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Asymmetrically and symmetrically coated tapered optical fiber for sensing applications

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ABSTRACT

The deposition of a non-metallic thin-film in a symmetrically coated tapered optical fiber leads to the generation of resonances due to guidance of a mode in the thin-film. At certain conditions, the resonances overlap each other, which can be avoided with an asymmetric coated tapered optical fiber, which permits to obtain resonances for TM and TE polarization separately. Numerical results showing the sensitivity to coating thickness and surrounding medium refractive index are also presented for both polarizations.

Keywords: thin-films, tapered optical fiber, polarization, resonance based sensors

1. INTRODUCTION

The evanescent field of an optical fiber is increased by tapering. This permits a higher interaction of the device with the external medium and, consequently, it is widely used for sensing purposes.

In adiabatic tapers, due to a soft diameter decrease in the transition region, the fundamental mode (HE_{11}) is propagated with losses lower than 1 dB, preserving the input spectrum [1]. By combination of this type of optical structure with another element that permits light coupling in certain wavelength ranges in the optical spectrum, wavelength based detection systems can be developed. Two examples are tapered optical fiber with a long period grating [2], and thin-film coated tapered optical fiber [3-6].

In the latter group, two different types of coating materials have been explored: metallic [3,4] and non-metallic [5,6]. With metallic coating a surface plasmon resonance (SPR) was obtained with both a symmetrical and an asymmetrical coating on the optical fiber substrate [3]. However, with non-metallic coating only the symmetrical configuration has been explored [5,6]. This configuration leads to the generation of a lossy mode resonance (LMR) [7], also considered by other authors as guided mode resonance [8]. The term lossy mode resonance is used because the condition for generation of the resonance is a complex refractive index of the thin-film. The light coupling to the thin-film occurs when two modes guided in the optical fiber start to be guided in the thin-film [5-7], a phenomenon observed both in long period fiber gratings and in single-mode–multimode–single-mode structure [9,10].

In this work, it will be proved, for the first time to our knowledge, that the coupling obtained with a symmetrically coated structure when the two lossy modes are guided in the thin-film can be separated, with an asymmetrically coated structure, into one coupling obtained for TE polarized light and another one with TM polarized light. This permits to reduce the bandwidth of the LMR, which was initially reduced in [6] with the tapered configuration in comparison with the non-tapered configuration. In order to understand the implications in the selection of the thin-film material, the deposition of two materials with different refractive indices, a polymer (PAH/PAA) and Indium Tin Oxide (ITO), will be explored.

2. THIN-FILM COATED TAPERED OPTICAL FIBERS

In Figure 1(a) a section of a symmetrically coated tapered optical fiber (SCTOP) and an asymmetrically coated tapered optical fiber (ACTOP) are shown. The ACTOP can present different percentage of the surface coated. For the sake of simplicity a 40% is coated, which resembles the result obtained by coating with a sputter machine. After this explanation, the performance of both structures will be analyzed.

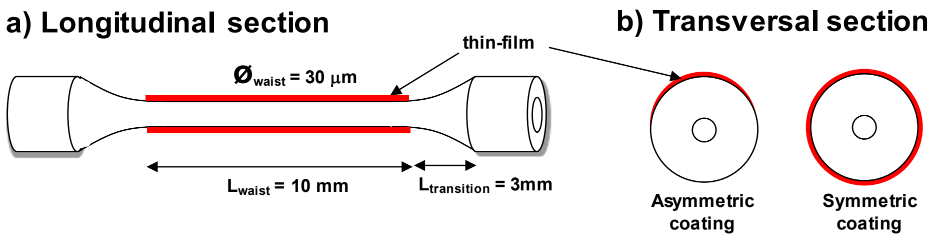

Figure 1. Longitudinal and transversal section of symmetrically and asymmetrically coated tapered optical fiber

2.1 Symmetrically coated tapered optical fibers (SCTOF)

As it was indicated in the introduction, two materials will be explored for the thin-film coated tapered optical fibers. The first material is PAH/PAA, which owns a low refractive index of 1.548+0.0105i [6]. Consequently, the mode transition occurs for high thickness values [7]. In Figure 2(a-b), it is easy to observe for a 300 nm PAH/PAA SCTOF device that a double resonance occurs at the transition to guidance in the thin-film of two modes guided in the waveguide. If the thin-film is considered as a slab waveguide these modes turn into TE and TM mode. That is why in the literature they have been considered as TE and TM LMRs [5-7]. However, in a circular waveguide they are an HE and an EH mode. Consequently, they are a HE and an EH LMR.

The second material is ITO, with a real part of the refractive index ranging from 1.87 and 1.845 in the wavelength range analyzed, and with an imaginary part of 0.025 [11]. In Figure 2(c-d), for a 100 nm ITO SCTOF device, the HE and EH LMRs are separated from each other and they can be observed at 850 and 1400 nm. Again, the transition to guidance of a mode occurs exactly when the LMR is created in the optical spectrum.

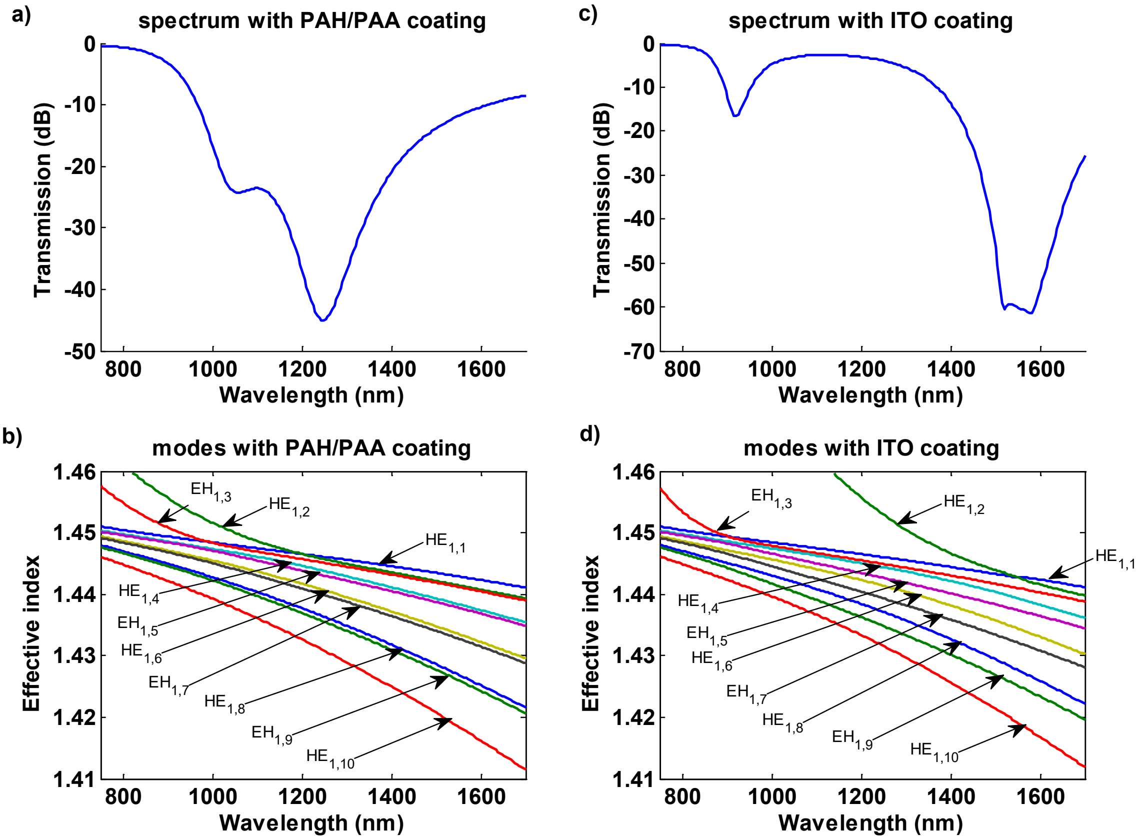

Figure 2. Spectrum and effective indices for PAH/PAA and ITO symmetrically coated tapered optical fibers

2.2 Asymmetrically coated tapered optical fibers (ACTOF)

The presence of two resonances is problematic for low refractive index materials. Two overlapping peaks are in Figure 2(a) and this may cause confusion when the central wavelength of the resonance is tracked. However, this can be avoided with an asymmetric coating. If asymmetrically coated structures with the same parameters of the symmetrically coated structures of section 2 are analyzed, it is easy to observe in Figure 3, both for ITO and PAH coatings, that for TE polarized light one of the resonances almost disappears whereas the other one is prominent and the opposite occurs for TM polarized light.

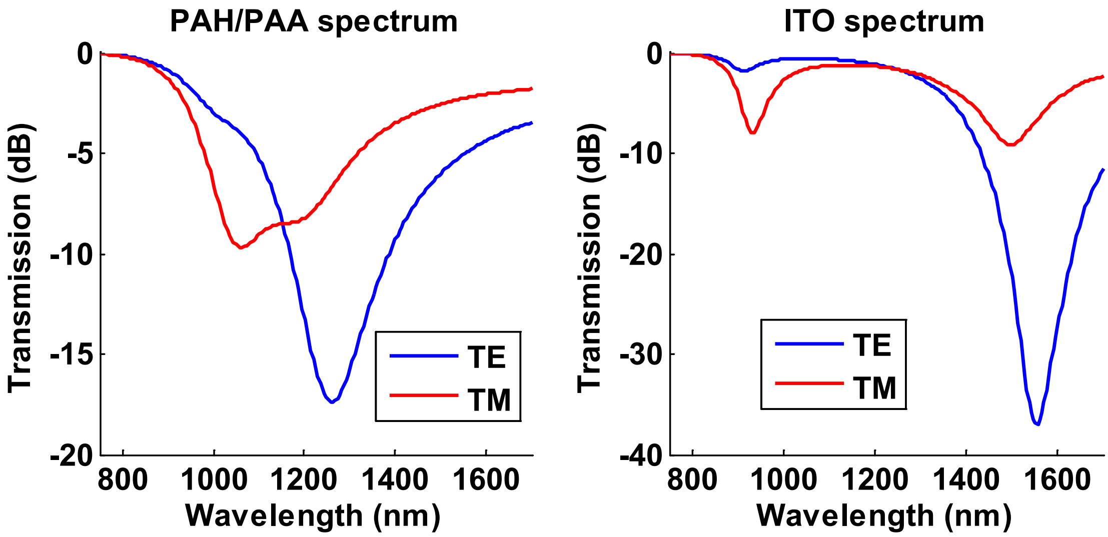

Figure 3. Spectrum for PAH/PAA and ITO asymmetrically coated tapered optical fibers. TE and TM polarization plots are included.

3. REFRACTIVE INDEX SENSORS

In order to prove the adequate performance of the proposed device, the sensitivity to surrounding refractive index (SRI) of ACTOP devices is compared in Figure 4(a) by considering both TE and TM resonances with PAH/PAA thin-film. For PAH/PAA ACTOP, sensitivities of 5633 nm/RIU and 7117 nm/RIU are obtained for TM and TE polarization, indicating that a better sensitivity can be obtained by adequate selection of the polarization.

In addition to this, the sensitivity of the LMR obtained at 930 nm with an ITO ACTOF in Figure 3 for TM polarization is analyzed also as a function of the refractive index in Figure 4(a). The sensitivity is 5667 nm/RIU, quite similar to that obtained with PAH/PAA. The LMR located at 1600 nm is not explored because in view that all resonances experiment a wavelength shift to the red, it cannot be tracked in the wavelength range analyzed if the SRI is increased.

Contrary to the performance of PAH/PAA and ITO coated device against the SRI, which is quite similar, if the sensitivity to an increase in the coating thickness is analyzed (see Figure 4(b)), the ITO device offers a better response than the PAH/PAA device. This is because the ITO coating is initially only 100 nm and the PAH/PAA is 300 nm. The explanation is that small changes is a thinner waveguide induce higher wavelength shifts [7].

From Figure 4(b), the sensitivities are obtained as a wavelength shift in nm per thickness increment in nm. For TM and TE polarization with a PAH/PAA coating, the sensitivities are 4.8 nm/nm and 3.96 nm/nm respectively. However, for TM polarization with an ITO coating a sensitivity of 9.23 nm/nm is obtained, which is a two-fold increase compared to the PAH/PAA coating.

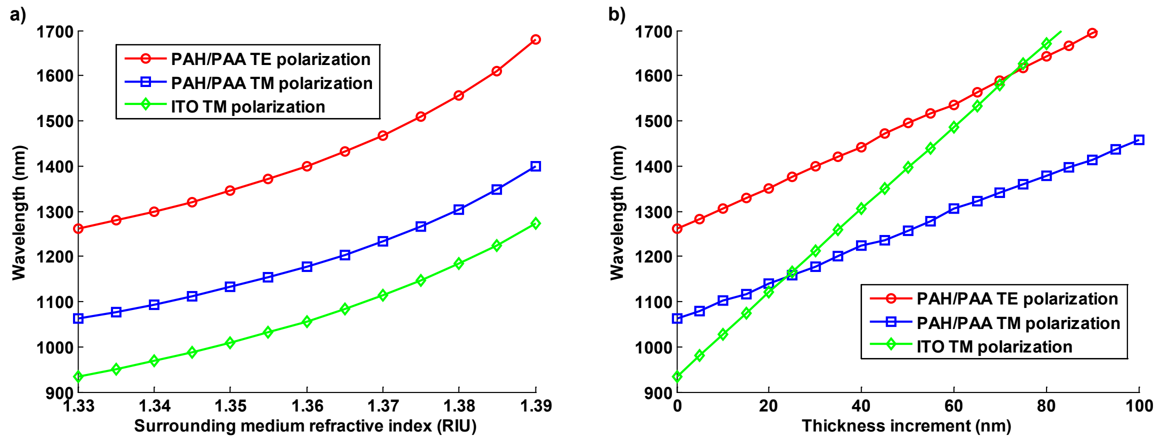

Figure 4. For PAH/PAA and ITO asymmetrically coated tapered optical fibers: a) Wavelength versus surrounding medium refractive index, b) Wavelength versus coating thickness increment

4. CONCLUSIONS

To sum up, with asymmetrically coated tapered optical fiber (ACTOF) it is possible to avoid the resonance overlap obtained with symmetrically coated tapered optical fiber when a non-metallic material is used for the coating. In addition to this, it is possible to obtain with ACTOF devices different sensitivities depending on the polarization used. For TE polarized light the sensitivity to surrounding medium refractive index is higher than for TM polarized light. Moreover, depending on the selection of the coating material (ITO or PAH/PAA), the sensitivity to coating thickness variation is higher or lower respectively.

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