices, such as laser diodes and photodiodes, in terms of performance, cost, reliability, etc, comparatively little advancement has been seen for deploying advanced active integrated optical components. In contrast to the effort on basic device functionality, integration, the squeezing of the last fractions of a volt or decibel etc, the development of device packaging seems to have received far less attention, even though it determines the cost, reliability, and ultimate performance of today’s components.

The establishment of reliable, cost effective packaging of components is not glamorous and is rarely publicised. Yet the packaging of optical and opto-electronic components requires that we as technologists must solve a combination of optical, mechanical and electrical problems, many of which have not been previously encountered within the electronics industry and require novel solutions. The problems are often highly interactive and an understanding of all of the issues is generally required in order to develop a successful, manufacturable product. The latter is often ignored as we strive to design and demonstrate new components.

In this paper I will comment on the various problems encountered in establishing a reliable packaging strategy for active integrated optical components, including the alignment and fixing of optical components to sub-micrometer tolerances, the problems of chip bonding and interconnection, including large chips of unusual materials, the increasing need for high speed connections as well as the purely optical characteristics of the component.

By way of the practical problems encountered in such developments I will describe a high performance packaging approach for high bandwidth lithium niobate modulators which has been established by Integrated Optical Components Ltd (IOC).

Packaging of Active Components

The exact starting point of the existing packaging strategies for lithium niobate are difficult to define but probably resulted from extending existing techniques for microwave components to optical circuits. In this manner the dominant design is a large housing with SMA electrical connectors. Meanwhile the laser, the detector, the drivers, etc, have all gone surface mount. Thus IOC’s strategy was totally different to other suppliers ... namely the final component will
be compatible with current telecommunications practices. Further it must facilitate the establishment of rapid, reliable and simple packaging operations such that we can achieve the required price reductions as the components are deployed in high volume.

It is at this point that you have begun the roadmap for your packaging, since you have defined the application environment. In our case at IOC, it was to provide a compact surface mount package which allows us to establish a manufacturing facility which is capable of producing integrated optical components at volumes in excess of 10,000 circuits per annum. Still low volume to the silicon industry but high for integrated optics at this point.

So at IOC the package design was finalised before we even committed the final cell designs for the optical components. Since we wanted a surface mount package we immediately reduced the options available, or at least that is how it appears at first sight. The package could be plastic, ceramic or metal, but the key is the electrical feed-through. The operating bit-rate of telecommunications has seen dramatic increases during recent years and continues unabated at this point. Thus the feed-through technology selected, whilst required to only operate at 622Mb/s or 2.5Gb/s at the point of our starting, had to be capable of migrating to potentially 40Gb/s, via 10Gb/s and 20Gb/s. As a result, we selected co-fired ceramic feed-throughs similar to those employed in Butterfly laser packages and most high speed ICs. Here we can provide feed-throughs operating at the required frequencies with different impedances or geometries. At this point, we have standard products operating to 10Gb/s available with these feed-throughs with the package suppliers capable of 40GHz feeds shortly, and through to 100GHz should the need arise! In addition, with co-fired ceramics we can utilise an additional range of options including multi-layer conductors, allowing us to change the internal electrical configuration without changing the external assignment, ie we can maintain the external interface for life whilst allowing substantial chip re-design at later dates.

Next comes the package material, where already co-fired feeds reduce the options, and the unusual geometry of lithium niobate circuits, (long and thin), meant that we settled on a metal body. The dominant metal package body is Kovar which is widely available and allows cheap packages in volume, but is thermally mismatched to lithium niobate. Stainless steel is matched thermally but cost analysis showed that packages would be approximately five to ten times more expensive, and generate other problems since now the package is mismatched to the feed-throughs. Kovar won, and we had now defined the limits for the other aspects of packaging.

First comes die attach. This is an area where particular attention should be paid, since if this is not secure and stable, you are fighting a losing battle. In general, it is considered that all we have to do is 'glue' the chip down. Well, in essence, that is all we are doing but the 'glue' must be capable of bonding to both the chip and the package, and it must maintain that join over a wide temperature range. Further, with lithium niobate we are now bonding large chips, typically between 20-60mm long and 2-5mm wide, with a pyroelectric and piezoelectric material. Hence, with the wrong material choice we can induce large stresses within the chip leading to large variations in device performance, normally bias point instability. In addition the large thermal mismatch means that the die attach must be capable of absorbing large stresses.

The use of singlemode optical circuits place stringent demands for efficiently coupling between elements, but also upon the package to maintain the coupling with extremely tight positional tolerances. The most frequently tackled coupling problem to date has been that for semiconductor lasers, and is usually achieved via lensed fibres. However, not all singlemode coupling problems require the use of such transforming optics. In lithium niobate the waveguide mode size can be made to be a close match to the optical fibre. The positional toler-
Hybridization and Packaging Technologies

Ances are slightly less severe, at around ±1 lam, but this is still a very small distance in any industry other than optics. It is the problems of aligning to these tolerances, and then maintaining them in the packaged component over its lifetime and in conditions of high temperature, humidity, and probably strain on the fibre that account for much of the difficulty in packaging single mode optical devices.

At present the vast majority of integrated optical components are packaged using active alignment techniques as the micro-machining approaches and piece-part tolerances are not fully solved. Usually with a laser, a clear maximum exists which facilitates alignment via automation techniques under computer control. However, with lithium niobate circuits the maximum is when the fibre is butt-coupled directly which means additional feedback is required to prevent the fibre being rammed into the endface etc. A further complication of optical circuits is the need to actively operate the devices during alignment and fixing, further increasing the complexity and cost of the tooling required. One further complication with integrated optical components is the fact that we generally have input and output ports. By a combination of tooling and operator training, IOC are able to simultaneously pigtail the input and output ports of its devices, thus reducing cycle times.

The butt-coupled interface of optical fibre and lithium niobate circuit are fixed via the use of a command cure resin. This approach was adopted, at IOC, since we could tailor the material properties to the requirements of the joint, ie shear strength, compliance etc. Generally the fibre is bare between package wall and chip such that the interfaces are decoupled. However, this requires the use of complex pigtailling tooling and places demands upon the manufacture and handling of such delicate assemblies without introducing flaws etc, giving rise to failures during operation. Such an approach is shown in figure 1a. We at IOC took an alternative approach whereby we employ a single piece fibre assembly which may be manufactured by multiple external suppliers using standard fibre connector techniques. This approach is then directly applicable to all fibre types, singlemode, multimode, PMF, polarizing etc. Now the single piece assembly defines the feed-through technology as we now have a joint subject to thermally induced stress via the mismatch in chip and package. Thus the joint has to be compliant, hence a resin is employed which again is selected based upon the stress levels etc, present within the design. Whilst not strictly hermetic in the generally accepted view IOC have shown that devices with this approach are capable of exceeding the leak-rate requirements for hermeticity. This packaging approach is shown in figure 1b and is the subject of a pending patent.

Figure 2 shows the insertion loss variation for two assembled devices as they were cycled 100 times between -40°C and +85°C using this approach. At present IOC’s standard packaging is employed by customers over the range -50°C to +70°C. We have now got the component mounted and pigtailed, with the ceramic feed-throughs electrical connections are simply made directly from the package pads even for components operating at 10Gb/s.

At this point all that remains is to seam-seal the lid of the package on using conventional equipment and label it. Figure 3 shows IOC’s standard 2.5Gb/s amplitude modulator. IOC’s packaging strategy has been such that we can offer a path to increasing bit-rates without redesigning the package interface, since all of IOC’s digital modulators from 622Mb/s through to 10Gb/s are housed in packages with the same footprint and pin-assignment. The strategy is also employed in our parallel ranges of phase modulators, analogue modulators and custom devices, including sensors, acousto-optic tunable filters etc. Figure 4 shows IOC’s surface mount 10Gb/s modulator package.
Environmental Screening & Reliability Testing

Packaging affects two aspects of the component once it has been shipped, how will it respond to environmental fluctuations and how long will it survive. Hence, active integrated optical components must be tested against two sets of environmental limits. The first, which is essential to initial system deployment, is the environmental aspect. In this we will take the component and operate it over a restricted range of temperatures, humidity etc, and define absolute variations in performance together with rates of change. It is at this point that you should be in detailed discussions with your potential customers since only they will provide the only information which says these are acceptable. No packaged device is totally steady ... they all have variations ... even minor ones can trip a system up.

At this point you may need to rapidly re-iterate the packaging and/or chip to remove or reduce variations to acceptable limits, and if you have not done so already, you should be performing additional environmental stress tests. The dominant body of knowledge here comes from Bellcore, who have Generic Requirement and Quality Assurance practices covering most technologies within telecommunications ... except integrated optics (explicitly). Here integrated optical components must meet their competition head on environmentally, eg silica or glass splitters are just another type of branching component and tested just like fused fibre couplers. Thus amplitude modulators are essentially covered by laser requirements. The aim here is to build up results which show the ruggedness of the packaging technology and establish confidence that it will survive the system environment for 25 years or more.

Stress testing takes many forms including extended dry heat, temperature cycling, damp heat, mechanical shock, vibration, fibre retention, and thermal shock. At this point in time, IOC have performed the Bellcore tests on its 2.5Gb/s amplitude modulator with satisfactory results. Figure 5 shows some of the results for mechanical testing, whilst figure 6 shows some aging results, which to date extend to 10,000hrs at 70°C.

Once you've jumped these hurdles you need to start generating failure rates and lifetime estimates, based upon accelerated aging tests for large number of components. In some ways, getting the package designed and the components working is the easy part. The environmental testing, qualification testing, lifetime estimates, etc, are activities rarely seen by materials technologists, circuit designers, etc. You should - it puts the work on packaging and the interaction of all elements in the package from what electrode metal to which mode-size, etc, into a clear perspective.

Acknowledgements

The author would like to thank his colleagues at IOC who have contributed to the company's manufacturing and product developments and to our customers who have been willing to discuss and establish the requirements and benchmarks against which we test components and can deploy them in current systems.
2.5Gb/s Amplitude Modulator
Insertion Loss versus Temperature Cycles
(Temperature Cycle -40C to +85C)

**Figure 2**

**Figure 3**: 2.5Gb/s Amplitude Modulator

**Figure 4**: 10Gb/s Amplitude Modulator
Figure 5: Mechanical Shock & Vibration Test Results

Figure 6: Accelerated Aging Test Results

70°C DRY HEAT

CYCLIC MOISTURE:
- 20-65°C 90-100%RH for 10 cycles
  (min 5 cycles -10°C)
- MIL-STD-883D Method 1004

BIASED HUMIDITY:
- 40°C 95%RH 1000hrs (maximum to date)
- 70°C 85% RH 2000hrs (maximum to date)
AN OPTICAL TRANSCEIVER ON A SILICON MOTHERBOARD

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Abstract
We describe the first demonstration of a full silica waveguide based transceiver on a single silicon motherboard chip. The optoelectronic components are passively aligned using micromachined features in the silicon, and are optically interconnected with planar silica waveguides. Electronic components are also hybrid integrated, and interconnected by a metal layer.

Introduction
Silicon hybrid optical motherboards are silicon substrates incorporating optical and electrical interconnects together with micromachined alignment slots, into which electronic and optoelectronic devices can be inserted, giving passive alignment. The use of passive alignment techniques has the potential to reduce assembly costs, whilst the integration of whole optical, electronic and optoelectronic systems onto a single silicon substrate brings the potential for reduced packaging costs. We have previously demonstrated separately the various interfaces which comprise a motherboard [1]; now we present the first demonstration of a full silica waveguide based motherboard, in which these building blocks been combined into a single processing route.

The transceiver which we have built is shown schematically in Figure 1. The transmitter comprises a directly driven laser, passively aligned to a silica waveguide, whilst the receiver consists of a hybrid integrated pin photodetector and electronic amplification circuit. The module transmits at 1.3 \( \mu m \) and receives at 1.55 \( \mu m \) via a single fibre interface, with multiplexing of the two signals performed in a silica waveguide directional coupler. Electrical interconnection is by means of aluminium coplanar waveguide structures deposited directly onto the silicon. The module is fully packaged with a fibre pigtail and standard electrical connectors.

![Figure 1 - Schematic diagram of silicon motherboard transceiver](image-url)
Optical Interconnects
The silica waveguide optical interconnect was based on an arsenosilicate glass (ASG) core, and undoped silica buffer and cladding layers, all of which were deposited by chemical vapour deposition (CVD), with annealing of the core layer carried out at 1000°C. This technique is fully compatible with subsequent micromachining, as the low temperatures used prevent crystal damage to the silicon. The refractive index difference between the core and cladding layers, Δn, was high (=0.03), and hence the mode match to lasers and other semiconductor devices was better than for conventional low Δn waveguides. The waveguide core layer was 2 μm thick, and was reactive ion etched to produce a rib waveguide of 3 μm width. The optical loss for a straight waveguide was around 1 dB/cm.

Since the transceiver was designed to transmit at 1.3 μm and receive at 1.55 μm via a single fibre, a silica waveguide wavelength division multiplexer (WDM) based on a directional coupler (DC) was incorporated. The DC had a coupling length of 1838 μm, a waveguide width of 2 μm and a pitch of 6 μm. Figure 2 is a wavelength scan showing the power emerging from each of the output arms when white light was coupled into an input arm. The results indicate that approximately 80% of the 1.55 μm light is cross-coupled, whilst around 76% of the 1.3 μm light passes straight through, giving satisfactory routing of the two wavelengths. Further optimisation of the WDM design should enable an optimum performance of 100% cross-coupling at 1.55 μm and 100% straight through at 1.3 μm to be achieved.

![Figure 2 - Wavelength spectrum for silica waveguide directional coupler](image).

In order to achieve efficient coupling between the output waveguide and a single mode fibre, the waveguide was tapered to a width of 1.25 μm close to the fibre interface, giving a less tightly confined mode, which better matched that in the fibre. In the absence of such tapers, the fibre to waveguide coupling loss is around 3.8 dB, and will be greater still if there is any misalignment of the fibre relative to the waveguide [2]. Incorporation of the taper reduces this loss to around 1 dB per interface for an optimally aligned fibre.

Transmitter
Passive alignment of the laser chip was achieved using the method illustrated in Figure 3, in which the edges of the laser chip are aligned against a set of 8 μm high silica stops on the silicon motherboard. V-grooves were defined in the laser wafer during processing, which were used to propagate cleaves, so that the laser chip dimensions could be accurately defined [3]. Vertical alignment was achieved by depositing the waveguide layers into an etched recess, such that the core
layer was at the same height as the laser active region. Once the laser was in position, a layer of solder underneath the laser active region was reflowed, causing it to ball up and make contact with the laser. This served, not only to hold the laser chip in position, but also formed the electrical contact to the p-side of the laser diode. A short length of bond-wire connected the n-side to an adjacent metal bond-pad. Aluminium electrodes were defined on the motherboard to interconnect the bond-pads with the package wall. The laser was modulated using an external laser driver.

![Figure 3 - Method for aligning precision-cleaved laser to silica waveguide](image)

The source was a 1.3 μm MQW buried heterostructure (BH) laser. This type of laser was chosen for its relatively low divergence (farfield FWHM angles = 19° x 22°), giving a relatively good mode match to the ASG waveguide, and for its temperature insensitivity, which is important, since the laser is thermally isolated from the silicon heat-sink by a 3 μm thick layer of silica.

We have achieved laser to waveguide coupling efficiencies of up to 27.5% using passive alignment, which corresponds to misalignments in the vertical and horizontal directions of less than 1 μm.

**Receiver**

The light emerging from the waveguide was reflected from a micromachined mirror into a substrate entry pin photodetector, mounted on the surface of the silicon, and aligned using a series of visual alignment markers [1]. The micromachined mirror was formed by anisotropic etching of the silicon, followed by deposition of a layer of silica and subsequent metallisation, as shown in Figure 4. For 90 μm diameter detectors, coupling efficiencies of up to 52% were achieved, and the 3 dB alignment tolerance was ±85 μm.

An electronic receiver circuit was hybrid integrated onto the motherboard, to amplify the detector output. This consisted of a transimpedance amplifier, surrounded by a series of decoupling capacitors, and was constructed from chip components bonded to the electrical interconnect layer on the silicon motherboard. The receiver was shown to have a 3 dB bandwidth in excess of 2.4 GHz.

**Conclusions**

We have demonstrated a fully packaged transceiver based on a silicon hybrid optical motherboard. The optoelectronic components were passively aligned, and electronic components were also integrated. The coupling efficiency at the laser to waveguide interface was 27.5%, whilst that at the waveguide to detector interface was 52%.
Figure 4 - Method for coupling from silica waveguide to photodetector

References


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The authors wish to thank Peter Ayliffe and Paul Harrison at BNR Europe Limited for their valuable contributions to the design and fabrication of the transceiver. The following colleagues at BT Laboratories are also acknowledged for their assistance with design, processing and measurements: Richard Earwaker, Barry Tooke, Steve Brown, Andrew Swanton and Adrian Thurlow. This work was partly funded by the U.K. Department of Trade and Industry under the LINK project SOPHI.
SURFACE NORMAL CASCADED PLANAR INTERCONNECTION WITH EASY ALIGNMENT

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Abstract
A robust scheme for the surface normal optical interconnection of arrays of opto-electronic devices is demonstrated. Allowing for inversion, the optical system maintains registration between input and image planes, thus making for stable and accurate interconnection between elements of arrays.

Introduction
Many optical systems call for free-space interconnection of planar arrays of active devices, such as laser diode, modulator and detector arrays or more complex smart pixel arrays. Robust and accurate positioning of the optical elements, and integration of the active and passive elements in a practical package presents major problems for systems engineers.1 A number of schemes have been proposed. In the stacked optics approach planar arrays of transmissive optical components, such as micro-lens arrays, Selfoc lenses or transmissive modulator arrays, are stacked side-by-side.2 Alignment methods for stacked optics have been proposed such as OBIS (optical bus interconnection system).3 Planar optics, where active and passive elements are integrated on one or both sides of a solid glass block, is a robust technique which can exploit advances in lithography and diffractive optical element design.4 This system primarily uses reflective components. However, planar optics rely on off-axis imaging operations which presents difficulties of device operation and lens design.5 Either scheme requires that the active and passive elements be positioned within micron accuracy and that they maintain this alignment. Although experiments with planar optical systems suggest this accuracy can be attained,6 it places very severe constraints on the manufacture and stability of any such system.

Trends in integration suggest that it will be possible, and indeed preferable, that active device arrays will be integrated on a single substrate using wafer scale or hybrid integration techniques. Fig. 1 shows the general concept of an optical highway interconnection system where arrays of opto-electronic elements are integrated on a single plane with passive optical components providing fixed interconnection between arrays. Both the active device arrays and optical components can be made with high accuracy, the key issue is providing stable and accurate positioning of the two blocks. In this paper, we propose a novel approach to achieve cascaded, normal incidence interconnection imaging between arrays using a pupil division configuration of relay lenses and prism arrays. Surface normal incidence is preferable for lens design and for many devices e.g. any laser or modulator incorporating a Fabry-Perot cavity. Given that the active arrays and the optical components can both be integrated in solid blocks, this system has the advantage of being insensitive to small lateral displacements between the blocks, since the prism/lens combination conserves any small displacements, thus making for stable and accurate interconnection.

Principle of surface normal planar cascaded interconnection
Fig. 2 shows a schematic of the cascaded interconnection system. The vertices of the prisms are aligned with the centres of the corresponding lenses, thus splitting the lens pupil into an input and an output half. The object/image plane is put at a focal length distance. Referring to fig 2, light from object point o1 is collimated by the right hand side of relay lens 1 and incident on the prism 1. Light reflected by the right-hand side of prism 1 is then reflected by the left-hand side of prism 2 and onto relay lens 2, at the same angle as the light exits from relay lens 1. Thus, the light is focused onto point o2 which is at the same position, relative to the optic axis, as that of object point o1. If plane 2
is replaced with a mirror (or a reflective modulator array) light will be reflected from point $o_2$ at the same angle relative to the optical axis, in obedience to the laws of reflection. Thus, in a manner similar to the above, the light will propagate through lens 2, prism 2, prism 3 and lens 3 to reach point $o_3$, on plane 3, again with the same relative displacement from the optic axis.

Fig's 3 (a and b), each show the 2D imaging relationship between the planes. The lens has the function of inverting an image vertically and horizontally. Reflection by the prism inverts an image horizontally. As shown in fig. 3(a), when a centred image is input at plane 1, an image inverted about the x-axis appears at plane 2. If plane 2 is replaced by a mirror, an erect image appears at plane 3. When the input image is displaced, as shown in fig. 3(b), the inverted image at plane 2 is similarly displaced, while the image at plane 3 shifts by the same amount in the same direction as the input image. Thus the interconnection relationship of plane 1 and the plane 3 is maintained constant at all times, given a reflecting element at plane 2. Equally well, if the pixel order at plane 2 is reflected in the x-axis a point to point relationship can be maintained. Thus, in this optical system, high alignment accuracy is not required with respect to x- or y-axis displacements between the optics and the array plane. However, it should be noted that rotational errors will not be accommodated.

**Experiment demonstration of the optical system**

An experimental optical system was designed and fabricated to demonstrate the concept. Fig. 4(a) and (b) are photographs of the components. Fig. 4(a) is an overview of the components including the prism array, a spacer block, lenses and a lens holder and fig. 4(b) is a photograph of the individual components. The components are made of a glass (BK7, refractive index = 1.515). The lenses have a focal length of 16 mm in air, and a diameter of 8±0.15 mm. Since the effective focal length in glass is longer, the thickness of the spacer is duly increased to 22.80 mm. The lens holder consists of a glass plate with holes at 15±0.1 mm intervals and of diameter 8±0.1 mm into which they were glued. The prism array is made by fixing 4 prism blocks using UV-resin. The pitch is 15±01 mm. The vertical angle is 90±5 seconds. The deviation of 5 seconds may displace the position by 200 μm. The rough fabrication of the lens array and the low accuracy of the prism angle resulted in small errors in the imaging positions.

Fig. 5 is a schematic diagram of the experimental system. Test slide patterns, as shown in fig. 5(b) and 5(c) were fabricated by photographic reduction. The pattern consists of 10 x10 pixels at a pixel pitch of 300 μm. The mask slide is fixed on a glass plate in front of the system. Slide 5(b) is used when the first image plane is to be observed, and slide 5(c) is used to view the second plane. Point source illumination at the input plane is simulated using a micro-lens array. Collimated light from a HeNe laser is incident on a micro-lens array whose pitch is 250 μm. This is imaged to the input plane using a reducing telescope to give an effective point source pitch of 100 μm.

Fig. 6 shows the experimental results for the optical system. Fig. 6(a) shows: (1) the input pattern; (2) the first image plane as viewed with test slide 5(b); and (3) the second image plane as viewed with slide 5(c) respectively. As expected, the first image is inverted about the y-axis direction and the second image plane is erect. Fig. 6(b) shows the same experimental results for an offset input image, showing how the displacement is maintained, in an inverted form at the first plane, and directly at the second plane. Thus registration is maintained constant at all times between arrays, given an inversion at the odd image planes.

**Discussion**

The system described above requires high accuracy in the manufacture of the solid state opto-electronic arrays, and of the passive optical block. In both cases this can be achieved using the individual technologies. The advantage of this system is in not requiring high accuracy when combining the two different technologies in a hybrid system. If the resolution required at the arrays becomes very small (1-10 μm), then this would place a very heavy burden on the optical system quality. The requirement on lens quality could be reduced by using a hybrid optical approach, where a combination of micro-lenses are used with the larger relay lenses. In this case the micro-lenses must be integrated with the opto-electronic devices to maintain the latitude of movement between the two blocks. These and other details will be discussed fully in the presentation.
References

Active opto-electronic device array
( Optical sources, Modulators,
Photodetectors, Local electronics)

Passive optics

Fig. 1 Concept for free space optical highway interconnections system.

Fig. 2 Schematic diagram of cascaded interconnection

Fig. 3 Image relationship at the planes

Fig. 4 Photograph of the components of the optical system
Fig. 5 Schematic diagram of the experimental system and test targets

(a) Experimental system

(b) Test target for the first image plane

(c) Test target for the second image plane

Fig. 6 Experimental results of (a) a centred input pattern and (b) a shifted input pattern
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