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Planar Waveguide LMR based Sensors: Engineering the depth of characteristic curves

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Abstract—Lossy mode resonance (LMR) based sensors have been proved as one of the exponentially growing research fields since last decade. These sensos have demonstrated their capabilities in the detection of several physical, chemical, and biological entities such as refractive index, humidity, gases, enzymes etc. Conventionally, LMR based sensors are developed using optical fiber as sensing platform, but to increase the broad range of application and better tunability planar waveguide substrate for LMR realization are introduced in last few years. This provides a greater degree of freedom for sensor design such as tunability in substrate thickness, material, and better surface immobilization. Current study focuses on evaluating the effect of substrate thickness on LMR based optical sensor to achieve higher sensing performance. For experiments, 150 µm thick glass cover slips are used as thin planer substrate are used, which is then coated with a few nanometers thick, LMR supported SnO_2 layer using DC sputtering method. Further, to monitor the effect of changing substrate thickness, the width of glass cover slip is reduced through chemical etching process using 40% HF solution, and simultaneously, the changes in LMR spectra are analyzed. The study shows that the depth of LMR curves strongly dependent on the thickness of waveguide providing LMRs with lower substrate thickness possess the higher depth. Greater depth in LMR curves is a crucial factor in identifying the minimum transmission wavelength of resonance, making it easier to track and detect the targeted parameter. This characteristic greatly enhances the applicability of LMR-based sensors in industrial applications.

Index Terms— Full width half minimum (FWHM), lossy mode resonance (LMR), optical sensors, waveguide.

I. INTRODUCTION

In the past decade, technological advancements have propelled the field of optical sensing, enabling significant progress and expanding its applicability for real-world commercial device applications. In this field, optical fiber sensors are one of research areas that have shown a greater growth due to their utilization towards surrounding refractive index sensing, chemical and biological sensing, providing applications in ease flexibility, online monitoring and remote sensing, [1]. Several sensing mechanisms have been integrated through incorporating optical fiber substate as sensing platform intrinsically and as well as extrinsically. A few of them includes evanescent wave-based sensors [2], grating based sensors [3], interferometry-based sensors [4], and thin film resonance-based sensors [1]. Considering the thin film based optical sensors, two main mechanisms are broadly used: surface plasmon resonance (SPR) and the other is lossy mode resonance (LMR). SPR based sensors are divided in two main categories: propagating (or extended SPR) and the other is localized SPR (LSPR). The first is achieved through depositing a few nanometres thick plasmonic (usually noble metals such as Ag, Au) film over the unclad core of fiber [5], while LSPR is achieved through depositing the plasmonic nanostructures over the fiber optic substrate [6], [7]. On the other hand, in case of LMR based sensors, metal oxides or polymeric materials with nanoscale thick film are used [8]. The reason is, surface plasmons can only be supported where real part of permittivity of the materials present at the interfaces shows opposite sign [9], while LMRs can be generated when the real part of the thin film is positive and higher than the own imaginary part as well as the medium surrounding including the waveguide and outer sensing medium [10].

The SPR based sensors have been a tremendous development in almost last three decades and considered as one of the gold standard techniques in chemical/biosensing application. Several propagating SPR based commercial devices are present in the market now, which can provide a minimum refractive change up to the order of 10^{-7} [11]. Similar to propagating SPR, a high number of studies fiber optic LSPR based sensors are also reported in the literature and demonstrated applicability for industrial applications [12]–[18]. However, LMR based sensors were introduced a bit later and since then its growth have shown significant comparative potential for biosensing applications [19], [20]. The basic advantages of LMRs over SPRs are the higher

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tunability of LMR supported materials, overcoming the limitation of light polarization, etc. Additionally, one can select the LMR working wavelength based on material thickness as the optical spectrum is directly dependent to the thin film thickness. And another interesting point is that multiple LMRs can also be generated both in TE and TM polarization.

One important parameter for developing a sensor for commercialized application is the sensitivity (change in resonance wavelength per unit refractive index), where LMR based sensor also show a great competition with SPR. Numerous studies reports the sensitivity improvement in LMR based sensors through different materials in the substrate and as well as the LMR thin film properties. In addition, certain special fiber geometry such as D-shaped fiber as substrate for LMR sensor has shown an improved full width half minimum (FWHM) compared to conventional multimode fiber, which permits to improve the sensitivity[21]. In this study, the high sensitivity is obtained for a broad regime of refractive index covering from water refractive index (1.33) to the refractive index of fused silica (1.45) [22]. The study is performed using indium tin oxide (ITO) as LMR support layer deposited on D-shaped fiber substrate, possessing the highest sensitivity of 304,360 nm/RIU for surrounding RI of 1.45, while in case of surrounding RI of 1.33, the sensitivity of obtained as 5,855 nm/RIU. Additionally, using tin oxide (SnO_2) as LMR layer, the RI sensitivity around water is obtained as 14,510 nm/RIU. The high sensitivity using D-shaped is obtained due to the fact the fiber geometry allows the light coupling from single mode guided from fiber core to the modes in LMR supported thin films. Additionally, the structure can provide distinguish TE and TM polarizations due to the non-cylindrical geometry, which help to avoid overlapping [22]. Furthermore, studies to obtain highly sensitive LMR based sensors are reported such as tapered optical fiber with uniform core and ITO as LMR material showing the sensitivity of 18,425 nm/RIU[23], photonic crystal fiber with an exposed core possessing the extremely high sensitivity of 67,000 nm/RIU for RI range of 1.33-1.39 rubber polymer/TiO_2/HfO_2 tri-layer [24] .

As mentioned, a broad range of sensors have been implemented using optical fiber as a sensing platform. Our group has been able to replace the optical fiber by a planar waveguide configuration, which provides more feasibility towards developing commercial devices. Preliminary advantages are the ease of thin film deposition, biofunctionalization, high degree of substrate tenability, etc. For planar waveguide configuration, the light is launched laterally at the edge, allowing the almost 90° incidence at the edge, which also increases the device robustness as it removes the additional fiber splicing requirement each time. Furthermore, after guiding the light from the waveguide, the polarizer can be used to block additional polarizing component and it the polarizing stage can be changed from TE to TM just by rotating the polarizer. Hence, the planar waveguide can also have the advantages of cost reduction, higher range of application such as generating two or multiple LMRs on single substrate [25], SPR and LMR on a single chip platform [26] and many more. Recently, our group has reported the sensitivity enhancement of planar waveguide based LMR based sensor and successfully achieved a high sensitivity of 41,034 nm/RIU for RI ranges from 1.3318 to 1.3347 [27]. In the study, we showed that lower refractive index of planer substrate provides increased sensitivity of LMR based sensors.

However, it is worth mentioning that the depth of LMR curves is also one essential parameter in addition to the sensitivity as a deeper LMR curve will help to recognize the resonance wavelength more precisely and quickly. In one of our previous studies, it is already mentioned that thin waveguide substrate provides more deeper LMR curves while working with 500 µm thick PFA substrate and 160 µm thick coverslips [27]. Hence, a preliminary effort has been made to obtain almost zero transmittance dip at resonance by changing the thickness of LMR substrate. The concept is proved by continuously monitoring the LMR curves when thickness of substrate is decreasing through the etching process.

II. EXPERIMENTAL DETAILS

A. LMR Chip Fabrication

As mentioned in previous section, the coverslips for a microscope glass slide (18x18 mm) with 160 µm thickness provide deeper LMR curves compare to the thicker substrate. Hence, we used the same coverslips as optical waveguide and a thin film of SnO_2 was deposited using a DC sputtering system. During the chip fabrication, the deposition rate is maintained at 0.15 nm/sec with current intensity around 150 mA in presence of Argon having the pressure of $8x10^{-2}$ mbar. It is to be noted that the whole chip was not covered with SnO_2 thin film to get rid of possible interference from the SnO_2 deposition on lateral faces of cover slip.

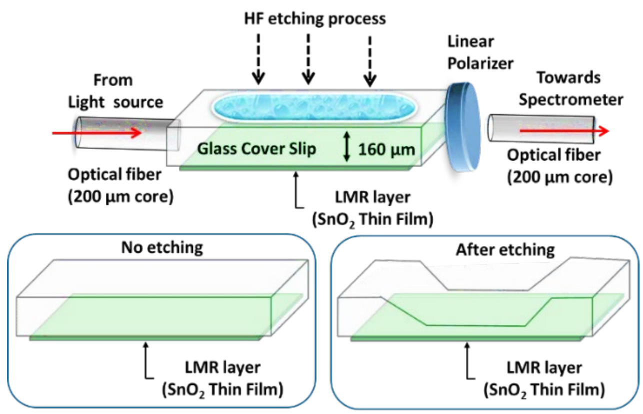

Fig. 1. Experimental Setup for monitoring LMR curves.

In order to find the effect of decreased thickness of coverslip, the bottom face of chip was etched by 40% hydrogen fluoride (HF) and the corresponding LMR transmission was continuous monitored using the experimental setup as shown in Figure 1. During the etching process, the LMR supporting material was kept isolated to avoid any kind of reaction with HF.

B. Experimental Setup

Figure 1 depicts a pictorial representation of the experimental setup. A TAKHI-HP white light source from Pyroistech, was used to launch the light at the one end of the SnO_2 deposited cover slip using conventional multimode fiber with 200 µm core. At the output edge of the chip, the light was passed through a linear polarizer LPVIS050 from Thorlabs to collect only TM polarized light, which helps to avoid additional effects of TE polarized light and achieve sharper LMR curves. Finally, the output light is collected using another multimode fiber with 200 µm core and passed to UV-Visible spectrometer (Ocean Optics USB4000). More details of the experiment can be found elsewhere [25].

III. RESULTS AND DISCUSSIONS

A. LMR Characterization

The fabricated chip was kept in the experimental setup as shown in Figure 1. The chip was mounted reversed as shown in the setup such that there should not be any effect of HF fumes on the SnO_2 layer. It is also worth mentioning that the experiments were done having air as surrounding material. In the next step, 40% HF was dropped on the other interface of the cover slips to start the etching process. The chip was regularly cleaned few times in between to remove the glass residues. LMR curves were recorded with the spectrometer simultaneously. The dynamical evolution of the LMR curve is shown in Figure 2 (a), which clearly shows that the depth of the curves increases as the thickness of waveguide decreases. Figure 2(b) shows the microscopic image of the final chip, where a minimum transmission of 20% was obtained with around 35 µm thick coverslip. However, we would like to mention here that we could have achieved even lower transmission with lesser thickness, which was possible with slow rate etching, as we were limited by spectrometer response and fast etching.

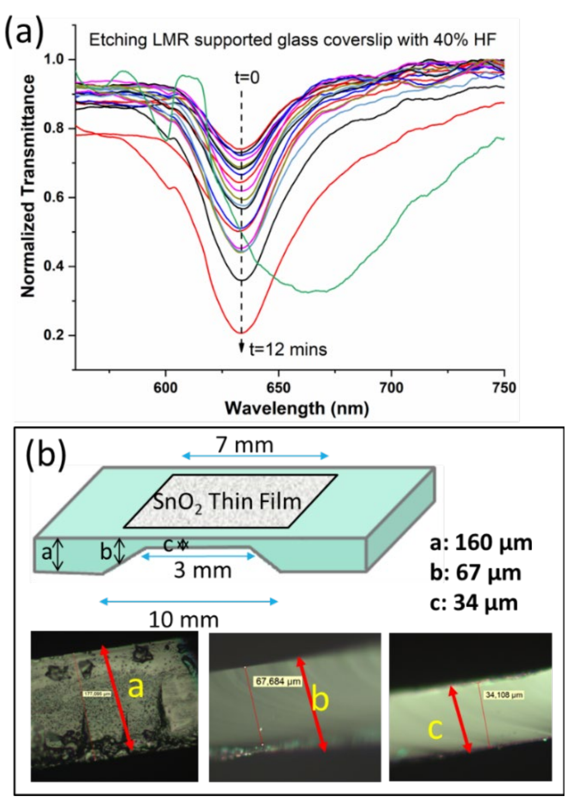

Fig. 2: (a) Evolution of LMR depth with respect of etching time, (b) Microscopic measurement of the final chip at minimum transmittance, shown in figure 2(a).

B. Dynamical Transmittance and FWHM

Figure 3(a) shows the changes in the transmittance at resonance wavelength with time, which also concludes that LMR depth increases as etching time increases (thickness of coverslips decreases).

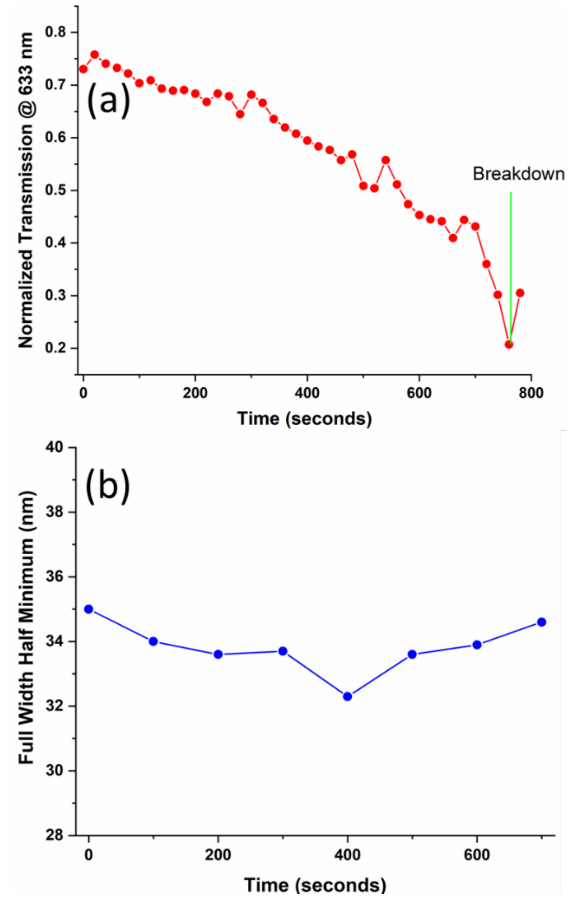

Fig. 3. Dynamic change in (a) Transmittance at resonance wavelength (633 nm) and (b) Full width half minimum (FWHM) as etching progresses.

The chip breakdown was obtained within 700 seconds. However, no significant change in the broadening of LMR curves is found as FWHM remains the same during the etching progresses, as shown in figure 3(b). Additionally, getting back to figure 1(a), one can also conclude that the resonance wavelength does not have any effect by changing the waveguide thickness. This also concludes that the sensitivity of the LMR device is not mainly dependent on substrate thickness but any LMR curve with high sensitivity with a very small dip also makes the sensor difficult to translate for commercial purposes.

It is worth noticing that the figure of merit (FOM) is a key parameter used to evaluate the performance of a sensor, calculated as the ratio of sensitivity to the full width at half maximum (FWHM). A higher FOM can be achieved by increasing sensitivity or by sharpening the characteristic curve (reducing FWHM or using curves with shallower slopes). However, it's important to consider the depth of the curve as well, as it plays a significant role in the sensor's performance. A greater depth in the curve enables easier identification and tracking of the minimum point. To illustrate this point, let's consider a sensor response with a high FOM but only 10% depth. In such a scenario, it would be challenging to accurately identify and track the minimum. On the other hand, a sensor with nearly 100% depth would excel in these tasks. This also provides an additional advantage of minimum detection errors as compared to the LMR curves with similar FOMs and different depth.

IV. CONCLUSIONS

To summarize, a first principal study has been done to identify the effect of the waveguide thickness on LMR curves. The study was performed using SnO_2 deposited glass cover slips. The thickness of coverslip was reduced by chemical etching method and, during the etching process, LMR spectra were recorded simultaneously to obtain the real time changes. Results showed that depth of LMR curves increases as waveguide thickness decreases. However, it is worth noticing the FWHM and sensitivity of LMR curves is unaffected by the waveguide thickness, but the study becomes quite significant to obtain the zero transmittance at resonance, helping to find the resonance more accurately. Difficulties in tracking the minimum not only increase the time required but also raise the possibility of errors when measuring the resonance wavelength. This complexity necessitates the use of more advanced algorithms for minimum detection, making it time-consuming for real-world industrial applications. Furthermore, sensors with higher depth offer better sensitivity for intensity-based measurements compared to others, making them more suitable for industrial applications. In the next steps, ultra-thin waveguide with low refractive index will be used to obtain high sensitivity at the same time sharp LMR are obtained [27].

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