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Resonance-based refractometric response of cladding-removed optical fibers with sputtered indium tin oxide coatings

C.R. Zamarreño*, S. Lopez, M. Hernaez, I. Del Villar, I.R. Matias, F.J. Arregui

Sensor Research Laboratory, Electrical and Electronic Engineering Department, Universidad Pública de Navarra, Edif. Los Tejos, Campus Arrosadia, 31006 Pamplona, Spain

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ABSTRACT

Here it is presented the fabrication of thin and homogeneous indium tin oxide (ITO) coatings onto cladding-removed optical fibers by means of the sputtering technique. ITO coatings permit to couple light at specific resonance from the optical fiber core to the coating. Fabricated devices show a resonance shift in the visible and near infrared region when the refractive index of the surrounding medium in contact with the coating is varied, which makes possible its utilization as a refractometer. It has been also demonstrated that a post-processing of the sputtered ITO coatings by means of a thermal annealing enables to shift the resonances. Furthermore, the high attenuation of the resonances in the visible spectral range facilitates the observation of a change in the output light color, which could be useful for the fabrication of optical filters or even the determination of refractive index by means of color detection.

1. Introduction

Refractometers are a versatile tool in the field of sensing devices since they can be applied to directly measure the surrounding medium refractive index (SMRI) or they can be also used combined with sensing coatings whose refractive index depends on an specific parameter. More specifically, resonance-based optical fiber refractometers can take advantage of the intrinsic properties associated to optical fiber, such as light weight, small size, remote sensing or immunity against electromagnetic interferences [1–4], as well as the advantage of wavelength detection technique associated to the resonance phenomena [5,6].

Different types of resonances can be described attending to the dielectric properties of the outer thin-film surrounding the optical waveguide. Surface plasmon resonances (SPRs) 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) [7]. Lossy mode resonances (LMRs) occur when the real part of the thin-film permittivity is positive and higher in magnitude than both its own imaginary part and the real part of the permittivity of material surrounding the thin-film [7,8]. As a rule of design, the material should own a high refractive index real part and not null imaginary part as it has been demonstrated experimentally by adding ITO [9], TiO_2 [10] or In_2O_3 [11] coatings. In contrast to SPRs, LMRs are produced by both TE or TM polarized light [12,14]. Thus, a separation of the polarizations or the utilization of polarization maintaining optical fibers could be suggested in order to obtain better sensitivities, which is beyond the scope of this work.

Taking advantage of LMRs it is even possible the generation of multiple resonance peaks as a function of the coating thickness and without modifying the optical fiber geometry [13]. Thus, an adequate selection of the thin-film to be deposited onto the optical fiber core will enable the fabrication of resonance-based optical fiber refractometers.

Previous studies have proven that the dielectric properties of indium tin oxide (ITO) coatings enable to observe both SPR and LMR resonances in different spectral regions [13,14]. Additionally, ITO coatings fabricated onto the core of cladding-removed multimode fibers (CRMMF) can produce selective optical power absorption at certain wavelengths, LMRs, as a function of the SMRI with sensitivities in the order of 4000 nm/refractive index unit [9,13,14]. Cross-sensitivity of ITO-based refractometers with temperature has been already studied in previous works within the range 20–80 °C, obtaining a resonance shift of less than 2 nm [15].

However, in most cases, the fabrication processes used for the deposition of the LMR-supporting coatings is time-consuming [9–13], which prevents the mass-production of the devices. Here it is presented an alternative approach, which basically consists of the application of the sputtering technique in order to produce thin and homogeneous ITO coatings. Since the conditions during the fabrication of the ITO layers can severely modify the final characteristics of the resonances, the sputtering technique can also help to guarantee the repeatability of the experiments. Additionally, the

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* Corresponding author. Tel.: +34 948166044; fax: +34 948169720.
E-mail address: carlos.ruiz@unavarra.es (C.R. Zamarreño).

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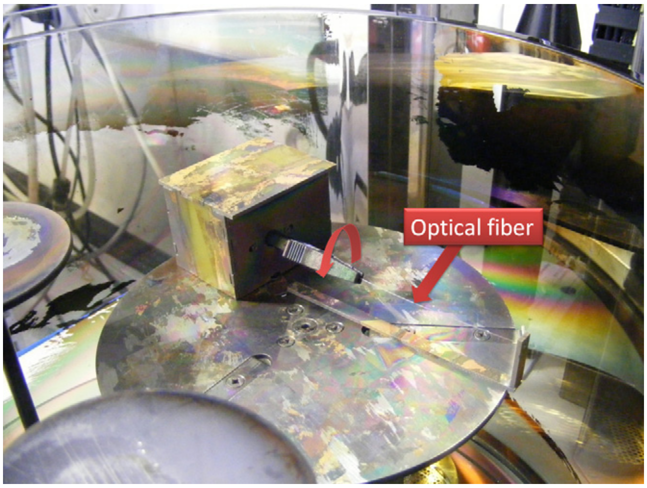

Fig. 1. Spinning mechanism used for the sputter coating deposition.

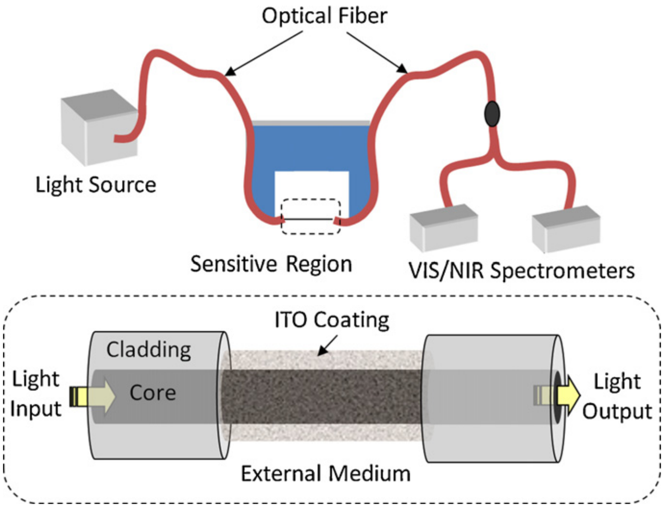

Fig. 2. Top: optical fiber transmission setup. Bottom: detail of the sensitive region.

influence of a post-thermal treatment in the resonance has been also studied.

The paper is organized as follows. First, the characteristics of the fabricated ITO coatings have been examined. Then, the refractometric response of the fabricated devices is studied and compared showing the possibilities for the fabrication of sensing devices.

2. Experimental details

2.1. Coating fabrication

Plastic cladding silica fibers (PCS) (FT200EMT from Thorlabs Inc.) with 200/225 μm core/cladding diameter were used as substrates. A 10 cm portion of the fiber was chemically uncladded. CRMMF was coated with ITO by means of the sputter coating deposition technique (K675XD from Quorum Technologies Ltd.). ITO coatings were fabricated using a target with a In:Sn ratio of 90:10, a partial pressure of Argon between 6×10^{-3} and 9×10^{-3} mbar and current intensity of 150 mA, which allowed deposition rates between 0.2 and 0.4 nm/s. In order to produce homogeneous coatings around the cylindrical core, the fiber was attached to a rotating mechanism and placed into the sputtering deposition chamber. Then, the fiber was spun at constant speed during the deposition (see Fig. 1).

Obtained ITO-coated optical fibers were characterized in terms of thickness, roughness and composition by using a scanning electron microscopy (SEM) (UltraPlus FESEM from Carl Zeiss Inc.), atomic force microscopy (AFM) (Innova from Veeco Inc.) and energy-dispersive X-ray spectroscopy (EDX) (Oxford Instruments) respectively. In particular, coating thickness was measured by cleaving the fibers perpendicularly by means of an automatic fiber cleaver (LCD-200, Vytran Inc.) in order to observe the coating around the fiber.

2.2. Characterization setup

Transmittance spectra were collected by using a typical optical transmission setup as represented in Fig. 2. This setup is based on a white halogen lamp (ASBN-W-150-H from Spectral Products), connected to one end of the optical fiber in order to couple light into the optical fiber. Then, the coupled light passes through the sensitive region located in the transmission path and arrives to a CCD-based VIS-NIR spectrometer (HR4000M and NIR512 from Oceanoptics Inc.), connected to the other end of the fiber. The sensitive region consisted of a 4 cm long ITO-coated optical fiber cleaved perpendicularly at both ends and spliced (FITEL S176, Furukawa Co. Ltd.) to 200/225 μm core/cladding optical fiber patch cords. The sensitive region was also attached to a U-shaped holder in order to avoid undesired bends during all the measuring processes. The response of the devices was recorded for different SMRI, such as air and different glycerin in water solutions at concentrations of: 0%, 10%, 20%, 30%, 40%, 50%, and 60%, which correspond to refractive index values of 1 (air), 1.333, 1.347, 1.363, 1.377, 1.392, 1.407 and 1.42 respectively [16]. All the measurements were performed at room conditions (30% RH and 25 °C).

3. Results and discussion

As it has been reported in previous works, thin-film coatings fabricated onto the core of optical fibers can produce selective optical power absorption at certain wavelengths, also known as resonances. The nature of these resonances will depend on the dielectric properties of the coating. In other words, materials with different dielectrical properties can produce different types of resonances, as for example silver [17] or polymers [18], which can generate SPR and LMR resonances respectively. What is more, the same material can produce different types of resonances with the only condition of accomplishing the resonance criteria in the selected spectral region as it is shown with ITO coatings that can produce both LMR and SPR resonances [13,14]. Concerning the LMRs, as it has been described in previous works [12–14], some design recommendations should be also taken into account prior to the fabrication of the device. Among others, it is suggested a coating material with high refractive index real part and low refractive index imaginary part (extinction coefficient). The thickness of the coating should be chosen as a compromise between the resonance spectral width and the sensitivity, which is in both cases higher for the first LMRs [14]. A minimal sensitive region length is also desirable in order to reduce the imperfections of the films although it does not affect directly to the device spectral response.

In the next paragraphs, it will be shown that thin-film coatings fabricated by sputtering can produce LMRs and also that the processing of the coatings can modify the resonance characteristics. Particularly, ITO coatings fabricated by sputtering have been subjected to a thermal treatment in order to modify the crystallization structure [19–21]. Then, the spectral response of the first ITO coated device without thermal treatment has been compared with another ITO coated device with different thickness, which has been subjected to a thermal treatment.