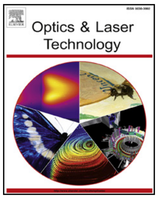
Optics and Laser Technology 111 (2019) 303–306

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec



Full length article

Real-time refractive-index sensing by using liquid core/liquid cladding optofluidic waveguide

Mohammadreza Oraie, Hamid Latifi*

Laser and Plasma Research Institute and Department of Physics, Shahid Beheshti University, Tehran 1983963113, Iran

HIGHLIGHTS:

- Optical methods for Refractive index measurements have many applications in science.
- The optofluidic waveguide is based on the liquid core/liquid cladding waveguide.
- The changes in intensity are measured by using a portable powermeter.
- It is shown that the sensor ultimate resolution is 7×10^{-6} RIU.
- The sensor dynamic range is 0.07 RIU from 1.342 to 1.411.

ARTICLE INFO

Keywords:
Microfluidic sensors
Optofluidics
Refractive index sensing
Liquid waveguides

ABSTRACT

In this study, an optofluidic refractive index (RI) sensor is realized by employing the liquid core/liquid cladding (L^2) waveguide through measuring the output power of the waveguide. It is shown that the sensor is capable of measuring the RI changes with a dynamic range of 0.07 RIU from 1.342 to 1.411 which can cover a wide range of applications in the Lab-on-a-Chip technology. The maximum resolution of the sensor is 7×10^{-6} RIU.

1. Introduction

Refractive index (RI) measurements have many applications in biology, chemistry and physics. The optofluidic RI measurements by means of integrating microfluidic circuits with optical components known as optofluidics (especially the optical fibers) has attracted the attention of many researchers in the last decade [1]. The optofluidic sensors benefit from two main characteristics: tunability and integrability. Also, the optofluidic sensors are fabricated on the same platform that the other microfluidic components are fabricated. This characteristic makes them suitable for applications in micro-total analysis (μTA).

In the last two decades, a great effort has been put on the development of novel optofluidic sensors for RI and Δ(RI) measurements which typically include the Photonic Crystal Fibers (PCFs) [2–5], interferometer-based optical fiber sensors [6–8], waveguide-based (WG) sensors [9–13] and surface plasmon resonance (SPR) sensors [14,15]. Although the above sensors are sensitive to the small changes in the concentration and the RI of the sensing liquids, the difficulty in the fabrication process and their integration into the microfluidic chips still remains challenging. Moreover, the expensive and complicated measurement techniques are also the drawback of the common proposed sensors.

Among these RI sensing methods, the WGs are more promising to be integrated into the chips, since the fabrication processes are simpler than other methods and the detection methods used in WG-based RI sensors are easier to employ for real-time detections. In these sensors, light propagates through the waveguide core while the sensing liquid is placed around it. The evanescent field of light confined within the core interacts with the sensing cladding region leading to the phase shift or variations in the intensity. The interaction between the confined light and the sensing liquid is limited by the penetration depth of the evanescent field into the sensing liquid. Therefore, in order to realize a strong interaction, the fluidic waveguides can be used instead of the solid ones. In the fluidic waveguides, the RI of core can be tuned for different sensing liquids [16]. One of the fluidic waveguides that has attracted the attention of researchers in the field of microfluidics is the liquid core/liquid cladding (L^2) waveguide [17,18]. We have already developed and characterized a sensor for flow rate detection based on this waveguide [19].

In this work, we have used the L^2 waveguide for measuring the RI of one of the claddings of the waveguide with respect to the other cladding. These waveguides are shown to be capable of measuring the

---

* Corresponding author.
E-mail addresses: m_oraie@sbu.ac.ir (M. Oraie), latifi@sbu.ac.ir (H. Latifi).

https://doi.org/10.1016/j.optlastec.2018.10.006
Received 29 April 2018; Received in revised form 9 August 2018; Accepted 4 October 2018

changes in RI as an evanescent field sensor [10]. In the current study, the evanescent RI sensor has been improved by means of the detection method and test procedure. In Ref. [10], the authors have used different concentrations of $CaCl_2$ to test the sensor, however, we have benefited from an integrated microfluidic mixer developed by our research group to inject liquids with different RIs into the microchannel. The generation of different RIs is based on the flow rates of the liquids injected into the micromixer. The integration of the micromixer enables us to test the sensor continuously without stopping the test procedure and also prevents the formation of bubbles inside the microchannel. Also, in Ref. [10], the captured image of the output intensity profile of the waveguide went through the image post-processing to detect the intensity changes due to the RI variations. However, in this work the changes in intensity are measured by using a portable powermeter connected to the output optical fiber of the waveguide. The measurements by the powermeter are reliable and reproducible and does not require further post image processing. This detection method makes the measurements real-time.

In the text following, we introduce the sensor working mechanism, explain the experimental procedure and discuss the obtained experimental results.

2. Working mechanism

2.1. Sensor configuration

As described above, the current proposed sensor is based on the L^2 waveguides. The schematic of the sensor structure is shown in Fig. 1. In this sensor, one of the cladding streams is considered as the “Reference Cladding” with the known RI (n_{ref}) and the other as the “Sensing Cladding” with an unknown RI (n_{sense}).

In order to realize several homogenous RIs for the sensing cladding, a microfluidic micromixer presented by our group [20] is integrated into the L^2 waveguide. Using this micromixer enables us to feed the sensor with new RIs without stopping the sensor and also preventing the formation of bubbles inside the waveguide. As is shown in Fig. 1, the low RI (n_i) liquid with a flow rate of Q_i and the high RI (n_{ii}) liquid with a flow rate of Q_{ii} are injected into the inlet (i) and the inlet (ii) of the micromixer, respectively, to achieve a homogenous RI, n_{sense}. The reference cladding and the core stream are fed by liquids of low RI (n_{ref}) and high RI (equal to n_{ii}) that are kept constant throughout the experiments.

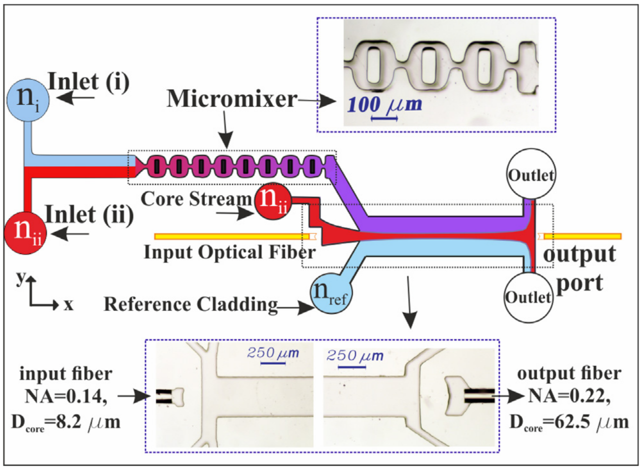


Fig. 1. The schematic of the proposed RI sensor based on the L^2 waveguide. Inlet (i) and (ii) feed the integrated micromixer with a low and high RI liquid, respectively. These two liquids are homogenously mixed as they pass through the micromixer. The mixed liquid has an RI of n_{sense} and forms one of the cladding streams of the L^2 waveguide. The core stream is fed by a high RI liquid (n_{ii}) and the Reference Cladding is fed by a low RI ($n_{ref} = n_i$) liquid. The waveguide is excited by a single mode optical fiber and the output light is captured using a multimode optical fiber. The insets in this figure show the optical micrograph of the different parts of the fabricated sensor. The fabrication procedure is described in Section 3.1.

Table 1
The properties of materials used in this study.

Symbol	Parameter	Value (@ 25 °C, 100 KPa)
n	Refractive index	1.432 for ethylene glycol 1.333 for DI water
D	Diffusion Coefficient	$1.16 \times 10^{-5}\,cm^2\,s^{-1}$

Since it is desirable to observe the sensitivity of the sensor to the changes of n_{sense}, we have to keep $Q_i + Q_{ii}$ as constant since it is shown that the changes in flow rate can lead to the variations in power as well [19]. In order to introduce an input port for the waveguide, a single mode optical fiber and a multimode optical fiber for capturing the output light are employed.

2.2. Generating different RIs via micromixer

As it is shown in Fig. 1, the planar micromixer consists of 8 mixing chambers with rectangular obstacles. We have carried out the Computational Fluid Dynamics simulations along with the time-independent continuity equation and the mass balance equations to show the mixing capability of the planar micromixer. The simulation procedure and governing equations are given in [19,20].

The RI of the materials used in these simulations and the following experiment are shown in Table 1 as extracted from [21,22]. The results of simulations are shown in Fig. 2(a). These simulations performed by choosing different sets of (Q_i,Q_{ii}) reveal that the liquids are well-mixed after passing the micromixer. It is notable that in all of the simulations and the following experiment, $Q_i + Q_{ii}$ is kept constant as explained in Section 2.1. It can be shown that the RI of the mixed liquid after passing through the micromixer can be calculated to be:

$$n_{sense} = \sum_{j=i,ii} n_j c_j = \sum_{j=i,ii} n_j \frac{Q_j}{Q_i + Q_{ii}} = \frac{n_i Q_i + n_{ii} Q_{ii}}{Q_i + Q_{ii}}; \tag{1}$$

According to (1), the RI of the mixed fluid in 9 sets of (Q_i,Q_{ii}) is calculated and shown in Fig. 2(b). This graph and the simulations in Fig. 2(a) shows that the RI increases as the flow rate of the high RI liquid (Q_{ii}) is increased.

2.3. Theoretical results

Based on the Navier–Stokes equation, the width of the sensing cladding, w_{sense}, can be expressed as [23]:

$$w_{sense} = W_{channel}[1-1/(1 + 2\eta_{sense}Q_{sense}/2\eta_{co}Q_{co})] \tag{2}$$

where η is the viscosity of fluid, Q_{co} is the flow rate of the core stream and $W_{channel}$ is the width of the microchannel. As the concentration (i.e. RI) of the sensing cladding is increased, its viscosity increases as well [24]. This increase in the viscosity will increase the width of the sensing layer. For example, if the RI of the sensing cladding is increased from 1.333 (corresponding to pure DI water) to 1.393 (corresponding to the 60% Ethylene glycol aqueous solution) at the same flow rate, the viscosity is changed from 0.894 mPa s to 5.021 mPa s [24]. This increase in the viscosity leads to the increase in the width of the sensing layer from 19 μm to 87 μm which reduce the size of the core stream as well. Since the energy loss is a result of the total internal reflection, these modifications in the width of core and cladding streams change the power transmitted through the waveguide. In fact, the total internal reflection angle as defined by