Phased-array wavelength demultiplexers and their integration with photodetectors
The photograph on the cover shows a 4-channel phased-array wavelength demultiplexer integrated with photodetectors (see also figure 6.3 of this thesis).
Phased-array wavelength demultiplexers and their integration with photodetectors

PROEFSCHRIFT

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Summary

Wavelength Division Multiplexing (WDM) exploits the huge bandwidth of the optical fiber by parallel transmission of several independent channels located at different wavelengths and in addition has the potential of all-optical routed networks. A key component in such a WDM-system is a low-loss wavelength demultiplexer for spatial separation of the different channels. This thesis describes the design, realization and characterization of wavelength demultiplexers for the 1.55 $\mu$m-window and their monolithic integration with photodetectors.

The transfer of light from the demultiplexer to the photodetector is achieved by means of evanescent field coupling. Special attention has been paid to the optimization of this coupling technique. A simple method has been developed for determination of the optimum detector absorption layer thickness. Experimental results confirm the validity of this model.

The wavelength demultiplexer is based on the dispersive properties of a planar waveguide array. In this thesis it is demonstrated that these demultiplexers combine low-loss with excellent spectral resolution. Moreover they can be realized with relatively simple process technology. Monolithic integration of the demultiplexer with pin-photodetectors has been demonstrated. The external responsivity and the channel separation of this integrated WDM-receiver are the best so far reported.

The polarization dependence of phasar demultiplexers has been analyzed in detail. Different solutions are proposed to achieve polarization independent operation.

The wavelength response of the demultiplexer has been flattened by employing multimode output waveguides. A 1-dB transmission bandwidth of 1 nm with a 2 nm wavelength spacing has been realized. This flattened response relaxes the matching of the laser wavelength with respect to the transmission maximum of the demultiplexer.

A novel waveguide array demultiplexer is proposed employing Multi Mode Interference (MMI) couplers in a generalized $N \times N$ Mach-Zehnder Interferometer configuration. This device has a potential for very low-loss operation and high transmission uniformity of the individual channels.

Finally, a new measurement technique is demonstrated for non-destructive measurement of waveguide losses, which is a first step towards full-wafer characterization of integrated optic components.
Samenvatting

De golfstengtemultiplexing techniek (WDM) benut de enorme potentiële bandbreedte van de glasvezel door verschillende golfstengen te gebruiken voor parallelle transmissie van meerdere informatiekanaal en biedt tevens de mogelijkheid tot volledig optisch gerouteerde netwerken. Een belangrijke component van zo'n systeem is een golfstengedemultiplexer voor de ruimtelijke scheidin van de verschillende kanalen. Dit proefschrift beschrijft het ontwerp, de realisatie en de eigenschappen van golfstengedemultiplexers voor het 1.55 µm-golfstengtegebied en hun monolithische integratie met fotodetectoren.

Het licht uit de demultiplexer wordt in de fotodetectoren gekoppeld door middel van een techniek die te vergelijken is met quantum mechanisch 'tunnelen'. Speciale aandacht is besteed aan de optimalisatie van deze koppelmethode. Er is een simpele procedure ontwikkeld voor de bepaling van de optimale absorptielagdikte van de detector. Experimentele resultaten zijn in overeenstemming met dit model.

De golfstengedemultiplexer is gebaseerd op de dipersieve eigenschappen van een planaire golfstengeleiderarray. Dit proefschrift toont aan dat deze demultiplexers lage verliezen kunnen combineren met een uitstekende spectrale resolutie. Bovendien kunnen ze met een relatief eenvoudige technologie worden gerealiseerd. De demultiplexer is monolithisch geïntegreerd met pin-fotodetectoren. De externe responsiviteit en de kanaalscheidin van deze geïntegreerde component zijn de beste waarden die tot nu toe gepubliceerd zijn.

Een nieuw type golfstengeleiderarray demultiplexer wordt voorgesteld, gebruik makend van Multi-Modale Interferentie (MMI) koppelaars in een gegeneraliseerde N x N Mach-Zehnder interferometerconfiguratie. Deze component heeft de mogelijkheid om zeer lage verliezen te combineren met een uitstekende uitgangsuniformiteit.

Tot slot wordt een nieuwe, niet-destructieve, meetmethode beschreven voor de bepaling van golfstengeleiderverliezen. Deze methode is een eerste stap in de richting van 'op de plak' karakterisatie van geïntegreerde optische componenten.
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Chapter 1

Introduction

This chapter sketches the development of optical communications and discusses the relevance of the subject of this thesis, and outlines the contents of the thesis.

1.1 Development of optical communications

Optical communication has been triggered by two major developments. The first one is the development of the optical fiber as a medium for transfer of information with low attenuation and an enormous potential bandwidth. Since the proposal in 1966 of Kao and Hockham [1] to use glass fibers as a waveguide medium for optical communications, the losses of optical fibers have been reduced from a few thousands dB/km to only 0.2 dB/km at 1.55 \( \mu \)m wavelength today, which seems to be the theoretical limit for quartz-based dielectric waveguides. Parallel to this the semiconductor laser has been developed as a compact reliable low-cost source of intense coherent radiation, that can be modulated in many different ways to transmit information.

Nowadays 40 millions of kilometers of optical fibers are installed worldwide in the long and medium distance network and the optical fiber is gradually penetrating the local network. The Japanese telecommunications company NTT envisages that by ‘the year 2015’ all houses will be connected by optical fiber [2].

Implementation of the optical fiber into the local network will most likely start with the connection of high bandwidth requiring business users such as banks, software houses, and research institutes. These users may have their local optical network, which is connected to the core network via an electrical or (a more advanced) optical interface.

A unique opportunity to extend the optical fiber into the local network has been created by the reunification of Germany. As many as 1.2 million homes and business users in the former Eastern-Germany should be connected by optical fiber in the year 1995 [3]. For this project both fiber-to-the-curb (FTTC) and fiber-to-the-building (FTTB) solutions will be implemented. A number of interactive and broadband distributive services will be transmitted from the optical
network unit 'in the street' to the customer via copper pairs and coaxial cable respectively.

In the medium and long distance network exciting developments are also going on. The development of the erbium-doped fiber amplifiers (EDFA's) allows for the compensation of propagation and component loss without transfer to the electrical domain. The first all-optical transoceanic connection, operating at 5 Gb/s will be installed in 1995. The technology for this so-called TPC-5 network has been jointly developed by AT&T and KDD [4].

The extension of the fiber to the private user today is mainly hampered by large equipment and installation costs combined with the lack of high-bandwidth requiring services justifying these costs. A possible solution to break this vicious circle may come from the considerable progress that has been made during the last years on data compression techniques of digital audio and video signals. It is likely that in the near future these techniques will be exploited by offering a number of multimedia services via existing CATV networks [5]. However, as the number of services and users increases, the existing network will no longer be able to satisfy the ever increasing demands of the customer. This demand of higher bandwidth may become the driving force for the extension of the fiber-to-the-home, thus turning the present technology-push approach into market-pull direction.

1.2 Scope of this thesis

One of the most powerful properties of the optical fiber is the possibility to transmit different channels in parallel on the same fiber using the wavelength as an additional degree of freedom. At the receiver different methods may be used to separate the individual channels again. A coherent transmission scheme [6] mixes the incoming signal with a local oscillator signal
and provides the highest sensitivity and theoretically the most efficient usage of the available bandwidth. However, the complexity of coherent receivers and the stringent requirements on the stability of the local oscillator makes it unlikely that they will soon become commercialized.

An alternative concept is a Wavelength Division Multiplexed (WDM) direct detection system. Figure 1.1 shows the simplest implementation of such a transmission system. Optical multiplexers are used to combine signals with different wavelength into the transmission fiber. At the receiver end these signals are separated by similar optical demultiplexers, and directly coupled to photodetectors. The high potential bandwidth is a frequently mentioned motivation for research of WDM components and networks, but it is not the most important one. The potential of creating all-optical routed, rearrangeable, and scalable networks [7] is the most significant advantage of WDM compared to other transmission methods. As a simplified example figure 1.2 shows a configuration to establish a ‘collision free’ connection between N transmitters and N receivers employing tunable lasers and a demultiplexer at the node of the network to route the signals to the receiver.

Receivers for WDM systems using bulk-optic components [8] have been demonstrated with low losses and good channel separation. A 32-channel demultiplexer with 1 nm channel spacing has been realized by D.R. Wisely [9], using a diffraction grating as the dispersive element and a microlens array bonded to the face of a fiber array to separate the different wavelength channels. These hybrid demultiplexers require very accurate assembly of the subcomponents and are therefore not ideally suited for low-cost mass production. They are also vulnerable to environmental influences such as vibrations, temperature changes and humidity.

The work presented in this thesis is the realization of a wavelength demultiplexer monolithically integrated with photodetectors (see figure 1.3). The following advantages flow directly
from monolithic integration:

- Optical components can be fabricated in a self-aligned way by lithographic techniques. Moreover, photolithography allows for the realization of device shapes that cannot easily be achieved by bulk optic fabrication techniques.

- Due to the rigid connections between different components the integrated multiplexer will be almost insensitive to mechanical vibrations.

- The processing techniques of integrated circuits allow for large scale production and reduce packaging cost. This is expected to result in cost reduction for the total device.

The wavelength demultiplexer applied in this thesis is based on the focusing and dispersive properties of an array of planar optical waveguides, as proposed by M.K. Smit [10]. The integrated demultiplexer is intended for operation in the 1.55 $\mu$m-window (for which reliable optical amplifiers can be made and the fiber exhibits the lowest propagation loss). It has therefore to be integrated in material, which allows for the realization of transparent waveguide components, as well as absorbing photodetectors at this wavelength. Such a material is provided by the quaternary III-V compound semiconductor $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ on InP substrate.

The outline of this thesis is as follows:
Chapter 2 summarizes the material properties of InP/InGaAsP and processing technologies relevant to the realization of the integrated demultiplexer.

Chapter 3 treats the modelling and the optimization of the coupling between the output waveguides of the demultiplexer and the photodetector.

Chapter 4 presents the fabrication and experimental results of the integrated waveguide detector.

Chapter 5 describes the general design aspects of the wavelength demultiplexer.

Chapter 6 presents experimental results on phased-array demultiplexers and their monolithic integration with photodetectors.

Chapter 7 describes a novel measurement technique of waveguide losses, which arose as a spin-off investigation from the development of the integrated waveguide detector technology.
Chapter 2

InP material properties and technology

This chapter gives an overview of the material properties of InGaAsP lattice matched to InP relevant to the realization of integrated WDM demultiplexers. The device technology that is needed for the fabrication of these devices will also be treated. A more rigorous overview of InP material properties can be found in [11] and a good overview of InP processing technology is given by [12].

2.1 III-V compound semiconductors

Figure 2.1 shows the bandgap energy of various III-V compound semiconductors as a function of the lattice constant. In this diagram the markers represent binary or fixed composition ternary alloys, the lines variable composition ternary alloys, and vertical dotted lines lattice matched quaternary alloys. Due to the availability of a limited number of good quality substrates (InP and GaAs) the choice of lattice matched III-V semiconductors is limited practically to Al$_{1-x}$Ga$_x$As on GaAs substrate and In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ on InP substrate, of which the Al$_{1-x}$Ga$_x$As alloy is less suitable for applications in optical communications due to its large bandgap. The first successful preparation of In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ lattice matched on InP was reported by Varian Associates in 1972 [13]. Since the report of the first hetero-junction InGaAsP laser operating at room temperature [14], the research effort on InGaAsP has increased dramatically and a vast number of devices for fiber-optic communications has appeared.

In$_{0.52}$Al$_{0.48}$As can also be grown lattice matched on InP and is a promising candidate for the fabrication of high speed hetero-junction devices. However, the presence of aluminum in this material complicates device processing due to oxidation problems when aluminum containing layers are exposed to air.
Figure 2.1 Bandgap energy and absorption wavelength versus lattice constant for various III-V compound semiconductors.

In the last few years a new family of semiconductor devices has appeared, exploiting the properties that can be obtained by deliberately growing epitaxial layers with controlled amounts of tensile or compressive strain. Strained multiple quantum wells have mainly been applied to reduce the threshold current of semiconductor lasers, increase their differential gain, and to shift the emission wavelength into the visible spectrum. In this thesis, however, we will limit ourselves to the more classical material $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ lattice matched on InP substrate (the vertical dotted line in figure 2.1) For convenience this material will be called $\text{InGaAsP}$ for the following of this thesis, or more specifically ‘Qx’ with ‘x’ the bandgap absorption wavelength (in $\mu$m) of the material.

### 2.2 Material properties of InGaAsP

This section treats the key properties of InGaAsP that are relevant to the design of optoelectronic devices in this material system.

#### 2.2.1 Lattice constant and energy gap

The lattice constant of $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ $A(x,y)$ can be obtained by applying Vegard’s law, using the well known lattice constants of the binary compounds [15]:

$$A(x,y) = xyA_{\text{GaAs}} + x(1-y)A_{\text{GaP}} + (1-x)yA_{\text{InAs}} + (1-x)(1-y)A_{\text{InP}}$$  \hspace{1cm} (2.1)
2.2 Material properties of InGaAsP

Figure 2.2 InGaAsP refractive index at $\lambda = 1.55 \, \mu m$, as reported by Fiedler and Schlauchetzki [17], Adachi [18], Henry et al. [19] and Burkhard et al. [20].

From this equation, the condition for lattice matching to InP can easily be derived as:

$$x = \frac{0.1896y}{0.4175 - 0.0124y} \quad \text{for} \quad 0 \leq y \leq 1$$

(2.2)

The bandgap energy of lattice matched InGaAsP $E_g(x, y)$ is given by interpolating between the InP and In$_{0.53}$Ga$_{0.47}$As bandgap energy [16]:

$$E_g(x, y) = E_g(\text{InP}) + E_g(\text{In}_{0.53}\text{Ga}_{0.47}\text{As})y + C_{III} x(1 - x) + C_V y(1 - y)$$

(2.3)

The constants $C_{III}$ and $C_V$ are the bowing parameters and are due to alloy disorder, disturbing the periodic crystal potential. By fitting expression 2.3 to room temperature photoluminescence and electroreflectance measurements, the following empirical relation has been obtained:

$$E_g = 1.35 - 0.775y + 0.149y^2 \, eV$$

(2.4)

2.2.2 Refractive index

The knowledge of the refractive index of InGaAsP is of crucial importance for the design of waveguide devices. For example the center wavelength of the phased-array demultiplexer presented in chapter 6 critically depends on the refractive index of the Q1.3 material of the guiding layer. An error of 0.3% of this refractive index corresponds to a shift of already 4 nm of the wavelength response of the demultiplexer.

Figure 2.2 shows the refractive index of InGaAsP at $\lambda = 1.55 \, \mu m$ as a function of the As-fraction as reported by different authors. The authors referenced obtained these curves
by fitting Vegard's interpolation formula to experimental data. However there is no general consensus what physical quantity actually should be used for interpolation. For example, Fiedler and Schlachetzki [17] use the oscillation energy and dispersion energy of a modified single oscillator model for interpolation. Burkhard et al. [20] argue that the physical quantity that really matters is the atomic polarizibility, and applying Claussius Mossoti's equation interpolate the quantity \((\chi - 1)/(\chi + 2)\). It appears that for a low As-fraction there is only a small difference between the different models. For photon energies close to the bandgap energy, however, the difference between those models can be significant.

For photon energies above the bandgap energy the reported data of (complex) refractive indices are very limited. Erman et al. [21] measured a real refractive index of \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) at \(\lambda = 1.52\ \mu\text{m}\) of 3.5435 using spectroscopic ellipsometry. Deri et al. [22] use a refractive index of \(3.532 - i0.088\) at \(\lambda = 1.55\ \mu\text{m}\) for ternary material. Humphreys et al. [23] measured the absorption constant of \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) as a function of wavelength by transmission measurements through epitaxial layers. They found at \(\lambda = 1.55\ \mu\text{m}\) an absorption constant of \(\alpha = 6.8 \cdot 10^3\ \text{cm}^{-1}\), corresponding to an imaginary part of the refractive index of \(-0.084\).

In this thesis the model of Fiedler and Schlachetzki, which seems to be a good compromise between the different models, has been used for all theoretical calculations. The refractive index of \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) was taken to be \(3.532 - i0.088\).

### 2.2.3 Carrier mobility

A basic knowledge of the charge carrier mobility is important for the realization of high speed (opto)electronic components. Figure 2.3 shows the low field room temperature electron and hole mobility of InGaAsP as a function of composition. Due to the substantially higher effective mass of holes compared to electrons, the low field hole mobility is more than a factor 30 lower than the electron mobility. The low field mobility is determined by the following three scattering mechanisms:

- **Polar optical phonon scattering**: This is the dominant mechanism at room temperature with low doping levels.

- **Ionized impurity scattering**: Dominant at high doping levels.

- **Alloy scattering**: Dominant at low temperature with low doping levels.

Due to the reduced device dimensions of devices fabricated nowadays, the electrical fields are sufficiently high for the charge carries to reach their saturation velocity. Therefore the high field mobility is usually a more interesting parameter. For example it is well known [16] that in \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) already at electric fields around 3 keV/cm velocity saturation occurs due to electron transfer into one of the side minima of the conduction band. This transfer is usually (in high-purity material) combined with a negative differential mobility regime. The electron and hole saturation velocities in \(\text{In}_{0.53}\text{Ga}_{0.47}\text{As}\) are in the \(10^7\ \text{cm/s}\) range [16].
2.3 InP-based technology

In this section an overview will be given of the technological aspects that are specifically relevant to the fabrication of the integrated WDM-demultiplexer, such as epitaxial growth, etching and ohmic contacts.

2.3.1 MOVPE

During the last five years metal organic vapor phase epitaxy (MOVPE) has become the most mature technique for growing InGaAsP epitaxial layers. Compared to liquid phase epitaxy (LPE), it offers higher flexibility, increased layer thickness control and better uniformity. Today MOVPE can almost compete with molecular beam epitaxy (MBE) systems and it is more suitable for growing phosphorous containing compounds. Most MOVPE systems nowadays operate under low pressure conditions. This offers better uniformity, improved interface abruptness, higher flexibility in choice of precursors and reduced gas consumption. The majority of the devices presented in this thesis have been realized in LP-MOVPE layers, grown by the Department of Information Technology (INTEC) of the University of Gent, Belgium. A detailed study of the MOVPE growth of InGaAsP in Gent is presented by I. Moerman [24].

The most frequently used precursors for MOVPE growth of InGaAsP are the hydrides AsH₃ and PH₃ (gases) for the group V elements, and In(CH₃)₃ (solid) and Ga(CH₃)₃ (liquid)
for the group III elements. Usually $\text{H}_2$ is used as a carrier gas. Proper design of the reactor chamber is crucial to the fabrication of high uniformity (thickness and composition) epitaxial layers with abrupt junctions. Care has to be taken to avoid turbulence and memory effects, and to compensate for gas depletion. Another important point is the proper mixing of the gasses before the entrance of the reaction chamber. By introducing two mixing devices before the inlet of the reactor Moerman et al. [25] realized 0.6% longitudinal and 1% lateral uniformity over a two-inch wafer (see figure 2.4). The standard deviation of the photoluminescence peak wavelength at 77 K for a In$_{0.53}$Ga$_{0.47}$As layer was measured to be only 2.9 nm.

 Paramount to the realization of various optoelectronic devices such as pin-photodetectors is the ability to control the majority carrier concentration accurately by incorporation of dopants in the crystal lattice. Not intentionally doped MOVPE-grown InP is typically n-type with doping levels ranging from $3 \cdot 10^{13}$ cm$^{-3}$ to $2 \cdot 10^{16}$ cm$^{-3}$. This residual doping is attributed to impurities in the precursors [26] or reduction of quartz in the reactor chamber [27]. For n-type doping of InGaAsP silicon and sulphur are the most frequently employed dopants, using SiH$_4$ and H$_2$S as precursors. Because of the relatively high solubility, Zn is usually employed for p-doping, using Zn(CH$_3$)$_2$ and Zn(C$_2$H$_5$)$_2$ as precursors. The high diffusion coefficient of Zn may cause dopant redistribution during growth, which has to be taken into account during device design. Therefore, in devices where the actual location of the pn-junction is critical, the doping levels have to be chosen carefully. Alternatively, other (more toxic) dopants such as Be or Cd might be used.
2.3.2 Wet etching

Wet etching of InGaAsP is still an important and versatile technique for the patterning of III-V devices. Comparing with more sophisticated dry etching techniques such as reactive ion etching, wet etching offers the possibility of perfect selective, inexpensive and damage free etching. Quantum wires with lateral dimensions as low as 10 nm [28] have been realized by selective chemical etching. A disadvantage of wet etching is that the amount of underetching depends on the masking material and etching solution. Moreover the etch profile is usually dependent on the crystallographic orientation *. Therefore wet etching is less suitable for etching waveguide bends.

For the etching of semiconductor material three different etching mechanisms can be distinguished [29]:

- **Anodic etching**: Etching of the semiconductor material requires dissolution of positive ions of semiconductor material. Therefore, the semiconductor is connected to the positive pole of a DC-voltage source. An inert counter electrode in the solution is connected to the negative pole. For p-type material the required holes will be obtained from the valence band of the semiconductor. For n-type material the holes have to be generated by illumination of the material. Anodic etching is not frequently applied in semiconductor fabrication technology, because electrical contacts have to be made to the semiconductor material before etching, which is usually undesirable.

- **Electrodeless etching**: In this case no external voltage source is used and the solution contains an oxidizing agent that provides the holes to the semiconductor material. This oxidation reaction causes a passivation layer on the semiconductor. Etching of the semiconductor can only occur if this passivation layer is properly dissolved.

- **Chemical etching**: Characteristic of chemical etching is that no mobile charges are involved. The reactions are due to breaking old and establishing new bonds. Such a mechanism occurs, for example, when etching InP in a HCl-solution [30]. It was found that HCl etches InP only in concentrated or non-aqueous solutions. This is explained by the dissociation of HCl that occurs in diluted aqueous solutions.

As mentioned before a profound advantage of wet etching is the possibility to etch InP selectively with respect to quaternary material and the other way round.

HCl and HBr based solutions selectively etch InP on InGaAsP [31, 32]. For a HCl : H₃PO₄ (1:4) solution we found an etch rate of 0.46 ± 0.02 μm at room temperature, quite well in agreement with the result of Buchmann et al. [33]. Quaternary material can be etched selectively over InP in a H₂O₂ : H₂SO₄ : H₂O (1:1:10) solution [34], with the etchrate increasing with the As-fraction. These selective etchants have been routinely used for patterning of the photodetectors and accurate determination of layer thicknesses. Due to their almost perfect selectivity a save overetch time can be applied. However, care has to be taken with the

* This is due to the fact that the InP unit cell, contrary to silicon, has no inversion symmetry.
choice of the masking material. In general, photoresist suffers from a considerable amount of underetch. Using a SiO$_2$-layer as an etch mask gives already a significant improvement. The most ideal mask is a thin layer of semiconductor material. For example figure 2.5 shows a rib which has been etched without any undercutting, with the HCl/H$_3$PO$_4$ solution using a thin layer of Q1.3 material as a mask.

### 2.3.3 Reactive ion etching of InP

In the previous section it has been mentioned that wet etching of InP suffers from underetching and dependence of the etched profile on the crystallographic orientation. Therefore waveguides are preferably defined using dry etching techniques. This section will be devoted to reactive ion etching (RIE) [35] as this is the most common dry etching technique.

The most frequently employed etching chemistry for InP/InGaAsP was introduced by Niggebrügge et al. [36] and is based on hydrocarbon etching gasses. Chemically the etching process can be considered to be a reverse MOCVD process, with hydrides and metal-organics as a reaction product. Compared to Cl$_2$-based RIE [12], the hydrocarbon process is less toxic and non-corrosive and shows negligible mask erosion due to hydrocarbon polymer deposition onto the mask. However this polymer deposited on the edge of the mask can introduce striations on the (waveguide) ridge, increasing the scattering losses of the waveguide.

To reduce polymer buildup, a process of an alternating sequence of CH$_4$/He RIE and O$_2$-
2.3 InP-based technology

Figure 2.6 SEM-micrograph of a ridge waveguide of the spectrally flattened phasar demultiplexer presented in section 6.5.

descumming steps has been developed in our laboratory [37]. With this process waveguide losses below 1 dB/cm have been realized up to a lateral refractive index contrast of 0.03 for monomode waveguides [38]. Figure 2.6 shows a SEM-micrograph of a ridge waveguide of the phased-array demultiplexer, presented in section 6.5, which has been fabricated with the same process. These waveguides had a lateral refractive index contrast of 0.04 for TE-polarization. Waveguide losses were found to be 2.0 dB/cm for both TE and TM polarization. From these experiments it can be concluded that this modified RIE-process allows the realization of low-loss waveguides with a relatively high lateral refractive index contrast.

2.3.4 Ohmic Contacts

Since our optoelectronic devices also need an electrical connection to the outside world electrical contacts have to be made to the semiconductor material. For the contact of a photodetector there are two options: a Schottky or an ohmic contact. As it is still hard to make reliable Schottky contacts to InP, the majority of optoelectronic devices in InP/InGaAsP uses ohmic contacts. These contacts should have a low contact resistance (preferably a specific contact resistance below $10^{-5} \ \Omega \text{cm}^2$ ) and show limited interfacial reactions to avoid spiking of the junctions. In addition, they should show long term stability and be compatible with the overall device manufacturing scheme.

Although the fabrication of good quality ohmic contacts is still more an art than a science,

\footnote{With this lateral refractive index contrast low-loss waveguides bends with radii of 500 $\mu\text{m}$ have been realized.}
Figure 2.7 Measured contact resistance of Ti/Pt/Au on p-In$_{0.53}$Ga$_{0.47}$As. Contacts were annealed for 30 min in RTP.

there is more or less a general consensus on the mechanisms involved in the formation of ohmic contacts. Basically, an ohmic contact is nothing but a Schottky contact with a low barrier height and/or a thin barrier width (achieved by high doping of the interfacial region), allowing respectively thermionic emissions over or tunneling through the barrier. Two different approaches exist to achieve this highly doped interfacial layer. The classical solution is to add the dopant to the metallization, followed by a subsequent annealing step to drive the dopant into the semiconductor. More recently [39], ohmic contacts to InP/InGaAsP have been achieved by high doping of the contact layer in the epitaxial growth and deposition of a metal reducing the native oxide on the semiconductor in the annealing step. This is preferably performed in a rapid thermal processor (RTP) in order to limit interfacial reactions and to maintain interface integrity. The long term stability of these contacts is superior to the classical Au-based [40] contacts and moreover the same metallization can be applied to n and p-type contacts [41].

Motivated by the results of Ivey et al. [42] and Appelbaum et al. [43] initially in our laboratory experiments were performed using Ni/Au on n and p-InP substrates. The measurement method of Cox and Strack [44] was used to evaluate the contact resistance. As expected specific contact resistances below $10^{-5} \ \Omega\text{cm}^2$ (which is the estimated measurement accuracy of this method) were easily achieved on n$^+$-substrate. On p-InP the minimum contact resistance was found to be only $1 \cdot 10^{-3} \ \Omega\text{cm}^2$ at an annealing temperature of 375 °C in a conventional furnace. Moreover the contact was not completely ohmic. Therefore we moved to the more promising Ti/Pt/Au metallization on highly doped In$_{0.53}$Ga$_{0.47}$As layers. Annealing of the contacts was performed in a Heatpulse 410i Rapid Thermal Processor. During this annealing step the sample was placed in a SiC-coated graphite susceptor, in order to reduce phosphorous
loss and stress build-up (due to non-uniform heating of the sample). Figure 2.7 shows the measured contact resistance on p-In$_{0.53}$Ga$_{0.47}$As for this metallization as determined from TLM (Transmission Line Method) measurements. A minimum contact resistance of $3 \cdot 10^{-6} \text{ \Omega cm}^2$ was measured at a doping level of $2 \cdot 10^{19} \text{ cm}^{-3}$, an annealing temperature of 375 °C, and an annealing time of 30 s. Although this value is already quite acceptable for most applications, it is still an order of magnitude higher than the results obtained by Katz et al. [12]. Moreover the measured contact resistance shows only a weak dependence on temperature, but is very reproducible. Based on these observations (and comparing the measured contact resistance with the sheet resistance) we conclude that these results can be partly explained by the accuracy of applied measurement method. New experiments are currently in progress to confirm this supposition.
2. InP material properties and technology
Chapter 3

Design and optimization of the waveguide integrated detector

This chapter is concerned with modelling and the optimization of the waveguide integrated detector, that will be used later in this thesis to establish the coupling between the outputs of the demultiplexer and the photodetector array.

An integration scheme will be presented that is a trade-off between maximum performance and technological boundary conditions. This structure will be analyzed and optimized using guided mode theory. The results are verified by using alternative modelling tools.

3.1 Structure definition

Monolithic integration of waveguide based optical components with photodetectors is mainly motivated by the reduction of packaging cost, improved reliability and insensitivity to mechanical vibrations due to the fixed ‘self-aligned’ connection between the optical component and photodetectors. Constraints due to integration are likely to affect the performance of the photodetector. An excellent assessment of the trade-offs between performance and integrability is given in a recent review article by R.J. Deri [45]. This section will discuss the performance criteria and integrability issues relevant to the realization of the integrated WDM chip.

3.1.1 Performance criteria

The waveguide integrated photodetector will be applied in a high speed opto-electronic receiver operating in the 1.55 μm wavelength region. The following performance criteria for the integrated detector can be formulated:
3. Design and optimization of the waveguide integrated detector

- **Internal quantum efficiency**: This parameter defines the number of charge carriers generated into an external circuit per photon propagating in the optical waveguide just before the detector and is an indication of the coupling efficiency from the waveguide to the photodetector.

- **External efficiency**: This parameter includes waveguide losses and fiber to waveguide coupling loss and is the most interesting parameter from a system point of view.

- **Detector capacitance**: The bandwidth of the receiver is mainly determined by the RC-product of the input capacitance times the load resistance. Detector capacitance minimization is therefore of crucial importance to high-speed operation. In addition the detector capacitance is the leading cause of receiver noise (as it appears as $C^2$ in the usual frontend circuit models). Efficient light transfer from the waveguide to the photodetector will limit the photodetector size and capacitance. Therefore a great deal of this chapter will be devoted to the calculation and optimization of this transfer of light to the detector.

- **Dark current**: The dark current will contribute to the shot noise of the integrated receiver, it should be limited and typically be $< 100 \text{ nA}$ at low speed.

- **Polarization dependence**: As, in general, the state of polarization in the waveguides will be undefined and variable, the applied coupling technique should exhibit only a weak polarization dependence.

- **Optical bandwidth**: For WDM applications the coupling efficiency should exhibit little variation over the spectral range (1.53 $\mu$m to 1.56 $\mu$m) of the Er-doped fiber amplifier.

### 3.1.2 Integrability issues

Optimization of the integrated detector not only involves the performance criteria mentioned above, but also more subjective integrability requirements have to be taken into account. High yield and low cost can only be achieved by limiting the number of process steps and avoiding costly or yield limiting steps as much as possible. Special attention should be paid to the following points:

- The number of growth steps should be limited. Ideally only one epitaxial step on a planar substrate should be required.

- The integration scheme should allow the fabrication of low-loss waveguides preferably compatible with 'standard' waveguide fabrication technology.

- Device non-planarity should be minimized to allow further integration involving fine line lithographic steps, such as needed for high speed receiver circuits.
3.1 Structure definition

(a) Butt coupling

(b) Evanescent field coupling

(c) Mixed coupling

(d) VIM coupling

(e) TIR coupling

Figure 3.1 Schematic representation of different integration techniques for coupling light from a waveguide into a photodetector.

3.1.3 Integration technique

Basically two major approaches have been used for waveguide detector coupling. Theoretically the most straightforward and efficient solution is to butt-couple waveguide and photodetector as depicted in figure 3.1(a). However this approach complicates device processing as at least two epitaxial steps are required.

An alternative structure that has become increasingly popular [46, 47, 48], and can be grown in one epitaxial step, is based on the evanescent coupling of light from the waveguide into the photodetector (figure 3.1(b)). Table 3.1 compares the obtained performance with both coupling techniques for some state-of-the-art examples. In this table some variations on those major integration techniques are presented as well. Soole et al. [50] obtained excellent results using an integration method which is a mixture of butt- and evanescent coupling. To improve the efficiency of evanescently coupled detectors Deric al [22] proposed to insert a ‘vertical impedance matching’ (VIM) layer between the waveguide core and the absorption layer. This
Table 3.1 Summary of the performance of waveguide integrated detectors.

<table>
<thead>
<tr>
<th>Integration technique</th>
<th>Butt</th>
<th>Evanescent</th>
<th>Mixed</th>
<th>VIM</th>
<th>TIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>[49]</td>
<td>[47]</td>
<td>[50]</td>
<td>[51]</td>
<td>[52]</td>
</tr>
<tr>
<td>Ext. efficiency %</td>
<td>18</td>
<td>-</td>
<td>-</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>Int. efficiency %</td>
<td>46</td>
<td>96</td>
<td>90</td>
<td>90</td>
<td>83</td>
</tr>
<tr>
<td>Capacitance pF</td>
<td>0.035</td>
<td>0.1</td>
<td>0.051</td>
<td>0.14</td>
<td>-</td>
</tr>
<tr>
<td>Dark current nA (-x V)</td>
<td>200 (-5)</td>
<td>0.6 (-10)</td>
<td>10 (-5)</td>
<td>25 (-4)</td>
<td>10 (-10)</td>
</tr>
<tr>
<td>Breakdown voltage V</td>
<td>20</td>
<td>-</td>
<td>10-15</td>
<td>-</td>
<td>&gt;25</td>
</tr>
<tr>
<td>Measured bandw. GHz</td>
<td>22</td>
<td>9.6</td>
<td>15</td>
<td>12-13</td>
<td>4.8</td>
</tr>
<tr>
<td>Waveguide loss dB/cm</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>2.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

layer acts like a classical anti-reflection coating and may considerable improve the coupling efficiency. More recently a very useful coupling technique was demonstrated in GaAs/AlGaAs by Bossi et al. [52] based on ‘total internal reflection’ (TIR) at a dovetail-like mirror. The structure can be realized by one epitaxial step on a planar substrate, and unlike other methods there is no restriction on the waveguide geometry, but does need a thicker detector layer to absorb the light.

Another important issue is the choice of the photodetector type. Because of ease of fabrication (p-side up) p-i-n photodetectors are most frequently applied. The conducting n⁺-substrate (or contact layer), however, adds significant parasitic capacitance of bond pads, and complicates integration with transistors. Detectors utilizing interdigitated metal-semiconductor-metal (MSM) electrodes are more suitable for integration with FET transistors due to their planar structure. These detectors, however, require a high-bandgap intermediate layer (usually In₀.₅₂Al₀.₄₈As) between the metal and the absorption layer, to reduce the leakage current of the Schottky-junction.

Emphasizing the need for simple fabrication technology and compatibility with ‘standard’ waveguide fabrication technology [53], we have chosen the evanescent field coupling method. This choice was motivated as well by the boundary condition of no internal MOVPE facility. In order to minimize turn around times, single epitaxial step processing was highly desirable.

Given these constraints we tried to improve the coupling efficiency to the detector by optimization of the different layer thicknesses. A p-i-n photodetector on a n⁺-substrate was used, as we did not yet aim at monolithic integration of a preamplifier. Figure 3.2 shows the layer structure that has been used, with an InGaAsP(1.3)/InP double-hetero waveguide layer, similar to the structure used by other members of our lab [53, 54, 55]. The detector consist of an In₀.₅₃Ga₀.₄₇As absorption layer and an InP upper cladding on top of the waveguide layers. The rest of this chapter will treat the calculation and optimization of the efficiency of this evanescently-coupled waveguide photodetector.
3.2 Optical modelling

The waveguide integrated detector has been analyzed by applying modal analysis, as this technique gives more insight in the nature of the coupling than beam propagation methods (BPM). Section 3.2.1 outlines the general modelling method. In section 3.2.2 the calculation of the eigenmode(s) is treated. Then the total detector absorption is calculated using a simplified steady state model. These results are compared with more rigorous multimode analysis and BPM-simulations. Finally, a simple model is presented that allows rapid evaluation of the optimum absorption layer thickness.

3.2.1 General modelling method

Figure 3.3 shows how the absorption in the detector has been calculated. As the refractive index contrast in the lateral region is small compared to the transverse contrast, the structure has been approximated as a slab waveguide. First the eigenmode(s) in the input waveguide and the detector waveguide structure were calculated. The calculation of these eigenmodes will be explained in the next section. The excitation coefficient $c_m$ from the field distribution in the input waveguide $U_{in}(x)$ to the m-th detector (system) mode $U_m(x)$ is calculated by the overlap integral technique:

$$c_m = \int_{-\infty}^{\infty} U_{in}(x)U_m(x) \, dx$$  \hspace{1cm} (3.1)

provided that the eigenmodes are normalized according to:

$$\int_{-\infty}^{\infty} U_m(x)U_n(x) \, dx = \delta_{mn}$$  \hspace{1cm} (3.2)
Figure 3.3 Calculation of the detector absorption using a guided mode description.

Notice that this is the so-called unconjugated form of the overlap integral, which is valid for lossless as well as absorbing and gain media [56]. The total propagating field in the detector can be expressed as a superposition of eigenmodes:

$$U(x, z) = \sum_{m} c_m U_m(x) \exp(-i\beta_m z)$$  \hspace{1cm} (3.3)

Finally, the remaining power in the detector is calculated by:

$$P(z) = \int_{-\infty}^{\infty} U^*(x, z) U(x, z) \, dx$$  \hspace{1cm} (3.4)

### 3.2.2 Eigenmode calculation

The major effort of the modal analysis of the integrated detector is the calculation of the complex propagation constants of the eigenmodes in an n-layer structure which has absorbing layers.

The calculation of the propagation constants of a multi-layer structure is usually performed using transfer matrix [57] or scattering matrix [58] formalisms. Both methods use the well-known solution of the Helmholtz equation in layer $j$ with complex refractive index $n_j$:

$$U_j(x, z) = U_j(x) \exp(-i\beta z)$$

$$U_j(x) = A_j \exp(a_j(x - d_j)) + B_j \exp(-a_j(x - d_j))$$  \hspace{1cm} (3.5)
3.2 Optical modelling

![Graph showing admissible region for complex refractive index]

**Figure 3.4** Admissible region for the complex refractive index of the integrated detector eigenmodes.

with

\[ a_j = \sqrt{\beta^2 - n_j^2 k_0^2} \quad ; \quad k_0 = 2\pi / \lambda \]  

(3.6)

Imposing the proper boundary conditions at the interfaces and infinity yields a transcendental equation of \( \beta \), that can be solved by numerical procedures. Once the complex propagation constant has been found, the corresponding field distribution is readily calculated by substitution in equation 3.5. To save computation time it is convenient to know where to search for roots of this equation. By applying the frequency-domain power equation (which is nothing but the law of conservation of energy) to bounded modes, specific limits can be found for the complex propagation constant [59]. For dielectric waveguides (\( \mu = \mu_0 \)) and TE-polarized modes these limits are:

\[
N_{re}^2 - N_{im}^2 \leq \max(Re(\epsilon_r)) \\
\min(Im(\epsilon_r)) \leq 2N_{re} N_{im} \leq \max(Im(\epsilon_r))
\]  

(3.7)

with the effective index \( N_{eff} = N_{re} - iN_{im} \) defined as \( N_{eff} = \beta / k_0 \). Figure 3.4 shows the admissible region for the location of the effective index for our waveguide detector structure. It should be mentioned that for these absorbing waveguides guided modes can occur with a real effective index below the substrate index [60].
3. Design and optimization of the waveguide integrated detector

Figure 3.5  Calculated detector absorption according to equation 3.9 versus thickness of the absorption layer. $D_{cl}$ is the thickness of the InP waveguide upper cladding.

3.2.3  Steady state calculations

Once the complex propagation constants and their corresponding field distributions have been determined the total power propagating in the detector can be calculated using equation 3.4. Due to power non-orthogonality in lossy waveguides the total power is not just a simple sum of exponential functions, but also includes multimode interference contributions. However it appears that the (system) eigenmodes of coupled waveguides carry the major part of their power in one of the decoupled waveguides [61], except in the case of exact symmetry (where the two guiding layers considered separately would have modes with exactly the same propagation constant). Therefore, as a first approximation, only the mode number $m$ which carries the major part of its energy in the waveguide layer has been considered. The total power as a function of $z$ can then easily be determined as:

$$P(z) \approx c^2_m \exp\left(-\beta_{im} z\right) \quad ; \quad \beta = \beta_{re} - i\beta_{im}$$  \hspace{1cm} (3.8)

and the corresponding detector absorption $A_{det}$ in dB/cm:

$$A_{det} = 20(\log e)\beta_{im} = 8.67\beta_{im}$$  \hspace{1cm} (3.9)

Figure 3.5 shows the calculated detector absorption as a function of the absorption layer thickness using this approximation. These curves have been composed by plotting, at each absorption layer thickness, the absorption of the mode with the lowest absorption coefficient.
3.2 Optical modelling

**Figure 3.6** Calculated detector absorption *versus* thickness of the waveguide upper cladding layer.

**Figure 3.7** Calculated detector absorption for TE and TM polarized light. The thickness of the InP waveguide upper cladding was taken to be 0.3 μm.
The lower two curves consist of only one waveguide mode. For the upper two curves, a mode transition occurs at the first resonance peak. Absorption resonances that occur at specific layer thicknesses can be exploited to reduce the length and, most important, the capacitance of the integrated detector. The location of the resonances is nearly independent of the InP upper waveguide-cladding and their magnitude decreases with increasing thickness of the absorption layer. This damping effect of the resonances is due to the lossy nature of this layer and will even be more pronounced for layers with higher absorption coefficients. The magnitude of the resonances decreases exponentially with increasing thickness of the InP upper waveguide-cladding (figure 3.6), as might be expected for an evanescently coupled detector.

Finally figure 3.7 shows the polarization dependence of the absorption resonances, which is most pronounced for the first resonance.

3.2.4 Multimode and BPM calculations

Although the steady-state model presented in the previous paragraph is quite suitable for predicting qualitative results, care should be taken interpreting the absolute numbers of those calculations. As was pointed out by Pennings et al. [62], quenching of the absorption resonances can occur due to multimode interference effects in the detector. For quantitative calculations the more rigorous equation 3.4 should be used. In figure 3.8 those calculations
are compared with the simple steady-state model and finite-difference BPM simulations (using software that was kindly provided by the University of Twente [63]). As the absorption per unit length is not constant in the detector an ad hoc definition of the average absorption was used, taking the length at which 90% of the light coupled into the detector is absorbed as a reference. Significant quenching of the first absorption resonance and slight quenching of the second resonance can be observed. However, the location of the resonances is identical for all methods. Thus it can be concluded that the simple steady-state model is suitable to predict the location of the absorption resonances, but does not allow accurate calculation of the exact absorption. MMA and BPM calculations were found to be in excellent agreement.

### 3.2.5 Vertical coupler method

In this section a simple model is presented which explains the occurrence of the absorption resonances and allows rapid evaluation of their location. This model has been presented at the ECIO'93 in Neuchâtel, Switzerland [64].

The waveguide structure analyzed in the previous section can be considered a transverse variant of a conventional directional coupler (figure 3.9). To achieve maximum detector absorption complete power transfer from the lower to the upper waveguide is necessary. It is well known [65] that for those asymmetric couplers complete power transfer from one waveguide to another can only occur if the real parts of the propagation constants of the individual waveguides are equal. For this reason, the first absorption resonance occurs when the
3. Design and optimization of the waveguide integrated detector

![Graph showing Neff vs. D_abs (μm) with Absorption in dB/cm on the right y-axis.]

**Figure 3.10** Effective indices of the decoupled waveguides. The horizontal line represents the (decoupled) lower waveguide fundamental mode effective index. The three (solid) dispersion curves show the (decoupled) upper waveguide effective index for the three lowest order (TE)-modes. The crossings between these curves and the horizontal line occur where the detector absorption (dashed line) has its maxima.

(real) fundamental mode propagation constants of the (decoupled) lower and upper waveguide are identical (figure 3.10). Higher order resonances can be explained by the matching of the lower waveguide fundamental mode propagation constant with the propagation constants of higher order upper waveguide modes. This model presents a simple conceptual description of the waveguide integrated detector and allows rapid evaluation of the location of the absorption resonances when varying detector parameters.

### 3.3 Electronic properties

The most interesting electronic property of the detector is its high-frequency performance. In general this can be limited by RC products, charge carrier diffusion, transit times and charge carrier trapping at hetero junctions. It appears that most of those limiting factors may be minimized by proper design of the detector or only play a significant role at very high (> 10 GHz) frequencies. This section briefly discusses these factors for evanescently-coupled pin-detectors:

- **RC-products:** The high-frequency performance of evanescently coupled photodetectors is usually limited by the RC-product of the load resistance and the junction capacitance.
3.3 Electronic properties

[47, 50]. For example a junction capacitance $C_j$ of 0.2 pF connected to a simple transimpedance amplifier ($R_{tran} = 1 \, \text{k\Omega}$ and gain $A_g = 10$), will give a 3-dB bandwidth of:

$$B_{3dB} = \frac{A_g}{2\pi R_{tran}C_j} = 8 \, \text{GHz} \quad (3.10)$$

- **Carrier diffusion**: If the absorption layer of the detector is not completely depleted, the high-frequency response of the detector can be limited by the relatively slow process of carrier diffusion. This problem is likely to occur in butt-coupled detectors, with the depletion region not covering the waveguide/detector interface region [66].

- **Transit times**: In conventional top illuminated photodetectors the bandwidth efficiency product is limited by the trade-off between high efficiency (requiring a thick absorption layer), and small transit times (requiring a relatively thin absorption layer). In the previous sections it has been shown that evanescently coupled photodetectors can have high efficiency with thin absorption layers. For example, for an absorption layer thickness of 0.26 $\mu$m (the optimum layer thickness found in the previous sections) the transit time across this layer will only be a few picoseconds and not limit detector speed.

- **Charge trapping at hetero-junctions**: For the detectors with low capacitance and transit times, hole pile-up at the In$_{0.53}$Ga$_{0.47}$As-InP hetero-junction may become the speed limiting factor. This problem can be solved by application of graded hetero-junctions [67].
3. Design and optimization of the waveguide integrated detector
Chapter 4

Waveguide detector experiments

In this chapter experimental results are presented for the waveguide integrated detector that has been modelled in the previous chapter. It starts with a description of the mask and the fabrication technology. Following this, the experimental setup and the measurement results are presented. Finally these results are compared with theoretical calculations.

4.1 Mask layout

As the purpose of these experiments was to determine the relation between the detector efficiency and detector length, a number of waveguide-detectors were fabricated with different lengths. Initially a mask set was used with the detector length ranging from 40 to 600 µm. As it turned out that this range of values was not suitable for accurate determination of the detector absorption, a second mask set was designed with the detector length ranging from 10 to 200 µm. Figure 4.1 shows an optical microscope image of the integrated detectors fabricated with the second mask set. The detector mesas were extended with a relatively large probing pad, such that no interconnect metallization is required. Absorbing mesas were put before the detectors in order to avoid that any light, scattered from the input waveguide can be absorbed underneath the probing pad and thereby modify the effective length of the detector.

A number of straight reference waveguides without detectors has been included to estimate the losses of the input waveguides.

4.2 Fabrication

A number of wafers has been grown by MOVPE with a variable thickness of the absorption layer, in order to be able to verify the absorption resonances predicted in the previous chapter. The layer structure is summarized in table 4.1. The layer structure was grown on an n⁺-
**Figure 4.1** Optical microscope image of the waveguide integrated detectors used for determination of the required detector length.

<table>
<thead>
<tr>
<th>description</th>
<th>composition</th>
<th>thickness (nm)</th>
<th>doping (cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>substrate</td>
<td>InP</td>
<td>1500</td>
<td>(n = 1 \sim 5 \cdot 10^{18})</td>
</tr>
<tr>
<td>buffer</td>
<td>InP</td>
<td>600</td>
<td>undoped</td>
</tr>
<tr>
<td>waveguide core</td>
<td>InGaAsP(1.3)</td>
<td>300</td>
<td>undoped</td>
</tr>
<tr>
<td>waveguide cladding</td>
<td>InP</td>
<td>180,240,270,300,360</td>
<td>undoped</td>
</tr>
<tr>
<td>absorption</td>
<td>InGaAs(1.67)</td>
<td>300</td>
<td>undoped</td>
</tr>
<tr>
<td>pn-junction</td>
<td>InP</td>
<td>100</td>
<td>undoped</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>(p = 2 \cdot 10^{17})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>400</td>
<td>(p = 5 \cdot 10^{17})</td>
</tr>
<tr>
<td>p-contact</td>
<td>InGaAs(1.67)</td>
<td>100</td>
<td>(p = 5 \cdot 10^{18})</td>
</tr>
<tr>
<td>protection</td>
<td>InP</td>
<td>50</td>
<td>undoped</td>
</tr>
</tbody>
</table>

**Table 4.1** Layer structure that has been used for realization of the integrated waveguide detector.

substrate to facilitate the processing of the detector. The doping of the pn-junction layer has been graded to minimize back-diffusion of Zn into the absorption layer. The layer structure
with a 270 nm absorption layer was processed using the first mask set described above.

The integrated detectors have been processed as follows (see figure 4.2). After MOVPE growth the InP protection layer was selectively removed and an SiO\textsubscript{2} etch-mask was deposited to serve as a mask for etching the detectors. The first photolithographic step defined the detector mesa. All lithographic steps were performed using a Canon FPA143 1 to 4 reduction projection aligner. The SiO\textsubscript{2} layer was etched in a 10% HF-solution. A small amount of TRINTON has been added to reduce the surface tension of the solution. The p-contact, pn-junction and absorption layer were etched using the selective etchants described in section 2.3.2 and the SiO\textsubscript{2} mask was subsequently removed in an HF-solution.

A new SiO\textsubscript{2} layer was deposited onto the whole sample. This layer served both as an etching mask for the patterning of the waveguides and as passivation of the detectors. The waveguide pattern was defined into the SiO\textsubscript{2} layer by CHF\textsubscript{3} reactive ion etching. A 0.2 \( \mu \text{m} \) deep waveguide ridge was etched by CH\textsubscript{4}-He reactive ion etching [37]. Windows were etched
into the SiO₂ layer to access the p-contact of the detector. The p-contact metallization (Ti/Pt/Au) was deposited using e-beam evaporation and patterned by means of lift-off, using AZ-5214 image reversal resist in the negative mode. To create the n-contact, the same metallization was evaporated on the back of the wafer. Finally, the contacts were annealed in an RTP for 30 s at 375° to reduce the contact resistance. Figure 4.1 shows a microscope image of the final device, displaying three 20 μm and one 10 μm detectors.

4.3 Measurement setup

For characterization of the integrated waveguide detector, light was end-fire coupled into the waveguides as depicted in figure 4.3. The light source is a Fabry-Perot laser* with low coherence length. Camera 1 is used to monitor the spot reflected at the front facet of the chip. Occasionally a lensed fiber (lens radius = 10 μm) was used to launch light into the waveguides.

The light emanating from the reference waveguides was imaged onto an infrared camera or onto a Ge-diode by inserting the lenses L3 and L4 and the pinhole into the optical path. The photocurrent of the detector was measured using a standard (Karl Süss) micro-manipulator and fed into a Keithly transimpedance amplifier. Lock-in detection was used to achieve maximum sensitivity and to eliminate the dark current of the detector.

* Kindly provided by Philips Optoelectronics Center (POC)
Figure 4.4 Photocurrent of the integrated waveguide detector (D_{abs} = 0.27 \mu m versus the current of a Ge reference diode. The external efficiency of this integrated detector is 23% at TE polarization.

4.4 Measurement results

Figure 4.4 shows the photocurrent at zero bias for an 80 \mu m long detector versus the incident power. No saturation of the photocurrent can be observed within the measurement range (e.g. up to -10 dBm power into the detector). The external quantum efficiency is 23% for this diode.

The internal quantum efficiency can be estimated from the external efficiency by accounting for coupling losses to the waveguide and propagation losses in the waveguide. The coupling loss is due to mode mismatch and reflection. A mode mismatch loss of 4 dB has been estimated by a two-dimensional overlap integral between the focussed spot and the waveguide eigenmode. The focussed spot (out of the lensed fiber) was approximated as Gaussian beam with a diameter of 4 \mu m. The 2-D waveguide eigenmode was calculated using a scalar Finite Element Method mode solver. A reflection loss of 1.8 dB (at TE polarization) has been calculated using the approximation given by Buus [68]. The input waveguide loss was estimated to be 0.8 dB (= 3 dB/cm average waveguide loss \times 0.28 cm input waveguide length).

Using these approximations an internal efficiency of 105% is obtained. Taking into account the uncertainty of the loss estimation, we believe the actual internal efficiency is between 90 and 100%.

The wavelength dependence of the integrated detector was investigated by using an HP 8168A tunable laser as the light source. When tuning the wavelength from 1500 to 1560 nm, the variation of the external efficiency was less than 10% for a 40 \mu m long detector.

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1 This software has been developed by the ETH-Zürich.
Figure 4.5  Measured external detector efficiency for an absorption layer thickness of 0.24 $\mu$m at TM polarization. The solid line is a simple $\eta_{max}(1 - \exp(-\alpha L))$ curve fit. The dashed line is based on multimode calculations.

Figure 4.5 shows the external detector efficiency versus detector length for an absorption layer thickness of 0.24 $\mu$m. It appears that for short detectors the efficiency does not accurately satisfy a simple $\eta_{max}(1 - \exp(-\alpha L))$ curve fit. Alternatively these data were fitted with the more rigorous multimode analysis. The maximum efficiency $\eta_{max}$ and the absorption coefficient of the absorption layer were used as a fitting parameter. Both models provide a similar accurate fit to the measured data. The 'average' detector absorption as a function of the absorption layer thickness is displayed in figure 4.6. To calculate the average absorption the length at which the efficiency $\eta(L) = 0.9\eta_{max}$ has been chosen as a reference. The theoretical values have been calculated for the actual measured layer thicknesses. The occurrence of an absorption resonance around 0.25 $\mu$m can be clearly observed, in agreement with theoretical calculations. However, the absolute magnitude of the absorption resonance is lower than predicted. This deviation is most significant for the detectors with a 0.24 $\mu$m thick absorption layer and not yet clearly understood. The relatively high spread in the waveguide losses of this particular sample might cause this deviation.

The experiments presented in this chapter demonstrate that high efficiency evanescently coupled waveguide detectors can be realized with relatively short detector lengths ($< 100$ $\mu$m) and low capacitance. The coupling efficiency shows negligible wavelength and only weak polarization dependence. The latter may be compensated by save design of the detector length.
Figure 4.6  Measured (solid lines) and calculated (dashed lines: BPM) absorption of the integrated waveguide detector as a function of the absorption layer thickness.
4. Waveguide detector experiments
Chapter 5

Demultiplexer design principles

This chapter describes the design principles of a number of different types of phased-array demultiplexers. After a brief review of integrated demultiplexers some specific design aspects of the phasar demultiplexer are highlighted. Non-birefringent waveguides are analyzed in order to achieve broadband polarization-independent operation. A spectrally flattened version of the phasar demultiplexer, by employing multimode output waveguides, is also presented. Finally, a novel generalized MMI-MZI demultiplexer is proposed.

5.1 Introduction

Monolithic wavelength demultiplexers have been realized in the last decade, employing different demultiplexing concepts [8]. Passive realizations are based on wavelength-selective coupling, filtering or angular dispersion. The major drawback of demultiplexers based on selective coupling (such as MZI (Mach-Zehnder Interferometer) based devices [69] and meander couplers [70]) is that only two channels can be demultiplexed in one stage* and hence several have to be cascaded in order to demultiplex more channels, thus increasing device dimensions and insertion loss. The same argument is true for demultiplexers based on integrated filters.

Integrated demultiplexers employing the dispersive and focusing properties of curved reflection gratings [71, 72], have demonstrated precise demultiplexing of a high number of closely-spaced wavelength channels and have also been integrated with photodetector arrays [73, 74]. However, these devices require advanced processing technology such as high resolution lithography and a critical vertical mirror etching step. The performance obtained with those devices is still far away from the theoretical limits.

Therefore we have chosen to use demultiplexers based on the focusing and dispersive properties of an array of curved waveguides. This phased-array (PHASAR) demultiplexer was proposed in 1988 by Smit [10] and was first realized in aluminum oxide waveguides

*Note that in section 5.5 a novel generalized N×N MMI-MZI wavelength demultiplexer is presented!
5. Demultiplexer design principles

[75]. The major advantage of phased-array demultiplexers is that they can be fabricated with relatively simple process technology. The demultiplexer may even be processed simultaneously with other waveguide circuitry (which usually has to be fabricated anyway), thus requiring no additional processing steps. Experimental results appear to be close to the theoretical limits. These unique properties of phased-array demultiplexers have not remained unnoticed by other laboratories. In the last few years the number of papers on phasar demultiplexers has increased significantly [76, 77, 78, 79, 80, 81, 82, 83].

5.2 Operation principle

This section briefly summarizes the operation principle of the phased-array demultiplexer. Figure 5.1 shows a schematic representation of a phased-array demultiplexer. The device consists of two slab waveguide star couplers, connected by a dispersive waveguide array. The operation principle is as follows: Light propagating in the input waveguide will be coupled into the array via the first star coupler. The array has been designed such that (for the central wavelength of the demultiplexer) the optical path length difference between adjacent array arms equals an integer multiple of the central wavelength of the demultiplexer. As a consequence, the field distribution at the input aperture will be reproduced at the output aperture and at this wavelength the light will be focussed in the center of the image plane. If the input wavelength is detuned from this central wavelength the wave front at the output aperture will be tilted due to the linear phase transfer of the array. Consequently the focal point in the image plane will be shifted away from the center. Putting the output waveguides at proper positions in the image plane allows separation of the desired wavelength channels. This wavelength dependent shift is calculated as follows. Using the parameters defined in figure 5.1b, the wave front tilting angle $d\Theta$ due to a phase difference $d\Phi$ between adjacent array waveguides is expressed as

$$d\Theta = \arcsin \left( \frac{d\Phi / \beta_f}{d} \right) \approx \frac{d\Phi / \beta_f}{d}$$  \hspace{1cm} (5.1)

with $\beta_f$ the propagation constant in the slab waveguide and

$$d\Phi = d\beta_g \Delta l = \beta_g (dN_{eff}/N_{eff} - d\lambda/\lambda) \Delta l$$  \hspace{1cm} (5.2)

in which $\beta_g$ and $N_{eff}$ are the propagation constant and effective index of the waveguide respectively and $\Delta l$ the path length difference between adjacent array arms. Combining these equations gives

$$\frac{d\Theta}{d\lambda} = -\frac{rm'}{N_{eff}d}$$ \hspace{1cm} (5.3)

with $r = \beta_g/\beta_f \approx 1$ and $m'$ the order of the demultiplexer defined as

$$m' = \frac{\Delta l}{\lambda/N_{eff}} \left( 1 - \frac{\lambda}{N_{eff}} \frac{dN_{eff}}{d\lambda} \right)$$  \hspace{1cm} (5.4)
Figure 5.1  Schematic representation of a phased-array demultiplexer (a), and a magnification of the output focusing coupler (b).
The right-hand factor of this equation accounts for material and waveguide dispersion. Contrary to the case with glass waveguides, material dispersion cannot be neglected for InP-based waveguides as \((\lambda/N_{eff})(d\lambda/dN_{eff}) \approx 0.1\). Using the wavelength measured in the material \(\lambda_g = \lambda/N_{eff}\) with

\[
d\lambda_g = \frac{d\lambda}{N_{eff}} \left(1 - \frac{1}{N_{eff}} \frac{dN_{eff}}{d\lambda}\right)
\]  

(5.5)

the previous expression can be simplified to

\[
\frac{d\Theta}{d\lambda_g} = -\frac{rm}{d} ; \quad m = \frac{\Delta l}{\lambda_g}
\]  

(5.6)

Finally, with \(dy = f d\Theta\) the dispersive displacement \(dy/d\lambda_g\) of the spot in the image plane is easily determined to be:

\[
\frac{dy}{d\lambda_g} = -\frac{rmf}{d}
\]  

(5.7)

with \(f\) the focal length of the demultiplexer.

### 5.3 Design aspects

In order to arrive at an optimum demultiplexer design, different design aspects of the device have to be analyzed. These include waveguide geometry, array geometry and size, insertion loss, crosstalk and polarization dependence. An excellent discussion on those aspects is given by Smit [84]. The phasar demultiplexers presented in this chapter are to a great extent based on the design strategy he proposed and therefore this will not be repeated extensively here. Only the points that need more attention are discussed in this section.

#### 5.3.1 Waveguide geometry

The waveguide structure should have low propagation losses, allow for small bending radii and efficient integration with photodetectors. Figure 5.2 shows the crosssection of a 2 \(\mu\m\) wide ridge waveguide with the potential to meet the necessary requirements. With similar double-hetero ridge waveguides, losses below 1 dB/cm have been realized with a lateral refractive index contrast as high as 0.03 [38]. As demonstrated in the previous chapter, the relatively thin waveguide upper cladding layer thickness of 0.3 \(\mu\m\) allows for efficient integration with photodetectors.

The high sensitivity of the optical path length of the array waveguides to fabrication tolerances, demands that the device dimensions should be minimized as much as possible. In addition, smaller device size will lead to reduced device costs. These dimensions can only be reduced by applying low-loss waveguide bends with a small radius of curvature. The radiation loss of the waveguide of figure 5.2 has been calculated as a function of the etch depth and radius (see figure 5.3), employing the conformal transformation technique proposed...
Figure 5.2 Crosssection of the waveguide geometry that has been used for realization of the phased-array demultiplexer.

Figure 5.3 Calculated radiation loss of the curved ridge waveguide versus etch depth for a radius of 500 μm.

by Harris and Heiblum [85] to the lateral effective index profile. The propagation constant was calculated by applying the Transfer Matrix Method to a staircase approximation of the transformed refractive index profile [86]. An etch depth of 0.35 μm is sufficient to obtain low losses for the fundamental modes of both polarizations using a radius of curvature of 500 μm. Although the waveguides will be bimodal for this etch depth, higher order modes will radiate
out of the bend. Moreover, the amount of power coupled into the first order mode can be limited by proper symmetrical excitation at the input. Therefore this waveguide will almost behave as if it is monomode.

One disadvantage of this structure, however, is its polarization dependence. The effective index index difference $N_{TE} - N_{TM}$ between both polarizations is 0.01, which gives a TE-TM shift of the demultiplexer of 4 nm at 1.55 $\mu$m wavelength. This problem will be discussed in more detail in section 5.3.4 and 5.3.5.

### 5.3.2 Array geometry

From equation 5.7 it can be seen that the dispersion of the array is determined by the path length difference between adjacent array arms. The performance of the array is to a large extent independent on the actual shape of this array arm. In this thesis a geometry is used (see figure 5.4) which contains a minimum number of waveguide junctions. It consists of two straight waveguides smoothly connected to a curved waveguide. They form a non-concentric set of array arms, each of which is uniquely defined by its starting angle $\alpha_i$, the straight section length $S_i$ (for ease of calculation including the focal length $f$) and radius $R_i$ according to:

\[
S_i = \frac{1}{2} \left( l_i - \frac{L \alpha_i}{\sin \alpha_i} \right) / \left( 1 - \frac{\alpha_i \cos \alpha_i}{\sin \alpha_i} \right) \quad (5.8)
\]

\[
R_i = \frac{1}{2} L - \frac{S_i \cos \alpha_i}{\sin \alpha_i} \quad (5.9)
\]

\[
\alpha_i = \alpha_1 + (i - 1) \Delta \alpha \quad ; \quad \Delta \alpha = f/d \quad (5.10)
\]
with \( l_i \) the total path length from the transmitter to the receiver waveguide

\[
l_i = l_1 + (i - 1)\Delta l
\]

and \( L \) the distance between the focal points of the array, determined by choosing \( S_r \) and \( R_r \) at an arbitrary reference angle \( \alpha_r \)

\[
L = 2(S_r \cos \alpha_r + R_r \sin \alpha_r)
\]

This leaves three degrees of freedom which may be used to optimize the design. In order to reduce the dependence of the array transfer on bending effects, a normalized design strategy can be developed by imposing \( dR/d\alpha \) and \( d^2R/d\alpha^2 \) to be zero at the reference angle \( \alpha_r \). These constraints lead to respectively

\[
S_r = \frac{1/2 \delta y}{\tan \alpha_r}
\]

by imposing \( dR/d\alpha = 0 \) and

\[
R_r = \frac{1/2 \delta y}{\left( 1 + \frac{1}{\sin^2 \alpha_r} \right)}
\]

by requiring \( d^2R/d\alpha^2 = 0 \). However this strategy leads to relatively large device dimensions. A 4-channel demultiplexer with 2 nm wavelength spacing would measure \( 7.8 \times 3.4 \text{ mm}^2 \) (excluding input and output branches). Another empirical normalization condition [84] with

\[
R_r = \frac{1/2 \delta y}{\sin^2 \alpha_r}
\]

reduces device dimensions already to just \( 3.7 \times 2.2 \text{ mm}^2 \), with still a reasonably flat \( R(\alpha) \)-curve (figure 5.5a). As we wish to obtain small device dimensions, we dropped the condition of a flat \( R(\alpha) \)-curve and slightly adapted the design strategy, by requiring \( dR/d\alpha \) to be zero at \( \alpha_r \), but in addition imposing as a second requirement

\[
R_r = R_{min}
\]

with \( R_{min} \) the minimum allowed bending radius. Figure 5.5b shows the bending radius and the straight section length as a function of \( \alpha \) using \( R_{min} = 500 \mu \text{m} \) at \( \alpha_r = 75^\circ \). Using this approach, device dimensions of the critical part of the device (where the interference occurs) are just \( 1.2 \times 1.4 \text{ mm}^2 \). Due to the variation of the radius of curvature, corrections have to be made to account for the radius-dependent propagation constant in the bend.

### 5.3.3 Corrections for bending effects

If small bending radii are applied, the optical path length will change due to the radius dependent propagation constant in the curved portion of the waveguide and the physical path
Figure 5.5  Array arm dimensions as a function of the array arm angle $\alpha$ for (a) a flat $R(\alpha)$-curve, or (b) minimum device size. $R =$ radius, $S =$ straight section length, $h =$ array arm height, and $f =$ focal length.
5.3 Design aspects

Figure 5.6  Strategy to correct for the radius dependent propagation constant in the curved waveguide.

length should be adjusted accordingly. Using the present array geometry, the most straightforward solution for small corrections is to keep the position and size of the straight waveguides fixed and adjust the radius of the bend (figure 5.6). This correction can be calculated as follows: The phase transfer $\Phi$ of the original bend with radius $R$ is as though it were caused by a virtual waveguide bend of radius $R' = R + \Delta R_{ph}$ such that:

$$\Phi = 2\alpha \beta_\phi(R) = 2\alpha R' \beta_y$$

(5.17)

with $\beta_\phi$ the angular propagation constant in the curved waveguide. This gives:

$$\Delta R_{ph} = \frac{\beta_\phi(R)}{\beta_y} - R$$

(5.18)

The apparent increase of the radius should be compensated by decreasing the radius by $\Delta R_{ph}$, such that the actual radius $R''$ becomes

$$R'' = R - \Delta R_{ph}$$

(5.19)

The angular propagation constant in the bend $\beta_\phi$ has been calculated as outlined in section 5.3.1. The calculated values for $\Delta R_{ph}$ are plotted in figure 5.7. Although the absolute corrections seem to be very small, it should be realized that an offset of just 0.1 $\mu$m for a 180° bend corresponds to a phase correction as high as 240°. The offset for optimum phase transfer is approximately half the offset required for maximum coupling efficiency between the straight and curved waveguide [87]. As long as this offset is not too large, the best strategy is to choose
Figure 5.7  Correction of the radius of curvature for optimum phase transfer (ΔR_{ph}) and optimum coupling efficiency (ΔR_{co}).

Figure 5.8  Power coupled into the (TE) fundamental and first order lateral waveguide mode as a function of the offset between straight and curved waveguide (R = 500 μm).
the offset for optimum phase transfer and accept a small penalty for the coupling efficiency. In this case it gives a penalty of only 0.03 dB per junction at $R = 500 \mu m$.

A more serious problem is potential mode conversion at the waveguide junctions. Figure 5.8 shows the amount of power coupled into the straight waveguide TE\textsubscript{01} higher order mode when excited by the TE\textsubscript{00} fundamental mode of a curved waveguide with $R = 500 \mu m$. Choosing the optimum offset for coherent phase transfer, -20 dB power will couple into the TE\textsubscript{01} mode. Since the phase transfer of the array has only been optimized for the TE\textsubscript{00} mode, the power carried by the TE\textsubscript{01} mode will most likely be incoherent at the output of the array. This power will be randomly radiated into the effective numerical aperture of the waveguide. Using a Gaussian beam approximation to calculate the array waveguide far field, it can be shown that on the average a fraction of $2(w_e/f)(w_e/\lambda_f)$ of this light will couple into each receiver waveguide (with $w_e$ the effective mode width and $\lambda_f$ the wavelength in the slab waveguide). With $w_e/f \approx 0.01$ and $w_e/\lambda_f \approx 5$ this will result in a crosstalk level of about -30 dB. Therefore, with this correction procedure, a radius of curvature of about 500 $\mu m$ seems to be the lower limit, if bimodal waveguides are used.

5.3.4 Polarization dependence

As the state of polarization at the input of the demultiplexer will be undefined in general, the demultiplexer should ideally exhibit negligible polarization dependence. The propagation constant of the double-hetero ridge waveguide presented in section 5.3.1 is different for TE and TM polarized light. As a consequence the spectral response for both polarizations will be shifted with respect to each other. This shift can be calculated by comparing the wavelengths in the waveguide. If $\lambda'_{TE}$ and $\lambda'_{TM}$ are the vacuum wavelengths that will be coupled into the same output waveguide for respectively TE and TM polarized light, their internal wavelengths must be identical:

$$\frac{\lambda'_{TE}}{N_{TE}(\lambda'_{TE})} = \frac{\lambda'_{TM}}{N_{TM}(\lambda'_{TM})} \quad (5.20)$$

$$N_{TM}(\lambda'_{TM}) = N_{TM}(\lambda'_{TE}) - \Delta \lambda'_{pol} \left( \frac{dN_{TM}}{d\lambda} \right)_{\lambda'_{TE}} \quad (5.21)$$

$$\Delta \lambda'_{pol} = \lambda'_{TE} - \lambda'_{TM} \quad (5.22)$$

with $N_{TE}$ and $N_{TM}$ the effective index for TE and TM polarization respectively. After some manipulations we end up with:

$$\Delta \lambda'_{pol} = \lambda'_{TE} \left( 1 - \frac{N_{TM}(\lambda'_{TE})}{N_{TE}(\lambda'_{TE})} \right) / \left( 1 - \frac{\lambda'_{TE}}{N_{TE}(\lambda'_{TE})} \left( \frac{dN_{TM}}{d\lambda} \right)_{\lambda'_{TE}} \right) \quad (5.23)$$

For our DH InP/InGaAsP(1.3) ridge waveguide we find a TE/TM-shift of 4.1 nm. This value is of the same order of magnitude (or even higher) as the typical channel spacing in a DWDM (Dense Wavelength Division Multiplexing) system and should be reduced by at least a factor of
Figure 5.9 TE/TM shift of a DH-InP/InGaAsP slab waveguide (V=3) as a function of the As-fraction of the quaternary layer.

Often if negligible polarization sensitivity is to be produced. Different approaches exist to reduce this TE/TM-shift.

As the waveguide birefringence is due to the different field-continuity conditions at the interfaces for the two polarizations, it can be minimized by reducing the refractive index contrast between the waveguide core and the cladding layers. Figure 5.9 shows the polarization dispersion of a DH slab waveguide as a function of the As-fraction of the quaternary layer. The thickness of this layer has been chosen such that the normalized film parameter $V = 3$ and the InP upper cladding has been assumed to extend to infinity. From this figure it is concluded that it is possible to reduce the TE/TM shift below 0.20 nm by using a quaternary layer with an As-fraction below 0.17. However the following remarks need to be added:

- The values presented in this graph are slightly optimistic as they are calculated for a slab waveguide. For a ridge waveguide the shift will be slightly higher.

- Due to the strongly non-linear dependence of the composition of the InGaAsP layer on the AsH$_3$ partial pressure in a MOCVD reactor, it is very hard to control the composition of quaternary layers with a low As-fraction accurately.

- The small refractive index contrast limits the minimum usable radius of curvature and hence increases device dimensions.

- These low values can only be achieved by using a thick InP upper cladding. This will complicate integration with evanescently coupled photodetectors.
Another way to make the demultiplexer polarization independent [75] is to design it such that the TE-TM shift equals the demultiplexer periodicity, also known as free spectral range (FSR), by fixing the array order at:

$$m' = \frac{\lambda}{\Delta \lambda'_{\text{pol}}}$$  \hspace{1cm} (5.24)

The major disadvantage of this solution is that wavelength span of the demultiplexer has to be smaller than the TE/TM shift in order to prevent interference between different diffraction orders. This limits the number of available channels of the demultiplexer. Fixing the array order this way also determines the diffraction loss for the outermost output waveguide as explained below. Consider a demultiplexer with \( n_{\text{ch}} \) channels with a channel spacing \( \Delta \lambda'_{\text{ch}} \). This gives a maximum wavelength deviation \( \Delta \lambda'_{\text{max}} = 0.5(n_{\text{ch}} - 1)\Delta \lambda'_{\text{ch}} \) from the central wavelength (for which \( \Theta = 0 \)). The diffraction angle \( \Theta_{\text{max}} \) of this outermost channel follows from expression 5.3 upon substitution of equation 5.24:

$$\Theta_{\text{max}} = \frac{rm'\Delta \lambda'_{\text{max}}}{N_{\text{eff}}d} = \frac{r\lambda}{N_{\text{eff}}d} \frac{\Delta \lambda'_{\text{max}}}{\Delta \lambda'_{\text{pol}}}$$  \hspace{1cm} (5.25)

Using the Gaussian-beam approximation the corresponding far field intensity \( I(\Theta_{\text{max}}) \) is given by:

$$I(\Theta_{\text{max}}) = I_0 \exp \left( -2\left(\frac{\Theta_{\text{max}}}{\Theta_0}\right)^2 \right) \hspace{1cm} \Theta_0 = \frac{\lambda_f}{w_e\sqrt{2\pi}}$$  \hspace{1cm} (5.26)

with \( w_e \) the array waveguide mode effective width and \( \lambda_f \) the wavelength within the slab. Combining the previous two equations gives:

$$I(\Theta_{\text{max}}) = I_0 \exp \left( -\frac{4\pi}{r} \left( \frac{w_e}{d} \right)^2 \left( \frac{\Delta \lambda'_{\text{max}}}{\Delta \lambda'_{\text{pol}}} \right)^2 \right)$$  \hspace{1cm} (5.27)

Substituting expression 6.22b of reference [84] for the diffraction loss \( L_0 \) (in dB) of the (virtual) central wavelength channel:

$$L_0 \simeq 17 \exp \left( -4\pi w_e^2/d^2 \right)$$  \hspace{1cm} (5.28)

and \( r \approx 1 \) the outer channel diffraction loss \( L(\Theta_{\text{max}}) \) can be expressed as:

$$L(\Theta_{\text{max}}) = -10 \log \left( \frac{I(\Theta_{\text{max}})}{I_0} \right) = -10 \left( \frac{\Delta \lambda'_{\text{max}}}{\Delta \lambda'_{\text{pol}}} \right)^2 \log \left( \frac{L_0}{17} \right) \text{ dB}$$  \hspace{1cm} (5.29)

For example, a 4-channel demultiplexer with \( \Delta \lambda'_{\text{ch}} = 1 \) nm, a TE/TM-shift of 4.1 nm and \( w_e/d \approx 1/2 \) will have an output power uniformity of 1.8 dB.

Another solution of the polarization problem – one that doesn’t limit the FSR of the demultiplexer – is to employ waveguides with a different geometry, such that the waveguides have no birefringence. The design of these waveguides will be discussed in the next section.
5.3.5 Polarization independent waveguides

Figure 5.10 shows two possible ways to realize waveguides which have equal propagation constants for both polarizations. In this section the possible application of these waveguides for polarization independent demultiplexers is discussed.

Square waveguides

Clearly the most obvious way to achieve zero birefringence (in planar optical circuits) is to use square waveguides embedded in a homogeneous medium of constant refractive index. For application in phased-array demultiplexers these waveguides must be configurable in compact monomode bends. Figure 5.11 shows the calculated radiation loss of the TE_{00} fundamental mode for three different compositions of the quaternary layer. The width of the waveguide core was taken to be 2 μm, which we consider to be more or less the minimum waveguide dimension that can be realized reproducible using standard photolithographic techniques. Losses were calculated in a similar way as described in section 5.3.1. The effective index of the outermost regions was taken to be the cladding refractive index. The figure shows that to limit the radiation loss the As-fraction of the quaternary layer should not be to low. On the other hand, to high a refractive index contrast will cause the waveguide to become multimode. For example a 2 μm square waveguide with a radius of curvature of 500 μm employing a Q1.05 waveguide core has a radiation loss of only 0.2 and 0.5 dB/90° for the TE_{10} and TE_{01} mode respectively. Due too its multimode nature such a waveguide is not ideally suited for application in a phased-array demultiplexer.

A good compromise appears to be to employ Q1.00 material for the waveguide core, allowing the realization of low bending losses for the TE (and TM) fundamental mode, while higher order modes radiate effectively out of the curved waveguide. The calculations presented
5.3 Design aspects

Figure 5.11 Radiation loss of the $TE_{00}$ fundamental mode of a square waveguide with a 2 $\mu$m waveguide core, for different compositions of the quaternary layer.

here, however, demonstrate that these square waveguides require very accurate control of the composition of the quaternary layer.

Raised strip waveguides

Rectangular raised strip waveguides can also have zero birefringence. The basic principle is to compensate the polarization dispersion due to the refractive index contrast in the transversal direction by applying sufficient index contrast in the lateral direction. As was demonstrated by Chiang [88], the waveguide width needed to obtain polarization independence is:

$$W = d_Q \left( \frac{4\pi (\Delta_1 \Delta_2)^{1/2}}{d_Q^2 V' (\beta_E^2 - \beta_M^2)} \right)^{1/3} = \lambda \left( \frac{(\Delta_1 \Delta_2)^{1/2}}{\pi (n_Q^2 - n_{ln,P}^2)^{1/2} (N_{TE}^2 - N_{TM}^2)} \right)^{1/3}$$ (5.30)

with

$$\Delta_1 = \frac{n_Q^2 - n_{ln,P}^2}{2n_Q^2} ; \quad \Delta_2 = \frac{n_Q^2 - 1}{2n_Q^2} ; \quad V' = \frac{\pi d_Q}{\lambda} (n_Q^2 - n_{ln,P}^2)^{1/2}$$ (5.31)

with $N_{TE}$ and $N_{TM}$ the vertical effective refractive index of the middle region for TE and TM polarization respectively.

Another advantage of these raised strip waveguides is that they can be monomode at a relatively wide waveguide width and still allow for realization of compact waveguide devices due to the high lateral refractive index contrast. The cut-off mechanism is due to radiation
into the substrate. This may be examined by using the propagation constant calculated using Marcatili's approximation [89]:

$$\beta^2 = k_0^2 n_Q^2 - k_z^2 = k_0^2 N_{e,y}^2 - k_z^2$$  \(5.32\)

with \(k_0\) the wavenumber in vacuum, \(N_{e,y}\) the vertical effective index of the central region, and \(k_z\) and \(k_y\) the lateral and transverse wavenumber respectively. Because of the high lateral refractive index contrast, the lateral field distribution can be approximated as a cosine function. Thus:

$$k_z = \frac{(m + 1)\pi}{W_m}$$  \(5.33\)

with \(m\) the lateral mode number. The cut-off condition occurs if the effective index becomes lower than the substrate index \(n_{1nP}\) [90]. Using the approximations above, the cut-off width \(W_m\) of the \(m\)-th lateral mode becomes:

$$W_m = 1/2(m + 1)\lambda(N_{e,y}^2 - n_{1nP}^2)^{-1/2}$$  \(5.34\)

Figure 5.12 shows the cut-off conditions together with the zero birefringence condition, employing a Q0.97 waveguide layer. For waveguide thicknesses ranging from 1.5 to 2.6 \(\mu m\) monomode polarization independent waveguides can be realized by a proper choice of the waveguide width. A good strategy is to choose a waveguide thickness close to the maximum allowed value for monomode operation [90]. This minimizes the field intensity at the etched semiconductor/air interface and hence reduces scattering losses.
5.3 Design aspects

![Graph](image)

**Figure 5.13** Waveguide width dependence of the TE/TM-shift and the center wavelength $\lambda_c$ of a demultiplexer employing a 3.4 $\mu$m wide Q0.97 non-birefringent raised strip waveguide.

If these waveguides are applied in any practical device, they should be insensitive to fabrication tolerances. Therefore an assessment needs to be made of the sensitivity of the polarization dispersion to different parameters. Figure 5.13 shows the TE/TM-shift as a function of the deviation of the waveguide width from the design value of a 3.4 $\mu$m wide polarization independent Q0.97 raised strip waveguide. Assuming realistic width tolerances ($\pm 0.2 \mu m$) the TE-TM/shift should remain below 0.1 nm, which is quite an acceptable value, taking into account the channel spacings ($\Delta \lambda \geq 1 \text{ nm}$) used in WDM system experiments today.

It is also found that the sensitivity to width deviations increases rapidly with the refractive index contrast between the guiding layer and the substrate. E.g., when using a Q1.1 guiding layer this birefringence sensitivity $\Delta \lambda_{pol} / \Delta W$ is more than a factor 10 higher than for the Q0.97 composition. Use of Q1.1 material thus precludes the tolerant fabrication of polarization insensitive waveguides. Therefore, in order to realize this type of polarization independent waveguide successfully, quaternary material with a low As-fraction has to be applied. However, we also note here that use of a low-Q waveguide puts stringent demand on the composition control during epitaxial growth. Another potential problem of this waveguide is the loss occurring at the transition between the slab waveguide and the waveguide array.

It can be concluded that there are a number of options to realize demultiplexers with weak polarization dependence, with each of them having its own merits and drawbacks.
5.4 Wavelength flattened demultiplexer

The phasar demultiplexers presented so far have a relatively sharp spectral response curve. This necessitates accurate matching of the laser wavelength to the transmission maximum of the demultiplexer. In this section we propose a phasar demultiplexer with a flattened wavelength response, achieved by employing wide, multimode, output waveguides.

Figure 5.14 shows a schematic representation of the focussed spot in the image plane of the phasar demultiplexer. The shape of the spectral response curve is determined by the overlap of the field distribution in the image plane and the eigenmode(s) of the output waveguides. In phasar demultiplexers realized to-date, monomode in- and output waveguides were used with identical dimensions, giving a parabolic-like spectral response. The spectral throughput can be flattened by application of relatively wide multimode output waveguides, which is a common technique in bulk-optic demultiplexers [91].

Within a certain wavelength range, the focussed spot in the image plane will couple efficiently to the output waveguide. Although the power distribution between the output waveguide eigenmodes depends strongly on the relative position of the image, the total coupling efficiency will be close to 100% as long as the image is not too close to the edge of the output waveguide.

Due to the multimode excitation of the output waveguide, the demultiplexer outputs cannot be coupled efficiently to monomode output fibers. If they are coupled directly to photodetectors, however, all the guided power is detected independent of modal composition and the advantage of the flattened response can be fully exploited. The price that is paid for the flattened response
is an increase of the device size if the other parameters are kept constant.

5.5 Generalized MMI-MZI demultiplexer

A problem with phasar demultiplexers using deeply etched waveguides (such as the polarization independent raised strip waveguides proposed in section 5.3.5) is the relatively high loss occurring at the transition between the slab waveguide radiation coupler and the waveguide array. In this section a novel demultiplexer is proposed. In this device the radiation couplers are replaced by multimode interference (MMI) couplers, which avoids this problem. The device does not work exactly like a normal phasar demultiplexer, but rather like a generalized $N \times N$ Mach-Zehnder interferometer demultiplexer. Independently this concept was also developed by P.A. Besse of the ETH-Zürich [92].

Figure 5.15 shows a possible layout configuration of such a demultiplexer. It consist of two $N \times N$ multimode interference couplers (figure 5.16) connected by an array of $N$ waveguides. Unlike a phasar, demultiplexer the path length difference between adjacent waveguides is not constant, but follows a more complicated relation, as will be shown below. The operation principle of the device is as follows. Light is coupled into the first MMI coupler via one of the
input waveguides. This coupler acts like a 1 to N power splitter if the length \( L_{m_{mi}} \) is chosen to be [93]:

\[
L_{m_{mi}} = \frac{3L_\pi}{N} ; \quad L_\pi = \frac{\pi}{\beta_0 - \beta_1}
\]  

(5.35)

with \( L_\pi \) the beat-length between the fundamental and first order lateral mode in the MMI-section. After propagation through the array the light enters the second MMI-coupler, which acts as a recombiner . In this element the light constructively interferes into one of the output waveguides, provided that the proper phase distribution is present at the input. For example in the well-known case of a 2 × 2 coupler the input fields should have 90° phase difference to interfere constructively into one of the outputs. The phase at each input can be controlled by adjusting the path length of the corresponding array waveguide. The device will work as a demultiplexer if at each wavelength channel constructive interference occurs into a different output waveguide. It will be demonstrated below, for a 4-channel device, that specific length combinations exist which meet these requirements. The general proof that such a solution exist for the N-channel device, is given in the appendix of this chapter.

The phases \( \varphi_{q,j} \) at output \( q \) (see figure 5.16) due to light entered from input \( j \), for a 4 × 4 coupler, are presented in table 5.1. Due to reciprocity, traveling in the opposite direction, the light will constructively interfere into the second demultiplexer output \( j \) if the phase relations in column \( j \) of this table are satisfied (with a minus sign) at the input of this MMI-coupler. If, for each wavelength channel the phase relation of a different column can be satisfied, the device will work as a wavelength demultiplexer.

As the absolute phase is not important, we have calculated the required phase difference \( \Delta \varphi_{q,j} = -(\varphi_{q+1,j} - \varphi_{q,j}) \) between adjacent inputs of the second coupler. The results are presented in table 5.2. Assuming that for one wavelength (for example \( \lambda_1 \)) the desired phase distribution can be realized, the required phase distributions for the other wavelengths will also
Table 5.1 Phase relations for a $4 \times 4$ MMI-coupler.

<table>
<thead>
<tr>
<th></th>
<th>$j = 1$</th>
<th>$j = 2$</th>
<th>$j = 3$</th>
<th>$j = 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varphi_{1,j}$</td>
<td>$\pi$</td>
<td>$3\pi/4$</td>
<td>$-\pi/4$</td>
<td>$\pi$</td>
</tr>
<tr>
<td>$\varphi_{2,j}$</td>
<td>$3\pi/4$</td>
<td>$\pi$</td>
<td>$\pi$</td>
<td>$-\pi/4$</td>
</tr>
<tr>
<td>$\varphi_{3,j}$</td>
<td>$-\pi/4$</td>
<td>$\pi$</td>
<td>$\pi$</td>
<td>$3\pi/4$</td>
</tr>
<tr>
<td>$\varphi_{4,j}$</td>
<td>$\pi$</td>
<td>$-\pi/4$</td>
<td>$3\pi/4$</td>
<td>$\pi$</td>
</tr>
</tbody>
</table>

Table 5.2 The required phase difference $\Delta \varphi_{q,j}$ between adjacent inputs of the second $4 \times 4$ MMI coupler. The lower table shows how to reorganize the outputs to realize a wavelength demultiplexer.

<table>
<thead>
<tr>
<th></th>
<th>$j = 1$</th>
<th>$j = 2$</th>
<th>$j = 3$</th>
<th>$j = 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \varphi_{1,j}$</td>
<td>$\pi/4$</td>
<td>$-\pi/4$</td>
<td>$3\pi/4$</td>
<td>$-3\pi/4$</td>
</tr>
<tr>
<td>$\Delta \varphi_{2,j}$</td>
<td>$\pi$</td>
<td>$0$</td>
<td>$0$</td>
<td>$\pi$</td>
</tr>
<tr>
<td>$\Delta \varphi_{3,j}$</td>
<td>$3\pi/4$</td>
<td>$-3\pi/4$</td>
<td>$\pi/4$</td>
<td>$-\pi/4$</td>
</tr>
<tr>
<td>$\Delta \Phi_q$</td>
<td>$\lambda_1$</td>
<td>$\lambda_2$</td>
<td>$\lambda_4$</td>
<td>$\lambda_3$</td>
</tr>
</tbody>
</table>

be realized if the path length along the array $L_q$ satisfies:

$$L_{q+1} - L_q = \Delta L_q = \frac{\Delta \Phi_q}{\Delta \beta} ; \quad \Delta \Phi_q = -\frac{\pi}{2} q$$

(5.36)

with $\Delta \beta$ the propagation constant difference between adjacent wavelength channels:

$$\frac{\Delta \beta}{\beta} = \frac{\Delta N_{eff}}{N_{eff}} - \frac{\Delta \lambda}{\lambda}$$

(5.37)

Notice that this can be achieved for an equidistant wavelength spacing, which is the usual requirement in a WDM system. If the path lengths are designed according to these rules, the only thing that remains is to produce the proper phase distribution for $\lambda_1$ at the input of the second coupler. This can be done by minor corrections of the optical path length along
the array. It can be shown (see appendix) that these corrections only minimally influence the dispersive properties of the array.

The spectral response of a 4-channel MMI-MZI demultiplexer has been calculated using modal propagation analysis. Figure 5.17 shows the simulated spectral response of this demultiplexer. Excellent uniformity of the transmission intensity of the different channels is predicted with an insertion loss of just 1 dB. At the transmission maximum of the individual channels, a high crosstalk suppression can be achieved. However, for small wavelength variations around the transmission maximum, the crosstalk increases rapidly. Hence the laser source wavelength has to be matched accurately with the transmission maximum of the demultiplexer.

In the previous calculation it has been implicitly assumed that the path length of the array guides increases monotonously with $q$. Abandoning this condition, gives more possible combinations. For example the condition $\Delta \Phi_3 = -3\pi/2$ can be replaced by $\Delta \Phi_3 = \pi/2$. The advantage of this approach is that the phase changes, going from one wavelength to another, will remain within $2\pi$. This avoids the side-lobes that occur in figure 5.17. This design strategy is however not possible with the simple layout depicted in figure 5.15, as small angle crossings between the array waveguides would occur. Hence another layout will be required for this demultiplexer.

Comparing the generalized MMI-MZI demultiplexer with phased-array demultiplexers we anticipate the following advantages for the MMI-MZI approach:

- The MMI-MZI demultiplexer has inherently a better transmission uniformity of the individual channels, due to the uniform splitting ratio of MMI-couplers.
5.5 Generalized MMI-MZI demultiplexer

- Potentially MMI-MZI demultiplexers will have lower losses than phasar demultiplexers. Especially for deeply etched waveguides this advantage may be significant.

The following points will, however, be in favor of the phasar demultiplexer:

- MMI-MZI demultiplexers will be more sensitive to line width deviations, due to the quadratic dependence of the resonance length \( L_c \) on the MMI-section width. The radiation couplers applied in phasar demultiplexers are more tolerant to line width variations.

- MMI-MZI demultiplexers do require accurate alignment of the laser wavelength with respect to the transmission maximum of the demultiplexer. For phasar demultiplexers this requirement can be relaxed significantly (see section 5.4).

Appendix 5.A

The phase relations for the general N×N resonance were calculated by Besse et al. [93]. The phase \( \varphi_{q,j} \) at output q (see figure 5.16) due to light entered from input j is given by:

\[
\varphi_{q,j} = \varphi_0 + \frac{\pi}{4N}[(2N + 1 - q - j)(q + j - 1)] \quad \text{for } q+j \text{ odd}
\]
\[
\varphi_{q,j} = \varphi_0 + \frac{\pi}{4N}[(2N - q + j)(q - j)] \quad \text{for } q+j \text{ even}
\]

(5.38)

The required phase difference \( \Delta \varphi_{q,j} = -(\varphi_{q+1,j} - \varphi_{q,j}) \) between adjacent input channels of the second N×N MMI-coupler to get constructive interference in output j is given by:

\[
\Delta \varphi_{q,j} = -\pi + \frac{\pi}{4N}[(2N + 1 - q - j)(q + j - 1) - (2N - 1 - q + j)(q + 1 - j)]
\]
for q+j odd

\[
\Delta \varphi_{q,j} = \pi + \frac{\pi}{4N}[(2N - q + j)(q - j) - (2N - q - j)(q + j)]
\]
for q+j even

(5.39)

These expressions can be simplified to:

\[
\Delta \varphi_{q,j} = -\pi + \frac{\pi}{N}(j - 1)(1 - q/N) \quad \text{for } q+j \text{ odd}
\]
\[
\Delta \varphi_{q,j} = \pi - \frac{\pi}{N}j(1 - q/N) \quad \text{for } q+j \text{ even}
\]

(5.40)

Drawing these phases on the unit circle as a function of j, makes clear that they are equidistantly spaced with a difference \( \Delta \Phi_q = -2(1-q)\pi/N \) between adjacent points, traveling in clockwise direction (see for example figure 5.18 for q=7 and N=8). If the path length difference between adjacent array arms is defined as:

\[
\Delta L_q = \frac{\Delta \Phi_q}{\beta} = \frac{2q\pi}{N\beta}
\]

(5.41)
Figure 5.18  Required phase difference $\Delta \varphi_{q,j}$ between adjacent inputs of the second MMI coupler for $q=7$ and $N=8$.

and for an (arbitrary) reference wavelength $\lambda_1$ constructive interference occurs into output 1, the wavelength $\lambda_k = \lambda_1 + (k - 1)\Delta \lambda$ ($k = 1, N$) will recombine into output $2k - 1$ for $k = 1, N/2$ and into output $2(N - k + 1)$ for $k = N/2 + 1, N$. The proper phase relation for the reference wavelength can be produced by minor adjustments of the path length. Although these corrections seem to be in conflict with equation 5.41, it can be shown that they hardly influence the dispersion of the array. The maximum length correction $\Delta L_{max}$ will be:

$$\Delta L_{max} = \frac{1}{2} \frac{\lambda}{N_{eff}}$$  \hspace{1cm} (5.42)

This error in the path length will cause a maximum error in the dispersion $\Delta \Psi_{max}$ of the array:

$$\Delta \Psi_{max} = \Delta \beta \Delta L_{max} = \pi \frac{\Delta \lambda}{\lambda}$$  \hspace{1cm} (5.43)

Since $\Delta \lambda/\lambda \ll 1$ the maximum phase error $\Delta \Psi_{max} \ll 1$ and therefore will hardly affect the dispersion of the array.
Chapter 6

Demultiplexer experiments

This chapter describes the design parameters, fabrication and characterization of phased array demultiplexers on InP and their integration with photodetectors. Part of these experiments have been presented as postdeadline papers at the ECIO'93 [82] and the ECOC'93 [94] and published in IEEE Photonics Technology Letters [95]. The preliminary results obtained with the flattened response demultiplexer have been published in Electronics Letters [83].

6.1 Summary of experiments

The realization and performance of the following devices will be presented in this chapter:

- A 4-channel phased array demultiplexer on InP-substrate.

- A first prototype of a 4-channel demultiplexer integrated with photodetectors. The design of the demultiplexer is identical to the non-integrated demultiplexer. The waveguide detector integration technology presented in chapter 4 was applied for the realization of this device.

- An improved version of the demultiplexer integrated with photodetectors. This version has lower crosstalk than the first prototype described above, which was achieved through the use of absorbers between input and output waveguides.

- A 4-channel phasar demultiplexer with flattened wavelength response, obtained by employing multimode output waveguides (see section 5.4).

Fabrication and characterization

As the phasar demultiplexer is fabricated with a single waveguide fabrication process, the fabrication process of a demultiplexer integrated with photodetectors is identical to the fabrication
of the waveguide integrated photodetector* presented in chapter 4, and will therefore not be repeated here. The measurement setup for characterization of the integrated demultiplexer has also already been presented in chapter 4. The only difference is that the Fabry-Perot laser source has here been replaced by a HP 8168A tunable laser source, that can be tuned from 1480 to 1560 nm. The large coherence length of this laser requires an anti-reflection coating for demultiplexers not integrated with photodetectors, to avoid the occurrence of Fabry-Perot resonances.

6.2 Four-channel demultiplexer

Design

A four-channel demultiplexer with 2 nm channel spacing has been designed. The waveguide structure presented in figure 5.2 was chosen, as successful integration of this waveguide with photodetectors had already been demonstrated. We did not yet aim at polarization independent operation. Table 6.1 summarizes the design parameters for this demultiplexer.

At the input and output aperture the waveguides are closely spaced (1 µm gap) in order to limit the amount of power coupled into higher diffraction orders. The focal length was chosen to be 280 µm, allowing for 1 dB diffraction loss of the outermost receiver channels. This requirement fixes the array order at 88 for the center wavelength. To collect the light diffracted from the input waveguide, the array contains 46 arms with a path length difference of 41 µm between adjacent arms. The bending radius in the array varies from 500 to 720 µm. Corrections were made to account for the radius-dependent propagation constant in the curved waveguide using the procedure described in section 5.3.3.

Four input waveguides were used to allow for coarse tuning of the central wavelength. The spacing of the output (and input) waveguides was chosen to be 100 µm to allow for integration with photodetectors. The total device size is $2.3 \times 2.5$ mm² including input and output branches. Initially material dispersion was not taken into account in this design. The calculated values enclosed in brackets do include the effect of material dispersion.

Fabrication and characterization

The demultiplexer was realized using a single waveguide fabrication step as described in chapter 4. The waveguide facets were anti-reflection coated by evaporation of a single SiO₂-layer. The device was characterized with a HP 8168A tunable laser source by end-fire coupling into the input waveguides using a NA 0.65 microscope objective. The light emerging from the output waveguides was imaged onto a Ge photodiode.

* Apart from a few minor details, which are due to the fact that we used the same mask for the realization of the separate and the integrated demultiplexer.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of channels</td>
<td>4</td>
</tr>
<tr>
<td>channel spacing</td>
<td>2 (1.74) nm</td>
</tr>
<tr>
<td>central wavelength</td>
<td>1536 nm</td>
</tr>
<tr>
<td>TE-TM shift</td>
<td>4.8 (4.1) nm</td>
</tr>
<tr>
<td>free spectral range</td>
<td>17.5 (15.2) nm</td>
</tr>
<tr>
<td>maximum insertion loss</td>
<td>1 dB</td>
</tr>
<tr>
<td>crosstalk</td>
<td>$&lt;-30$ dB</td>
</tr>
<tr>
<td>$1/e^2$ far field half angle</td>
<td>$7^\circ$</td>
</tr>
<tr>
<td>array aperture</td>
<td>$27^\circ$</td>
</tr>
<tr>
<td>focal length</td>
<td>280 $\mu$m</td>
</tr>
<tr>
<td>array order $m'$</td>
<td>88 (101)</td>
</tr>
<tr>
<td>number of array waveguides</td>
<td>46</td>
</tr>
<tr>
<td>$\alpha_r$</td>
<td>$80^\circ$</td>
</tr>
<tr>
<td>$\alpha_{min}$</td>
<td>$80^\circ$</td>
</tr>
<tr>
<td>$\alpha_{max}$</td>
<td>$107^\circ$</td>
</tr>
<tr>
<td>minimum radius</td>
<td>500 $\mu$m</td>
</tr>
<tr>
<td>maximum radius</td>
<td>720 $\mu$m</td>
</tr>
<tr>
<td>total device size</td>
<td>$2.3 \times 2.5 \text{ mm}^2$</td>
</tr>
</tbody>
</table>

Table 6.1 Summary of the design parameters of the demultiplexer.

Results

The losses of reference waveguides were measured to be 1.3 and 2.0 dB/cm for TE and TM polarization, respectively, as determined from Fabry-Perot measurements performed before AR-coating of the sample. Figure 6.1 shows the spectral response for both polarizations. Measurements are calibrated against straight reference waveguide transmission losses. Table 6.2 summarizes the most important measurement results and compares them with theoretical calculations. These calculations take into account the effect of material dispersion. Assuming realistic fabrication tolerances, there is excellent agreement between calculations and experimental results. The excess loss is slightly higher than calculated, which may be due to radiation losses in the bends and some coupling losses at the in- and output aperture. These losses were not rigorously taken into account in the theoretical calculations. The experimental TE/TM shift is slightly higher than the value calculated, employing the effective index method. Scalar Finite Element Method (FEM) calculations predict a TE/TM shift of 4.7 nm, in excellent agreement with the experimental value of 4.8 nm. experiment. This might, however, be a coincidence, as deviation of waveguide dimensions from the design value and residual stress in the layers could
Figure 6.1 Spectral response of the phased-array demultiplexer for (a) TE and (b) TM polarization. Measurements are calibrated against the transmission loss of the straight reference waveguide.
Table 6.2 Comparison between theory and experiments of the 4-channel phasar demultiplexer.

explain part of the discrepancy.

For TE polarization the spectral response curves are asymmetric and have small side lobes, clearly above the background crosstalk level, on the long wavelength side. A possible explanation is that the focussed spot at the image plane is coupled into a curved waveguide, with an asymmetric mode profile. However the side lobes that occur are more than 10 dB higher than expected from theoretical calculations. Moreover this strong asymmetry is not observed in similar demultiplexers presented in the following sections. Therefore we believe the observed asymmetry is due to a fabrication imperfection in the waveguide array.

6.3 Demultiplexer integrated with detectors: first prototype

This section presents the experimental results of the first prototype phasar demultiplexer integrated with photodetectors. The demultiplexer design is that presented in the previous section. In fact, we even used the same waveguide mask for the lithography of the demultiplexer. The waveguide-integrated detector technology used was that discussed in section 4.2. The photodiode size was chosen conservatively to be 150×80 µm² for ease of fabrication and probing. For this device length the internal quantum efficiency is calculated to be greater than 90%. Light from the tunable laser source was end-fire coupled into the input waveguide using a NA 0.65 microscope objective. The photocurrent was measured at zero bias using a standard wafer prober.

Figure 6.2 displays the spectral response of this integrated demultiplexer. The excess loss of this demultiplexer is about 1 dB over the non-integrated demultiplexer. This excess loss difference is most likely due to a waveguide width, which is smaller than the design value, causing additional coupling loss at the input and output apertures of the array. This view is strengthened by the fact that the FWHM (Full Width at Half Maximum) value, which is 'only'
Figure 6.2 Spectral response for TE-polarization of the (prototype) demultiplexer integrated with photodetectors. Measurements are calibrated against the photocurrent of a detector integrated with a straight reference waveguide.

0.60 nm for this demultiplexer, compared to 0.75 nm for the non-integrated demultiplexer. The on-chip losses are estimated to be 3.5 to 4.5 dB, by adding the loss of the straight reference waveguide to the excess loss.

The relatively high crosstalk level, ranging from -12 to -21 dB, is caused by light which directly couples into the photodetectors from the input waveguides, without traveling through the demultiplexer. This is indicated by the fact that detector number 3, which shows the highest crosstalk level, is in line with the input waveguide. Choosing another input waveguide reduces the crosstalk level of this detector to -18 dB, but increases the crosstalk level of another detector. Providing optical isolation between input and output would be expected to eliminate this problem.

An external responsivity of 0.12 A/W (≈ 10% external efficiency) has been determined. Assuming an internal detector efficiency of 100%, the total demultiplexer insertion loss should be -10 dB, which consists of 3.5 dB on-chip and 6.5 dB coupling loss.

6.4 Demultiplexer integrated with detectors: second prototype

To eliminate the crosstalk observed in the integrated demultiplexer described above, a new device has been fabricated with an absorber between the input waveguides and the detectors, and between the output waveguides as well. This absorber is a simple mesa of ternary material,
Figure 6.3 Optical microscope image of a 4-channel phased-array demultiplexer integrated with photodetectors.
Figure 6.4  Spectral response at TE-polarization of the demultiplexer integrated with photodetectors. Measurements are calibrated against the photocurrent of a detector integrated with a straight reference waveguide.

which is etched in the same step as the detector mesa’s, so that no additional processing was required. Figure 6.3 shows a microscope image of the integrated demultiplexer.

The crosstalk level of the integrated demultiplexer has improved significantly by application of the absorber (see figure 6.4). Nearest neighbor crosstalk is now better than -25 dB. The weak side lobes observed at 1542 and 1544 nm are due to a small fraction of light coupled into the TM-mode.

The excess loss of the demultiplexer is 3 to 3.5 dB. Losses of straight reference waveguides are 4 dB/cm for both polarizations. These relatively high waveguide losses are attributed to the roughness of the RIE etched surface. As a consequence the external responsitivity of this demultiplexer is lower than for the previous device: 0.08 A/W (which includes a 1.2 dB loss occurring in a 3 mm straight input waveguide, which is not an essential part of the device).

The results obtained with this device were presented as a postdeadline paper at the ECOC’93 in Montreux, Switzerland[94].
6.5 Wavelength flattened demultiplexer

This section describes the realization of a spectrally flattened wavelength demultiplexer as proposed in section 5.4.

Design

The design was very similar to the conventional demultiplexer. The dimensions of the input and array waveguides were not changed. The output waveguide width was increased to 6 $\mu$m in order to flatten the spectral response. Figure 6.5 shows the calculated wavelength response of the conventional and the flattened demultiplexer. Both curves have been calculated for the waveguide structure presented in section 5.3.1, assuming a gap of 3 $\mu$m between the output waveguides, and a channel spacing of 2 nm. The highest order mode of the output waveguide was not taken into account in these calculations, as this mode will radiate from the bend. Increasing the output waveguide width from 2 to 6 $\mu$m causes significant flattening of the spectral response. The 1-dB transmission bandwidth of the demultiplexer is expected to increase from 0.45 to 1.12 nm.

The diffraction loss of the outer receiver channels was allowed to be 2 dB (versus 1 dB for the conventional device) in order to limit device dimensions. In order to limit the radiation losses of the higher order modes, the multimode output waveguides were subjected to a second etching step of 50 nm, and their radius of curvature was increased to 1.5 mm.
Figure 6.6  Spectral response at TE-polarization of the phasar demultiplexer with flattened wavelength response. Measurements are calibrated against 2 \( \mu \)m wide reference waveguides.

Fabrication

This demultiplexer was fabricated with two photolithographic steps. In the first step the entire pattern was etched to the desired depth using a SiO\(_2\) etch mask. In the second etching step, the entire device, except the multimode waveguide region, was covered with photoresist. As the waveguides were still protected by the SiO\(_2\)-mask, the alignment of the second pattern was not critical.

Results

Figure 6.6 shows the spectral response of this demultiplexer. The excess loss of the device is 2.5 to 4 dB. Losses of straight reference waveguides were determined to be 2 dB/cm using the Fabry-Perot technique. On-chip losses are estimated to be 3 to 4.5 dB by adding the loss of the straight reference waveguide to the excess loss. The crosstalk level is below \(-17\) dB. An average 1-dB bandwidth of 1.0 nm has been determined for TE-polarized light.

The insertion loss of this device is comparable to conventional phasar demultiplexers. The measured 1-dB bandwidth agrees well with theoretical calculations (just 10% lower than calculated). The crosstalk level is about 6 dB higher than for the conventional demultiplexer (section 6.2). This increased crosstalk is not really surprising, since we believe that the crosstalk is limited by local variations of the propagation constant in the array, which cause incoherent light to be randomly radiated into the numerical aperture of the array waveguide. As the output waveguide is three times wider for the flattened demultiplexer, and the focal length is almost identical in this particular case, crosstalk is expected to increase by about \(10 \log 3 \approx 5\) dB.
<table>
<thead>
<tr>
<th>ref.</th>
<th># channels</th>
<th>$\Delta \lambda$ nm</th>
<th>loss dB</th>
<th>cr.talk dB</th>
<th>size mm$^2$</th>
<th>$\Delta \lambda_{pol}$</th>
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</tr>
<tr>
<td>[74]*</td>
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<td>13-20</td>
<td>$&lt;-7$</td>
<td>$12 \times 2$</td>
<td>1.7</td>
</tr>
<tr>
<td>[96]</td>
<td>8</td>
<td>3.6</td>
<td>9.7</td>
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<td>4.8</td>
</tr>
<tr>
<td>[71, 97]</td>
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<td>4</td>
<td>10-17</td>
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<td>$2.5 \times 3.2$</td>
<td>0.4</td>
</tr>
<tr>
<td>[73, 97]*</td>
<td>35</td>
<td>4</td>
<td>10-17</td>
<td>$&lt;-15$</td>
<td>$4.7 \times 3.5$</td>
<td>2.5</td>
</tr>
<tr>
<td>[98]</td>
<td>8</td>
<td>4</td>
<td>6.5</td>
<td>$&lt;-30$</td>
<td>$1.8 \times 1$</td>
<td>1</td>
</tr>
</tbody>
</table>

**Phased-arrays:**

<table>
<thead>
<tr>
<th>ref.</th>
<th># channels</th>
<th>$\Delta \lambda$ nm</th>
<th>loss dB</th>
<th>cr.talk dB</th>
<th>size mm$^2$</th>
<th>$\Delta \lambda_{pol}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[77]</td>
<td>15</td>
<td>0.7</td>
<td>2-7</td>
<td>$&lt;-18$</td>
<td>$10 \times 10$</td>
<td>4.7</td>
</tr>
<tr>
<td>[78]</td>
<td>8</td>
<td>0.7</td>
<td>5</td>
<td>$&lt;-20$</td>
<td>$6 \times 9$</td>
<td>0</td>
</tr>
<tr>
<td>[82]</td>
<td>4</td>
<td>1.7</td>
<td>2.5-3.5</td>
<td>$&lt;-23$</td>
<td>$2.5 \times 2.3$</td>
<td>4.8</td>
</tr>
<tr>
<td>[94]*</td>
<td>4</td>
<td>1.7</td>
<td>4-5</td>
<td>$&lt;-25$</td>
<td>$3.0 \times 2.3$</td>
<td>4.2</td>
</tr>
<tr>
<td>[99]</td>
<td>8</td>
<td>2.0</td>
<td>5</td>
<td>$&lt;-25$</td>
<td>$2.6 \times 2.3$</td>
<td>0.0</td>
</tr>
<tr>
<td>[81]</td>
<td>16</td>
<td>1.8</td>
<td>11-12</td>
<td>$&lt;-9$</td>
<td>$33.5 \times 4.2$</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Table 6.3 Comparison of wavelength demultiplexers on InP-substrate. The * indicates that the device has been integrated with photodetectors. The bold printed data refer to devices realized by or in collaboration with the TU-Delft.

This agrees quite well with experimental observations.

6.6 Discussion and conclusions

The experimental results described in the previous sections have demonstrated the high potential of phased-array wavelength demultiplexers or filters for application in WDM-systems. Table 6.3 compares the performance of wavelength demultiplexers, realized in InP/InGaAsP.

The curved reflection grating type demultiplexers are capable of demultiplexing a high number of channels, but exhibit relatively high losses due to the application of the reflection mirror.

Phased-array demultiplexers, realized by AT&T, TU-Delft, and ,recently, Alcatel, demultiplex a more modest number of channels, but exhibit lower losses and can be realized with tolerant and relatively simple process technology. In this thesis, integration of this type of demultiplexer with photodetectors has been demonstrated for the first time. The crosstalk and the external efficiency of this integrated WDM-receiver are the best values so far reported. By using multimode output waveguides the spectral response of phasar demultiplexers can be flattened significantly at the cost of only a slight increase of crosstalk.

The main challenge to be addressed in the future is the achievement of a broadband polar-
6. Demultiplexer experiments

ization independent demultiplexer and its integration with photodetectors. A possible solution may be the use of non-birefringent raised strip waveguides, either applied in a 'conventional' phasar demultiplexer or using the generalized N×N MMI-MZI demultiplexer concept. Recently a first prototype of such a demultiplexer has been realized by a cooperation between the TU-Delft and Philips Optoelectronics Centre (POC) in Eindhoven. Raised strip waveguides as described in section 5.3.5 of this thesis were employed in a phasar demultiplexer. The device showed excellent polarization independent performance (see table 6.3). This work was presented as a postdeadline paper at the OFC'94 [99].
Chapter 7

Measurement technique for waveguide losses based on photoluminescence

This chapter describes a novel measurement technique for waveguide losses, which arose as spin-off of our efforts on waveguide detector integration. This measurement technique was presented at the SIOE’90 in Cardiff [100] and published in Electronics Letters [101]. The first section of this chapter will discuss the need for reliable non-destructive measurement techniques to characterize integrated optic components. The second section contains the manuscript of the novel measurement technique that has been reprinted with the permission of the editor of Electronics Letters.

7.1 Characterization of integrated optic components

A successful transfer of optoelectronic integrated circuits (OEIC's) from the R&D-stage to mass-production requires reliable non-destructive assessment of the optoelectronic performance of those circuits. It is gradually being recognized that the lack of reliable and easy characterization methods is one of the factors hampering the commercialization of OEIC's [102]. First attempts have been made to assess the reliability of different characterization methods of optical waveguide components: such as the 'round-robin' experiment of the COST240-group estimating the reliability of the Fabry-Perot method [103].

However the characterization method should not only be reliable, but preferably it should also allow for full-wafer testing without sacrificing device yield. A nice example of full-wafer optoelectronic testing has been developed by IBM [104]: They developed a full-wafer technology for the fabrication and characterization of semiconductor lasers.
The novel measurement technique of waveguide losses presented in the next section may be a first step towards on-chip characterization of integrated optic waveguide circuits.

7.2 Manuscript Electronics Letters

New measurement technique for waveguide losses based on photoluminescence


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Abstract

A new technique has been developed to measure optical losses of waveguide devices fabricated in III-V semiconductors by optical excitation of an integrated twinguide structure, which is nondestructive and also applicable to multimode and multiport devices. Reproducibility of excitation was found to be better than 0.2 dB.

Introduction

As OEIC’s are expected to play an important role in future telecommunication systems there is an increasing demand for accurate techniques for measuring transmission losses of waveguides fabricated in III-V semiconductors. Until recently the cutback method was widely applied to this type of measurement. In our laboratory it has been applied for determining the losses of straight and bent InGaAsP waveguides [54].

A disadvantage of this method is its destructive character. A quick and accurate nondestructive method, which has become increasingly popular, is the Fabry-Perot method [105]. This method is, however, restricted to singlemode two-port devices. We present a nondestructive measurement technique which is applicable to multiport devices with single or multimode waveguides.
Principle

The method is based on optical pumping of an integrated twinguide structure [106] (see figure 7.1). The twinguide consist of a low-bandgap layer [InGaAsP(1.55)] on top of the waveguide layer [InGaAsP(1.3)], separated by a thin InP etch-stop layer. Part of the photo-
Figure 7.3 SEM picture of integrated twinguide.

luminescence of the upper quaternary layer (λ = 1.55 μm) will be trapped in the twinguide and propagate in the form of twinguide modes. At the transition between the twinguide and the waveguide section a substantial part of this light is coupled into the transparent waveguide. the light emanating from the waveguide is imaged onto a photodiode. waveguide attenuation can be measured by fabricating a number of twinguide blocks at different distances from the cleaved edge (figure 7.2). Component losses are measured by comparing the output power with that of a straight waveguide.

Experiments

Integrated twinguide structures have been fabricated using MOCVD-grown layers (background doping level < 10^{15} cm^{-3}) on an SI-InP substrate. The layer structure consists of three layers for waveguide fabrication (InP buffer: 1.0 μm, InGaAsP(1.3): 0.4 μm, InP: 0.15 μm) on top of which (in the same epitaxial step) two additional layers (InGaAsP(1.55): 0.2 μm, InP cover: 0.25 μm) are grown for fabrication of the twinguide. Patterning of the integrated twinguide structures was performed by two steps of methane/He reactive ion etching at a power density of 0.4 W cm^{-2}. In the first step the first two top layers were removed everywhere except at the twinguide sections. In the second step waveguides with a ridge height of 0.55 μm were fabricated in the same way as for nonloaded structures. Figure 7.3 shows an SEM micrograph of a fabricated integrated twinguide. Optical pumping was achieved by focusing a stripe on top of the twinguide, using a GaAs/AlGaAs power laser with a center wavelength of 820 nm. The light emanating from the waveguides was focused onto a Ge photodiode with a ULWD
Figure 7.4 Output power against waveguide length for MOCVD integrated twinguides.

microscope objective.

Results

Reproducibility of excitation of the integrated twinguide was found to be better than 0.2 dB. The spread in the output intensity of integrated twinguides having identical waveguide lengths is about 0.3 dB. Figure 7.4 displays the output power of the integrated twinguide against waveguide length. Waveguide losses are $2.2 \pm 0.4$ dB/cm and $1.4 \pm 0.5$ dB/cm for 5 and 7 μm wide waveguides respectively. Measurements on 50 μm wide waveguides indicate that film losses are negligible.

Discussion

The relative small spread in the output intensity indicates a good excitation reproducibility from one waveguide to another. As a spread of 0.3 dB is quite typical for our waveguides, the actual spread in the power coupled into the waveguides is probably much smaller. The small spread for the 50 μm wide waveguides seems to confirm this supposition. Measurement accuracy thus compares quite well with existing methods.

In comparison with other methods the present method requires the growth of two additional layers and one additional noncritical etching step. Because the light source is an optically pumped LED the measurement is inherently incoherent. The method can easily be applied to multiport waveguide devices, such as couplers or power splitters, and is less sensitive to the occurrence of higher order modes than the Fabry-Perot method.
Conclusions

A new measurement technique has been presented to determine the losses of a wide variety of waveguide devices in III-V semiconductors. It is an alternative to the Fabry-Perot method if multiport or multimode waveguide devices have to be measured. Coupling light into the waveguide is easily achieved by optical pumping of an integrated twinguide structure with a reproducibility better than 0.2 dB. The method is a first step towards integrated teststructures for on-chip determination of the performance of optical devices.

Acknowledgement

These investigations in the program of the Foundation of Fundamental Research on Matter (FOM) have been supported by the Netherlands Technology Foundation (STW).
References


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The successful realization of many devices was due to the skillful contribution of technicians, who unfortunately often get too little recognition for performing excellent work. During the last year of my PhD-program Charles de Boer did the major part of the device processing. In addition, he performed the tedious task of measuring many integrated waveguide detectors. Frans van Ham took care of reactive ion etching of InP. Sputter deposition of SiO2 was performed by Aad de Vreede. The assistance of Koos van Uffelen with photolithography is also greatfully acknowledged. Ed Metaal (PTT-Research) proved to be a reliable ‘partner’ for reactive ion etching of SiO2. Adrie Looyen and Ab Küntze (Dept. of Appl. Phys.) took care of evaporation of metallizations and AR-coatings respectively.

Piet Demeester and Ingrid Moerman (University of Gent, INTEC) provided high-quality MOVPE-grown layers. It is my conviction that the performance of our devices is to a great deal due to the quality of their epitaxial layers. Roel Baets (University of Gent, INTEC) is gratefully acknowledged for many interesting discussions.

Luca Soldano has been a very pleasant roommate during these four years. We had many interesting discussions about integrated optics and other subjects and shared the joy of drinking or own illegal espresso coffee. Cor van Dam solved many computer related problems. During my stay in the USA, he excellently managed all the issues related to my promotion. Xaveer Leijtens and Leo Spiekman assisted in using \LaTeX. Leo de Vreede helped with MDS. Kees Steenbergen wrote the software for the multimode analysis of the integrated waveguide detector. Fokke Groen solved the mystery of the deviation of the channel spacing of the demultiplexer. Julian Soole (Bellcore) made many valuable suggestions concerning the proper use of the English language.

The following students made contributions: Rene Coppoolse, Wybren van Haga, Matthe van Stralen, Robert Hermsen, Richard Verhaar, Milo van de Werken, Jaccoo Pleumeekers, Rob van Dongen and Lars op den Brouw.
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Biography

Martin Amersfoort was born in Vlaardingen, The Netherlands on October 3rd 1965. When he finished high-school in 1984, he started studying applied physics at the Delft University of Technology, where he graduated in 1989. The subject of his graduation work was radiation damage assessment and endpoint detection for reactive ion etching.

Subsequently he started his PhD-program at the Department of Electrical Engineering at the same university. The scope of his PhD-program was the monolithic integration of optical and electronic components in InP/InGaAsP.

Since March 1994, he has been working as a postdoctoral research scientist at Bellcore, Red Bank, USA.