High sensitive refractometers based on lossy mode resonances (LMRs) supported by ITO coated D-shaped optical fibers

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Abstract: Tin doped indium oxide (ITO) coatings fabricated onto D-shaped optical fibers are presented as the supporting medium for Lossy Mode Resonances (LMRs) generation. The characteristic geometry of ITO-coated D-shaped optical fibers enables to observe experimentally LMRs obtained with both TM and TE polarized light (LMR_{TM} and LMR_{TE}). This permits to obtain a maximum transmission decay of 36 dB with a LMR spectral width of 6.9 nm, improving that obtained in previous works, where the LMRs were a combination of an LMR_{TM} and an LMR_{TE}. Surrounding medium refractive index (SMRI) sensitivity characterization of LMR_{TM} has been performed obtaining a maximum sensitivity of 8742 nm/RIU in the range 1.365-1.38 refractive index units (RIU) which overcomes that of surface plasmon resonance-based optical fiber devices presented in recent works.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2370) Fiber optics sensors; (260.0260) Physical optics; (260.5740) Resonance; (310.0310) Thin films; (310.7005) Transparent conductive coatings; (310.1860) Deposition and fabrication.

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1. Introduction

Optical fiber, owing to its intrinsic advantages (electromagnetic immunity, small size, light weight, low cost, low transmission losses and wavelength multiplexing among others), has emerged as an auxiliary or improvement tool for many sensing applications in the last decades [1,2]. Different measuring techniques have been explored, such as interferometry [3], fiber Bragg gratings [4], surface plasmon resonances (SPR) [5] and lossy mode resonances (LMR) [6].

When an optical waveguide is coated with a thin-film, the propagation of light is affected. Different types of electromagnetic resonances can be observed depending on the dielectric properties of the different materials involved in the system (waveguide, thin-film and surrounding medium) [7]. Surface Plasmon Resonance (SPR) is one of the most widely studied optical techniques [7, 8]. SPRs occur when the real part of the thin-film permittivity is negative and higher in magnitude than both its own imaginary part and the permittivity of the material surrounding the thin-film [7]. A different and less studied type of resonance is known as Lossy Mode Resonance (LMRs). This type of resonances occurs when the real part of the thin-film permittivity is positive and higher in magnitude than its own imaginary part and the real part of the permittivity of both the optical waveguide and that of the external medium surrounding the thin-film [6, 8].

However, SPR-based devices present some limitations. Firstly, SPRs are preferentially generated with conducting materials, such as gold and silver, which are expensive and sometimes difficult to use. In addition, SPR can be only generated with TM polarized light and the conditions for SPR generation are very specific within a limited spectral region and coating thickness.

On the other hand, LMRs can overcome some of the main drawbacks of the SPRs while maintaining the same or even higher sensitivity than SPRs. LMRs have been generated with many different materials, such as metal oxides [9] or polymers [10]. In addition, LMRs are generated by both TM and TE polarized light (LMR_{TM} and LMR_{TE}), as it has been theoretically [6,11] and experimentally [12] demonstrated in previous works.

This work describes the utilization of D-shaped optical fibers in order to demonstrate experimentally the distinct nature of LMRs generated by TE and TM polarized light on ITO coatings. Resonance quality factor has been also studied and compared with that of previous works based on LMR devices. In addition, the sensitivity of the device as a function of the SMRI has been characterized and compared with other optical fiber refractometers.

2. Experimental

2.1 Materials

D-shaped side-polished optical fibers, purchased from Phoenix Photonics LTD, consist of standard single mode fibers (Corning® SMF-28) with a cladding/core diameter of 125/8μm and a polished length of 1.7 cm (see detail in Fig. 1). Fiber polishing was monitored during fabrication in order to obtain an attenuation peak of 10 dB at 1550 nm in high refractive index oil (1.5). D-shaped fibers were used as the substrate in a DC sputter coating process (ND-SCS200 from Nadetech S.L.) with a partial pressure of argon of 9×10^{-2} mbar and intensity of 150 mA. The ITO target, 99.99% of purity, was purchased from ZhongNuo Advanced

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Material Technology Co. The solutions with different refractive index used to characterize the refractometric response of the device were prepared by adjusting the concentration of glycerol in water [13].

2.2 Fabrication measurement setup

The experimental fabrication arrangement is shown in Fig. 1. This setup consisted of two lasers (BCP 400A) operating at 1300 and 1500 nm. This lasers are connected to a wavelength division multiplexer (WDM), obtained from Intelnet Inc., in order to collect the light into one single output fiber. WDM output is then connected, via a through-hole, to one end of the D-shaped fiber, which is located into the sputtering chamber. The other end of the D-shaped fiber is attached via a through-hole to the single input of a second WDM. The second WDM separates both wavelength (1300 nm and 1550 nm), which are connected to two power meters (RIFOCS 575L) operating at these wavelengths.

This setup was used to monitor the optical output response at two different wavelengths as a function of the deposition time (thickness of the coating). The optical output response was collected at intervals of 1 second.

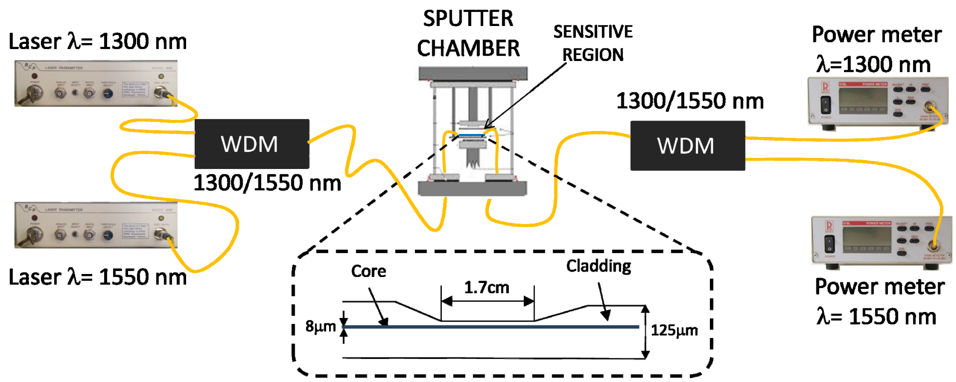

Fig. 1. Experimental fabrication setup used to monitor the ITO deposition process and detail of the D-shaped fiber (bottom).

2.3 Refractometer characterization setup

The characterization of the devices was performed using the setup shown in Fig. 2. This setup consisted of a white super luminescent emitting diode (HP_83437A - SLED) source, with an emission range from 1150 to 1680 nm, connected to a depolarizer (from Phoenix Photonics) in order to scramble the polarization of the light source. The depolarizer output is connected to a polarization controller (Agilent 9169A) used to adjust the polarization of the light that goes through the sensitive region. Then, the polarization controller is connected to the ITO-coated D-shaped fiber input and the output of the sensitive region is attached to an OSA (HP-86142A) in order to monitor the response of the device.

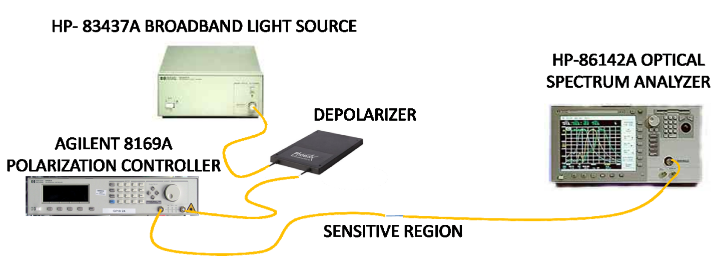

Fig. 2. Experimental characterization setup.

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3. Results

3.1 Device fabrication

The fabrication of the device was monitored using the setup described in Fig. 1. Process fabrication monitoring enables to control the device response and stop the process at the required conditions. The plot in Fig. 3 represents the optical power at the output of the fiber as a function of time for two different wavelengths, 1300 nm (continuous line) and 1550 nm (dotted line). The utilization of two different wavelengths permits to observe the displacement of the maximum absorption peaks as a function of time for different coating thicknesses. From Fig. 3 it is possible to distinguish several LMRs, four when the device is monitored at 1300 nm and three when the device is monitored at 1550 nm. More LMRs could be generated if the deposition process is continued but this is not interesting here since high order LMRs have previously shown lower sensitivities to SMRI variations [6, 8, 14]. Since previous works [11, 12, 14] revealed that LMR_{TE} is always followed by LMR_{TM} it is possible to associate the first and second peaks of the first order LMR to LMR_{TE} and LMR_{TM} respectively. It is also important to remark that the separation between LMR_{TE} and LMR_{TM} is reduced for higher order LMRs, which suggest that LMR_{TM} approaches LMR_{TE} when the coating thickness is increased, which has been also corroborated in previous works that used zinc oxide as the coating material [14].

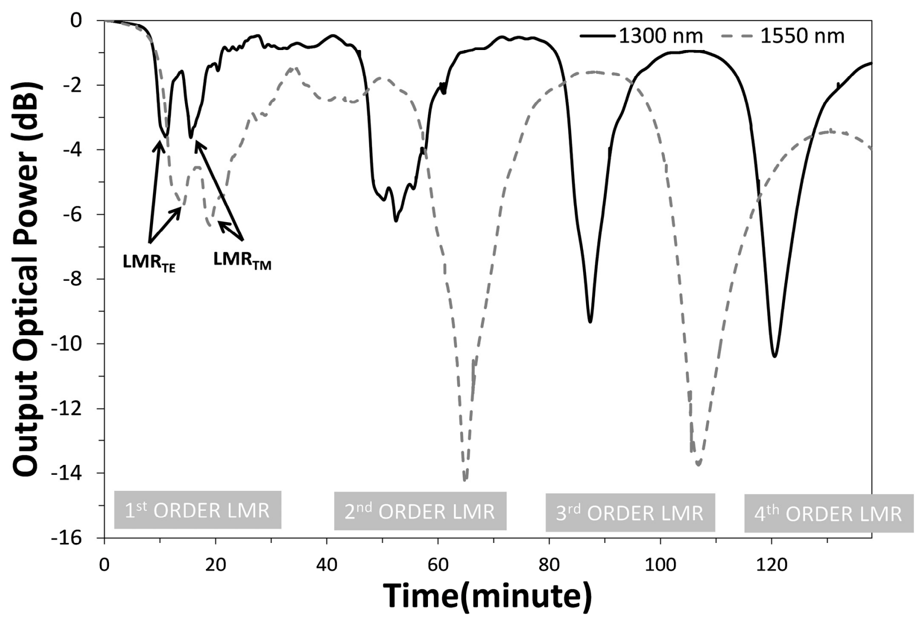

Fig. 3. Output optical power at 1300 nm and 1550 nm as a function of the deposition time (coating thickness).

3.2 LMR_{TM} and LMR_{TE} separation

First order LMR shows the largest distance between LMR_{TE} and LMR_{TM}, and also, from previous studies, the highest SMRI sensitivity, so this is the best choice to observe both contributions separately [8]. Then, a new device (device A) with a deposition time of 9 minutes was fabricated. The spectral response of the device without polarizer (see Fig. 4a, black line) shows the contribution of both LMR_{TE} (around 1420 nm) and LMR_{TM} (873 nm) with a separation between them of 534 nm. In order to quantify the spectral widths of the LMRs, the parameter $\Delta\lambda$ is defined as the wavelength range covered by the LMR at a transmission level 3 dB above the resonance minimum. Since both LMR contributions are

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very distant the attenuation of each one separately is not remarkable and the parameter Δλ is very large.

In order to distinguish between TE and TM contributions it is necessary to introduce a polarization controller at the input of the fiber as it is indicated in Fig. 2. Since the polarization controller only works in the range 1200-1700 nm we can only observe variations in that range. Thus, if we introduce the polarization controller and adjust TM polarization at the input of the device the response becomes flat, which means that the resonance in the studied region (Fig. 4a, red line) does not correspond to TM polarized light contribution. On the other hand, if we adjust TE polarization it is possible to observe a well-defined resonance peak at 1427 nm (Fig. 4a, blue line) with a Δλ = 11 nm.

Since LMR_{TM} falls out of the polarization controller range it is necessary to shift the resonance to the region of interest by immersing the sensitive area in water (n = 1.32). The dark line in Fig. 4b represents the response of the device without the utilization of the polarizer for a SMRI of 1.32. Again, the power decay is not noticeable because of the contribution of both TE and TM polarized light at the same time. Then, as it was explained in the previous paragraph, if the polarization controller is introduced in the optical path (see Fig. 2) and TM polarized light is adjusted it is possible to tune a deep and narrow resonance that corresponds to the LMR_{TM} alone. In this case LMR_{TM} shows a Δλ of 6.9 nm. Complementarily, if TE polarized light is introduced the resonance at 1272 nm fades out and the beginning of a resonance associated to TE polarized light can be observed at the right side of the spectrum, beyond the polarization controller working region (Fig. 4b, blue line).

The theoretical results presented in Fig. 4 were obtained with FIMMWAVE. The thickness of the ITO thin-film was 170 nm. The real part of the refractive index was obtained with an ellipsometer UVISEL with spectral from Horiba Scientific Thin Film Division and it ranges from 1.87 and 1.845 in the wavelength range analyzed. The imaginary part of the refractive index was 0.025.

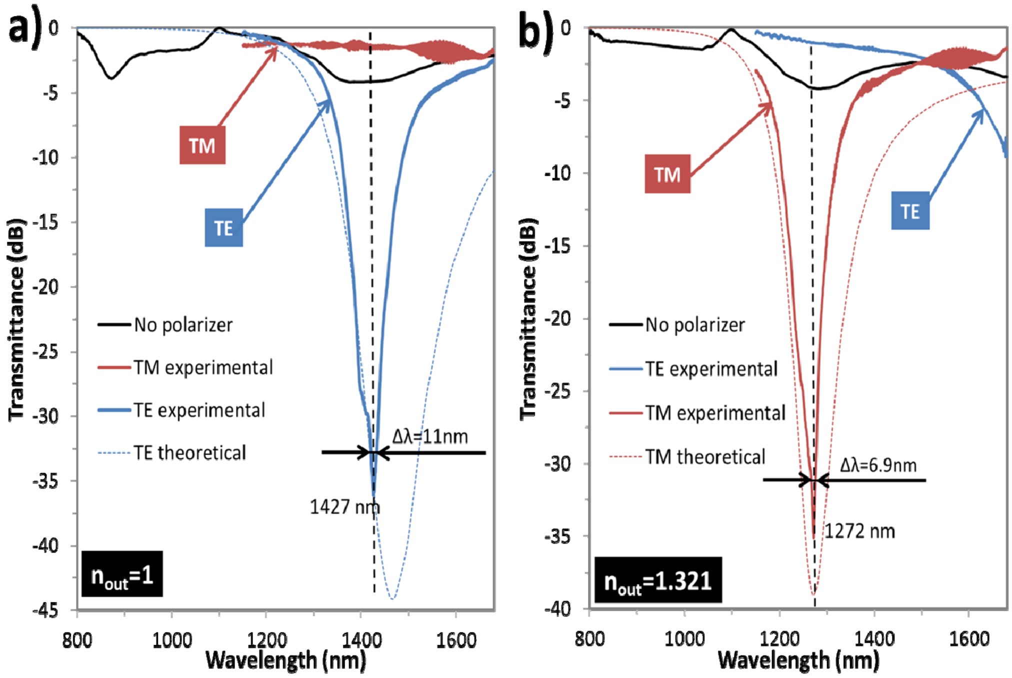

Fig. 4. Transmittance spectra without polarizer (black line), with TE polarized light (blue line), with TE theoretical (dotted blue line), with TM polarized light (red line) and TM theoretical (dotted red line) when the SMRI of device A is a) air (n = 1) and b) water (n = 1.32)

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3.3 Refractometer characterization

Since LMR_{TM} falls within the polarization controller range when the device is immersed in water, it is possible to study the response of the device for higher SMRI. The refractometric response of device A (LMR_{TM}) was characterized by immersing the sensitive region in different RI solutions from 1.32 to 1.38. The generated transmission spectra were captured and are plotted in Fig. 5a. Here, a wavelength redshift of the resonances can be observed when the refractive index is increased. A total wavelength shift of 356 nm in the range 1.32-1.38 RIU is obtained. These resonances also show a deep and narrow shape. In particular, if we attend to the $\Delta\lambda$ parameter of each resonance, values of 6.9 nm, 11.3 nm, 5.3 nm, 6.6 nm and 14.1 nm are obtained for a SMRI of 1.32, 1.335, 1.35, 1.365 and 1.38 respectively. The resonance wavelength shift has been also represented in Fig. 5b as a function of the SMRI. Here, the sensitivity for the entire range is 6009 nm/RIU but, if focus is centered on the last region from 1.365 to 1.38 RIU, it can be obtained a maximum sensitivity of 8742 nm/RIU. This overcomes that of optical fiber refractometers presented in recent works [3, 4, 15–17]. In other words, if an OSA with a picometer resolution was used, then, minimum variations of refractive index in the order of 1.14×10^{-7} could be detected.

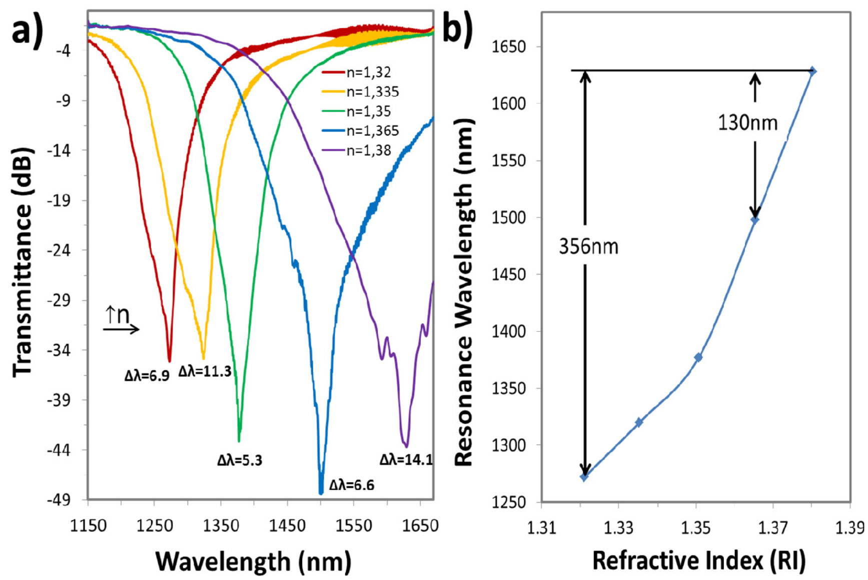

Fig. 5. a) Spectral response and b) maximum attenuation wavelength of LMR_{TM} (device A) when the sensitive region is immersed in solutions with different refractive index.

4. Conclusions

The generation of narrow and deep (low $\Delta\lambda$) LMRs produced by TE and TM polarized light has been experimentally demonstrated by means of the utilization of D-shaped ITO-coated optical fibers for the first time. These characteristics open the possibility to the utilization of multiplexed sensors by using several resonances positioned at different wavelengths within the same fiber. The characterization of LMR_{TM} as a function of the SMRI revealed a high sensitivity device suitable to be used in many different applications for direct detection or as a label-free sensing platform.

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