Multichannel Refractometer based on Lossy Mode Resonances

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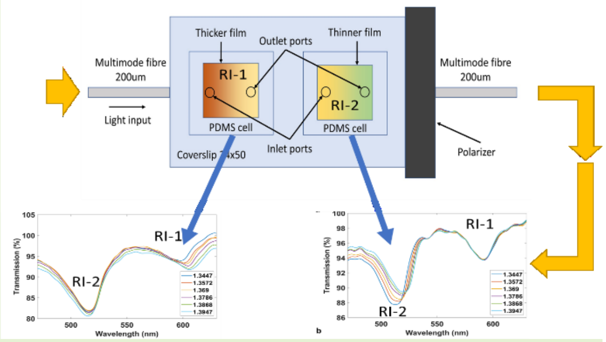
***Abstract*— In this work a new multiparameter sensor platform based on lossy mode resonances is presented. The structure consists of a soda-lime optical slab waveguide butt-coupled to multimode optical fibers. A variable thickness thin-film is deposited to generate multiple independent resonances on the same waveguide, which can be monitored using a single spectrometer. In order to show the potentiality of the structure, a broad resonance was selectively narrowed by etching sections of the LMR producer thin film. The spectral width is progressively reduced, allowing to selectively isolate independent resonances, which opens the path for multiple LMR generation in the same spectra in a multiparameter sensing platform. The experimental results were corroborated with a theoretical analysis based on the finite difference method (FDM). As a proof of concept, two refractometers on the same waveguide were fabricated and tested using PDMS cells. This platform can be easily miniaturized in order to integrate multiple sensors at low cost, what can be of interest for the development of multi-analyte biosensors probes.**



***Index Terms*— lossy mode resonance; multianalyte refractometer, optical sensor; slab waveguide.**

I. Introduction

MULTI-PARAMETER systems based on surface plasmon resonances have found application in the fields of life sciences, material sciences and biosensing. These systems are capable of detecting in real time multiple parameters on the same substrate but for which complex image monitoring systems based on near field optics are required [1], [2], [3], [4]. Throughout the last decade, another way of multiplexing several sensors has been proposed by employing fiber optic guides using lossy mode resonances (LMRs).

LMRs [5]–[7], occur when one mode guided through a substrate experiences a transition to guidance in the thin film deposited on top of it, thus generating a coupling of light from the rest of modes guided through the substrate to the mode guided in the thin film. This leads to the generation of an attenuation band in the spectrum. Some conditions must be satisfied to this purpose: the real part of the permittivity of the thin film must be positive and greater in magnitude than its imaginary part, as well as in the materials that surround the thin film [7], [8].

LMRs present some interesting properties. Firstly, as the optimal angle of incidence of this type of resonances is close to 90º [9], optical fibers covered with thin films are an adequate platform for the generation of this phenomenon. Another property is the possibility to generate both TE and TM resonances with high sensitivity to the external medium refractive index [10], [11]. On the basis of an exhaustive analysis, some rules were proposed to improve the sensitivity, always trying to increase the three most important parameters: thin film thickness, thin film refractive index and surrounding medium refractive index [12]. Finally, it is important to mention that the ratio between the parameters involved in the sensitivity is key for the development of optimized devices. In this sense, two paths to follow are proposed: trying to bring the surrounding medium refractive index closer to the refractive index of the substrate of the structure [13], or use, for a surrounding medium refractive index under study, a substrate with a similar refraction index [8].

Many sensor applications have been obtained with different fiber optic structures to generate LMRs: volatile organic compound sensors [14], gas sensors [15], or voltage detectors

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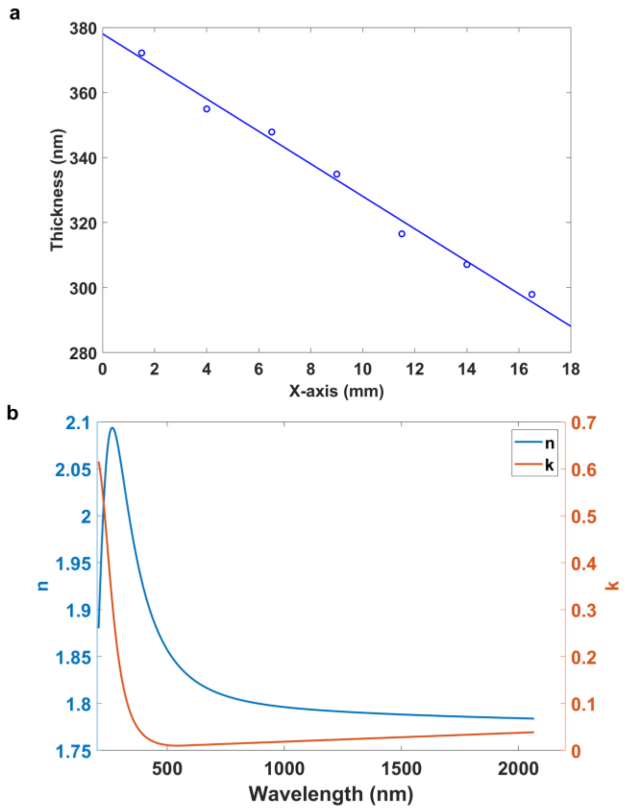

Fig. 1. (a) Profilometer based measurements of the coating thickness at different points in the axis where the gradient in thickness of the thin film is present. (b) Refractive index (n) and extinction coefficient (k) of ITO thin-film.

[16]. In the field of fluids, it is possible to detect biomarkers [17], antibodies [18], or even to use the structure as a spectro-electrochemical sensor [19].

Recently, planar waveguides have been proposed to fabricate LMR-based sensors, with similar characteristics to the D-shaped fiber structure, i.e. excitation at both TE or TM polarized light and capability to generate resonances using both sides of the substrate [20]. In addition, these structures have shown some practical advantages, such as easiness to handle and reduction of costs, opening the possibility to massively fabricate single-use sensors.

On the other hand, the ability to generate multiple resonances in the optical spectrum is of great interest as it opens the possibility to obtain multi-parameter sensors. As the resonance wavelength of LMR depends of the coating thickness [8], the best choice to obtain several independent resonances is to control the coating thickness along the waveguide. Here, a deposition method based on variable nanocoating thickness will be applied [21], allowing a single deposition on a planar waveguide structure to generate a sufficiently wide resonance in the optical spectrum, which will be separated into several resonances by a further selective etching process.

Hence, the remainder of this paper is organized as follows. Section II shows the generation of an LMR with a gradient in thickness and the further control of the shape of the LMR with an etching process. In section III, it is demonstrated the application of this technology to a dual LMR based sensing platform. Finally, some concluding remarks are given in Section IV.

II. LMR SHAPE CONTROL IN PLANAR WAVEGUIDES

A. Deposition of a thin film with variable thickness

A K675XD DC sputtering machine from Quorum Technologies, Ltd. was used to deposit a thin film on a soda lime glass coverslip from RS France (dimensions: 18 × 18 × 0.15 mm). The target for the deposition process was composed of indium tin oxide (ITO) with 57 mm in diameter, 3 mm in thickness and 99.99% purity, from ZhongNuo Advanced Material Technology. The deposition was performed under an Ar partial pressure of 8×10−2 mbar and an intensity 150 mA.

The particularity of this deposition process is that, contrary to the standard procedure, the substrate was positioned with an angle of 30º related to the plane of the target surface, which permitted to deposit a growing thickness in one of the axes of the coverslip [21]. The coating thickness was characterized with a profilometer (DektakXT from Bruker) at different points in the axis where there is a gradient in thickness. The results are presented in Fig. 1a, and they show that the film has a variable thickness between 288 and 378 nm.

In addition, an ellipsometer UVISEL from Horiba Scientific Thin Film Division, with a spectral range of 0.6–6.5 eV (190–2100 nm), was used to characterize the refractive index and the extinction coefficient of the thin film. The plots in Fig. 1b show the typical shape observed in other publications where no further annealing was applied to the ITO coating [11], [18]. All these values were used in the simulations performed to corroborate the results of the etching process in the next subsection.

B. Etching process to selectively shape the resonances

By depositing an LMR-generating film with variable thickness, the superimposed sum of multiple resonances is obtained. This produces a spectral response as shown in Fig. 2 (green line, before etching).

In order to show the behavior of the resonance when the length along the waveguide is being reduced, a progressive etching (using HCl) was performed.

The etching was monitored using an ASBN-W tungsten-halogen broadband source (Spectral Products Inc.) connected to one end of an MMF (Ocean Optics, 200/225 µm core/cladding diameter). The other end of the MMF was butt-coupled to the planar waveguide. The output light of the slab waveguide was received by another MMF connected to a USB2000 spectrometer (Ocean Optics Inc.) This setup permitted to monitor the wavelength range between 400 nm and 1000 nm.

Fig. 2(a) shows the registered spectra after etching different sections of the thin-film. The process consisted of 10 steps (etching 1, etching 2 up to etching 10). In each of them one tenth of the coating surface was removed. The results show that there is a progressive reduction of the LMR width, because each time a section of the variable thickness thin film was removed, the resonance was narrowed. In other words, the LMR can be

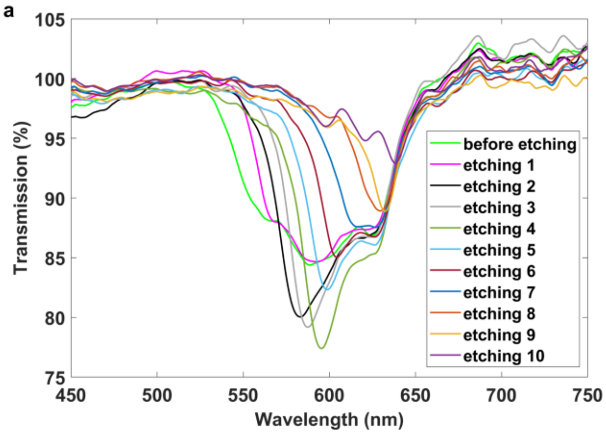

Fig. 2. Transmission spectra after each etching step, which reduces the length of the device in steps of 1.8 mm from 18 to 1.8 mm

considered as the sum of all sections removed during the etching process.

In addition, in Fig. 3, there is a representation as a function of time of the etching process. An LMR is derived from the main resonance after removing part of the nanocoating. Moreover, the same data are represented in Visualization 1 in order to observe these shifts and the progressive reduction of the LMR width, which indicates that each of these resonances contribute to the initial main dip.

C. Numerical analysis

The experimental results were corroborated with experiments in order to obtain a deeper knowledge on the phenomenon. The propagation through the slab waveguide was obtained with FIMMPROP, an integrated module of FIMMWAVE. The finite difference method (FDM) with the Quasi 2D version was used to calculate the modes and the fields in the cross section of the waveguide for a total number of 30 modes. In addition, a Gaussian source of 100 µm half width at half maximum was used according to the 200 µm multimode fibre used in the experiments for exciting the planar waveguide.

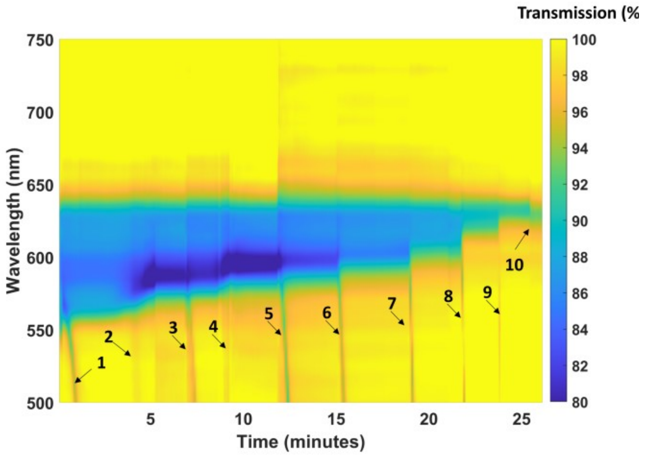

Fig. 3. Spectral evolution of the LMR as a function of time. The blue regions represent a lower power transmission due to the LMR effect. After each etching step (1 to 10), a part of the LMR is blue shifted and disappears at the same time the main LMR width is reduced.

Regarding the coverslip, made of soda lime glass, and the substrate that supported coverslip, poly(methyl methacrylate) or PMMA, their dispersion curves were also considered in the simulations [22], [23].

The simulation results in Fig. 4 confirm the same trend observed in Fig. 2. As the thin film is progressively removed, the LMR width is reduced because in each step it loses a part of the global resonance, which is the sum of the different sections.

In order to better understand this idea, Fig. 5 shows an analysis of the optical field intensity of TE_1 mode guided in the cross-section of a coverslip waveguide coated in the upper part with ITO. Ten different thickness values were analyzed representing the gradient in thickness shown by the measurements obtained with the profilometer. According to LMR theory, TE_1 experiences a transition from guidance in the substrate to guidance in the ITO thin film [24], in this case for values higher than 338 nm. In fact, it was necessary to show a zoom of the coating region in order to visualize the confinement of the field in the thin film for values higher than 338 nm. The wavelength used for the simulations was 570 nm, which is located in the middle of the broadest resonance in Fig. 2, corresponding to the case where all the coating with a gradient in thickness was analyzed.

III. DUAL PARAMETER PDMS CELL

A. Development of the sensing platform

The performance of the sensor will be tested with liquids of different refractive indices, which will induce different and independent wavelength shifts in the LMRs generated with the optical structure. After verifying that it is possible to isolate different LMRs in the transmission spectrum, a removable mask (32 × 24 × 0.15 mm polyethylene terephthalate) was placed on the surface of another coverslip to create a pattern with two deposited regions. The deposited regions (8 × 10 mm), with different thickness, will permit to generate two LMRs that are separated in the transmission spectrum. In order to obtain well defined resonances, the regions were separated 8 mm.

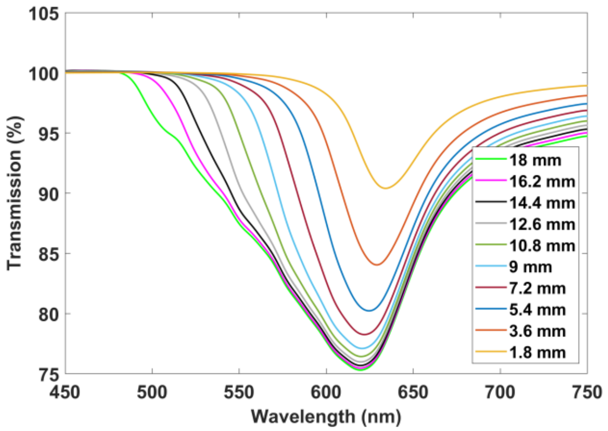

Fig. 4. Simulation with FIMMWAVE of the spectral evolution of the LMR as a function of time.

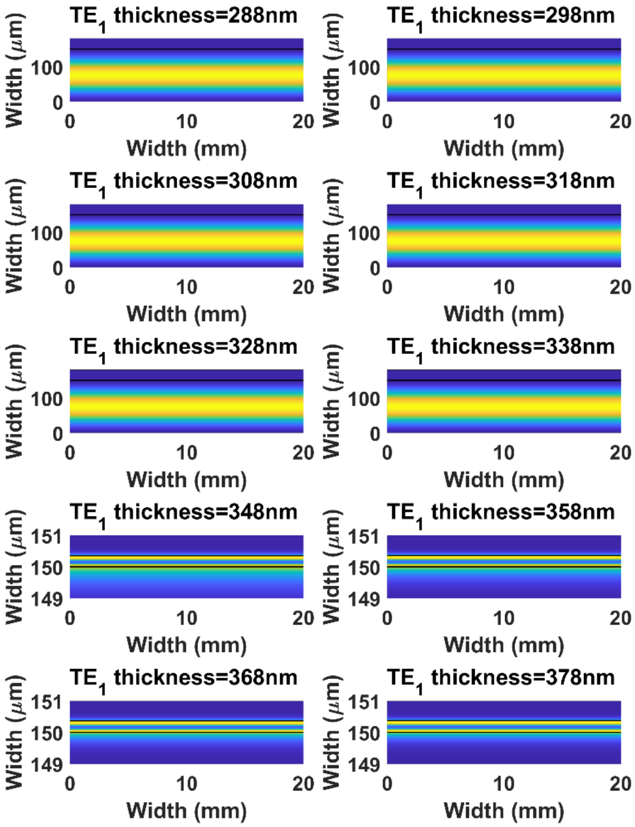

Fig. 5. Optical field intensity distribution of TE1, in the cross-section of a coverslip waveguide coated in the upper part with ITO. Different coating thicknesses were analyzed.

In each PDMS block one input and output 1 mm diameter tubes were inserted, with the aim of injecting separately liquid in the two regions with different thickness of the coverslip. In order to achieve good adhesion of the PDMS blocks to the soda lime substrate, both contact surfaces were exposed to UV ozone plasma treatment machine for 60 seconds. The surfaces are then adhered and cured in a hot plate at 100 degrees for 30 minutes.

In this way, the LMR corresponding to each region is controlled independently, though the optical part is common. In Fig. 6b a schematic of the final setup is shown, where light is launched by one edge of the waveguide and passes initially through the region deposited with a thicker coating and, after that, through the region deposited with a thinner coating. Finally, light passes through the polarizer to separate the TE or TM component.

The complete experimental setup is described in Fig. 6c, where the flow cell is connected to the peristaltic pump with the aid of a tube that is bifurcated to the output of both PDMS blocks to soak the liquid injected in both channels separately by two other tubes immersed in the liquid to inject. At the same time, the refractometer is excited and monitored with the same optical setup of section II.

B. Dual refractometer application

In order to test the sensing system, different liquids were introduced through both channel A and B. Each liquid was a solution of glucose in water at different concentration. All solutions were prepared and stirred for several minutes. Then, their refractive indices at a wavelength of 589 nm were measured with a commercial refractometer (Mettler Toledo® Refracto 30GS) with an accuracy of 0.0005.

The capability of isolating LMRs in the optical spectrum opens the path to the development of multiresonance platforms where multiple parameters can be detected. In order to test the

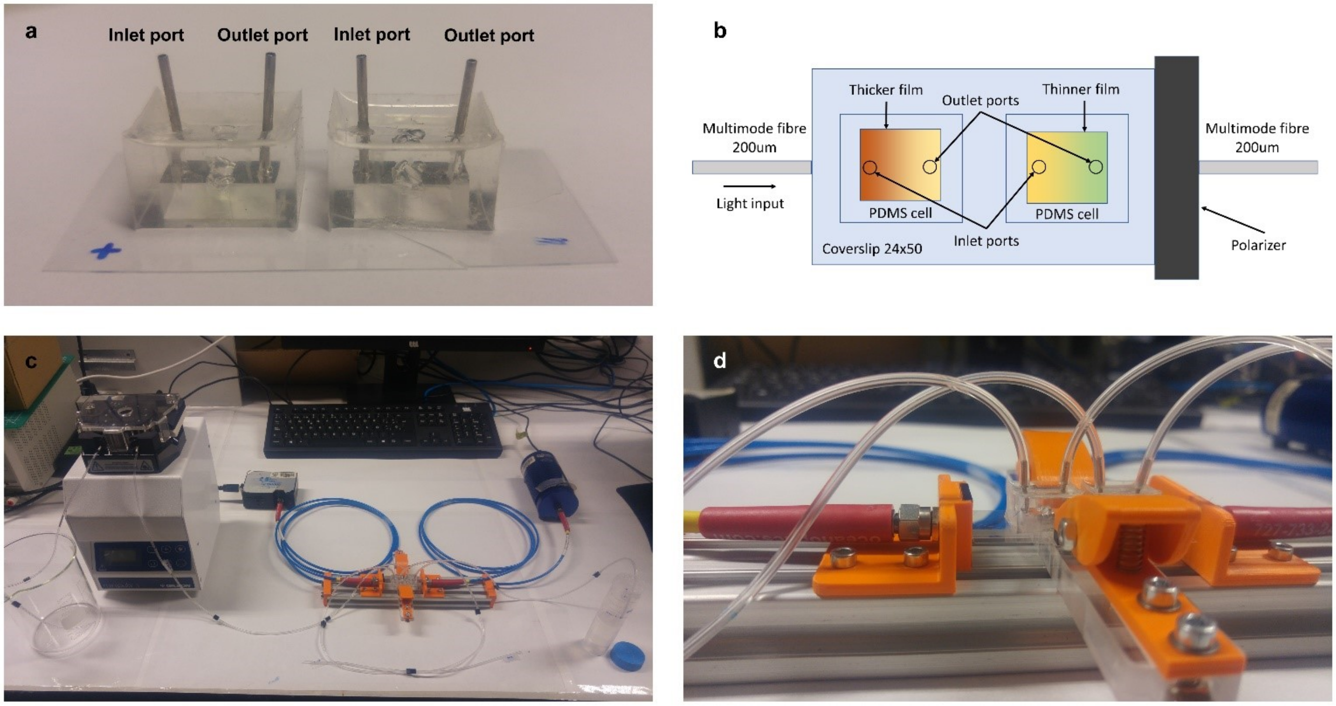

Fig. 6. (a) Coverslip deposited with a gradient in thickness and covered with two PDMS blocks with input and output tubes. (b) Schematic of the coverslip deposited with a gradient in thickness and covered with two PDMS blocks integrated in an optical setup for generation of two LMRs in the same spectrum. (c) Experimental setup for dual parameter sensing. (d) Zoom of the cell with the input and output channels.

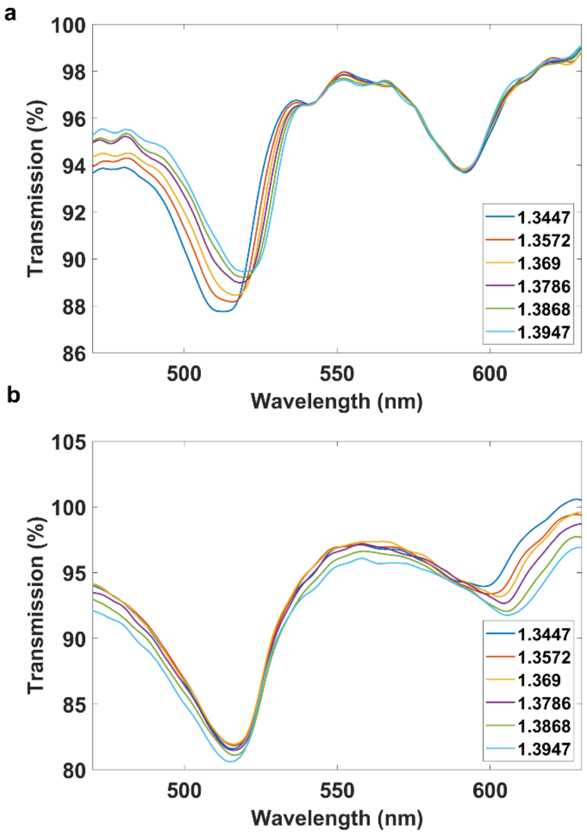

Fig. 7. (a) Transmission spectra when liquids of refractive indices ranging from 1.3447 to 1.3947 pass through channel A and a liquid or refractive index 1.3447 passes continuously through channel B. (b) Transmission spectra when liquids of refractive indices ranging from 1.3447 to 1.3947 pass through channel B and a liquid or refractive index 1.3447 passes continuously through channel A.

performance of the proposed device, two different liquids were introduced in both channels shown in Fig. 4. In Fig. 7(a) liquids with different refractive indices ranging from 1.3447 to 1.3947 were introduced through channel A, the region deposited with a thinner coating; whereas channel B, the region deposited with a thicker coating, was immersed in the index with lower index (1.3447).

The LMR located at shorter wavelengths, corresponding to the thinner coating, is shifted to longer wavelengths as a function of refractive index whilst the LMR corresponding to the thicker coating remains at the same position. In Fig. 7(b) the opposite case is analyzed, i.e. different refractive indices ranging from 1.3447 to 1.3947 were introduced through channel B, whereas channel A was immersed in the solution with lower index (1.3447). This time the LMR located at longer wavelengths was shifted as a function of refractive index whilst the LMR located at shorter wavelengths remained at the same position.

Fig. 8 shows the central wavelengths obtained with a least squares parabolic fit and the same tendency is observed. In addition, the sensitivity of the device was 143.5 nm/RIU for the LMR located at shorter wavelengths and 202.7 nm/RIU for the LMR located at longer wavelengths. The higher sensitivity at higher wavelengths is a well-known phenomenon in LMR sensors [16]. However, here the contrast is not as high as the contrast observed when comparing the first and the second LMR, where a decrease in sensitivity by a factor of 5 o 7 is obtained at TM or TE polarization with the second LMR compared to the first LMR [25].

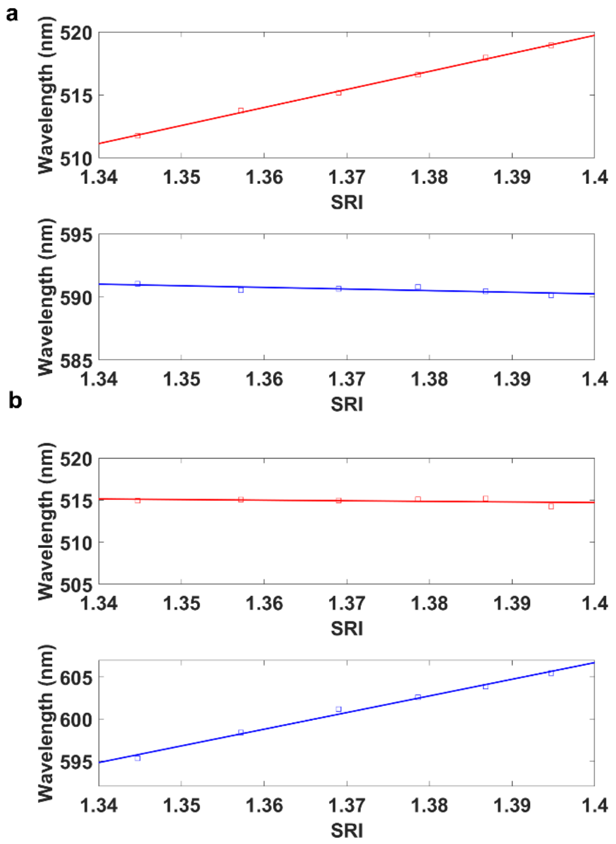

Fig. 8. (a) LMR central wavelengths when liquids of refractive indices ranging from 1.3447 to 1.3947 pass through channel A and a liquid or refractive index 1.3447 passes continuously through channel B. (b) LMR central wavelengths when liquids of refractive indices ranging from 1.3447 to 1.3947 pass through channel B and a liquid or refractive index 1.3447 passes continuously through channel A.

IV. CONCLUSIONS

Two simultaneously deposited LMRs could be used as refractometers. Resonances were generated by depositing a variable thickness thin film on a slab waveguide using a glass coverslip. A further etching process of the coating permitted to observe that the width of the LMR can be progressively reduced, and that it is possible to generate more than one LMR in the same optical spectrum and physical substrate.

This dual lossy mode resonance (LMR) optical sensor was integrated in a sensing platform where the refractive index of two different liquids were independently measured. The sensitivity, around 200 nm/RIU, corresponds to the second order LMR, which is much less sensitive than the first order one. Consequently, there is great margin for improving the sensitivity. In addition the path is open to the generation of multiple resonances for multi-parametric sensing, which is the final long-term objective of this work.

In future designs, it will be taken into account that it is possible to reduce the area of the thin films that generate LMRs and thus the channels may be narrower, making it possible to analyze substances in the order of microliters, which generates reduction of costs in experiment with very expensive analytes.

Regarding the domains of application, as stated in the introduction, chemical sensors and biosensors require multiparameter sensing.

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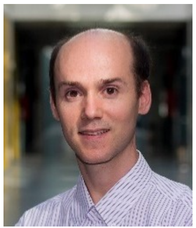

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