

Experimental demonstration of lossy mode resonance generation for TM and TE polarizations

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This work presents the fabrication of lossy mode resonance (LMR) devices based on titanium dioxide (TiO₂)/poly(sodium 4-styrenesulfonate) (PSS) coatings deposited on side-polished D-shaped optical fibers. TiO₂ thin-films have been obtained by means of the layer-by-layer (LbL) self-assembly technique. LbL enables to produce smooth and homogeneous coatings on the polished side of the fiber. This permits to couple light from the waveguide to the TiO₂-coating/external medium region at specific wavelength ranges. The generation of LMRs depends on the coating thickness so that thicker coatings can produce more resonances. LMRs are sensitive to the external medium refractive index, which allows its utilization as refractometers. The characteristic D-shaped architecture of the devices employed in this work enables to distinguish TE and TM polarizations, which had not been possible before with regular optical fibers due to their cylindrical symmetry. The results presented here show for the first time the experimental demonstration of the generation of LMRs produced by both TM and TE polarizations. More specifically, for these TiO₂/PSS thin films, the TM and TE modes of the LMRs show a wavelength shift of 226 nm for the first order LMR and 56 nm for the second order LMR. © 2013 Optical Society of America

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Thin-film coated optical waveguides have been a main matter of research during the last decades both in the theoretical analysis of the physics behind these phenomena [1–7], as well as in the development of novel devices for applications mainly focused on chemistry, biology and immunology [8–15].

Light propagation through semiconductor cladded waveguides has been studied in [2], where attenuation maxima of the light propagating through the optical waveguide, known as resonances, can be obtained for specific thickness values and at certain wavelengths or incidence angles [6]. Different types of resonances can be distinguished attending to the dielectric properties of the thin-films [3]. The well-known Surface Plasmon Resonances (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. Thus, SPRs are generated by TM polarized light [8] and can be obtained with materials with a high imaginary part of the refractive index (typically metals [8–11]). A different and less studied type of resonances occurs when the real part of the thin-film permittivity is positive and higher in magnitude than its own imaginary part as well as the real part of the permittivity of both the optical waveguide and the external medium surrounding the thin-film [5–7]. These are known as Lossy Mode Resonances (LMRs) or guided mode resonances [3, 12] (depending on the expression used by the author) since the phenomenon occurs when the lossy mode

of the thin-film is near cut-off, there are thin-film thickness values that lead to transmission attenuation maxima [2]. Consequently, LMRs can be achieved for a wide variety of materials with low imaginary part of the refractive index such as metal oxides like indium tin oxide (ITO) [5,13], TiO₂ [14] or indium oxide [15] or polymers [16]. Thus, LMRs constitute a promising research field that could compete with the largely established SPRs [8].

In addition, multiple LMRs can be generated without modifying the optical fiber geometry by only increasing the thin-film thickness [7] and what is more important, both TM and TE polarized light can produce LMRs (LMR_{TM} and LMR_{TE}) which are located at different wavelengths as it has been theoretically demonstrated [5]. However, the experimental corroboration of this fact, which is of great interest, had not been performed yet due to technical difficulties such as the adequate election of the material or the preparation of the thin film as well as the choice of the right setup and deposition substrate.

In order to solve the problems mentioned above it is presented a novel approach for the generation of LMRs. This approach basically consists of the utilization of single mode, D-shaped, polished fibres as substrates in the LbL technique. This work will be focused on the resonances produced by TiO₂/PSS coatings deposited onto D-shaped fibers. D-shaped optical fibers were obtained from Phoenix Photonics LTD. These fibers are standard single mode fibers (Corning® SMF-28) with a cladding/core diameter of 125/7 μm, a polished length of 1.7 cm (see Fig. 1)

and a typical attenuation of 10 dB at 1310 nm when immersed in a liquid of refractive index (RI) 1.48.

Thin TiO_2/PSS films have been fabricated on the polished side of the optical fibers using the LbL assembly technique as explained elsewhere [15]. This process basically consisted of the sequential adsorption on the substrate of positively and negatively charged molecules from a water-based solution. Each TiO_2/PSS pair forms what is known as bilayer. The experimental setup shown in Fig. 1 was used to monitor the spectral response after the fabrication of each bilayer. This setup consisted of a multi-LED light (HP83437A) as the excitation source connected to one end of the D-shaped fiber and the other end attached to an optical spectrum analyzer (OSA-HP86142A). The D shaped fiber was mounted on a holder that allowed 3D movements in order to immerse the fiber into the positively and negatively charged solutions. Polarization is not controlled during the fabrication due to the continuous movements of the fiber that would modify the polarization states at the input of the OSA.

In Fig. 2 it is plotted the spectral response of the device as a function of the number of bilayers added onto the fiber. From Fig. 2, the first LMR can be seen as sudden transmission power decay (dark region) between the second and forth bilayer while the transmitted power decay (dark region) associated to the second LMR can be observed between bilayer 17th to bilayer 26th. Hence, in the studied spectral range (from 1300 to 1650 nm) the 1st LMR wavelength shift as a function of the number of bilayers added onto the optical fiber core is faster than 2nd LMR wavelength shift, which had been observed in previous works with TiO_2 [14] and other materials [5, 13]. The plots of the first (after the fabrication of the 3rd bilayer) and second LMRs (after the fabrication of the 22nd bilayer) are shown in Figs. 3a and 3b respectively (continuous black lines). Here, the first LMR is broader than the second LMR, what if we assume from theory [5] that both, first and second LMRs are formed by the contribution of TM and TE polarization resonance modes suggest that LMR_{TM} and LMR_{TE} contributions should be more distant, in wavelength, for the first LMR.

A new setup was arranged in order to probe previous assumptions (see Fig. 4). This setup consisted of a light polarization controller (Agilent 8169A) connected between the light source and the TiO_2/PSS coated D-shaped fiber. The utilization of the polarization controller allows tuning the desired polarization at the input of the LMR device. At this point it is critical to maintain the entire arrangement completely static in order to avoid any polarization fluctuation. Here, the characteristic asymmetry of the planar region of D-shaped fiber enables to differentiate between TM and TE polarizations [10, 17].

A careful adjustment of the light polarization controller parameters is required in order to

separate TM and TE polarizations. Particularly, the separation of TM and TE resonance modes for the first and second LMRs is represented in Figs. 4a and 4b respectively. The first LMR in Fig. 4a (continuous black line) has been separated in the LMR_{TM} (dotted grey line) and LMR_{TE} (dashed grey line). The sum of both TM and TE resonances would give a signal that is almost the unpolarized light LMR signal (solid black line) but for a small difference. This small difference between the unpolarized light and the sum of both polarizations is almost linear because it is due to the insertion losses of the Agilent 8169A. In the same manner, the second LMR in Fig. 4b (continuous black line) has been separated in the LMR_{TM} (dotted grey line) and LMR_{TE} (dashed grey line), showing the same transmission decay attributed to the addition of the polarization controller. Apart from the transmission decay, it is easy to conclude that the addition of the polarization controller enables to obtain separately TM and TE components of first and second LMRs, which also confirms the distinct nature of LMRs and SPRs as it was demonstrated theoretically in [5].

It is also interesting to observe the separation between TM and TE resonances. The distances between LMR_{TM} and LMR_{TE} are 226 and 56 nm for the first and second LMR respectively. This also corroborates previous assumption that associated the width of the LMRs with the separation of their respective resonance components. In general, as it has been also observed in recent works [5-7, 12-15], the first LMR is wider than the next LMRs. Thus, TM and TE resonance modes are more distant in this case.

To conclude, TM and TE components of the LMRs have experimentally obtained with the first and second LMRs centred within the second and third telecommunication window range. The experimental results shown in this work reveal one of the special particularities of LMRs, such as the fact that they can be generated by both, TM and TE polarization modes. These results open the door to the development of a wide range of novel applications that can exploit the polarization control mechanisms in order to get dual reference measurements.

To our knowledge, this is the first time that TM and TE components of LMRs have been experimentally isolated.

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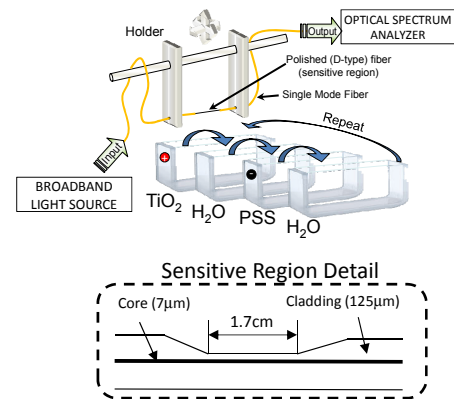


Fig. 1. Experimental fabrication setup with the light source, the detector and the side polished (D-shaped) single mode fiber.

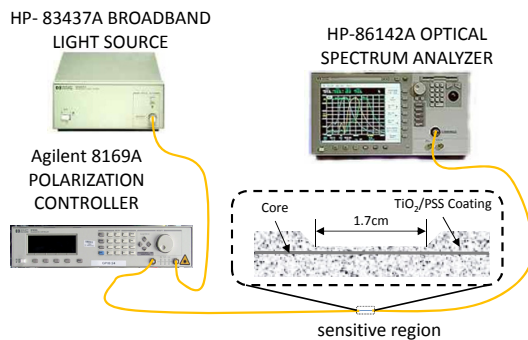


Fig. 4. Experimental measuring setup with the light source, the polarization controller and the detector and detail of the TiO_2/PSS coated sensitive region.

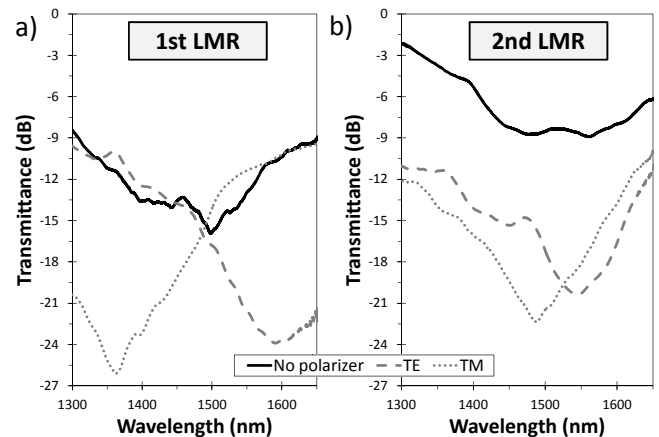


Fig. 3. Experimental results obtained with the TiO_2/PSS coated D-type optical fiber that show the separation of the TM and TE mode resonance components with a) first LMR (after 3 bilayers fabrication) and b) second LMR (after 22 bilayers fabrication).

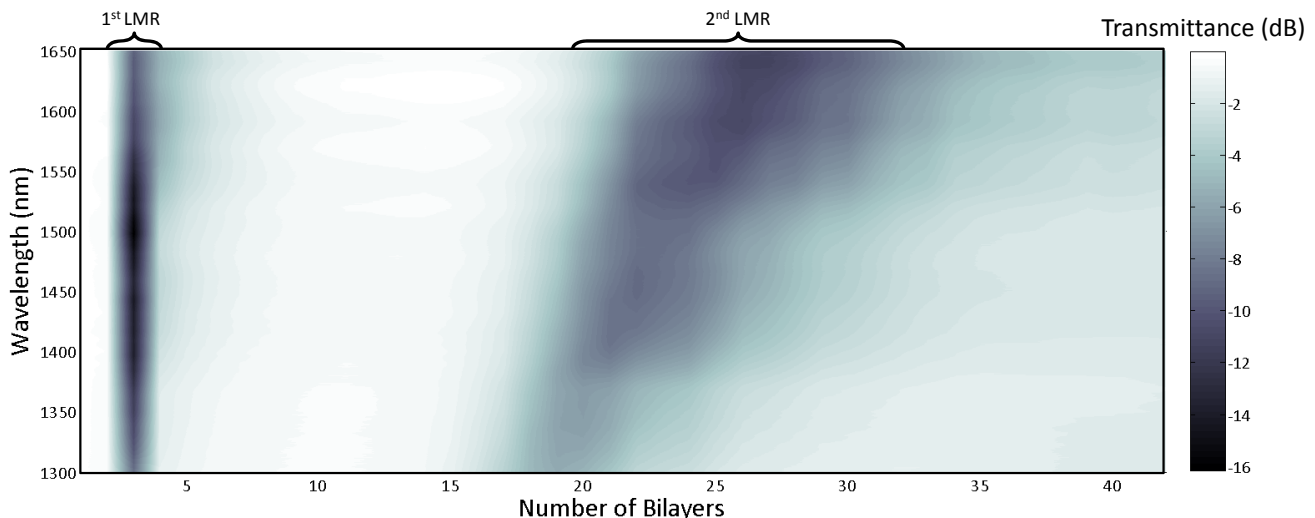


Fig. 2. Spectral response of the fabrication of the device as a function of the number of TiO_2/PSS bilayers added onto the fiber.

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