Lossy mode resonance generation with Indium Tin Oxide Coated Optical Fibers for Sensing Applications

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***Abstract*— Surface plasmon resonances and lossy mode resonances can be generated with Indium Tin Oxide (ITO) coated optical fibers. Both phenomena are analyzed and compared. Lossy mode resonances present important advantages: they do not require a specific polarization of light, it is possible to generate multiple attenuation bands in the transmission spectrum, and the sensitivity of the device to external parameters can be tuned. The key parameter is the thickness of the ITO coating. The work is supported with both theoretical and experimental results. The main purposes are sensing and generation of multiple-wavelength filters.**

***Index Terms*— Thin films, Indium Tin Oxide (ITO), optical resonance, optical fiber sensor, optical fiber filters.**

I. INTRODUCTION

During the last decades, much research has been done in the field of semiconductor and metal clad optical waveguides [1-6]. In both cases, the clad introduces losses to the propagation of light in the optical waveguide [2]. Depending on the properties of the cladding or thin-film three main cases can be distinguished [3]. The first case occurs 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 (i.e. the optical waveguide and the surrounding medium in contact with the thin-film). In this case coupling occurs between light propagating through the waveguide and a surface plasmon, which is called surface plasmon polariton [3], or surface plasmon resonance (SPR) [4-6]. The second case occurs when the real part of the thin-film permittivity is positive and higher in magnitude than both its own imaginary part and the material surrounding the thin-film. Some authors consider these modes as long-range guided modes [3], whereas others call them lossy modes [2,7]. Since lossy modes are a specific type of guided modes, we will use henceforward the name “lossy modes”. The third case occurs when the real part of the thin-film permittivity is close to zero, while the imaginary part is large [3]. This case, known as long-range surface exciton polariton, falls beyond the scope of this work and will no longer be studied. Hence, the study will be focused on the first two cases mentioned.

Some theoretical studies have been devoted to light propagation through semiconductor cladded waveguides [1,8]. The characteristics of these materials are adequate for generation of lossy modes. Moreover, for specific thickness values, attenuation maxima of the light propagating through the optical waveguide are obtained [1]. This is due to a coupling between a waveguide mode and a particular lossy mode of the semiconductor thin-film, which depends on two conditions: there is a considerable overlap between the mode fields, and the phase-matching condition (i.e. the equality of real parts of propagation constants) is sufficiently satisfied [2]. Since the phenomenon occurs when the lossy mode is near cut-off, it is stated in [1] that there are cut-off thickness values that lead to attenuation maxima. In other works similar conclusions are extracted after a thorough analysis of the modes. As the thickness of the thin-film on the waveguide is increased, some modes guided in the optical waveguide become guided in the thin-film, which causes a modal redistribution or modal conversion [8,9].

Previous studies have been focused on the variation of thickness. However, if the thin-film thickness is fixed, a resonance will be visible in the electromagnetic spectrum for those incident wavelength values where there is a mode near cut-off in the overlay. This is of great interest because one of the basic ways of using waveguides as sensors is by analysis of resonance wavelength shift. Hence, the phenomenon studied in this work is the generation of resonances in the electromagnetic spectrum based on near cut-off lossy modes. The right term should be Near Cutoff Lossy Mode Resonance (NCLMR). However, for the sake of simplicity the term Lossy Mode Resonance (LMR) will be used, which indeed is similar to that mentioned in [7].

During the last years, hundreds of publications have been devoted to the SPR, whereas the number of publications devoted to lossy modes is quite low [1-3,7]. Moreover, the utilization of LMR for sensing purposes has not been used before the present work. The main reason is that the selection of the thin-film material is critical. Among the materials whose characteristics meet the criteria for the generation of LMR, ITO is chosen for the present work. There are several reasons for selecting ITO. First it belongs to transparent conductive oxides (TCO), which have made a breakthrough in many scientific areas during the last decades: the fabrication of heat shields, liquid crystal displays, flat panel displays, plasma displays, touch panels, electronic ink, organic light-emitting diodes, solar cells, antistatic coatings or even electromagnetic interference shields [10,11]. This success is due to the good qualities that these materials present (electrochemical stability and high transmittance in the visible spectral range), if compared with other well-known conductive materials such as gold or silver. More specifically, ITO has been also used in many different sensing applications such as the fabrication of conductimetric or optical sensors [12-16], by exploiting the combination of conductive and transparency/reflectivity properties in the visible/infrared

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region respectively. In fact, it is this dual behavior what makes ITO an adequate candidate for the generation of LMR. In the region of high reflectance, the imaginary part of the ITO refractive index is of the order of metals. Consequently, this region is adequate for SPR generation. However, for the low-reflectance region, the imaginary part is lower and permits the LMR generation.

Another important question is the selection of the substrate. Among optical waveguides, the fine characteristics of optical fiber are well known: light weight, capability of multiplexing and immunity against electrical discharge [17,18]. In view of these properties, optical fiber is considered as an advantageous substrate for the deposition of ITO sensing films. The first approach to ITO coated optical fiber was done in [19]. However, the LMR phenomenon was not detected, which is vital for exploiting the sensing capability of ITO coated optical fiber sensors.

In the present work, the typical transmission configuration of metal coated optical fiber sensors is used [4]. ITO is deposited onto the uncladded core of an optical fiber. The result is the creation of an LMR with a high sensitivity in the wavelength range where there is a low reflectance. The characteristics of this novel fiber optic based device and its ability to detect changes in the surrounding refractive index are presented theoretically and experimentally for the first time in the literature. The sensitivity of these devices is located in the range of SPR sensors, which have been extensively used as refractometers during the last years [4,20,21].

One of the main differences with SPR is that LMR can be observed for both for TE and TM polarized light [3], which is also demonstrated in this work. Moreover, if the ITO thickness is increased, several LMR can be obtained in the transmission spectrum.

It is well known that depending on the parameters used for the fabrication of ITO, its characteristics can differ in a great manner [22-25]. Consequently, depending on the characteristics of ITO, the resonance wavelength can be tuned, which is another advantage of the utilization of ITO. In other words, the resonance can be located in the visible or the infrared region depending on ITO properties. Moreover, for a specific ITO parameterization it is also possible to tune the LMR simply by changing the ITO thin-film thickness. This value also determines the sensitivity of the device.

II. THEORY

There are several models both for the dispersion curve of ITO and for the analysis of the propagation of light through a metal coated optical fiber. In this section we describe the models used for the simulations presented in section 3.

A. *Propagation of Light through Metal Coated Optical Fiber*

The propagation of light through metal coated optical fiber has been analyzed in several works, [4,5,26-30].

For the sake of simplicity the light path consists on a typical optical transmission arrangement, which is schematically represented in Fig. 1a. In this configuration, light is launched into the optical fiber and it is collected at the other end of the fiber. In the middle of the optical path, there is a region where the optical fiber core is coated with ITO. The cross-section of this region is represented in Fig. 1b, and the propagation of light through the meridional-section is also represented in Fig. 1c.

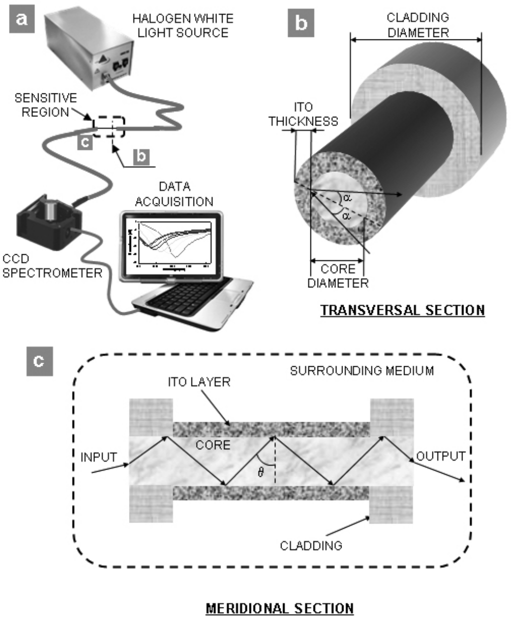

Fig. 1: ITO coated optical fiber sensor setup. a) Experimental setup with the light source, the detector and the optical fiber with the ITO coated region b) Transversal cross-section of the ITO coated optical fiber. c) Meridional cross-section of the ITO coated optical fiber

In order to obtain the transmitted optical power in the structure of Fig. 1 it is applied first the attenuated total reflection (ATR) method with a Kretschmann configuration [5]. This method calculates the reflection at the ITO - fiber core interface $R(\theta,\lambda)$ under the assumption that the structure is planar [4,5,26-30]. Consequently, two cases are considered: the TE and TM polarization of the incidence light. For a more exact analysis which considers the cylindrical geometry of the fiber hybrid modes must be used. Nonetheless, the expressions presented include skew rays (see Fig. 1b), which permits to obtain more exact numerical results than with the simple consideration of rays propagating in the meridional axis [30].

It is also important to highlight that the method can only be applied for specific core diameter dimensions (200 μm or more according to [30]), which is the case for the optical fiber under study in section III.

Depending on the length of the metal coated region and on the incidence angle, the number of reflections N at the ITO - fiber core interface is obtained:

$$N(\theta,\alpha) = \frac{L}{d\tan\theta\cos\alpha} \tag{1}$$

where L is the length of the of the metal coated region, d is the diameter of the optical fiber core, θ the angle between the ray and the normal to the core-metal interface (the projection of this angle in the meridional axis is represented in Fig. 1b), and α is the skewness angle (Fig. 1c).

The final step is to calculate the transmitted power. According to [27], depending on the sensor's application, the propagation of light can be analyzed considering remote sensing or non-remote sensing. Since the dimension of the fiber used in our experiments is short, it will be considered the non-remote case. The main issue now is to select an adequate equivalent of the light source $p(\theta)$ in the following expression used to calculate the transmitted power [30]:

$$T(\lambda)=\frac{\int_0^{\alpha_{\max}}\int_{\theta_c}^{90^\circ} p(\theta)R^{N(\theta,\alpha)}(\theta,\lambda)\,d\theta\, d\alpha}{\int_0^{\alpha_{\max}}\int_{\theta_c}^{90^\circ} p(\theta)\,d\theta\, d\alpha} \quad (2)$$

where θ_c is the critical angle, expressed as:

$$\theta_c=\sin^{-1}\left(\frac{n_{cl}}{n_{co}}\right) \quad (3)$$

where n_{cl} and n_{co} are the cladding and the core index respectively.

Following the same idea of [29], if we assume that the source is a white light source, this will be expressed as the propagating mode density. Since the model is two dimensional, following the expressions of [31], the modal density can be easily calculated:

$$p(\theta)\propto k_0^2 n_{co}^2 \sin\theta\cos\theta \quad (4)$$

Where k_0 is the quotient between 2π and the incidence wavelength and θ is the angle represented in Fig. 1c.

It is interesting to remark that expression (4) coincides with the expression of a Lambertian source, which is typically used in the description of LED sources [26] (the white light source can be considered as a combination of LED sources).

The final step is to replace $p(\theta)$ in expression (2) with the value of expression (4). It is also important to highlight that since the light introduced in the optical fiber is unpolarized, $R^{N(\theta,\alpha)}(\theta,\lambda)$ can be replaced in expression (2) with the following expression, which considers the reflected light as a combination of the reflected power in TE and TM mode polarization [26]:

$$R^{N(\theta,\alpha)}(\theta,\lambda)=\frac{R_{TM}^{N(\theta,\alpha)}(\theta,\lambda)+R_{TE}^{N(\theta,\alpha)}(\theta,\lambda)}{2} \quad (5)$$

B. ITO Layer

Depending on the technique used for the deposition of ITO on optical fiber or any other substrate, the properties of the metallic film may differ in a great manner [25,32-34]. The most widely used expression for modelization of ITO is the Drude model [32,34]:

$$\varepsilon(\omega)=\varepsilon_\infty-\frac{\omega_p^2}{\omega^2+i\dfrac{\omega}{\tau}} \quad (6)$$

where ε_∞ is the high frequency dielectric constant, τ is the electronic scattering time and ω_p is the plasma frequency.

Other more complex models are used in [25,33]. However, expression (6) has been used because our estimations are obtained from the transmission spectra of light propagating through ITO coated multimode optical fiber. Hence, it is not possible to separate in the analysis light polarized in TM and TE modes, or to obtain the transmitted and reflected power, as it is the case for deposition on glass slide [25,33].

By analyzing the results of several experiments, the following parameters have been estimated for ITO: $\varepsilon_\infty = 3.5$, $\tau = 6.58\times10^{-15}$ s/rad and $\omega_p = 1.533\times10^{15}$ rad/s.

According to the model of expression (6), the dispersion curves of index of refraction and extinction coefficient are represented in Fig. 2. It is important to remark that these curves are similar to those obtained in [33].

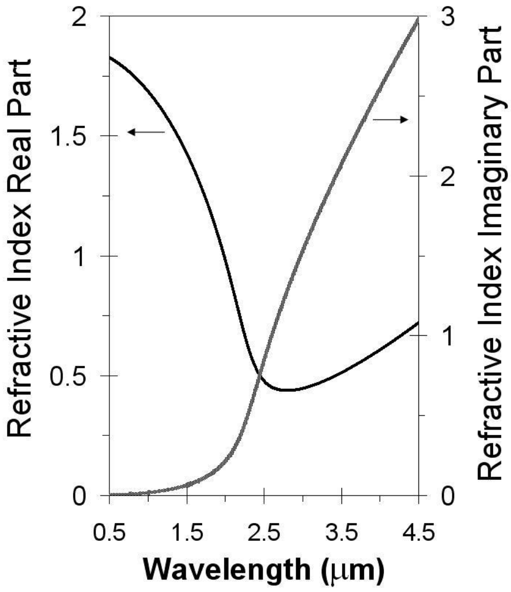

Fig. 2: ITO model. Index of refraction n and extinction coefficient k of ITO deposited layer

C. Silica core Layer

As it was stated above, the refractive index of fused silica can be estimated with the well-known Sellmeier equation:

$$n^2(\omega)=1+\sum_{j=1}^{m}\frac{B_j\omega_j^2}{\omega_j^2-\omega^2} \quad (7)$$

With parameters: B_1=0.691663, B_2=0.4079426, B_3=0.8974794, λ_1=0.0684043 μm, λ_2= 0.1162414, and λ_3= 9.896161, where $\lambda_j=2\pi c/\omega_j$ and c is the speed of light in vacuum [31].

III. LMR RESONANCES: THEORETICAL AND EXPERIMENTAL RESULTS

In this section some theoretical predictions are done with the methods explained previously. The results are corroborated with experimental results. For the sake of simplicity the results are presented in two sections dedicated to the generation of a single LMR and multiple LMR respectively.

A. *Single lossy mode resonance (LMR) generation*

In Fig. 1 it is presented the experimental setup, which basically consists of a halogen white light source (DH2000, Avantes Inc.) that launches light into the optical fiber, the optical fiber (FT silica/TEQS™, Thorlabs Inc. 200/225 µm of core/cladding diameter) with a sensitive region where ITO has been deposited (see Fig. 1b-c) and the detector (NIR512, Oceanoptics Inc.). Sol-gel dip-coating deposition process was selected because it was considered as an effective and simple method for the fabrication of ITO coatings onto non-planar substrates as optical fibers. Additionally, this technique had been proven as a suitable method for the fabrication of ITO coating with good conductive and optical properties in several works before.

The optical fibers were cleaved and pretreated by chemically removing with acetone a 10 cm. portion of the plastic cladding. These fibers were sonicated in ultrapure water and boiled in acetone. Then, they were used as substrates in a dip-coating deposition process in order to fabricate the ITO outer layer around the fiber core, as described by R. Ota [33]. The immersion and pulling-out speed was 4 cm/s. The fabrication process was stopped at 10 and 20 dips in order to obtain ITO thicknesses of 115 nm and 220 nm respectively. After the deposition process, a portion of the ITO coated optical fibers of length L was cleaved and spliced to optical fiber patch cords at both ends.

The parameters of the optical fiber used both for the experiments and simulations of light transmitted through the setup are: 200/225 µm of core/cladding diameter in the optical fiber, length of the ITO coated region of 4 cm, numerical aperture of the optical fiber 46º, and it is assumed that the core is made of fused silica. Hence, the Sellmeier equation is used [36]. The performance of the sensor as a refractometer was tested by obtaining the transmission response of the devices for several surrounding media refractive indices: 1.321, 1.339, 1.358, 1.378, 1.400, 1.422 and 1.436, which were obtained from different water/glycerin concentration solutions from 0% to 85% respectively [37-39].

The transmission spectra from 850 nm to 1700 nm are represented in Fig. 3a and 3b for ITO thickness values of 115 nm and 220 nm. The plots presented in each figure correspond to different refractive index values of the outer medium, as indicated previously. The combined contribution of TE and TM polarization of expression (5) is used to calculate the transmission in expression (2). A resonance is observed in all spectra. Here, it is important to note that as the refractive index increases there is an optical red shift of the resonance. In addition to this, as the coating thickness increases, the sensitivity (i.e. the resonance shift depending on the surrounding refractive index) is reduced. In other words, the thickness can be used for controlling the sensitivity of the device, which is 1617.4 nm per refractive index unit (RIU) for the sensor coated with a 115 nm film and 2952.6 nm per RIU for the sensor coated with 220 nm. These values are in the range of SPR sensors (1000 to 10000 nm per RIU) [21].

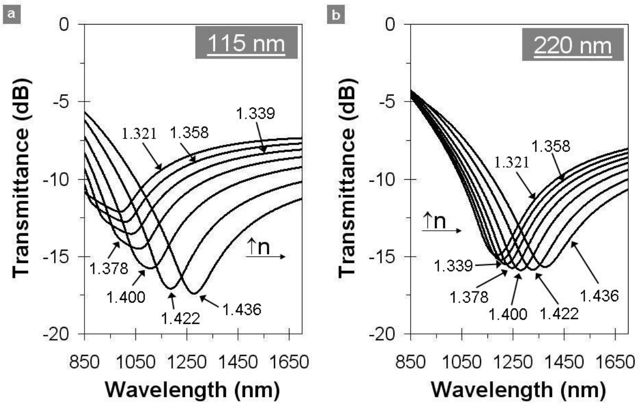

Fig. 3: Theoretical results of Lossy Mode Resonance (LMR) sensitivity versus surrounding refractive index (SRI): transmission spectra obtained when the ITO coated region is surrounded by different refractive indices for different ITO layer thickness values: a) 115 nm, b) 220 nm. ITO layer length: 4 cm.

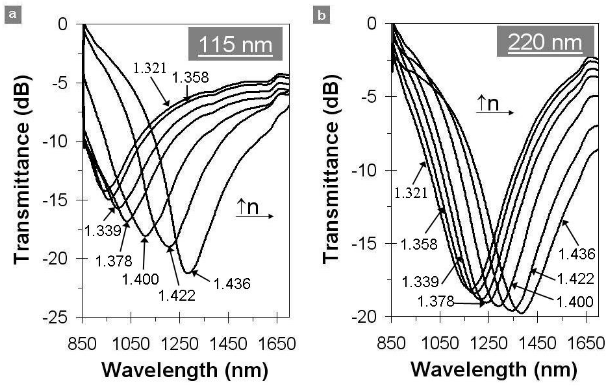

Fig. 4: Experimental results of Lossy Mode Resonance (LMR) sensitivity versus surrounding refractive index (SRI): transmission spectra obtained when the ITO coated region is immersed in different refractive index solutions (the refractive indices are the same as those analyzed in Fig. 3) for different ITO layer thickness values: a) 115 nm, b) 220 nm. ITO layer length: 4 cm.

The wavelength range analyzed in Fig. 3 and 4, which is the range that the combination of the white light source and the spectrometer permits to detect, corresponds to the region of low-reflectance in Fig. 2. Hence, the attenuation bands of Fig. 3 and 4 are actually LMR. In order to give a more evident prove of this, the wavelength range analyzed in Fig. 3a is expanded to 0.7 – 4.0 µm in Fig. 5a. For the sake of simplicity only the plot corresponding with surrounding refractive index SRI 1.321 is plotted. It is also analyzed the separate contribution of TE and TM polarizations when the refractive index of the external solution is 1.321. The results obtained for TM polarization in Fig. 5b show that there is another resonance located in the range between 2.5 and 4.0 µm. In addition, this resonance is located in the high-reflectance region (see Fig. 2), which indicates that it is an SPR. In Fig. 5a it is not clearly visualized due to combined effect of TE and TM polarizations. Obviously for TE polarization (see Fig. 5c) the SPR is not visible. On the other hand, the LMR is visible for all polarizations. In fact, the wavelength of the LMR is not the same for both TE and TM polarizations. Consequently, the resonance of Fig. 5a is a combination of two LMR, one with TE polarization and the other one with TM polarization.

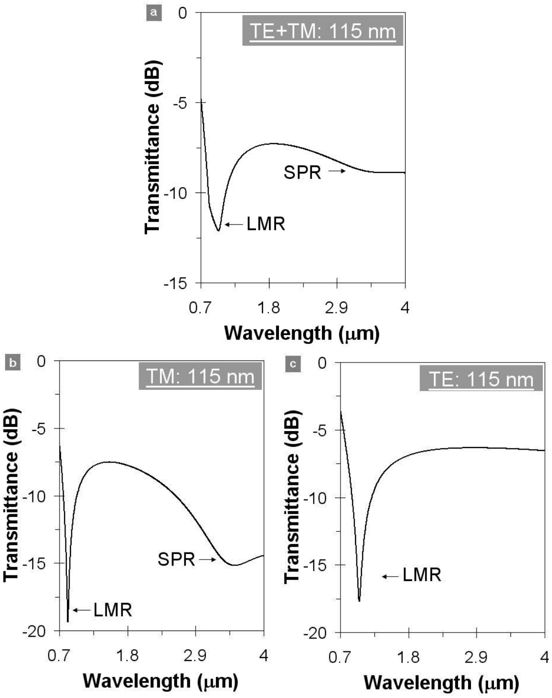

Fig. 5: Theoretical results of Lossy Mode Resonance (LMR) and SPR for different polarizations of incident light: transmission spectra obtained when the ITO coated region is surrounded by a refractive index of 1.321. ITO layer thickness and length: 115 nm and 4 cm respectively. a) combination of TE and TM polarization. b) TM polarization. c) TE polarization.

In view of the results of Fig. 5 it can be concluded that the SPR in the high-reflectance region is only visible for TM polarization, whereas the LMR in the low-reflectance region is visible for both TE and TM polarizations. This is one important difference between SPR and LMR. The main advantage in this last case is the possibility of avoiding the use of polarized light to see the resonance, which is advantageous in sensing configuration schemes. This is the case for the experimental results obtained in Fig. 4, where non-polarized light was used.

B. Multiple lossy mode resonance generation

It was observed in Fig. 4 that when the ITO thickness is increased, the sensitivity of an LMR to the surrounding refractive index decreases. In this section a second effect of the variation of the ITO thickness will be presented. According to [1,9] there are attenuation maxima in the light transmitted through a coated optical fiber as a function of the coating thickness. These maxima coincide with a near cut-off mode in the coating. The same conclusion should be valid for the generation of LMR in the transmission spectrum. For specific wavelength values there are near cut-off modes in the coating. So far a single LMR has been visualized. However, if the ITO thickness is increased there should be more modes guided in this region. The consequence would be the generation of multiple LMR resonances. To this purpose, in Fig. 6 theoretical and experimental results are presented, which prove the multiple LMR generation. The parameters used are the same as those of Fig. 3, 4 and 5. The ITO thickness is 440 nm. The phenomenon can be exploited for the generation of multiple wavelength filters and sensors with multiple points of reference.

The reason why the LMR is sharper for the theoretical results than for the experimental results in Fig. 6 (oppositely to the results of Fig. 3 and Fig. 4) is a change in the immersion and pulling-out speed used in the dipping process. The speed was increased to 10 cm/s, which permitted to save time in the development of the ITO film. However, the roughness of the film was increased which also accounts for a less sharp LMR. It is also remarkable to say that for low wavelength values the optical fiber used in the experiments presents a high attenuation. This is the main cause for a decrease in the sharpness of the LMR.

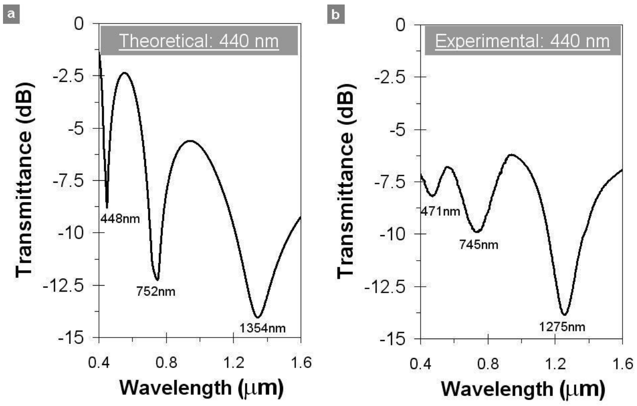

Fig. 6: Multiple Lossy Mode Resonance (LMR): theoretical and experimental results with same parameters as in Fig. 5 but for ITO layer thickness 440 nm. Three LMR can be visualized in the transmission spectrum. a) Theoretical results. b) Experimental results.

In Fig. 7 the transmission spectrum for an ITO thickness of 1.6 μm and a wavelength range from 0.4 to 4.0 μm is analyzed. The purpose of using a thick ITO region is the generation of an important number or LMR resonances and to observe that all of them are located in the low-reflectance region. On the other hand, no resonance is visible for the high-reflectance region. This is another important difference with SPR; LMR permits to generate multiple resonances as the thin-film thickness increases, whereas SPR is shifted to higher wavelengths and no additional resonances occur. The reason is that LMR are based on near cut-off lossy modes in the coating. To prove this last question, it is analyzed in Fig. 8 both for TE and TM polarization the effective index of the modes guided in the thin-film coating as a function of wavelength for the same ITO design as in Fig. 7. It is easy to see that the wavelength values where the modes cross the cut-off condition fit adequately with the wavelengths of the resonances observed in Fig. 7. This confirms the theoretical works of [1,7,8].

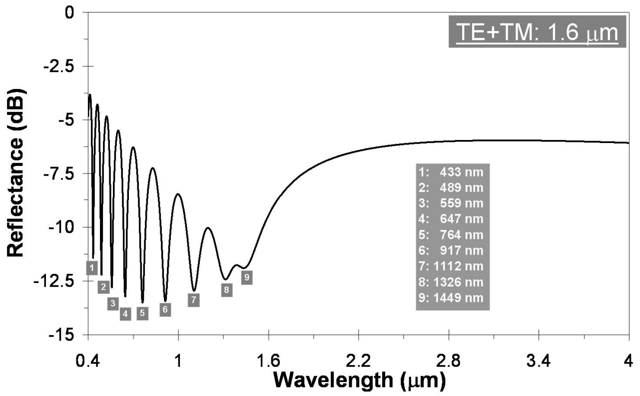

Fig. 7: Theoretical results of Lossy Mode Resonance (LMR) and Surface Plasmon Resonance (SPR) for thick ITO layer: transmission spectra with same parameters as in Fig. 5 but for ITO layer thickness 1600 nm. Nine LMR are observed in the low-reflectance region (wavelengths lower than 1500 nm) and no resonance is observed in the high-reflectance region (wavelengths higher than 1500 nm).

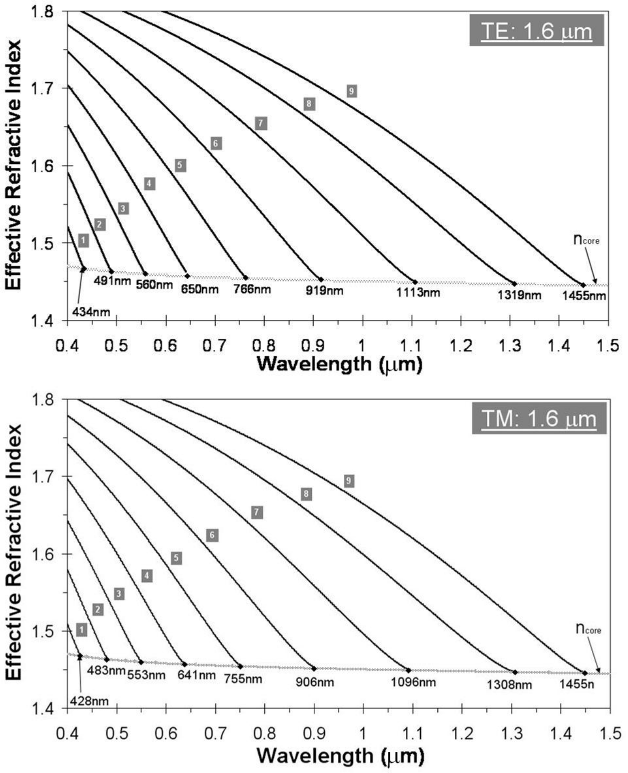

Fig. 8: Effective indices of TE and TM modes for the same parameterization of Fig. 7.

IV. CONCLUSION

The results presented above represent, to our knowledge, the first experimental data obtained with coated optical fiber sensors based on the phenomenon of lossy mode resonance (LMR). The detection technique is based on the monitorization of the LMR wavelength. The results are supported with theoretical results. In some of them the analysis was focused on the variation of the coating thickness, whereas in others the interest was centered on the generation of attenuation bands in the electromagnetic spectrum. This last case has centered the attention of this work because wavelength detection is one of the most powerful techniques used in optical fiber sensors.

The phenomenon of SPR is also obtained with coated waveguides. The difference with LMR is the coating optical losses. That is why LMR and SPR were compared throughout this work. The number of SPR based devices has experienced an exponential increase during the last two decades and applications can be found in many disciplines such as chemical sensors and biosensors, and detection of molecular adsorption. Applications based on optical fiber have been used in a similar way to the setup used in this work for LMR. However, the main issue is that SPR is only visible for TM polarization and it is difficult to control the polarization of light in a multimode optical fiber. Consequently, the visibility of attenuation bands is masked by the combined effect of TE and TM polarized light. This was proved with the analysis of the separate contribution of both TE and TM polarized in the transmission spectrum, and with the combination of both polarizations. LMR overcomes the problem of the polarization because it can be generated both for TE and TM polarizations. In addition to this, it permits to control the sensitivity of the device simply by changing the coating thickness. This question is also possible in SPR but the behavior is different. LMR based on thin coatings leads to high sensitivity whereas LMR based on thick coating leads to low sensitivity. On the other hand, SPR leads to a maximum sensitivity for a specific thickness value. Finally, the thickness is also responsible for the generation multiple LMR devices, which should find application in sensor devices and in optical communications as multiple-wavelength filters or other devices. This is not possible for SPR based devices. In fact, as the thickness increases the SPR is shifted to higher wavelengths and is no longer visible in the wavelength range analyzed.

Moreover, it is important to remark that the combination of ITO and optical fiber enables the fabrication of robust and cost-effective resonance based devices, which are capable to exploit both SPR and LMR resonance phemomena.

In view of the expansion that SPR based devices have experienced during the last decades it seems that LMR based devices, with the important advantages discussed in this work, should also find exciting applications in both sensor and communication fields within the next years.

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