

Experimental Demonstration of Refractive Index Sensor Based on Lossy Mode Resonance with Planar Optical Waveguide Configuration

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ABSTRACT

A refractive index sensor based on lossy mode resonance technology and optical planar waveguide is presented experimentally. The sensing device is an optical planar waveguide (OPW) with a thin-film layer of Indium Tin Oxide (ITO) deposited. Besides, we design a self-alignment platform for light coupling through optical fiber instead of traditional prism coupling techniques. Therefore the repeatability of our measurement platform is very high and the LMR variation is below 2.7 nm. Characteristics of the LMR sensor with different ITO thicknesses have been studied. Its sensitivity can reach 456.7 nm/RIU. The sensor has some merits, e.g. easy alignment, high mechanical stability, simple fabrication process and lower cost for mass-production. This OPW structure of refractive index sensor based on LMR technology is valuable for chemical, biological, and biochemical sensing development potential in the future.

Keywords: lossy mode resonance, planar optical waveguide, sensor, ITO thin film, refractive index

以實驗展示基於損耗模態共振型原理的平面波導結構折射率感測器

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摘要

此論文以實驗展示了基於模態損耗原理及光波導原理的折射率感測器。研究中，我們設計了一種自動對準平台，利用光纖進行耦合，而不是傳統的稜鏡耦合技術。因此，我們元件的 LMR 量測結構的可重複性非常高，LMR 波長的變動可低於 2.7 nm 以下。研究中也發現具有不同 ITO 厚度的 LMR 傳感器的特性，其靈敏度可達 456.7 nm / RIU。此外，感測器具有易於對光、高機械穩定性、製程簡單及大量生產成本低等優點，使得這種基於 LMR 技術的折射率感測器對於化學、生物和生物感測具有重要價值與發展潛力。

關鍵詞：損耗模態共振，平面光波導，感測器，氧化銦錫薄膜，折射率

I. INTRODUCTION

As it has been reported in previous works, thin-film overlays fabricated onto the core of optical fibers can produce selective optical power absorption at certain wavelengths, also known as resonances [1, 2]. Different types of resonances can be described according to the dielectric properties of the outer thin film surrounding the optical waveguide. Thin film coating of optical waveguides with semiconductor or metallic materials has become a widely explored technique in the field of sensors. The most well-known phenomenon is surface plasmon resonance (SPR), which can be obtained when the material meets some specific criteria: the real part of the thin-film permittivity must be negative and higher in magnitude than both its own imaginary part and the real part of the permittivity of the material surrounding the thin-film (i.e. the optical waveguide and the surrounding medium in contact with the thin-film) [3, 4]. In recent years, SPR sensors have been extensively studied because of many applications ranging from biomaterial [5, 6] inspection, chemical detection [6, 7], gas monitoring [8, 9] and physical sensing etc. [10]. Another lossy mode resonances (LMRs) explained as a coupling between optical waveguide modes and a lossy mode of a semiconductor-clad waveguide were demonstrated by Marciniack [11]. In that publication the LMRs were observed with a wavelength sweep. This phenomenon is not limited to semiconductor claddings but it can be also observed for dielectric claddings. In fact, LMRs occur when the real part of the cladding permittivity is positive and higher in magnitude than both its own imaginary part and the real part permittivity of sampling materials. The generation of LMR with absorbing thin films was analyzed with electromagnetic theory [4, 12-15]. The LMRs modal as a function of wavelength for thin film coated on cladding removed silica optical fibers has been presented.

From the point of view of cost effective fabrication in order to generate LMRs, many materials can be used with the only condition of having optical losses rather than using expensive noble metals, such as gold or silver. From another point of optical performances, LMRs

can be generated for both TM (transverse magnetic) and TE (transverse electric) polarizations. Furthermore, carefully choosing the material could yield almost the same spectral band for both the TM mode and TE mode of LMR. It would enhance the signal-to-noise ratio of LMR sensors. So, the utilization of an optical polarizer, such as the SPR devices need, can be avoided. This simplification encourages the development of LMR sensors where only a wide-band light source and an optical spectrometer are necessary to set up the measurement. Compared with prism based LMR sensors [16, 17], optical fiber LMR sensors are fundamentally simpler in construction, less costly, more portable, more convenient to use and moreover, it provides an on-line remote detection of the refractive index variation of the bulk medium owing to optical fiber network implemented and wavelength spectrum integration adopted. So, during recent decades a lot of research has been dedicated to LMR sensors based on optical fiber type [18-26]. However, optical fibers are frangible and not easy to handle during the cleaning procedures, coating processes and surface modification for special target detection. Especially, in order to enhance the sensitivity to a certain physical parameter, the guiding properties of the fiber have to be weakened. The side polishing method for the removal of a portion of the cladding and core of silica fiber are often used. Such sensing structures are not conducive to mass production in the future.

Although, LMRs have been widely demonstrated experimentally using dielectric coated optical fiber [18, 19, 21, 25, 27-29]. The main reason for this is that SPRs are obtained typically for angles ranging between 40° and 70° [30], whereas LMRs arise typically at near-grazing angle incidence, i.e., angles approaching 90°, which are adequate for optical fiber excitation or OPW endface coupling if light is directed onto the lateral sides. In addition, the OPW sensor demonstrates the advantages of easy alignment, high mechanical stability, and simple fabrication processes. The great potential of LMR based sensor technology for the detection of chemical and biological substances has been receiving growing interest from the scientific community. Therefore, in this paper, we propose planar glass as an optical waveguide

substrate and combined with the industry's mass production of mature ITO coating technology to develop a LMR sensor to detect surrounding different refractive indices and calculated its sensitivity. As per our knowledge, no study has been published on combining advantages of LMR and OPW.

II. EXPERIMENT

For generality, Fig.1 gives the three-layer configuration consisting of an OPW with refractive index n_1 , an ITO cladding layer of refractive index n_2 , and a sample layer with refractive index n_3 . The meridional cross section of this Kretschmann configuration, light is launched into one side of OPW and it is collected at the other side.

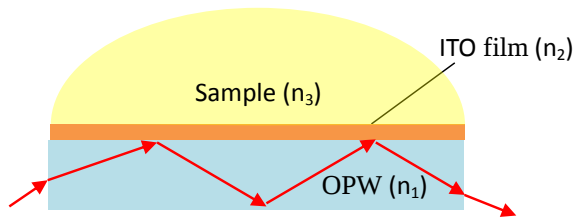


Fig.1 three-layer configuration for LMR sensor

Gorilla planar glass of 1.0 mm thickness was used as the substrate in a sputter coating process, IZOVAC Co. supplied the equipment, with a partial pressure of argon of 9×10^{-2} mbar and intensity of 160 mA. The resulting station had a gas system based on 2 MFC (Ar and O_2). Each magnetron had 3-zone gas distribution system with manual needle valve for uniformity adjustment. The magnetrons were powered by 10kW DC power supplies. Base vacuum before the process start, was 5×10^{-3} Pa. The operation gases were argon 99.99% purity and oxygen 99.99% purity. The ITO target, 99.99% of purity, was purchased from Solar Applied Materials Technology Co. Three kinds of LMR sensor with different ITO thicknesses of 80 nm, 100 nm and 120 nm were deposited by controlling sputter duration. The solutions with different refractive indices used to characterize the refractive response of the device were prepared by adjusting the concentration of glycerol in pure water, from 0% to 100% in step of 20%. The refractive indices of samples were verified with hand held refractometer, R-5000 from

ATAGO Co. The picture for the 20% concentration of glycerol is shown in Fig.2 and the relationship between the refractive index and concentration of glycerol solutions is summarized in Table I.

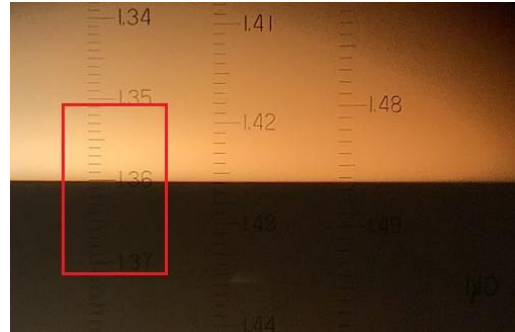


Fig. 2 the picture of refractometer for the 20% concentration of glycerol measurement.

Table I Refractive index of glycerol solution.

concentration	RIU
0%	1.3320
20%	1.3601
40%	1.3895
60%	1.4180
80%	1.4400
100%	1.4670

We used a halogen white light (4303B from ANDO Co. Ltd.) with wavelength of 400~1800 nm worked as the input source and the optical spectrometer (USB 2000+ from Ocean Optics®) as the receiver to measure the spectrum of sensor. A schematic giving the details of experimental setup is shown in Fig.3(a). The photo graph of the LMR sensor with the alignment bulk platform displays in Fig.3(b). An optical fiber patchcord with FC connector from light source was inserted into the hole of the right side and another optical fiber patchcord with SMA connector is inserted into the left side, which links to spectrometer. Both the optical fiber patchcords were 400 μ m in core diameter. For the purpose of self-alignment, the bulk platform was design to fit all components and the optical axis was along with the center of OPW. Since all the mechanical parts were well

designed and within 10 μm deviation, there is no need for precise alignment tools in the setup. The coupling loss was about -1.8 db, which occurred mainly at the optical fiber/air interface and fiber/waveguide misalignment. However, this is a multi-mode optical fiber/waveguide system and the optical power is much larger than the single mode fiber system. So, the coupling loss is not the critical issue. For our LMR measurement, the background light was deducted to reduce the influence of coupling loss. At first, we recorded the spectrum without any liquid but the air surrounding the sensing region as referenced spectrum. Then, we introduced drops of different samples without disturbing optical fiber and LMR sensor and recorded the spectrum, respectively. Finally, all the data were calculated by transmission definition.

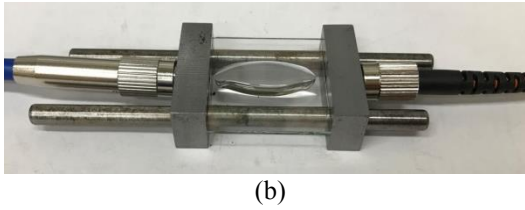
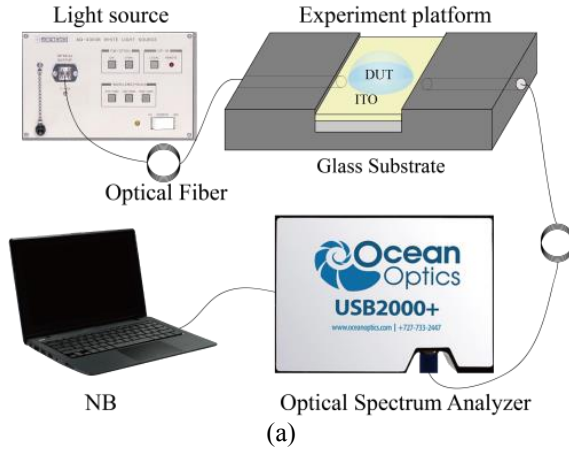


Fig.3. (a) LMR measurement system diagram; (b) photo graph of LMR sensor and alignment bulk platform.

III. RESULTS

The light was directed at the ITO coated surface through an optical fiber at a fixed position and adsorption induced changes on the sensor surroundings were observed by monitoring the changes in wavelength where the LMR minimum occurred. These shifts were

converted into the changes in bulk index of refraction of glycerol/water solution. The stability of an experimental platform determines the credibility of the experimental data, so we do repetitive experiments on the measurement platform in advance to verify its repeatability. We repeated dropping some pure water on the three kinds LMR sensors for 10 times to observe the LMR phenomenon and verified the repeatability of the experimental platform. The LMR wavelength variation are 2.5 nm, 2.4 nm and 2.7 nm for the LMR sensor with ITO thickness of 80 nm, 100 nm and 120 nm, respectively, and all data are plotted in Fig. 4. The results show the LMR measurement platform is stable and its variation is as low as 2.7 nm, which converting to percentage is about 0.34%.

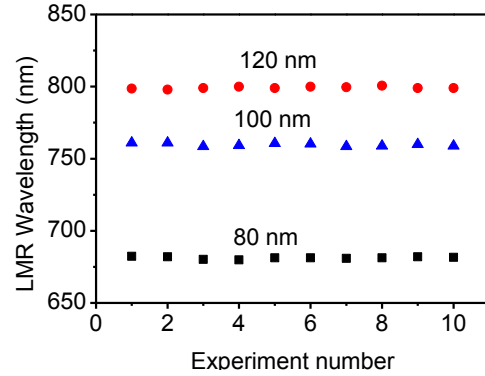


Fig. 4 Repeatability of LMR wavelength for ITO thickness of 80 nm, 100 nm and 120 nm.

Transmission spectra according to refractive index of samples from 1.3320 to 1.4670 in step of about 0.028 are shown in Fig. 5. LMR transmission curves with thickness of ITO layer (a) 80 nm (c) 100 nm (e) 120 nm; the variation of LMR wavelengths and transmission deeps responded to ITO thicknesses are shown in (b), (d) and (f), respectively. From a set of six LMR spectra for a certain ITO, it is observed that the resonance wavelength becomes longer and the transmission approaches lower as the refractive index of the solution increases. The shift of LMR wavelengths is about 60 nm for surrounding index from 1.3320 to 1.4670. Resonance wavelengths and minimum transmission deep for each sensor vary as the ITO thickness changes. In Fig. 5(b), (d) and (f) as the ITO thickness increases, the LMR spectrum shifts toward longer wavelengths

from 682 nm (ITO 80 nm) to 792 nm (ITO 120 nm) at the refractive index of 1.330 sample solution. Accordingly, the shift range is 110 nm. At the same time, the amplitude of transmission spectrum decreases from -0.91 dB to -0.68 dB. This decrease in the amplitude suppresses the increase in the LMR effect especially as ITO thickness is greater than 120 nm. So, there is an remarkable advantage of LMR devices. Their spectral position can be fine-tuned just by changing the thickness of the lossy coating.

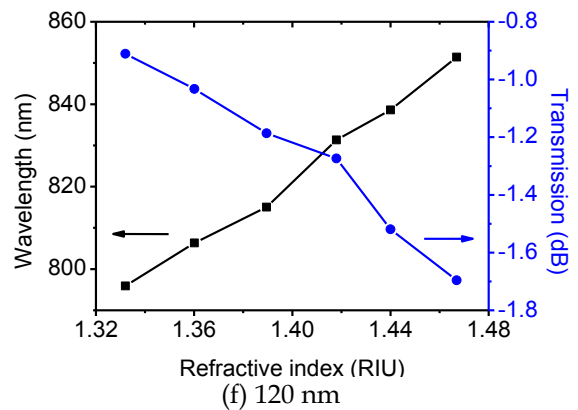
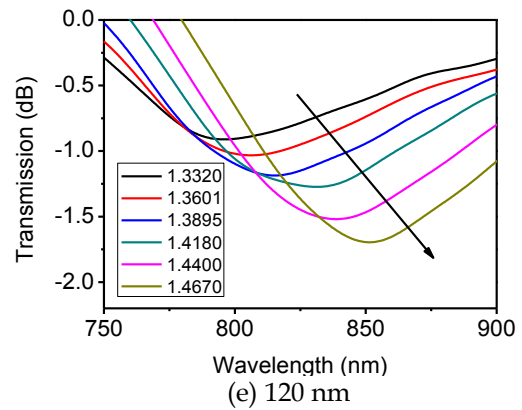
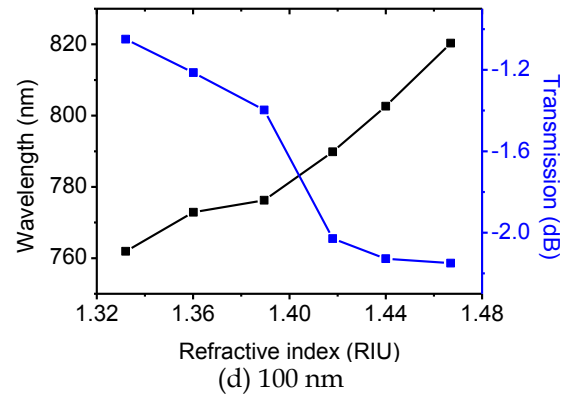
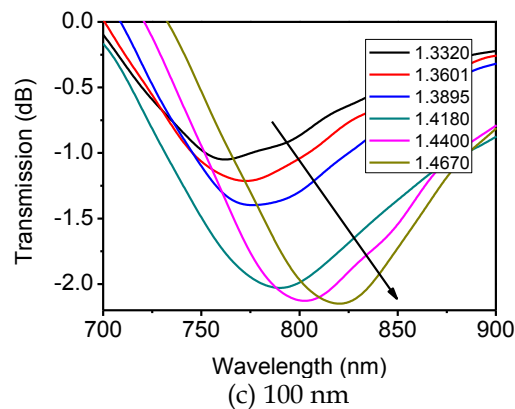
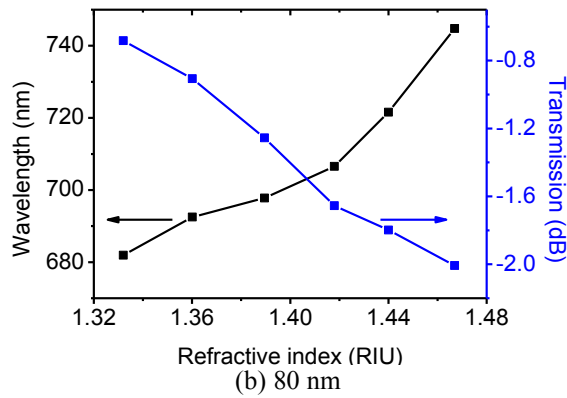
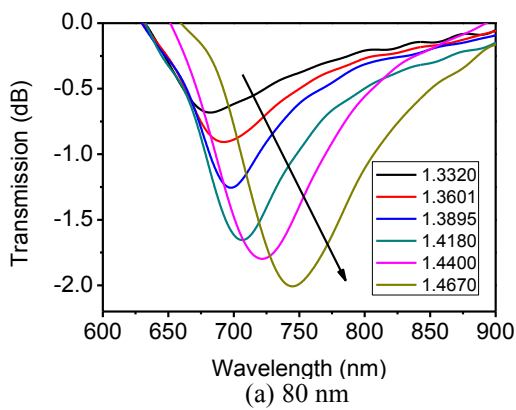


Fig.5 LMR transmission curves with thickness of ITO layer (a) 80 nm (c) 100 nm (e) 120 nm for refractive index of samples from 1.3320 to 1.4670 in step of about 0.028; the variation of LMR wavelengths and transmission deeps according to ITO thicknesses are shown in (b), (d) and (f), respectively.

Sensitivity is the ratio of change in LMR wavelength to the change in refractive index. The performance of a LMR sensor is generally evaluated in terms of its sensitivity. For a sensor, it should be as high as possible. Larger the shift of LMR wavelength is, higher the sensitivity will be.

If the refractive index of the sensing sample is altered by δn , the resonance wavelength shifts by $\delta \lambda_{res}$. The sensitivity (S_n) of an LMR sensor with spectral interrogation is defined as eq.(1).

$$S_n = \frac{\delta \lambda_{res}}{\delta n} \quad (1)$$

To calculate the sensitivity, LMR wavelengths are plotted as a function of surrounding refractive index variation for different ITO thicknesses, as shown in Fig.6. The sensitivities according to the ITO thickness of 80 nm, 100 nm and 120 nm are plot as the slope of each fitting line in Fig.6 and the slopes are 456.7 nm/RIU, 424.5 nm/RIU and 403.5 nm/RIU, respectively. Thus in terms of above discussions, it could be concluded that LMR sensor with thinner ITO displays good sensing behavior and approaches high sensitivity 456.7 nm/RIU. The resolution (Δn) of the LMR sensor can be defined as the minimum amount of change in refractive index detectable by the sensor. This parameter definitely depends on the spectral resolution ($\delta \lambda_{meter}$) of the spectrometer used to measure the resonance wavelength. Therefore, if there is a shift of $\delta \lambda_{res}$ in resonance wavelength corresponding to a refractive index change of δn , then resolution can be defined as eq.(2) and the calculated result was 2.2×10^{-4} in the experiment.

$$\Delta n = \frac{\delta n}{\delta \lambda_{res}} \cdot \delta \lambda_{meter} \quad (2)$$

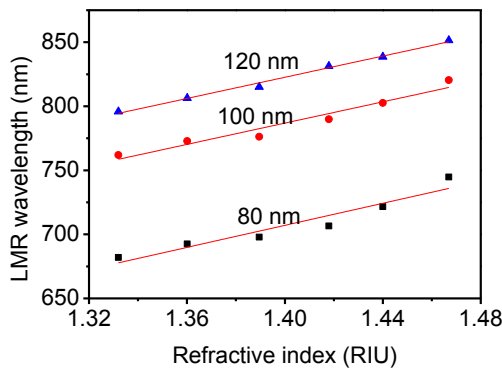


Fig.6. LMR wavelength is plotted as a function of sample refractive index variation for different ITO thicknesses of 80 nm, 100 nm and 120 nm

IV. CONCLUSIONS

The LMRs refractive index sensor has been experimentally demonstrated by means of the utilization of ITO-coated planar optical waveguide for the first time. The ITO thickness is the key parameter to adjust the LMR wavelength. In terms of sensitivity, the results show that the thinner ITO results in higher sensitivity. Based on the advantages of easy alignment, high mechanical stability and simple fabrication process, the LMR sensor as a function of the surrounding sample reveals a high sensitivity device suitable in mass-production and to be used in many different applications for direct detection or as a platform to do surface-modification. Furthermore, the characteristics of adjusting ITO thickness open the possibility to the utilization of multi-sensing by using several different resonances positioned at different wavelengths within the same planar waveguide.

ACKNOWLEDGEMENTS

The authors would like to thank the Ministry of Science and Technology for financial support under the contracts MOST 106-2221-E-130-011 and thanks to Acute Touch Technology Co., Ltd for providing coating technology.

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