

Wavelength and Phase Detection Based SMS Fiber Sensors Optimized With Etching and Nanodeposition

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Abstract—The development of an optical fiber refractometer by hydrogen fluoride etching and sputtering deposition of a thin-film of indium tin oxide on a single-mode-multimode-single-mode fiber structure has been analyzed with the aim of improving the sensitivity to the changes of the refractive index (RI) of the external medium. The device is sensitive to the RI changes of the surrounding medium, which can be monitored by tracking the spectral changes of an attenuation band or with a fast Fourier transform (FFT) analysis. By using an optical spectrum analyzer combined with a simple FFT measurement technique, the simultaneous real-time monitoring is achieved. The results show that the sensitivity depends on the thin-film thickness. A maximum of 1442 nm/RIU (refractive index unit) in the 1.32–1.35 RIU range has been attained. In addition, a theoretical analysis has been performed, where simulations matched with the experimental results. As a practical application of the developed optical fiber structure, a °Brix (°Bx) sensor has been implemented with a sensitivity of 2.13 nm/°Bx and 0.25 rad/°Bx respectively for wavelength and phase shift detection.

Index Terms—Etching, optical fiber sensor, refractive index, single-mode-multimode-single-mode (SMS), thin-films.

I. INTRODUCTION

OPTICAL fiber refractometers have been extensively studied for chemical, medicine, and biological applications due their multiple advantages such as compact size and high resolution. They can be used in harsh environments and allow for minimally invasive procedures to be performed [1].

Up until now, several technologies have been used to develop optical fiber refractometers. Some of these technologies include: fiber gratings [2], [3], long period fiber gratings [4], resonances [5], [6], evanescent field [7] and interferometers [8].

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Within the last group, a single-mode-multimode-single-mode SMS fiber refractometer has been studied and a sensitivity of 1199.8 nm / RIU for the range of refractive indices from 1.321 to 1.382 has been reported [9]. In this work, the experimental and theoretical demonstration of a novel and high-sensitivity refractometric sensor is reported. The developed sensor relies on multimodal interference in etched SMS fiber structures coated with a thin-film that improves the previously sensitivity reported with this structure [9]. Moreover, by application of fast Fourier transform analysis (FFT), it is possible to use both wavelength and phase monitoring of the parameter to detect.

The proposed SMS configuration of this work consists of input and output single-mode fibers (SMFs) that are spliced to a section of a multimode coreless fiber (MMF) of a certain length. The operation mechanism of this refractometer is based on the multimode interference (MMI). When the light propagating along the input SMF enters the MMF section, several eigenmodes of the MMF are excited and interference among different modes occurs during the propagation along the MMF section. Finally, the light is coupled into the output SMF at the end of the MMF section [10]. Through the reduction of the diameter in the MMF section, the evanescent field penetrates further into the surrounding medium, thus increasing the sensitivity [11], [12]. Furthermore, a deposited high refractive index thin-film enhances the interaction with the environment surrounding the fiber and also permits to increase the sensitivity.

To sum up, the enhancement of the sensitivity in the SMS configuration in this work is achieved by gathering two different phenomena, diameter reduction and thin-film deposition.

II. METHODS AND MATERIALS

Coreless MMF segments from POFC Inc. (Taiwan) and standard SMF pigtailed from Telnet Redes Inteligentes Inc. (Zaragoza, Spain) were used in this study. The SMS structure consists on a 14-mm segment of coreless MMF spliced on each end to standard SMF pigtailed, as shown in Fig. 1(a). This structure was etched using hydrofluoric acid 40% (HF) until the diameter of the fiber was reduced to approximately 25 μm [see Fig. 1(b)]. This process took 70 minutes. Finally, a thin-film of Indium Tin Oxide (ITO) was deposited by sputtering on the etched region [see Fig. 1(c)]. The effect of the etching and the deposition was studied theoretically and experimentally.

The theoretical analysis was performed with FIMMWAVE. The propagation was obtained with FIMMPROP, a module in-

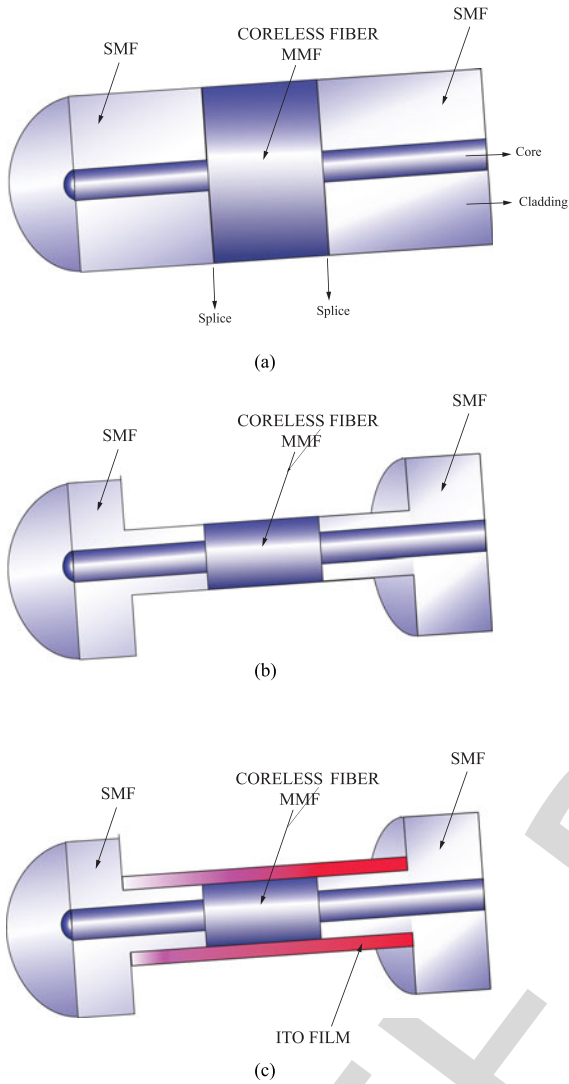


Fig. 1. (a) 14-mm segment of coreless MMF spliced on each end to standard SMF forming an SMS structure, (b) SMS structure after the HF etching, (c) etched SMS structure with an ITO thin-film deposition.

78 integrated with FIMMWAVE. Finite difference method FDM was
 79 used for the SMF and MMF sections, since it is the most accurate
 80 method available for cylindrical waveguides. In the SMF
 81 sections only the fundamental mode was analyzed, whereas for
 82 the MMF section 30 modes were analyzed, thus allowing to
 83 achieve convergence in the results.

84 A. Diameter Reduction

85 Light from a white SLED source was launched through the
 86 SMS structure during the etching stage in a 40% HF solution until
 87 the diameter of the fiber was reduced to approximately $25 \mu\text{m}$.
 88 The transmission spectrum was recorded by an Optical Spectrum
 89 Analyzer (OSA). Fig. 2 depicts the experimental setup.

90 B. Film Deposition

91 Three SMS structures were etched with the aforementioned
 92 procedure, hereafter called Sensor 1, Sensor 2, and Sensor 3,

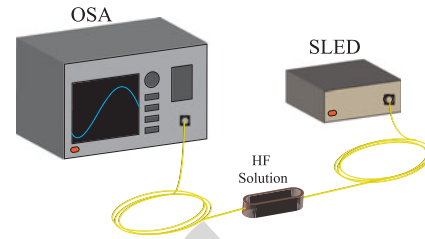


Fig. 2. Experimental setup for etching the SMS structure.

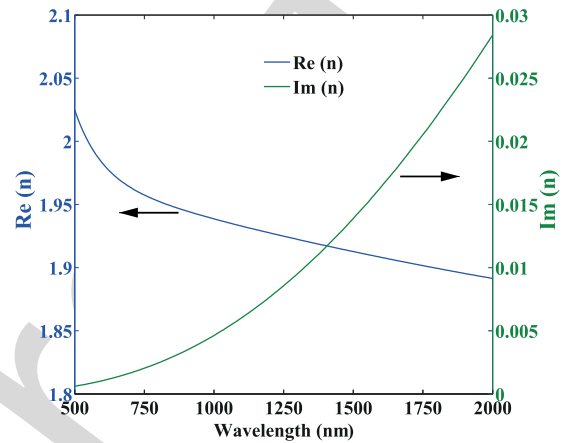


Fig. 3. Ellipsometry analysis of the ITO film used in this work.

93 respectively. Light from a white SLED source was launched into
 94 the structures while an ITO thin-film was deposited by sputtering
 95 (first on Sensor 2, and then on Sensor 3). An Optical Spectrum
 96 Analyzer (OSA) recorded the transmission spectra during the
 97 deposition.

98 Sensor 1 had no thin-film, Sensor 2 and Sensor 3 were
 99 deposited with ITO during 45 and 75 seconds respectively in a
 100 sputtering device (K675XD from Quorum Technologies, Ltd.)
 101 using 150 mA current and 8×10^{-3} mbar pressure.

102 To study the effect of the ITO thin-film deposition theoretically,
 103 it was necessary to obtain its dispersion curves. Fig. 3 depicts
 104 the ellipsometry analysis performed. This ellipsometric
 105 information allowed to compare the theoretical wavelength
 106 spectra before and after the deposition.

107 C. Device Characterization by Wavelength Shift

108 After the fabrication of the sensors, the same setup shown in
 109 Fig. 2 was used to characterize them when subjected to changes
 110 in the external RI. In order to observe the wavelength shift, the
 111 sensitive structure was immersed in various solutions of glycerol
 112 in water at different concentrations [13], [14]. The sensitivity
 113 curves were studied by tracking the spectral changes of the
 114 nearest attenuation band to a wavelength of 1550 nm.

115 This characterization was performed to all three sensors fab-
 116 ricated: Sensor 1, Sensor 2, and Sensor 3.

117 Theoretically, the sensor characterization was performed by
 118 simulating with FIMMWAVE the SMS structure after the etching
 119 procedure for the three film conditions proposed, for different
 120 refractive indices of the surrounding medium. The refractive

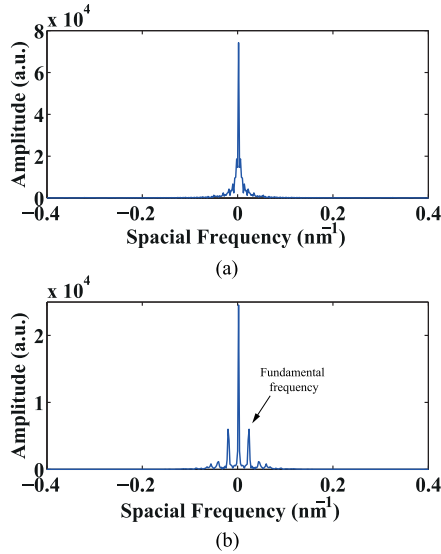


Fig. 4. Amplitude of the fast Fourier transform before (a) and after (b) of the theoretical spectrum obtained by etching.

121 index of the optical fiber cladding, made of fused silica, was es-
 122 timated by using the Sellmeier equation:

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

123 with parameters: $B1 = 0.691663$, $B2 = 0.4079426$, $B3 =$
 124 0.8974794 , $\lambda1 = 0.0684043 \mu\text{m}$, $\lambda2 = 0.1162414$, and $\lambda3 =$
 125 9.896161 , where $\lambda_j = 2\pi c/\omega_j$ and c is the speed of light in
 126 vacuum [15]. The optical fiber core refractive index for the
 127 simulations was obtained, according to the specifications from
 128 the fiber manufacturer, by increasing the refractive index of the
 129 cladding 0.36%.

130 *D. Degrees Brix ($^{\circ}\text{Bx}$) Sensor Monitored by Both Wavelength*
 131 *and Phase Shift Detection*

132 Typically, sensors are characterized by tracking the wave-
 133 length of an attenuation band using an optical spectrum ana-
 134 lyzer, or alternatively by measuring the intensity variations
 135 at a fixed wavelength using a power meter. The fast Fourier
 136 transform (FFT) analysis, which permits to extract the phase of
 137 the optical spectrum, is not a broadly used technique despite
 138 it provides useful and clear information to be used in sensing
 139 applications and permits to use interrogators instead of optical
 140 spectrum analyzers [16], [17].

141 The sinusoidal spectrum of the SMS sensors after etching
 142 permits to see a sharp peak corresponding to the fundamental
 143 frequency (see in Fig. 4 the comparison between the magnitude
 144 of the fast Fourier transform before and after etching). Con-
 145 sequently, it is possible to obtain a phase sensitive device by
 146 tracking the phase of this fundamental frequency as a function
 147 of the parameter to detect.

148 In order to probe the feasibility of this method for the devel-
 149 oped sensor shown here, a degrees Brix sensor by phase shift
 150 detection is presented. The ITO thickness film to the sensor
 151 used in this application is approximately 60 nm. A MATLAB

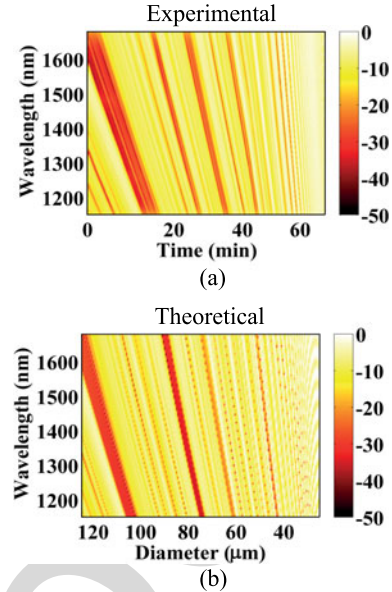


Fig. 5. Evolution of the wavelength spectrum due to reduction of the diameter by HF etching: (a) Experimental; (b) theoretical.

script was implemented to obtain the phase of the fundamen-
 152 tal frequency in the optical spectrum response of the sensor.

153 Degrees Brix is a scale of relative density used in the sugar
 154 and winemaking industry. It indicates the percentage of cane
 155 sugar by weight in a solution or juice of unfermented grapes.
 156 Its measurement is crucial in many applications, such as fruit
 157 juice, carbonated beverage industry, and wine making.

158 The solutions used here were prepared by dissolving sucrose
 159 in distilled water. One (1) $^{\circ}\text{Bx}$ equals one (1) gram of sucrose
 160 dissolved in 100 grams of solution.
 161

162 *E. Phase Shift and Temperature Cross Sensitivity*

163 A 40-nm thickness ITO thin-film deposited sensor fabricated
 164 following the same procedure described for Sensor 2 was placed
 165 in a water cell with temperature control. The temperature was
 166 set to 40 $^{\circ}\text{C}$ and the spectra started being recorded after reaching
 167 this set point, for 10 minutes. After this time, the control was set
 168 to 30 $^{\circ}\text{C}$ and kept at this constant temperature for 20 minutes.
 169 Finally, the temperature control was set back at 40 $^{\circ}\text{C}$ for 10
 170 minutes once this temperature was reached. The real time phase
 171 shift was recorded and processed along with the entire procedure
 172 of temperature variation.

173 III. RESULTS

174 A. Diameter Reduction

175 The experimental and theoretical evolution of the wavelength
 176 spectrum as a function of the fiber diameter are depicted in
 177 Fig. 5(a) and (b) respectively.

178 Fig. 6(a) and (b) show the theoretical and experimental trans-
 179 mission spectra for both, etched and unetched fibers. Video files
 180 of this experimental and theoretical evolution can be found in
 181 the supplementary material of this manuscript. According to [9],
 182 [18], the diameter reduction is proportional to the sensitivity in-
 183 crease to refractive index. Consequently, a reduction from 125
 184 to 25 μm should lead to a fivefold increase.

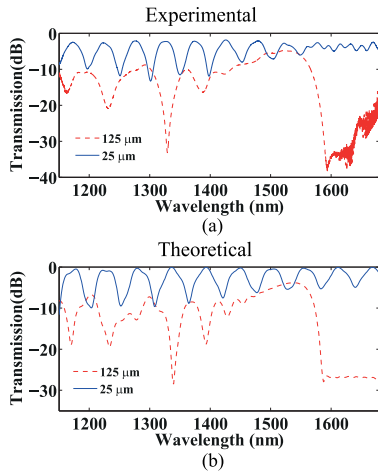


Fig. 6. Comparison between the spectra of unetched and etched fibers: (a) Experimental; (b) theoretical.

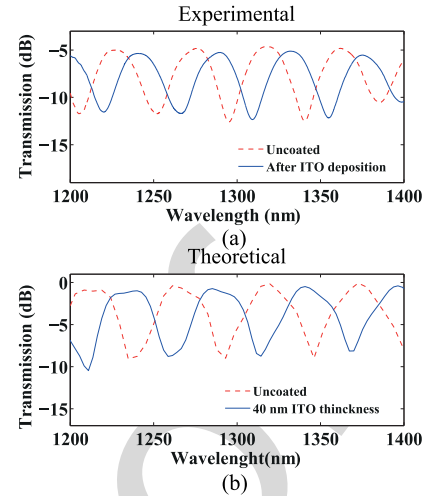


Fig. 8. Initial and final transmission spectra due to the ITO thin-film deposition on Sensor 2: (a) Experimental; (b) theoretical.

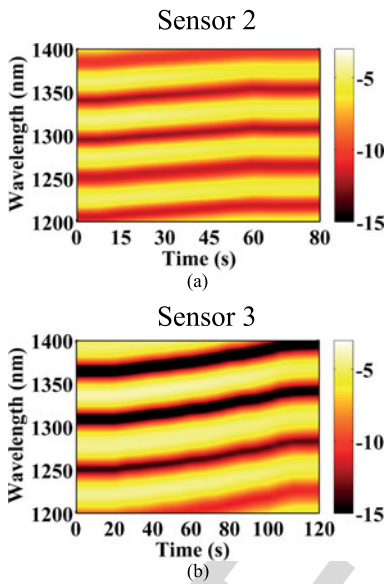


Fig. 7. Experimental evolution of the spectra during ITO deposition from: (a) Sensor 2; (b) Sensor 3.

185 In addition to the structural integrity of the fiber, it was ob-
 186 served that at this diameter the transmission evolved into a quasi-
 187 sinusoidal spectrum for a length of the coreless MMF of 14 mm.
 188 This behavior facilitates both the presence of multiple attenua-
 189 tion bands and the shift phase study.

190 B. Film Deposition

191 Fig. 7(a) and (b) present the spectral response obtained from
 192 Sensors 2 and 3 during the ITO films deposition.

193 For both cases, the transmission spectra underwent redshifts
 194 during the deposition, proving the existence of a relationship
 195 between the spectral position and the ITO film thickness. Sensor
 196 2 and Sensor 3 exhibited 23 nm and 40 nm redshifts, respectively.
 197 Fig. 8(a) and (b), and Fig. 9(a) and (b) show the experimental
 198 and theoretical spectra before and after the ITO film deposition
 199 for Sensors 2 and 3, respectively.

200 It can be observed that the experimental redshifts due to the
 201 ITO deposition were in essence the same as those obtained theo-

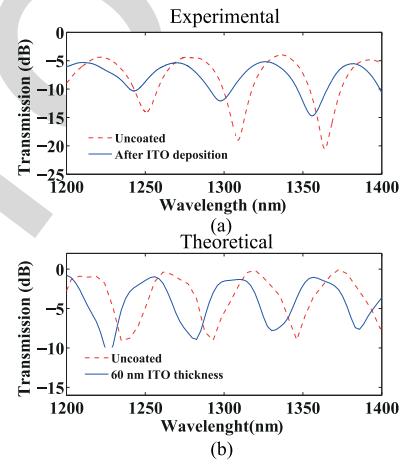


Fig. 9. Initial and final transmission spectra due to the ITO thin film deposition on Sensor 3: (a) Experimental; (b) theoretical.

retically. This probes that the transmission spectrum experiences
 a redshift as thin-film thickness grows.

Based on theoretical analysis, it can be concluded that the
 thicknesses of the deposited thin-film were of 40 nm and 60
 nm to Sensor 2 and Sensor 3, respectively. To support the good
 match between the experimental and theoretical results, Sensor 2
 was cleaved and observed using a scanning electron microscope
 (SEM). Fig. 10 shows the cross section, where the measure-
 ment of the film thickness was 44.18 nm. This supposes a 10%
 deviation with respect to the theoretical value for this sensor.

C. Wavelength Shift Characterization of the Device

Figs. 11, 12, and 13 show the theoretical and experimental
 transmission spectra as a function of wavelength for various
 refractive indices. A redshift can be observed in all cases when
 the RI increases, and there is a good agreement between the
 theoretical and experimental results.

Fig. 14 illustrates the wavelength shift as a function of the
 external refractive index, which allows the sensitivity to be cal-
 culated both experimentally [see Fig. 14(a)] and theoretically
 [see Fig. 14(b)]. In both cases the wavelength position was
 taken with the attenuation band closer to 1550 nm.

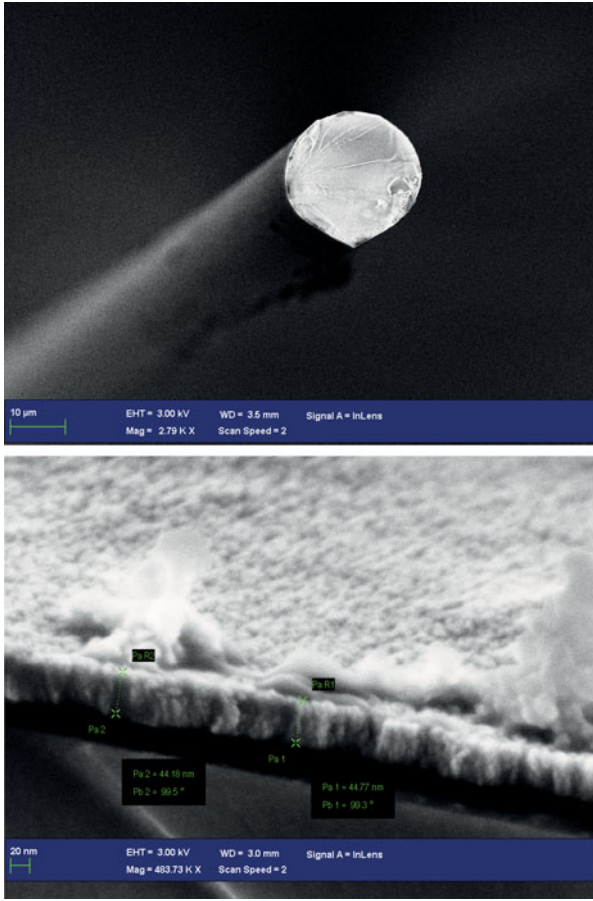


Fig. 10. SEM images of Sensor 2: Diameter 25 μm and ITO thin film 44 nm.

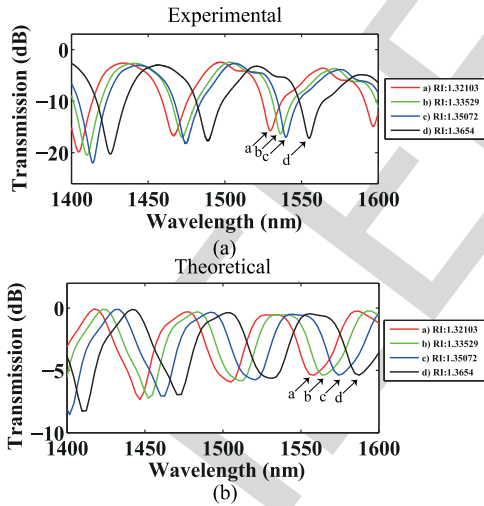


Fig. 11. Transmission spectrum for Sensor 1 as a function of the wavelength for different surrounding media refractive indices: (a) Experimental; (b) theoretical.

223 It can be noticed that an increase in the thin-film thickness
 224 leads to a higher sensitivity. Table I shows a summary of the
 225 sensitivities in the 1.32–1.35 refractive index range. The exper-
 226 imental sensitivity improves that obtained in [9]. Indeed, even
 227 though a sensitivity of 1200 nm/RIU was attained in that work,
 228 the SRI range was 1.32–1.38, with a higher sensitivity. More-

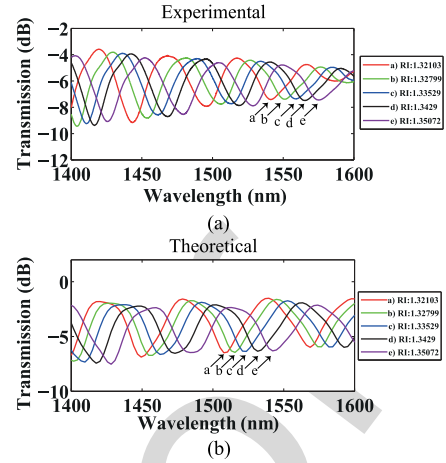


Fig. 12. Transmission spectrum for Sensor 2 as a function of the wavelength for different surrounding media refractive indices: a) Experimental; b) theoretical.

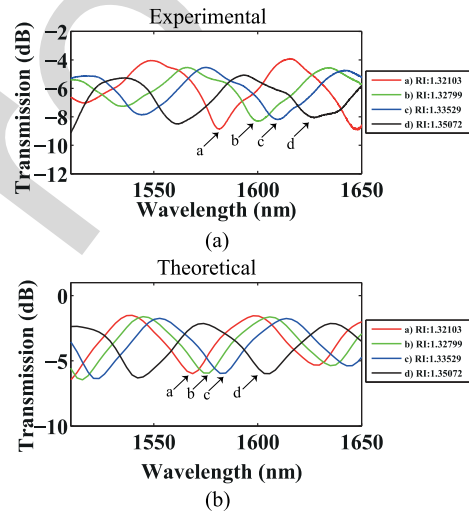


Fig. 13. Transmission a) experimental and b) theoretical for Sensor 3 as a function of the wavelength for different surrounding media refractive indices.

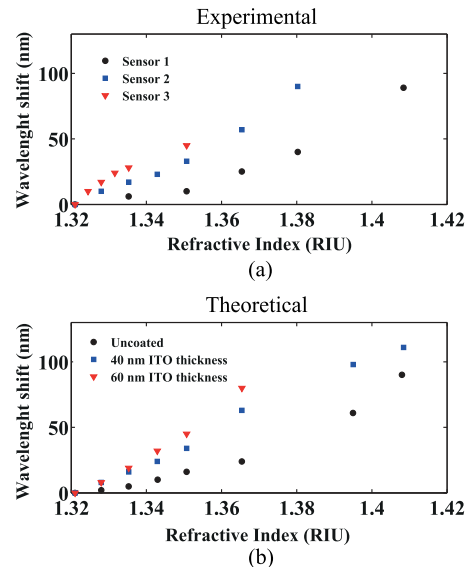


Fig. 14. Wavelength shift with refractive index to Sensor 1, 2 and 3, for both, a) experimental and b) theoretical cases.

TABLE I
COMPARISON SENSITIVITIES OBTAIN EXPERIMENTALLY AND THEORETICALLY
TO A 1.32–1.35 RIU RANGE

Thin-film Thickness (nm)	Experimental Sensitivity	Theoretical Sensitivity
Uncoated	335 nm/RIU $R^2=0.9812$	454 nm/RIU $R^2=0.9669$
~ 40	1062 nm/RIU $R^2=0.9906$	1131 nm/RIU $R^2=0.999$
~ 60	1442 nm/RIU $R^2=0.953$	1536 nm/RIU $R^2=0.9951$

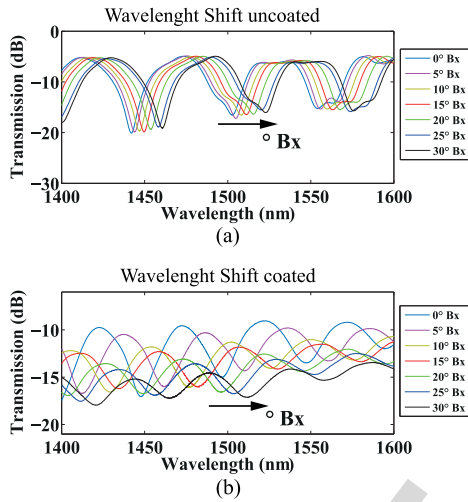


Fig. 15. Transmission as a function of the wavelength to different $^{\circ}\text{Bx}$ of an (a) etched SMS configuration without thin-film and (b) a 60 nm thin-film Thickness ITO etched SMS configuration.

229 over, though overcome by LPFGs optimized with a hard etching
230 [19], the device presented here is comparable with the sensitivity
231 obtained with LPFGs optimized with a soft etching [20], which
232 along with the possibility to monitor the phase shift indicates
233 that it is an interesting device for biosensing applications, where
234 a high degree of accuracy.

235 D. Degrees Brix ($^{\circ}\text{Bx}$) Sensor Monitored by Both Wavelength 236 and Phase Shift Detection

237 Fig. 15 shows transmission as a function of the wavelength for
238 different solutions of sucrose in water addressing two cases: an
239 etched SMS configuration without thin-film and a 60 nm thick-
240 ness ITO thin-film deposited on it. Both cases show a redshift
241 when the probe was immersed in.

242 The magnitude of the wavelength shift is more notorious in the
243 coated fiber, regardless of the attenuation observed, according
244 to what has been observed in the previous section.

245 Fig. 16(a) and (b) present the wavelength shift of an attenu-
246 ation band and the phase shift for both the etched SMS con-
247 figuration without ITO coating and the same configuration type
248 with a 60 nm thickness ITO thin-film. A simple linear fit of the
249 results evidences that the ITO film permitted to obtain a
250 three-fold sensitivity increase in both cases.

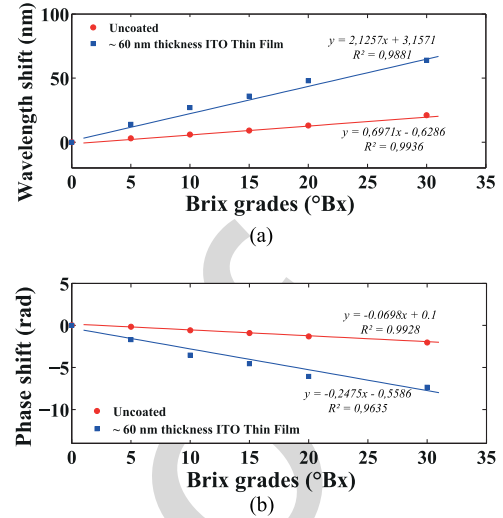


Fig. 16. Phase shift of a brix grades sensor: (a) Without ITO thin-film; (b) with 60 nm thickness ITO thin-film.

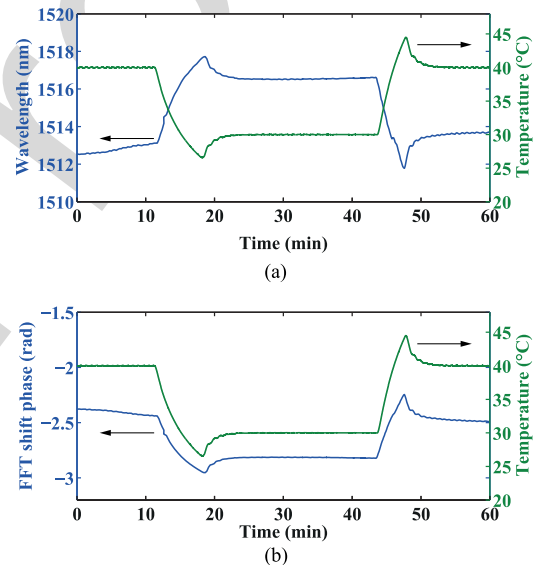


Fig. 17. (a) Wavelength shift and (b) phase shift temperature cross sensitivity.

251 E. Temperature Cross Sensitivity

252 Fig. 17(a) and (b) show the behavior of the wavelength shift
253 of an attenuation band and the phase shift with the temperature
254 setting as described in Section II-E. This probe was realized
255 with the 60 nm thin-film thickness sensor. The phase behavior
256 observed followed a trend imposed by the temperature's profile
257 generated as a consequence of the set points established. The
258 sensitivity was 0.3 nm/ $^{\circ}\text{C}$ and 0.034 rad/ $^{\circ}\text{C}$.

259 A 0.14 $^{\circ}\text{Bx}/^{\circ}\text{C}$ of sensitivity was calculated for the ITO thin-
260 film coated sensors analyzed in the previous section.

261 IV. CONCLUSION

262 This manuscript presented the optimization of SMS fiber
263 structures with a combined application of two techniques: etch-
264 ing and deposition of a thin-film. By an adequate design it
265 was possible to track both wavelength shifts of the optical spec-
266 trum and, by applying a simple FFT measurement technique, the

phase shift of the fundamental frequency. The FFT measurement used in the analysis is an easy method that can be most applicable to networks that require narrow band, multiplexing capability and that have some problems related with high losses and noise.

The results also showed that the sensitivity obtained for this configuration of SMS was enhanced by reduction of the fiber diameter and by increasing the ITO film thickness. A good agreement was achieved between the experimental and the simulated approaches for this sensing device. A sensitivity of 1442 nm/RIU was obtained by tracking the wavelength shift in a SMS with 25 μm diameter and a 60 nm ITO thickness film, whereas for the same device, the FFT phase shift analysis showed a 0.24 rad/RIU sensitivity.

These sensitivities, which are in the order of magnitude of other structures such as long period fiber gratings (LPGs) (but with an inherently simpler manufacture process), place the developed sensing device as a good option for applications where high sensitivities and compact structures are required. As an example, a degrees Brix sensor has been presented, where the deposition of an ITO thin-film enhances the sensitivity of the device by a factor of 3.

REFERENCES

- [1] C. R. Dennison, P. M. Wild, D. R. Wilson, and M. K. Gilbart, "An in-fiber Bragg grating sensor for contact force and stress measurements in articular joints," *Meas. Sci. Technol.*, vol. 21, no. 11, 2010, Art. no. 115803.
- [2] I. Del Villar, I. R. Matias, F. J. Arregui, and M. Achaerandio, "Nanodeposition of materials with complex refractive index in long-period fiber gratings," *J. Lightw. Technol.*, vol. 23, no. 12, pp. 4192–4199, Dec. 2005.
- [3] R. Kashyap, *Fiber Bragg Gratings*. New York, NY, USA: Academic, 1999.
- [4] F. Chiavaioli *et al.*, "Sol-gel-based titania-silica thin film overlay for long period fiber grating-based biosensors," *Anal. Chem.*, vol. 87, no. 24, pp. 12024–12031, 2015.
- [5] I. Del Villar, C. R. Zamarreño, M. Hernaez, F. J. Arregui, and I. R. Matias, "Lossy mode resonance generation with indium-tin-oxide-coated optical fibers for sensing applications," *J. Lightw. Technol.*, vol. 28, no. 1, pp. 111–117, Jan. 2010.
- [6] J. Homola, "Surface plasmon resonance sensors for detection of chemical and biological species," *Chem. Rev.*, vol. 108, no. 2, pp. 462–493, 2008.
- [7] Y. Cardona Maya, N. Gómez Cardona, and P. I. Torres Trujillo, "Low cost heat-and-pull rig for manufacturing adiabatic optical fiber tapers," *Revista Facultad de Ingeniería Universidad de Antioquia*, no. 70, pp. 167–172, 2014. [Online]. Available: <http://aprendeenlinea.udea.edu.co/revistas/index.php/ingenieria/article/viewFile/14820/16007>
- [8] T. Zhu, D. Wu, M. Liu, and D.-W. Duan, "In-line fiber optic interferometric sensors in single-mode fibers," *Sensors*, vol. 12, no. 8, pp. 10430–10449, 2012.
- [9] I. D. Villar, A. B. Socorro, J. M. Corres, F. J. Arregui, and I. R. Matias, "Refractometric sensors based on multimode interference in a thin-film coated single-mode-multimode-single-mode structure with reflection configuration," *Appl. Opt.*, vol. 53, no. 18, pp. 3913–3919, 2014.
- [10] Q. Wang and G. Farrell, "All-fiber multimode-interference-based refractometer sensor: Proposal and design," *Opt. Lett.*, vol. 31, no. 3, pp. 317–319, 2006.
- [11] J. Lou, L. Tong, and Z. Ye, "Modeling of silica nanowires for optical sensing," *Opt. Express*, vol. 13, no. 6, pp. 2135–2140, 2005.
- [12] A. W. Snyder and J. Love, *Optical Waveguide Theory*. Berlin, Germany: Springer, 2012.
- [13] P. R. Cooper, "Refractive-index measurements of liquids used in conjunction with optical fibers," *Appl. Opt.*, vol. 22, no. 19, pp. 3070–3072, 1983.
- [14] L. Hoyt, "New table of the refractive index of pure glycerol at 20 C," *Ind. Eng. Chem.*, vol. 26, no. 3, pp. 329–332, 1934.
- [15] I. Malitson, "Interspecimen comparison of the refractive index of fused silica*," *J. Opt. Soc. Amer.*, vol. 55, no. 10, pp. 1205–1209, 1965.
- [16] D. Barrera *et al.*, "Low-loss photonic crystal fiber interferometers for sensor networks," *J. Lightw. Technol.*, vol. 28, no. 24, pp. 3542–3547, Dec. 2010.
- [17] D. Leandro, M. Bravo, A. Ortigosa, and M. Lopez-Amo, "Real-time FFT analysis for interferometric sensors multiplexing," *J. Lightw. Technol.*, vol. 33, no. 2, pp. 354–360, Jan. 2015.
- [18] P. Wang, G. Brambilla, M. Ding, Y. Semenova, Q. Wu, and G. Farrell, "High-sensitivity, evanescent field refractometric sensor based on a tapered, multimode fiber interference," *Opt. Lett.*, vol. 36, no. 12, pp. 2233–2235, 2011.
- [19] I. Del Villar, J. L. Cruz, A. B. Socorro, J. M. Corres, and I. R. Matias, "Sensitivity optimization with cladding-etched long period fiber gratings at the dispersion turning point," *Opt. Express*, vol. 24, no. 16, pp. 17680–17685, 2016.
- [20] F. Chiavaioli *et al.*, "Towards sensitive label-free immunosensing by means of turn-around point long period fiber gratings," *Biosensors Bioelectron.*, vol. 60, pp. 305–310, 2014.

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Wavelength and Phase Detection Based SMS Fiber Sensors Optimized With Etching and Nanodeposition

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Abstract—The development of an optical fiber refractometer by hydrogen fluoride etching and sputtering deposition of a thin-film of indium tin oxide on a single-mode-multimode-single-mode fiber structure has been analyzed with the aim of improving the sensitivity to the changes of the refractive index (RI) of the external medium. The device is sensitive to the RI changes of the surrounding medium, which can be monitored by tracking the spectral changes of an attenuation band or with a fast Fourier transform (FFT) analysis. By using an optical spectrum analyzer combined with a simple FFT measurement technique, the simultaneous real-time monitoring is achieved. The results show that the sensitivity depends on the thin-film thickness. A maximum of 1442 nm/RIU (refractive index unit) in the 1.32–1.35 RIU range has been attained. In addition, a theoretical analysis has been performed, where simulations matched with the experimental results. As a practical application of the developed optical fiber structure, a °Brix (°Bx) sensor has been implemented with a sensitivity of 2.13 nm/°Bx and 0.25 rad/°Bx respectively for wavelength and phase shift detection.

Index Terms—Etching, optical fiber sensor, refractive index, single-mode–multimode–single-mode (SMS), thin-films.

I. INTRODUCTION

OPTICAL fiber refractometers have been extensively studied for chemical, medicine, and biological applications due their multiple advantages such as compact size and high resolution. They can be used in harsh environments and allow for minimally invasive procedures to be performed [1].

Up until now, several technologies have been used to develop optical fiber refractometers. Some of these technologies include: fiber gratings [2], [3], long period fiber gratings [4], resonances [5], [6], evanescent field [7] and interferometers [8].

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Within the last group, a single-mode-multimode-single-mode SMS fiber refractometer has been studied and a sensitivity of 1199.8 nm / RIU for the range of refractive indices from 1.321 to 1.382 has been reported [9]. In this work, the experimental and theoretical demonstration of a novel and high-sensitivity refractometric sensor is reported. The developed sensor relies on multimodal interference in etched SMS fiber structures coated with a thin-film that improves the previously sensitivity reported with this structure [9]. Moreover, by application of fast Fourier transform analysis (FFT), it is possible to use both wavelength and phase monitoring of the parameter to detect.

The proposed SMS configuration of this work consists of input and output single-mode fibers (SMFs) that are spliced to a section of a multimode coreless fiber (MMF) of a certain length. The operation mechanism of this refractometer is based on the multimode interference (MMI). When the light propagating along the input SMF enters the MMF section, several eigenmodes of the MMF are excited and interference among different modes occurs during the propagation along the MMF section. Finally, the light is coupled into the output SMF at the end of the MMF section [10]. Through the reduction of the diameter in the MMF section, the evanescent field penetrates further into the surrounding medium, thus increasing the sensitivity [11], [12]. Furthermore, a deposited high refractive index thin-film enhances the interaction with the environment surrounding the fiber and also permits to increase the sensitivity.

To sum up, the enhancement of the sensitivity in the SMS configuration in this work is achieved by gathering two different phenomena, diameter reduction and thin-film deposition.

II. METHODS AND MATERIALS

Coreless MMF segments from POFC Inc. (Taiwan) and standard SMF pigtailed from Telnet Redes Inteligentes Inc. (Zaragoza, Spain) were used in this study. The SMS structure consists on a 14-mm segment of coreless MMF spliced on each end to standard SMF pigtailed, as shown in Fig. 1(a). This structure was etched using hydrofluoric acid 40% (HF) until the diameter of the fiber was reduced to approximately 25 μm [see Fig. 1(b)]. This process took 70 minutes. Finally, a thin-film of Indium Tin Oxide (ITO) was deposited by sputtering on the etched region [see Fig. 1(c)]. The effect of the etching and the deposition was studied theoretically and experimentally.

The theoretical analysis was performed with FIMMWAVE. The propagation was obtained with FIMMPROP, a module in-

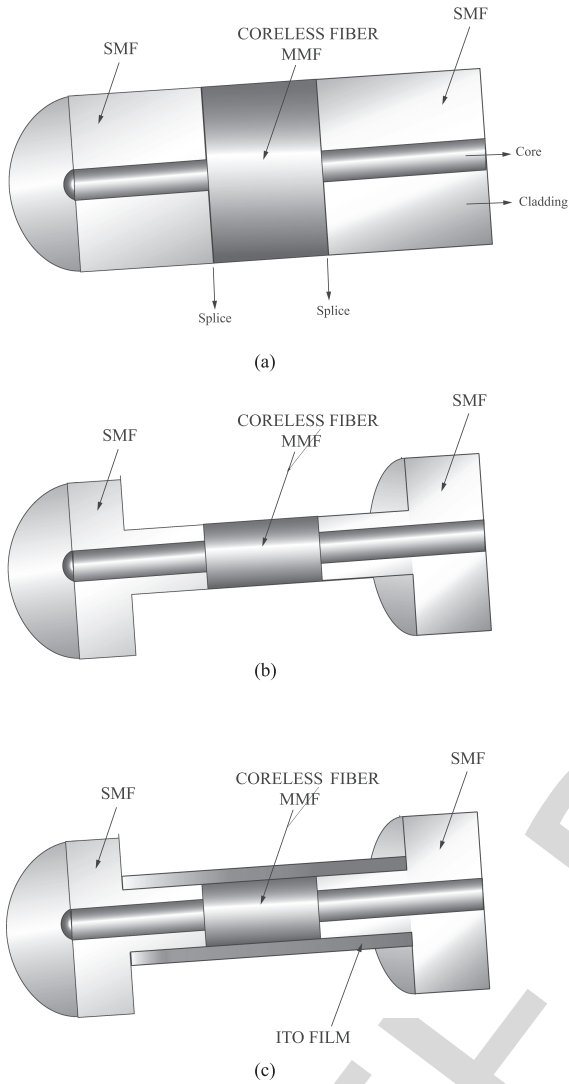


Fig. 1. (a) 14-mm segment of coreless MMF spliced on each end to standard SMF forming an SMS structure, (b) SMS structure after the HF etching, (c) etched SMS structure with an ITO thin-film deposition.

78 integrated with FIMMWAVE. Finite difference method FDM was
 79 used for the SMF and MMF sections, since it is the most accurate
 80 method available for cylindrical waveguides. In the SMF
 81 sections only the fundamental mode was analyzed, whereas for
 82 the MMF section 30 modes were analyzed, thus allowing to
 83 achieve convergence in the results.

84 A. Diameter Reduction

85 Light from a white SLED source was launched through the
 86 SMS structure during the etching stage in a 40% HF solution until
 87 the diameter of the fiber was reduced to approximately $25 \mu\text{m}$.
 88 The transmission spectrum was recorded by an Optical Spectrum
 89 Analyzer (OSA). Fig. 2 depicts the experimental setup.

90 B. Film Deposition

91 Three SMS structures were etched with the aforementioned
 92 procedure, hereafter called Sensor 1, Sensor 2, and Sensor 3,

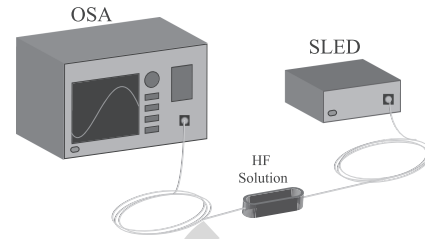


Fig. 2. Experimental setup for etching the SMS structure.

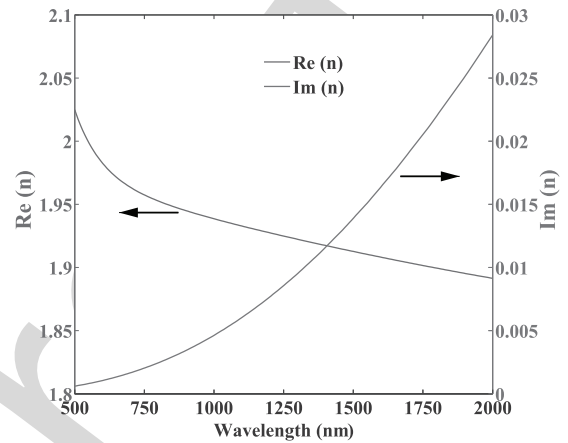


Fig. 3. Ellipsometry analysis of the ITO film used in this work.

93 respectively. Light from a white SLED source was launched into
 94 the structures while an ITO thin-film was deposited by sputtering
 95 (first on Sensor 2, and then on Sensor 3). An Optical Spectrum
 96 Analyzer (OSA) recorded the transmission spectra during the
 97 deposition.

98 Sensor 1 had no thin-film, Sensor 2 and Sensor 3 were
 99 deposited with ITO during 45 and 75 seconds respectively in a
 100 sputtering device (K675XD from Quorum Technologies, Ltd.)
 101 using 150 mA current and 8×10^{-3} mbar pressure.

102 To study the effect of the ITO thin-film deposition theoretically,
 103 it was necessary to obtain its dispersion curves. Fig. 3
 104 depicts the ellipsometry analysis performed. This ellipsometric
 105 information allowed to compare the theoretical wavelength
 106 spectra before and after the deposition.

107 C. Device Characterization by Wavelength Shift

108 After the fabrication of the sensors, the same setup shown in
 109 Fig. 2 was used to characterize them when subjected to changes
 110 in the external RI. In order to observe the wavelength shift, the
 111 sensitive structure was immersed in various solutions of glycerol
 112 in water at different concentrations [13], [14]. The sensitivity
 113 curves were studied by tracking the spectral changes of the
 114 nearest attenuation band to a wavelength of 1550 nm.

115 This characterization was performed to all three sensors fab-
 116 ricated: Sensor 1, Sensor 2, and Sensor 3.

117 Theoretically, the sensor characterization was performed by
 118 simulating with FIMMWAVE the SMS structure after the etch-
 119 ing procedure for the three film conditions proposed, for differ-
 120 ent refractive indices of the surrounding medium. The refractive

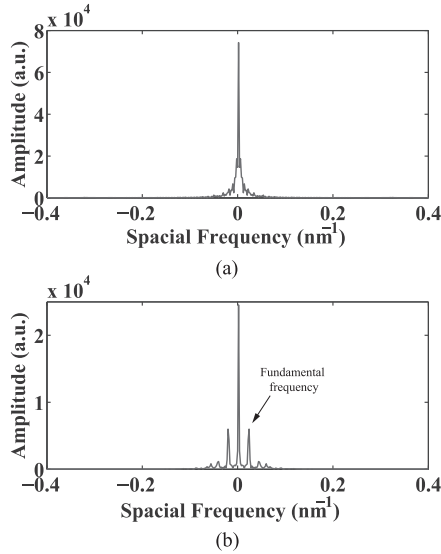


Fig. 4. Amplitude of the fast Fourier transform before (a) and after (b) of the theoretical spectrum obtained by etching.

121 index of the optical fiber cladding, made of fused silica, was es-
 122 timated by using the Sellmeier equation:

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

123 with parameters: $B1 = 0.691663$, $B2 = 0.4079426$, $B3 =$
 124 0.8974794 , $\lambda1 = 0.0684043 \mu\text{m}$, $\lambda2 = 0.1162414$, and $\lambda3 =$
 125 9.896161 , where $\lambda_j = 2\pi c/\omega_j$ and c is the speed of light in
 126 vacuum [15]. The optical fiber core refractive index for the
 127 simulations was obtained, according to the specifications from
 128 the fiber manufacturer, by increasing the refractive index of the
 129 cladding 0.36%.

130 *D. Degrees Brix ($^{\circ}\text{Bx}$) Sensor Monitored by Both Wavelength*
 131 *and Phase Shift Detection*

132 Typically, sensors are characterized by tracking the wave-
 133 length of an attenuation band using an optical spectrum ana-
 134 lyzer, or alternatively by measuring the intensity variations
 135 at a fixed wavelength using a power meter. The fast Fourier
 136 transform (FFT) analysis, which permits to extract the phase of
 137 the optical spectrum, is not a broadly used technique despite
 138 it provides useful and clear information to be used in sensing
 139 applications and permits to use interrogators instead of optical
 140 spectrum analyzers [16], [17].

141 The sinusoidal spectrum of the SMS sensors after etching
 142 permits to see a sharp peak corresponding to the fundamental
 143 frequency (see in Fig. 4 the comparison between the magnitude
 144 of the fast Fourier transform before and after etching). Con-
 145 sequently, it is possible to obtain a phase sensitive device by
 146 tracking the phase of this fundamental frequency as a function
 147 of the parameter to detect.

148 In order to probe the feasibility of this method for the devel-
 149 oped sensor shown here, a degrees Brix sensor by phase shift
 150 detection is presented. The ITO thickness film to the sensor
 151 used in this application is approximately 60 nm. A MATLAB

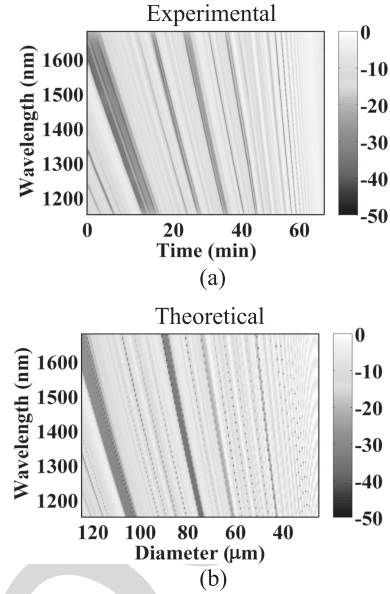


Fig. 5. Evolution of the wavelength spectrum due to reduction of the diameter by HF etching: (a) Experimental; (b) theoretical.

script was implemented to obtain the phase of the fundamental
 frequency in the optical spectrum response of the sensor.

Degrees Brix is a scale of relative density used in the sugar
 and winemaking industry. It indicates the percentage of cane
 sugar by weight in a solution or juice of unfermented grapes.
 Its measurement is crucial in many applications, such as fruit
 juice, carbonated beverage industry, and wine making.

The solutions used here were prepared by dissolving sucrose
 in distilled water. One (1) $^{\circ}\text{Bx}$ equals one (1) gram of sucrose
 dissolved in 100 grams of solution.

E. Phase Shift and Temperature Cross Sensitivity

A 40-nm thickness ITO thin-film deposited sensor fabricated
 following the same procedure described for Sensor 2 was placed
 in a water cell with temperature control. The temperature was
 set to 40 $^{\circ}\text{C}$ and the spectra started being recorded after reaching
 this set point, for 10 minutes. After this time, the control was set
 to 30 $^{\circ}\text{C}$ and kept at this constant temperature for 20 minutes.
 Finally, the temperature control was set back at 40 $^{\circ}\text{C}$ for 10
 minutes once this temperature was reached. The real time phase
 shift was recorded and processed along with the entire procedure
 of temperature variation.

III. RESULTS

A. Diameter Reduction

The experimental and theoretical evolution of the wavelength
 spectrum as a function of the fiber diameter are depicted in
 Fig. 5(a) and (b) respectively.

Fig. 6(a) and (b) show the theoretical and experimental trans-
 mission spectra for both, etched and unetched fibers. Video files
 of this experimental and theoretical evolution can be found in
 the supplementary material of this manuscript. According to [9],
 [18], the diameter reduction is proportional to the sensitivity in-
 crease to refractive index. Consequently, a reduction from 125
 to 25 μm should lead to a fivefold increase.

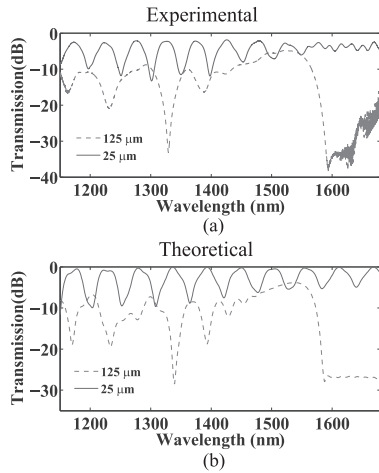


Fig. 6. Comparison between the spectra of unetched and etched fibers: (a) Experimental; (b) theoretical.

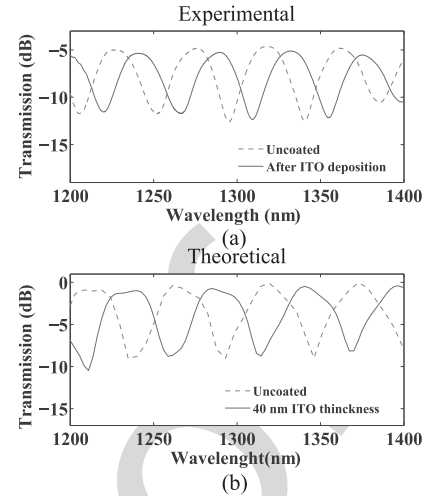


Fig. 8. Initial and final transmission spectra due to the ITO thin-film deposition on Sensor 2: (a) Experimental; (b) theoretical.

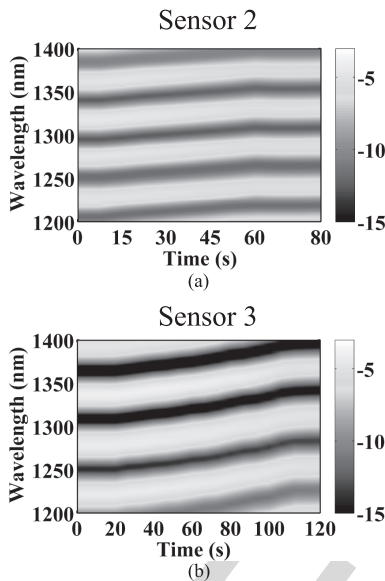


Fig. 7. Experimental evolution of the spectra during ITO deposition from: (a) Sensor 2; (b) Sensor 3.

185 In addition to the structural integrity of the fiber, it was ob-
 186 served that at this diameter the transmission evolved into a quasi-
 187 sinusoidal spectrum for a length of the coreless MMF of 14 mm.
 188 This behavior facilitates both the presence of multiple attenua-
 189 tion bands and the shift phase study.

190 B. Film Deposition

191 Fig. 7(a) and (b) present the spectral response obtained from
 192 Sensors 2 and 3 during the ITO films deposition.

193 For both cases, the transmission spectra underwent redshifts
 194 during the deposition, proving the existence of a relationship
 195 between the spectral position and the ITO film thickness. Sensor
 196 2 and Sensor 3 exhibited 23 nm and 40 nm redshifts, respectively.
 197 Fig. 8(a) and (b), and Fig. 9(a) and (b) show the experimental
 198 and theoretical spectra before and after the ITO film deposition
 199 for Sensors 2 and 3, respectively.

200 It can be observed that the experimental redshifts due to the
 201 ITO deposition were in essence the same as those obtained theo-

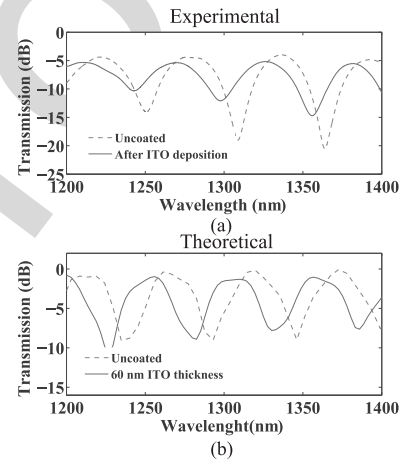


Fig. 9. Initial and final transmission spectra due to the ITO thin film deposition on Sensor 3: (a) Experimental; (b) theoretical.

retically. This probes that the transmission spectrum experiences
 a redshift as thin-film thickness grows.

Based on theoretical analysis, it can be concluded that the
 thicknesses of the deposited thin-film were of 40 nm and 60
 nm to Sensor 2 and Sensor 3, respectively. To support the good
 match between the experimental and theoretical results, Sensor 2
 was cleaved and observed using a scanning electron microscope
 (SEM). Fig. 10 shows the cross section, where the measure-
 ment of the film thickness was 44.18 nm. This supposes a 10%
 deviation with respect to the theoretical value for this sensor.

212 C. Wavelength Shift Characterization of the Device

213 Figs. 11, 12, and 13 show the theoretical and experimental
 214 transmission spectra as a function of wavelength for various
 215 refractive indices. A redshift can be observed in all cases when
 216 the RI increases, and there is a good agreement between the
 217 theoretical and experimental results.

218 Fig. 14 illustrates the wavelength shift as a function of the
 219 external refractive index, which allows the sensitivity to be cal-
 220 culated both experimentally [see Fig. 14(a)] and theoretically
 221 [see Fig. 14(b)]. In both cases the wavelength position was
 222 taken with the attenuation band closer to 1550 nm.

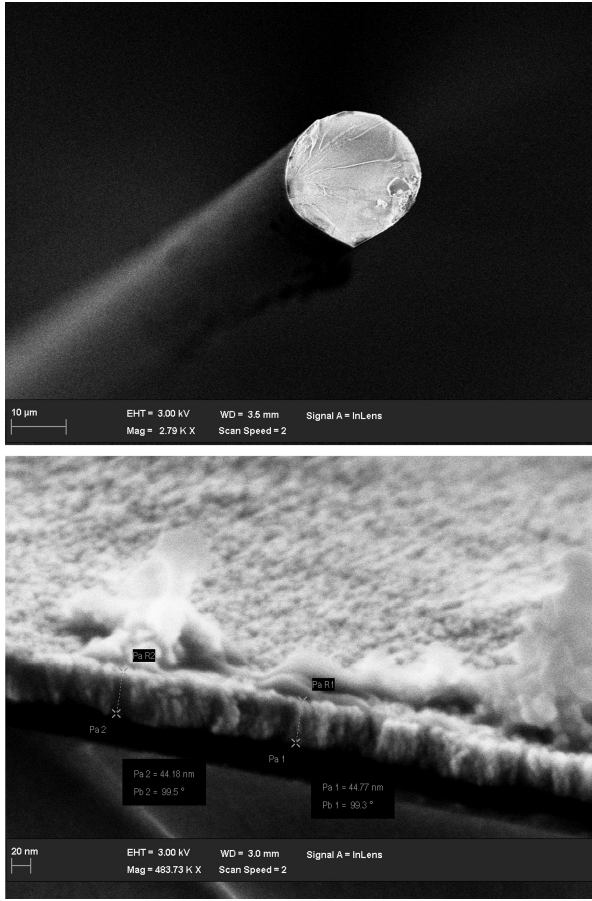


Fig. 10. SEM images of Sensor 2: Diameter 25 μm and ITO thin film 44 nm.

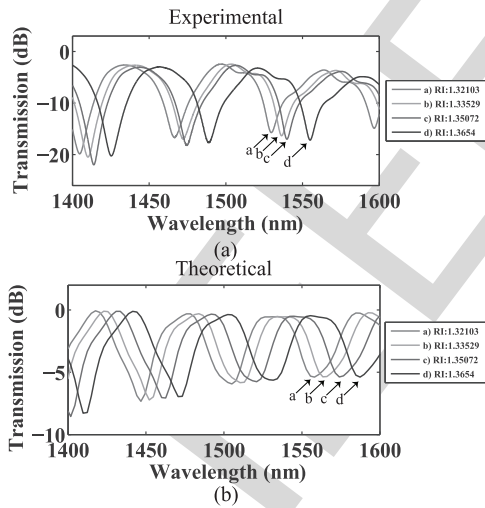


Fig. 11. Transmission spectrum for Sensor 1 as a function of the wavelength for different surrounding media refractive indices: (a) Experimental; (b) theoretical.

223 It can be noticed that an increase in the thin-film thickness
 224 leads to a higher sensitivity. Table I shows a summary of the
 225 sensitivities in the 1.32–1.35 refractive index range. The exper-
 226 imental sensitivity improves that obtained in [9]. Indeed, even
 227 though a sensitivity of 1200 nm/RIU was attained in that work,
 228 the SRI range was 1.32–1.38, with a higher sensitivity. More-

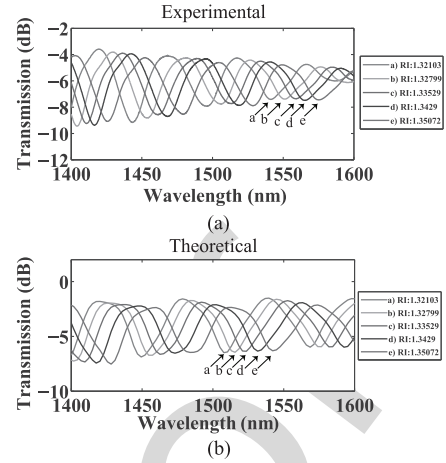


Fig. 12. Transmission spectrum for Sensor 2 as a function of the wavelength for different surrounding media refractive indices: a) Experimental; b) theoretical.

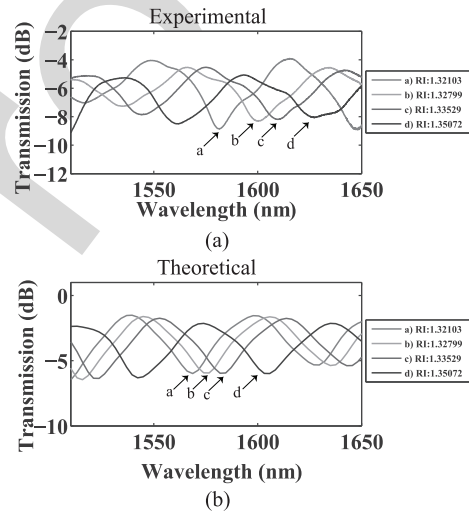


Fig. 13. Transmission a) experimental and b) theoretical for Sensor 3 as a function of the wavelength for different surrounding media refractive indices.

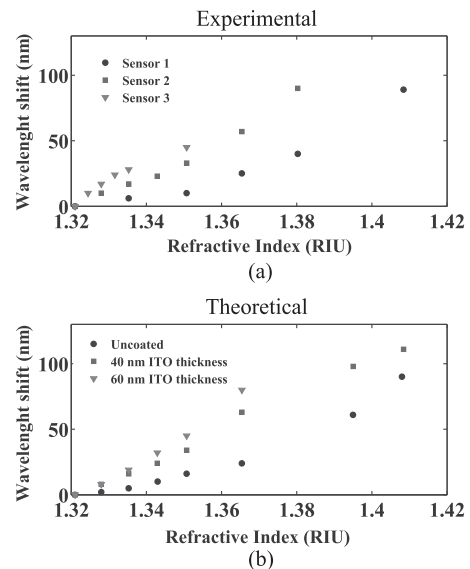


Fig. 14. Wavelength shift with refractive index to Sensor 1, 2 and 3, for both, a) experimental and b) theoretical cases.

TABLE I
COMPARISON SENSITIVITIES OBTAIN EXPERIMENTALLY AND THEORETICALLY
TO A 1.32–1.35 RIU RANGE

Thin-film Thickness (nm)	Experimental Sensitivity	Theoretical Sensitivity
Uncoated	335 nm/RIU $R^2=0.9812$	454 nm/RIU $R^2=0.9669$
~ 40	1062 nm/RIU $R^2=0.9906$	1131 nm/RIU $R^2=0.999$
~ 60	1442 nm/RIU $R^2=0.953$	1536 nm/RIU $R^2=0.9951$

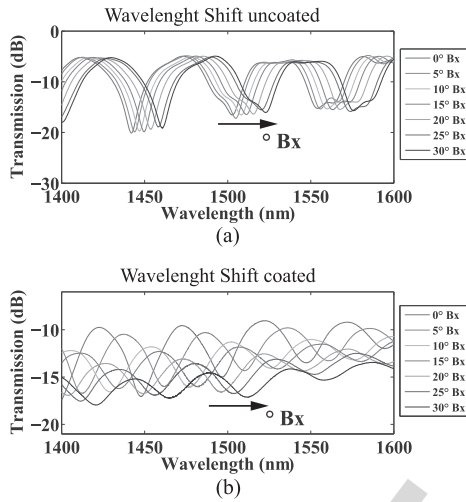


Fig. 15. Transmission as a function of the wavelength to different $^{\circ}\text{Bx}$ of an (a) etched SMS configuration without thin-film and (b) a 60 nm thin-film Thickness ITO etched SMS configuration.

229 over, though overcome by LPFGs optimized with a hard etching
230 [19], the device presented here is comparable with the sensitivity
231 obtained with LPFGs optimized with a soft etching [20], which
232 along with the possibility to monitor the phase shift indicates
233 that it is an interesting device for biosensing applications, where
234 a high degree of accuracy.

235 D. Degrees Brix ($^{\circ}\text{Bx}$) Sensor Monitored by Both Wavelength 236 and Phase Shift Detection

237 Fig. 15 shows transmission as a function of the wavelength for
238 different solutions of sucrose in water addressing two cases: an
239 etched SMS configuration without thin-film and a 60 nm thick-
240 ness ITO thin-film deposited on it. Both cases show a redshift
241 when the probe was immersed in.

242 The magnitude of the wavelength shift is more notorious in the
243 coated fiber, regardless of the attenuation observed, according
244 to what has been observed in the previous section.

245 Fig. 16(a) and (b) present the wavelength shift of an attenu-
246 ation band and the phase shift for both the etched SMS con-
247 figuration without ITO coating and the same configuration type
248 with a 60 nm thickness ITO thin-film. A simple linear fit of
249 the results evidences that the ITO film permitted to obtain a
250 three-fold sensitivity increase in both cases.

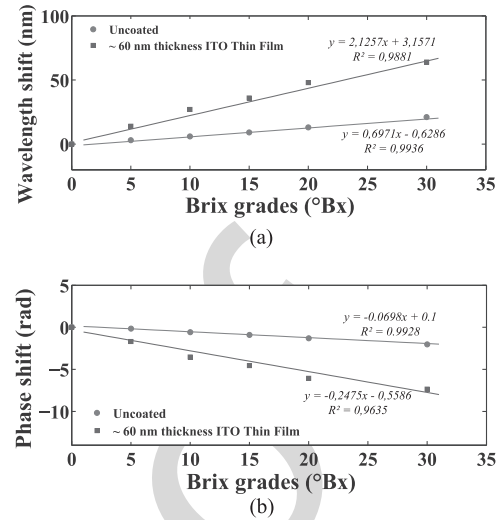


Fig. 16. Phase shift of a brix grades sensor: (a) Without ITO thin-film; (b) with 60 nm thickness ITO thin-film.

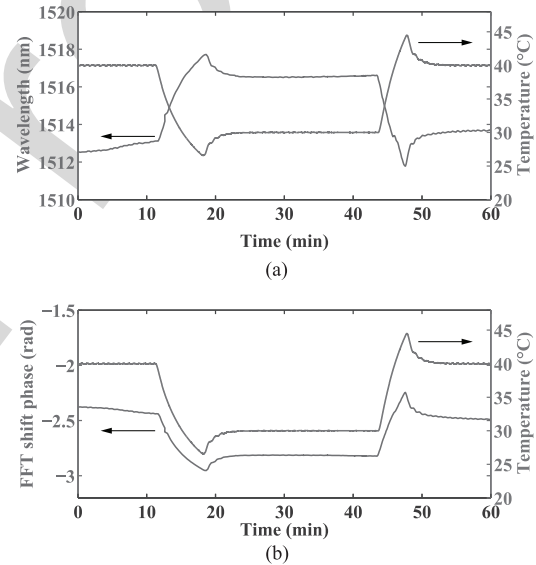


Fig. 17. (a) Wavelength shift and (b) phase shift temperature cross sensitivity.

251 E. Temperature Cross Sensitivity

252 Fig. 17(a) and (b) show the behavior of the wavelength shift
253 of an attenuation band and the phase shift with the temperature
254 setting as described in Section II-E. This probe was realized
255 with the 60 nm thin-film thickness sensor. The phase behavior
256 observed followed a trend imposed by the temperature's profile
257 generated as a consequence of the set points established. The
258 sensitivity was 0.3 nm/ $^{\circ}\text{C}$ and 0.034 rad/ $^{\circ}\text{C}$.

259 A 0.14 $^{\circ}\text{Bx}/^{\circ}\text{C}$ of sensitivity was calculated for the ITO thin-
260 film coated sensors analyzed in the previous section.

261 IV. CONCLUSION

262 This manuscript presented the optimization of SMS fiber
263 structures with a combined application of two techniques: etch-
264 ing and deposition of a thin-film. By an adequate design it
265 was possible to track both wavelength shifts of the optical spec-
266 trum and, by applying a simple FFT measurement technique, the

267 phase shift of the fundamental frequency. The FFT measurement
 268 used in the analysis is an easy method that can be most applicable
 269 to networks that require narrow band, multiplexing capability
 270 and that have some problems related with high losses and noise.

271 The results also showed that the sensitivity obtained for this
 272 configuration of SMS was enhanced by reduction of the fiber
 273 diameter and by increasing the ITO film thickness. A good
 274 agreement was achieved between the experimental and the simu-
 275 lated approaches for this sensing device. A sensitivity of 1442
 276 nm/RIU was obtained by tracking the wavelength shift in a SMS
 277 with 25 μm diameter and a 60 nm ITO thickness film, whereas
 278 for the same device, the FFT phase shift analysis showed a
 279 0.24 rad/RIU sensitivity.

280 These sensitivities, which are in the order of magnitude of
 281 other structures such as long period fiber gratings (LPGs) (but
 282 with an inherently simpler manufacture process), place the de-
 283 veloped sensing device as a good option for applications where
 284 high sensitivities and compact structures are required. As an
 285 example, a degrees Brix sensor has been presented, where the
 286 deposition of an ITO thin-film enhances the sensitivity of the
 287 device by a factor of 3.

288 REFERENCES

289 [1] C. R. Dennison, P. M. Wild, D. R. Wilson, and M. K. Gilbart, "An in-fiber
 290 Bragg grating sensor for contact force and stress measurements in articular
 291 joints," *Meas. Sci. Technol.*, vol. 21, no. 11, 2010, Art. no. 115803.
 292 [2] I. Del Villar, I. R. Matias, F. J. Arregui, and M. Achaerandio, "Nanode-
 293 position of materials with complex refractive index in long-period fiber
 294 gratings," *J. Lightw. Technol.*, vol. 23, no. 12, pp. 4192–4199, Dec. 2005.
 295 [3] R. Kashyap, *Fiber Bragg Gratings*. New York, NY, USA: Academic, 1999.
 296 [4] F. Chiavaioli *et al.*, "Sol-gel-based titania-silica thin film overlay for
 297 long period fiber grating-based biosensors," *Anal. Chem.*, vol. 87, no. 24,
 298 pp. 12024–12031, 2015.
 299 [5] I. Del Villar, C. R. Zamarreño, M. Hernaez, F. J. Arregui, and I. R.
 300 Matias, "Lossy mode resonance generation with indium-tin-oxide-coated
 301 optical fibers for sensing applications," *J. Lightw. Technol.*, vol. 28, no. 1,
 302 pp. 111–117, Jan. 2010.
 303 [6] J. Homola, "Surface plasmon resonance sensors for detection of chemical
 304 and biological species," *Chem. Rev.*, vol. 108, no. 2, pp. 462–493, 2008.
 305 [7] Y. Cardona Maya, N. Gómez Cardona, and P. I. Torres Trujillo, "Low cost
 306 heat-and-pull rig for manufacturing adiabatic optical fiber tapers," *Revista*
 307 *Facultad de Ingeniería Universidad de Antioquia*, no. 70, pp. 167–172,
 308 2014. [Online]. Available: [http://aprendeenlinea.udea.edu.co/revistas/
 309 index.php/ingenieria/article/viewFile/14820/16007](http://aprendeenlinea.udea.edu.co/revistas/index.php/ingenieria/article/viewFile/14820/16007)
 310 [8] T. Zhu, D. Wu, M. Liu, and D.-W. Duan, "In-line fiber optic interferometric
 311 sensors in single-mode fibers," *Sensors*, vol. 12, no. 8, pp. 10430–10449,
 312 2012.
 313 [9] I. D. Villar, A. B. Socorro, J. M. Corres, F. J. Arregui, and I. R. Matias, "Re-
 314 fractometric sensors based on multimode interference in a thin-film coated
 315 single-mode-multimode-single-mode structure with reflection configura-
 316 tion," *Appl. Opt.*, vol. 53, no. 18, pp. 3913–3919, 2014.
 317 [10] Q. Wang and G. Farrell, "All-fiber multimode-interference-based refrac-
 318 tometer sensor: Proposal and design," *Opt. Lett.*, vol. 31, no. 3, pp. 317–
 319 319, 2006.
 320 [11] J. Lou, L. Tong, and Z. Ye, "Modeling of silica nanowires for optical
 321 sensing," *Opt. Express*, vol. 13, no. 6, pp. 2135–2140, 2005.
 322 [12] A. W. Snyder and J. Love, *Optical Waveguide Theory*. Berlin, Germany:
 323 Springer, 2012.
 324 [13] P. R. Cooper, "Refractive-index measurements of liquids used in con-
 325 junction with optical fibers," *Appl. Opt.*, vol. 22, no. 19, pp. 3070–3072,
 326 1983.
 327 [14] L. Hoyt, "New table of the refractive index of pure glycerol at 20 C," *Ind.*
 328 *Eng. Chem.*, vol. 26, no. 3, pp. 329–332, 1934.
 329 [15] I. Malitson, "Interspecimen comparison of the refractive index of fused
 330 silica*," *J. Opt. Soc. Amer.*, vol. 55, no. 10, pp. 1205–1209, 1965.
 331 [16] D. Barrera *et al.*, "Low-loss photonic crystal fiber interferometers for
 332 sensor networks," *J. Lightw. Technol.*, vol. 28, no. 24, pp. 3542–3547,
 333 Dec. 2010.

[17] D. Leandro, M. Bravo, A. Ortigosa, and M. Lopez-Amo, "Real-time FFT
 334 analysis for interferometric sensors multiplexing," *J. Lightw. Technol.*,
 335 vol. 33, no. 2, pp. 354–360, Jan. 2015.
 336 [18] P. Wang, G. Brambilla, M. Ding, Y. Semenova, Q. Wu, and G. Farrell,
 337 "High-sensitivity, evanescent field refractometric sensor based on a taper-
 338 ered, multimode fiber interference," *Opt. Lett.*, vol. 36, no. 12, pp. 2233–
 339 2235, 2011.
 340 [19] I. Del Villar, J. L. Cruz, A. B. Socorro, J. M. Corres, and I. R. Matias,
 341 "Sensitivity optimization with cladding-etched long period fiber gratings
 342 at the dispersion turning point," *Opt. Express*, vol. 24, no. 16, pp. 17680–
 343 17685, 2016.
 344 [20] F. Chiavaioli *et al.*, "Towards sensitive label-free immunosensing by means
 345 of turn-around point long period fiber gratings," *Biosensors Bioelectron.*,
 346 vol. 60, pp. 305–310, 2014.
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