Optofluidics: Waveguides and devices

Genni Testa[a], Yujian Huang[b],Luigi Zeni[c], Pasqualina M. Sarro[b], Romeo Bernini[a*]
[a]IREA-CNR,Via Diocleziano 328, 80124 Napoli, Italy
[c]ECTM-DIMES, TUDelft, Feldmannweg 17, NL-2600 GB Delft, The Netherlands.
[b]DII, Seconda Università di Napoli, Via Roma 29, 81031 Aversa

ABSTRACT

In this work we review recent results of our work on optofluidics. We show that single mode optofluidic waveguides with low loss can be realized using antiresonant reflecting optical confinement (ARROW). These waveguides can be fabricated using full standard silicon technology or hybrid silicon-polymer processes. ARROW waveguides have been used in order to realize complex optofluidic devices like Mach-Zehnder interferometers and ring resonators. The advantage of using optofluidic waveguide results in very compact devices with a total length of 2.5 mm and a required liquid volume less then 0.16nl.

Keywords: Ring resonator, Optofluidics, Liquid core waveguides, Optical sensors

1. INTRODUCTION

Optofluidics merges optics with microfluidics in order to realize optical devices in which fluids act as an optical material. This approach enables an unprecedented level of integration, tunability and reconfigurability of optical devices[1,2].

In particular, the possibility to guiding light through a fluid offers very interesting applications especially in sensing field. The development of optical lab-on-chip requires the integration on the same chip of microfluidic and optical devices waveguides in order to continue to reduce the device size and cost, and improve the sensitivity. In this field, optofluidic waveguides can represent an important building-block for the realization of more complex devices and systems. In fact, they represent the maximum integration and functionality between waveguides, the key element of the optical structure, and microchannels, the key element of microfluidics.

While the term optofluidics was coined in 2003 to refer a new research field, the first demonstration of optofluidic waveguides was given by Daniel Colladon [3] and Jacques Babinet [4] in Paris in the early 1840s and few years later confirmed by John Tyndall [5]. They show the possibility to light guiding in a jet of water falling from a tank. This was also first example of guiding of light by refraction, the principle that makes conventional waveguides possible. Several years later, optical waveguides with a liquid core were explored for enabling light deflectors [6] or long-haul optical communications [2]. However, only in the last years a great effort has been devoted to the development novel and high efficient integrated optofluidic waveguides and devices.

The total internal reflection confinement mechanism on which are based conventional solid core waveguides cannot be easily replicated in optofluidic waveguides. In fact, the fulfillment of the total internal reflection (TIR) condition, when low refractive indices of aqueous solutions (1.33) are used as core materials, is very hard task when considering that common solid materials employed for microelectronic and microfluidic fabrication exhibit higher refractive indexes (1.4–3.5). Special materials like fluorinated polymers, such as Teflon AF [7], or nanoporous materials [8] that are optically transparent and exhibit refractive index of 1.04-1.31 have been also proposed in order to overcome this problem.

Another important approach of waveguide structure able to guide the light in a liquid channel is given by the slot waveguide [9-10]. A slot waveguide is composed by two high refractive index dielectric nanowires separated by a low refractive index gap region of tens of nanometer. In these devices, even if the light s guided by TIR mechanism, there is a strong enhancement and confinement of the optical field in a small gap filled with low-index material.

*bernini.r@irea.cnr.it, phone+39081570799, fax:+390815705734, www.irea.cnr.it.

Integrated Optics: Devices, Materials, and Technologies XVI, edited by Jean Emmanuel Broquin,
Gualtiero Nunzi Conti, Proc. of SPIE Vol. 8264, 826415 · © 2012 SPIE
CCC code: 0277-786X/12/$18 · doi: 10.1117/12.908683

The problem to confine the light in a low refractive index materials can be solved also using confinement mechanisms different from TIR one. Recently, dielectric cladding hollow optical waveguide based on Bragg reflectors [11], photonic band gap [12, 13] or AntiResonant Reflecting Optical Waveguiding (ARROW) [14, 15] has been proposed and fabricated. In particular, ARROW waveguide are very interesting because its fabrication as integrated device is easy and do not requires high periodicity and high index contrast between the cladding layers like Bragg a photonic band gap waveguides.

In this work, we show that single mode optofluidic waveguides with low loss can be realized using antiresonant reflecting optical confinement (ARROW). These waveguides can be fabricated using full standard silicon technology or hybrid silicon-polymer processes. These waveguides have been used as a basic component for fabrication of complex integrated optofluidic devices. In particular, we report the fabrication and the characterization of Mach-Zehnder interferometers and ring resonators.

2. OPTOFLUIDIC WAVEGUIDES

2.1. ARROW waveguide

In Fig.1(a) the transverse section of an integrated liquid core ARROW waveguide is shown. The device is composed by two wafer. On both wafer, two dielectric layers are deposited the silicon substrate, having refractive index and thickness n_2, d_2, and n_1, d_1, respectively. In this waveguide, the light is confined inside the core region, where the refractive index n_c is lower than the one of the surrounding media, by the two cladding layers designed to form a high reflectivity Fabry-Perot antiresonant cavity.

The advantage of these waveguides relies on the possibility to use the same microchannel for guiding light and for delivering the sample to be sensed. In this way the interaction efficiency between the propagating optical mode and the sample is optimized. Moreover, using these waveguides the microfluidic and the optical parts are integrated to form a very compact device.

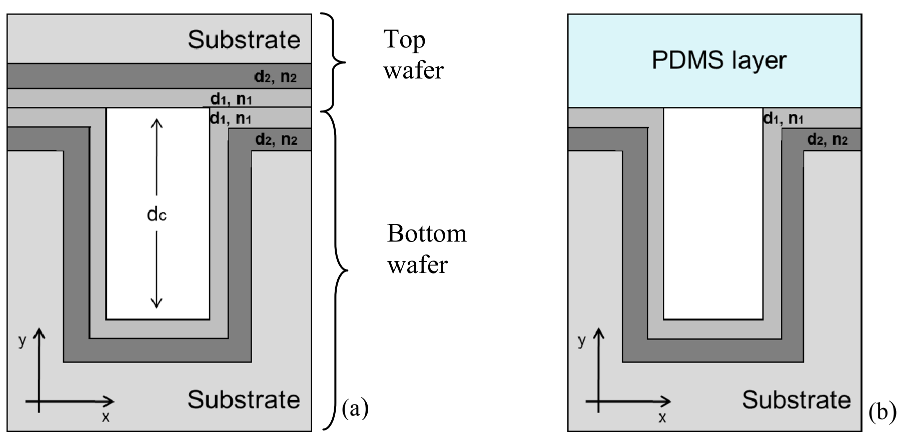

Fig.1 Waveguide schematic cross section: (a) Conventional full silicon ARROW, (b) Hybrid polymer –silicon ARROW.

Taking into account that ARROWs are leaky waveguides their design requires a special attention depending on their application. In particular, single mode behaviour is an important requirement for optical waveguide devices for use with single-mode fiber or for the fabrication of interferometric devices. With a suitable design large core waveguide with actual mono-mode behaviour can be achieved. In fact, higher order modes can be filtered out by loss discrimination due to the low reflectivity at the cladding layers for these modes. Hence, the core dimension of a single mode ARROW waveguides results from a trade-off between the quasi single mode behaviour and the fundamental mode losses. For water solution filled core waveguide (n_c=1.330) in order to ensure this condition the core dimension has been fixed to be 5x10μm^2 [16].

2.2 ARROW waveguide fabrication

ARROW waveguides can be easily fabricated using standard silicon technology processes [14-16]. In these waveguides the core microchannel is realized by dry etching trenches into a silicon wafer, then the cladding dielectric layers are deposited on the etched wafer as well as on a flat silicon wafer and finally the two wafers are bonded (Fig.1(a)). For the fabrication of these waveguides, material cladding such as silicon nitride (n=2.01-2.2) and silicon dioxide (n=1.46) have been widely used as they provide the requirement of a CMOS compatible process and high index contrast. Depositions are generally carried out using Plasma-Enhanced Chemical Vapour Deposition (PECVD) or low pressure chemical vapour deposition (LPCVD) [14, 15].

Alternatively, Atomic Layer Deposition (ALD) process could be used [16]. The ALD process is a self-limiting process with an average deposition rate very low (usually less than a nanometer per cycle). One of the most important advantages of this technique is that it allows the deposition of very thin cladding layer (sub-100nm) with an excellent conformality, reproducibility and with a high precision over the resulting thickness. Furthermore, this technique permits to considerably reduce the surface roughness, a suitable aspect for optical employment as it allows a strong reduction of optical scattering.

Using ALD ARROW waveguides were fabricated by alternating layer of silicon dioxide and titanium dioxide (n=2.49), where the deposition of the titanium dioxide is realized by ALD deposition technique. Among the possible dielectric materials that can be deposited by ALD (i.e. TiO2, Al2O3, MgO), we have chosen the titanium dioxide as it provides the higher index contrast with the SiO2. The waveguide exhibits a fundamental waveguide loss of 5.22cm^{-1}

However, ARROW waveguides based on standard silicon process don't permit an easy integration with fluid inlet and outlet and fluid reservoir. Furthermore, due to the optical absorption of silicon substrates in the visible region, the illumination and the collection of light are allowed only at the waveguide ends. This configuration strongly limits sensing application based on fluorescence or Raman spectroscopy, where multiple orthogonal excitation and collection are required. These problems can be overcome using hybrid silicon- poly(dimethysiloxane) (PDMS) optofluidic ARROW waveguides (h-ARROW). In these waveguides the top silicon wafer is substituted by a thin PDMS layer (Fig.1(b)).With a suitable design a broad-band output transmission spectrum can be achieved and the attenuation losses for the fundamental mode are 6.96 cm^{-1} a value comparable with that obtained for full silicon liquid core ARROW.

3. OPTOFLUIDIC DEVICES

In this section, we report on two interferometric optofluidic devices based on optofluidic ARROW waveguide. Mach-Zehnder interferometers (MZIs) and ring resonators have fabricated and successfully characterized.

3.1. Optofluidic Mach-Zehnder interferometer

A schematic layout of the MZI is reported in fig.2. Light is coupled into a straight waveguide followed by a taper with a starting width of 10 µm and a final width of 20µm .The taper length is 500µm. At the first T-branch the light is equally splitted into the upper and lower waveguides and recombined at the T-branch on the left. This configuration permits to realize a very compact device with a total length only L=2.5 mm and with required liquid volume is about 0.16nl [19].

This configuration permits to order to minimize the intensity unbalance between the two arms due to waveguide and bend losses and obtain very high visibility values with a strong improvement on the sensitivity of the device.

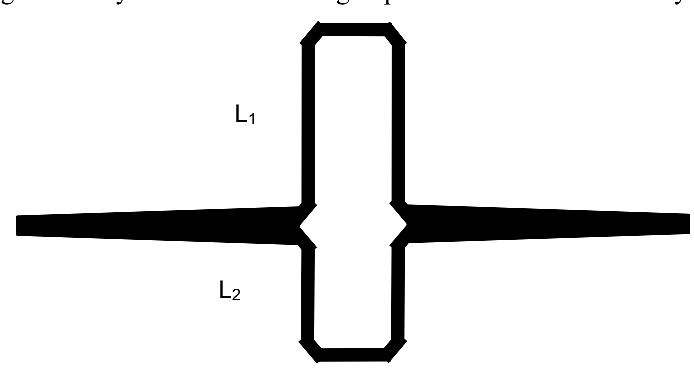

Fig.2 Schematic layout of the optofluidic MZI.

For the optical characterization of the devices, the light from a polarized diode laser (λ_{max}=640nm) was end-coupled into the waveguide core through a single-mode optical fiber with a 4.5μm core diameter. The transmitted spectrum was then collected with a single-mode optical fiber (4.5μm core) connected to a CCD spectrometer. The sample was mounted on a micrometer translation stage for the precise alignment of all components and the open-ended hollow waveguide core was filled with methanol (n_c=1.32).

In Fig.3 is showed the measured transmitted spectra from the MZI with a length difference ΔL=400μm between the two arms. The free spectral range (FSR) measured from the spectra around λ=660nm is 0.735nm, and agrees well with the theoretical one (0.8nm). Despite the MZI is strongly unbalanced, the measured visibility V is 0.956.

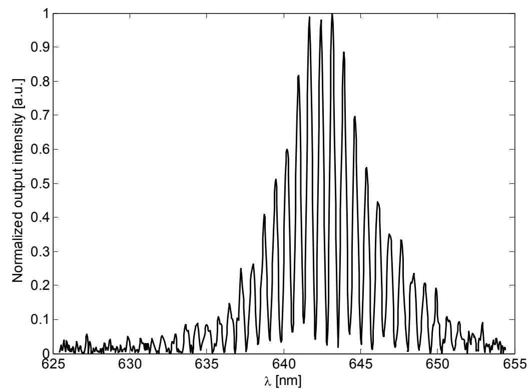

Fig .3 Normalized transmitted intensity from MZI. V=0.956, FSR=0.735nm.

4.1. Optofluidic ring resonator

The layout of the optofluidic ring resonator is shown in Fig. 4. Four 90°-bent ARROW waveguides with a width W=3 μm are used to form a rectangular ring resonator. Due to the ARROW confinement, an evanescent coupling between the ring and the bus waveguide is not possible, hence a multimode interference (MMI) liquid core ARROW coupler with a 50:50 splitting ratio acts as coupling element between the ring and the bus waveguide. With this design the optical part, used to realize the ring, and the microfluidic part, used to deliver the liquid sample, are integrated together and the need for any additional microfluidics is avoided [20].

The MMI coupler has a width of W_{MMI}=6μm and it has been designed to operate as a balanced power splitter at the working wavelength of λ=635nm for a water-filled liquid core (n_c=1.33). This results in a length of $L_{MMI}=2n_cW^2_{MMI}/\lambda$=151.3 μm. Moreover, for increasing the coupling efficiency with single mode optical fibers, we used linear tapered waveguides to connect the input and output ports of the MMI coupler with input and output straight access waveguides of 5 μm width. The round-trip length of the ring resonator is L_{RT}=342.6 μm while the total length of the device, including the input and output access waveguides, is L=2.5mm. The total liquid volume required is about 0.11 nl.

Optical measurements were performed by filling the entire device through the open-ended hollow core bus waveguide with methanol and dimethylformamide (DMF) (n=1.43) by capillary action.

The measured normalized transmitted spectrum from the DMF-filled core device is shown in Fig.5. From measurements a FSR=0.845 nm around λ=640nm and an extinction ratio of ER~5dB were estimated. The measured resonance linewidth (FHWM) is 0.434nm, leading to a quality factor Q~1482.

Fig. 4 Schematic layout of the ring resonator.

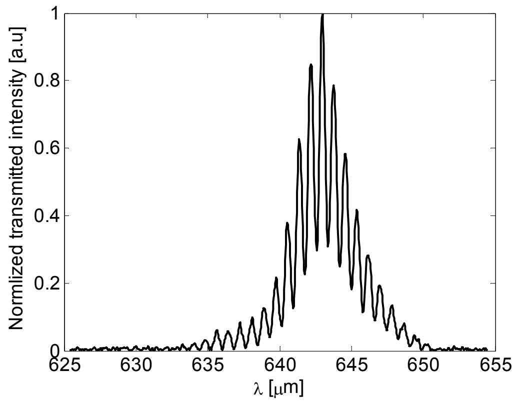

Fig. 5 Normalized transmitted intensity for DMF filled ring resonator (n_c=1.43)

5. CONCLUSIONS

We have demonstrated the feasibility of integrated optofluidic waveguides and devices. Using silicon technology or hybrid silicon-polymer processes low loss ARROW waveguides have been fabricated also for single mode geometry.

These waveguide have been used in order to realize interferometric device like optofluidic Mach-Zehnder interferometers and ring resonators. With the use of ARROW waveguides the optical and microfluidic part of the device are integrated together, avoiding the need for any additional microfluidics. The results are very compact devices that require less then 0.16nl of liquid volume.

ACKNOWLEDGEMENTS

The authors would like to thank the IC Process Group of DIMES for technical assistance in the device fabrication.

REFERENCES

[1] H.Schmidt, A.R. Hawkins, [Handbook of Optofluidics], CRC Press,1 (2010).
[2] Y.Fainman, L. Lee, D. Psaltis, C. Yang , [Optofluidics – Fundamentals, Devices, and Applications], McGraw-Hill, 1 (2009).
[3] D. Colladon, "On the reflections of a ray of light inside a parabolic liquid stream", Compt. Rend 15, 800-802 (1842).
[4] J. Babinet, "Note on the transmission of light by sinuous canals", Compt Rend 15, 802 (1842).
[5] J.Tyndall, "On some phenomena connected with the motion of liquids", Proc R Inst Great Britain 1, 446 (1854).
[6] G. W. Taylor, "Liquid Optical Fibers", App. Optics 11, 786-790 (1972).
[7] A. Datta, I. Eom, A. Dhar, P. Kuban, R. Manor, I.Ahmad, S. Gangopadhyay, T. Dallas, M. Holtz, H. Temkin, P. Dasgupta, "Microfabrication and characterization of teflon AF-coated liquid core waveguide channels in silicon", IEEE Sens Journal 3, 788–795 (2003).
[8] V. Korampally, S. Mukherjee, M. Hossain , R. Manor, M. Yun.,K. Gangopadhyay, L. Polo-Parada,S. Gangopadhyay, "Development of a Miniaturized Liquid Core Waveguide System With Nanoporous Dielectric Cladding: A Potential Biosensing Platform", IEEE Sens Journal 9, 1711-1718 (2009)
[9] V.R. Almeida, Q. Xu,C.A. Barrios, M. Lipson,"Guiding and confining Light in void nanostructure", Opt Lett 2, 1209-1211 (2004).
[10] N.N. Feng, J. Michel, L.C. Kimerling,"Optical field concentration in low-index waveguides", IEEE J. Quantum Electron 42, 885-890 (2006)
[11] S.S. Lo, M.S. Wang, C.C. Chen, "Semiconductor hollow optical waveguides formed by omni-directional reflectors", Opt. Exp 12, 6589-6593 (2004).

[12] R. G. DeCorby, N. Ponnampalam, H. T.Nguyen, M. M. Pai, T.J. Clement,"Guided self-assembly of integrated hollow Bragg waveguides", Opt. Exp 15, 3902-3915 (2007).

[13] E. Epp, N. Ponnampalam, W. Newman ,B. Drobot, J.N. McMullin, A.F. Meldrum, R.G. DeCorby, "Hollow Bragg waveguides fabricated by controlled buckling of Si/SiO2 multilayers", Opt. Exp 18, 24917-24925 (2010).

[14] R. Bernini, S. Campopiano, L. Zeni, "Silicon Micromachined Hollow Optical Waveguides for Sensing Applications", IEEE J. Selected Topics in Quantum Elect 8, 106-110 (2002).

[15] D. Yin, D.W. Deamer , H. Schmidt, J.P. Barber, A.R. Hawkins, "Integrated optical waveguides with liquid cores", Appl. Phys. Lett 85, 3477-3479 (2004).

[16] G. Testa, Y. Huang, L. Zeni, P. M. Sarro and R. Bernini, "Liquid Core ARROW Waveguides by Atomic Layer Deposition", IEEE Photon. Technol. Lett 22, 616-618 (2010).

[17] H. Schmidt, D. Yin, J. P. Barber, and A. R. Hawkins, "Hollow-core waveguides and 2-D waveguide arrays for integrated optics of gases and liquids", IEEE J. Sel. Top. Quantum Electron 11, 519-527 (2005).

[18] R. Bernini, G. Testa, L. Zeni and P. M. Sarro, "Integrated optofluidic Mach–Zehnder interferometer based on liquid core waveguides", Appl. Phys. Lett 93, 011106 (2008)

[19] G. Testa, Y. Huang, P. M. Sarro, L. Zeni, and R. Bernini, "High-visibility optofluidic Mach–Zehnder interferometer", Opt. Lett 35, 1584-1586 (2010).

[20] G. Testa, Y. Huang, P. M. Sarro, L. Zeni, and R. Bernini, "Integrated silicon optofluidic ring resonator", Appl. Phys. Lett 97, 131110 (2010)