Invited Paper

Optofluidics: a new tool for sensing

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

ABSTRACT

Over the last years optofluidics has emerged as a very promising field. The integration at microscopic level between optics and microfluidics provides a number of unique characteristics that cannot be obtained with solid materials only. This paper briefly reviews the state of the art on optofluidics for sensing applications. We first describe the different approaches in order to realized optofluidic waveguides. These waveguides allow an increased interaction efficiency between the light and the liquid substance that can be very useful in sensing applications (fluorescence, absorption spectroscopy, etc.). We then illustrate high sensitive optofluidic devices such as Mach–Zehnder interferometers, Fabry–Pérot cavities and ring resonators. Examples of applications of optofluidic sensors for chemical and biological analysis are given.

Keywords: Optofluidics, Optofluidic waveguides, Optical sensors

1. INTRODUCTION

Optofluidics essentially merges optics and microfluidics at micro and nano scales [1-2]. This approach permits to realize innovative optical system in which fluids can act as an optical material providing a significantly enhanced performance and functionality that cannot be achieved without this seamless integration [3-4]. The possibility to guiding and manipulating light through a fluid offers very interesting applications in sensing fields enabling high interaction efficiency between the light and the substance with unprecedented sensitivity and limit-of-detection. In particular, the performances of biological and chemical sensors could strongly benefit from this effective integration between complex integrated microfluidic networks and the optical detection part. To date most of microfluidic sensors employ a separate microfluidic network to prepare and delivery very small sample volumes (femtoliter to microliter) under analysis that is simply connected to the optical sensing part degrading the sensing performances. In other cases, also if an integration has been achieved, the design of optical part has been privileged respect to microfluidic one, sacrificing the feasibility and the final sensitivity of the device. In fact, while microfluidics enable compact systems, recent results show that performances of biosensors can be seriously limited in a fluidic environment by the inefficient analyte transport instead of their intrinsic optical detection capabilities.

This work briefly summarizes the present state of the art on optofluidics for sensing applications. We first describe the different approaches in order to realized optofluidic waveguides. We then illustrate high sensitive optofluidic devices such as Mach–Zehnder interferometer, Fabry–Pérot cavities and optical resonators. Examples of applications of optofluidic sensors for chemical and biological analysis are given.

2. OPTOFLUIDIC WAVEGUIDES

Optofluidic waveguides are optical waveguides in which the light and the liquid are confined in the same microchannel [1-2] These devices merge at a microscopic level optical waveguides and microfluidic channels that are the key elements of optics and microfluidics, respectively. Optofluidic waveguides can represent an important tool for sensing applications and a building-block for the realization of more complex optofluidic devices and systems. However, the fabrication of optofluidic waveguides using total internal reflection (TIR) confinement mechanism, on which are based conventional solid core waveguides, is not an easy task. In fact, common solid materials employed for optic and microfluidic fabrication exhibit refractive indexes (1.4–3.5) much higher of aqueous solutions commonly under analysis (1.33). Many techniques have been proposed in order to overcome these problem. One of most simply confining method is to use thin film metal cladding in order to confine the light into the core [5]. These waveguides have the great advantages of guiding light thorough a liquid core regardless of refractive index, but they are characterised by high propagation losses at optical frequencies that make them ill-suited for sensing applications. A proposed approach to achieve TIR confinement with liquid core is to use a class of fluorinated polymers, such as Teflon AF, that are optically transparent and exhibit very low refractive indexes (1.29-1.31). Liquid core fibers consisting of either Teflon AF tubes or glass capillaries coated

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

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internally with Teflon AF have been applied in sensing since 1990s [6]. More recently the integration silicon, glass or PDMS substrates of these waveguides has been also demonstrated [7-8]. However, the use of Teflon AF is not easy and poses strong limitations. In fact, due to its chemistry, Teflon AF has poor adhesion to commonly-used substrates and, for the same reason, its surface offers little possibility for chemical functionalization. Fluorinated polymer can be substituted by nanoporous materials formed by introducing nanosized air pores into a solid matrix material. Because, the refractive index of the composite material is a weighted average of the refractive index of air and that of the host material, it is possible fabricate cladding films with refractive indexes as low as 1.047 by varying the degree of porosity [9].

As alternative to optofluidic waveguides based on liquid-core/solid-cladding, liquid-core/liquid-cladding (L2) waveguides have been fabricated using both glass capillary technology [10], and planar geometry by replica molding polymeric techniques [11-13]. These waveguides are microfluidic devices in which the light is confined inside a high refractive index liquid (the core) by a low refractive index liquid (the cladding), both liquids flowing laminarly inside a microchannels. Because L2 waveguides are dynamic, many optical properties (refractive index contrast, geometry, etc.) can be easily changed. Furthermore they have optically smooth side walls independently of the channel roughness. The Liquid core/liquid cladding guiding concept has been implemented both in one and in two-dimensional geometries [14,15]. However, the choice of liquids poses strong limitations due to the requirement that the refractive index of the liquid "core" exceed that of the liquid "cladding.". In particular, light could not be guided in water (n=1.33) or in low refractive index aqueous solutions without the addition of dissolved species to increase the refractive index of aqueous core. An interesting solution to this problem is represented by optofluidic water jet waveguide where a high speed water stream produced by means of a micro nozzle acts at the same time as the solution to analyze and optical waveguide [16].

Another important approach of waveguide structure able to guide the light in a liquid channel is given by the slot waveguide [17]. 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. Usually slot waveguides are based on Silicon-on-Insulator (SOI) technology and realized by defining two silicon wires at a distance of few hundred of nanometer on a silicon dioxide substrate. More recently, slot waveguide based on silicon nitride or titanium dioxide on silica have been proposed [18, 19]. Due to the very tight confinement and interaction area, slot waveguides represent a promising approach for waveguide sensing into nanofluidic structure allowing at extremely low analyte concentrations. Furthermore, because slot waveguides are single mode they can used in order to realize more complex interferometric or resonant devices.

A different approach in order to confine the light in a low refractive index materials is based on interference phenomena in dielectric claddings. This different mechanism affords great potential in terms of design freedom and novel applications. Recently, dielectric cladding hollow optical waveguide based on Bragg reflectors [20] or photonic band gap [21] has been proposed and fabricated. Liquid-filled hollow-core photonic crystal fibers (HC-PCFs) are perfect optofluidic waveguides, uniquely providing low-loss optical guidance in a liquid medium [22]

A different way to realize optofluidic waveguides is the use of leaky waveguide such as AntiResonant Reflecting Optical Waveguide (ARROW) [23-25]. In ARROW waveguides the field is confined in the core region by dielectric cladding layers designed to form high reflectivity Fabry-Perot mirrors. This structure are very interesting because its fabrication as integrated device is easy and don't requires high periodicity and high index contrast between the cladding layers like Bragg a photonic band gap waveguides. Even though the ARROW modes are leaky, low-loss propagation over large distances can be achieved. Furthermore, singlemode waveguides can be realized also with large core dimensions. These waveguides can be easily designed using very simply optical equations that take into account the interference phenomena in the cladding layers.

In Fig. 1a) the transverse section of the integrated liquid core ARROW waveguide proposed by our group is shown. The device is composed by two halves. On both halves, two dielectric layers are deposited on a silicon substrate, having refractive index and thickness n_2, d_2, ,and n_1, d_1, respectively. 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. As alternative to silicon nitride also titanium dioxide (n=2.49) has been tested obtaining low loss waveguide [26]. 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) [27]. In these waveguides the top silicon wafer is substituted by a thin PDMS layer (Fig.1b). 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 5.22cm^{-1} obtained for full silicon liquid core ARROW.

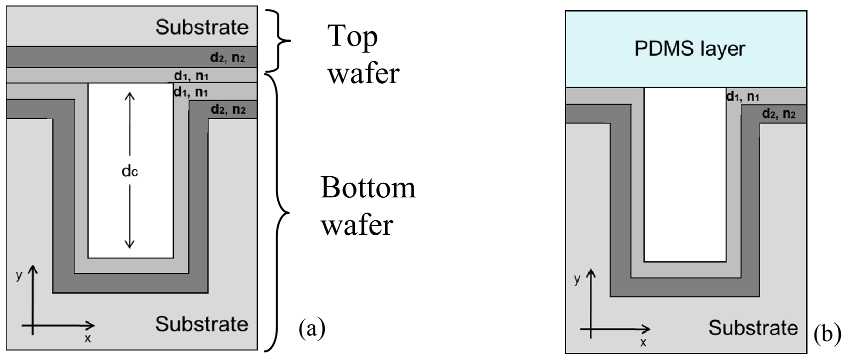

Fig.1 (a) Conventional wafer-bonding based ARROW waveguides (b) H-ARROW waveguide schematic cross section.

3. OPTOFLUIDIC SENSING DEVICES

The use of optofluidic waveguides permits a direct optical probing of the liquid sample with a strong advantage in the integration and with increased interaction efficiency. Taking into account of this advantage, optofluidic waveguides have been used as powerful tool for absorbance-based sensing or spectroscopy analysis like fluorescence [28-30]. Furthermore, they can be used as a basic component for fabrication of complex optofluidic devices. In the following, we review high sensitive optofluidic sensing devices like interferometers and resonators.

3.1. Optofluidic interferometers

Optical interferometer is one of the most used and sensitive device for sensing applications. Typically, interferometers devices are based on conventional solid core waveguides in which the analyte interacts with the evanescent part of the waveguide mode. In the last years, a great effort has been devoted to find new sensing strategies based on optofluidic waveguides.

Optofluidic Mach-Zehnder interferometers (MZIs) have been developed integrating solid-core waveguides with liquid-core waveguides or microchannels. An interesting fabrication technique allowing the seamless integration of solid-core and liquid-core waveguides has been demonstrated and applied to MZIs, for integrated refractometry [31]. The technique allows single-mode liquid-core waveguides to be realized. An optofluidic fiber based Mach-Zehnder interferometer has been used for measuring the dry/wet mass of a single living cell using. The device integrate a fiber optic trap, that capture a single living cell, and then the cell's refractive index and diameter are simultaneously determined by MZI [32]. Recently a new class of highly compact single-beam microfluidic Mach-Zehnder interferometer has been demonstrated. In these devices the phase differences has been introduced by propagating a beam across a fluid/air discontinuity [33]. Typically, guided optic based interferometers are based on Mach-Zehnder configuration because it avoids the need of optical mirrors. However, using the flexibility given by optofluidics a Michelson interferometer has been demonstrated. The device is based on a droplet grating formed by a stream of plugs, of two immiscibile liquids, in a microchannel with constant refractive index variation. It has a real-time tunability in the grating period through varying the flow rates of the liquids and index variation via different combinations of liquids. The optofluidic Michelson interferometer is highly sensitive and is suitable for the measurement of biomedical and biochemical buffer solutions [34]. An optofluidic Mach-Zehnder interferometer (MZI) has recently been realized by our group using liquid-core ARROW waveguides [35-36]. The device is based on small core 5x10µm waveguides resulting in quasi-single mode behaviour that is an essential feature for interferometric device. The device is based on T-branches and 90°-bent waveguides (Fig.1a and b). Differently from conventional MZI, because the whole device is filled with the liquid under analysis, the two arms must have different length resulting in an asymmetric device in order to induce a relative phase shift at the output. The geometry has been optimized in order to minimize the intensity unbalance between the two arms also for high asymmetric Mach-Zehnder obtaining very high visibility. The device has a total length of L=2.5 mm and the required liquid volume is about 0.16nl.

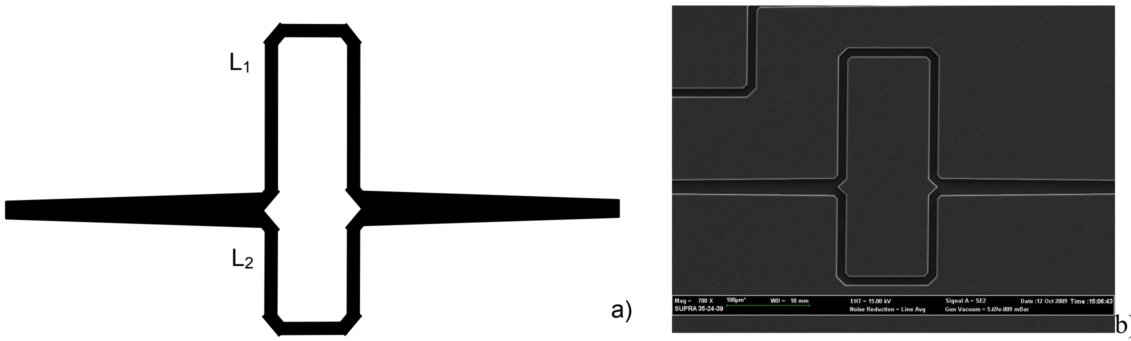

Fig.2. a) Schematic layout of the optofluidic MZI. b) SEM Picture of the optofluidic MZI bottom layer

4.1. Optofluidic resonators

Optical resonators are an emerging technology for high sensitivity miniaturized biological or biochemical sensing [37]. Because in these devices the interaction length between the light and liquid sample is not limited by the physical length but is related to the number of revolutions of light in the resonator, characterised by the quality factor Q, they allow to obtain high sensitivity with very compact dimensions. However, in order to achieve high performance, these structures requires an optimized integration of the optical and microfluidic parts.

Microdroplet resonators are the first example of optofluidic resonators and have been extensively studied because they offer a unique integration between the microfluidics and the resonator and exhibits very high Q-factor due to the best surface quality that ensure very low surface scattering losses [38]. However, droplets suffer from several practical limitations, related to the complexity associated with manipulating and controlling droplet structures and the difficult to coupling the light. A great advance in the feasibility of optofluidic resonator sensors is represented by liquid core ring resonator (LCORR) [39]. In LCORR a fused silica capillary acts simultaneously as a fluidic channel, to effectively deliver the sample, and as ring resonator. The evanescent field of the whispering gallery mode (WGM) in the core detect the refractive index change near the interior surface. This device has been successfully applied in chemical and biochemical detection like cancer biomarkers [40, 41].

Using a similar approach integrated silicon optofluidic ring resonator based on ARROW waveguide has been demonstrated [42] by our group. In this device four 90°-bent ARROW waveguides are used to form a rectangular ring resonator and a multi-mode interference (MMI) liquid core ARROW coupler with a 50:50 splitting ratio acts as coupling element between the ring and the bus waveguide. A sensitivity of about 260nm/RIU has obtained with required liquid volume of about 0.11nl.

Optofluidic resonators have been also fabricated using photonic crystals. The optical field inside the holes of photonic crystal is significantly stronger than the evanescent fields of WGM sensors, thereby strengthening the light-matter interactions and enabling a limit of detection on the order of 63 ag total bound mass. Furthermore these devices can be easily multiplexed for simultaneous detection of multiple analytes [43].

Recently, optofluidic Fabry-Perot (FP) resonators have been developed using gold coated fiber-based FP [44], fiber–Bragg-grating [45] or integrated vertically etched silicon Bragg reflectors [46]. All these devices use the change in optical path length in the cavity when light propagates through different samples to determine the refractive index of the sample. Based on the measured refractive index value, researchers can determine the concentration of solute in a solution or study the relation of living cell's RI with the cell permeability, cell viability, the effective indexes and sizes of cancerous cells [47]. In order to increase the sensitivity optofluidic Fabry–Perot cavity sensor with integrated flow-through micro-/nanofluidic channels has been proposed [48]. The sensor employs a microsized capillary with many built-in micro-/nanosized placed inside a between a FP cavity. This micro-/nanohole arrays enable three dimensional surface detection which greatly enhances the sensitivity.

5. CONCLUSIONS

Optofluidics represents a novel approach to sensing in which fluidics and optics works synergistically to provide enhanced performance and functionality, which are not achievable through the design of either optics or fluidics alone.

The strong enhancement of the light–matter interaction with a simultaneous reduction of the sample volume permits to realize devices with unprecedented sensitivity and limit-of-detection. We believe that in forthcoming years optofluidics will contribute to strongly advance biological and chemical sensing

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