A. B. Socorro, M. Hernaez, I. Del Villar, J. M. Corres, F. J. Arregui, and I. R. Matias "A comparative study between SMS interferometers and lossy mode resonace optical fiber devices for sensing applications", Proc. SPIE 9517, Smart Sensors, Actuators, and MEMS VII; and Cyber Physical Systems, 95171U (21 May 2015); https://doi.org/10.1117/12.2179684

A comparative study between SMS interferometers and lossy mode resonace optical fiber devices for sensing applications

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ABSTRACT

Optical fiber sensors are of great interest due to their intrinsic advantages over electronic sensors. In this work, the sensing characteristics of two different and novel optical fiber devices are compared, after simultaneously depositing a thin-film using the layer-by-layer assembly deposition process. The first one is an SMS structure, formed by splicing two single-mode fiber pigtails on both sides of a coreless multimode fiber segment. This structure induces an interferometric phenomenon that generates several attenuation and transmission bands along the spectrum. These bands are sensitive to variations in the surrounding refractive index, although this sensitivity has been enhanced by a TiO_2/PSS thin-film. The other device is a 40 mm uncladded segment of a 200 µm-core multimode optical fiber. When coated by a TiO_2/PSS thin-film, part of the light transmitted into the uncladded core is coupled into the thin-film, generating a lossy mode resonance (LMR). The absorption peaks due to these phenomena red-shift as long as the thin-film thickness increases or the external RI becomes higher. The performance of these devices as refractometers and relative humidity sensors are tested. Results show that the LMR-based sensor is more sensitive in both situations, in spite of its lower sensitivity. Particularly, it presents a 7-fold sensitivity enhancement when measuring surrounding medium refractive index changes and a 10-fold sensitivity enhancement when measuring environmental relative humidity. To our knowledge, this is the first time that a comparative study between SMS and LMR sensors is performed.

Keywords: Optical fiber sensors, lossy mode resonances, SMS structure, interferometry, thin-films, layer-by-layer assembly, refractometer, humidity sensor.

1. INTRODUCTION

Optical fiber sensors have been analyzed and reported extensively during the last decades[1,2]. Moreover, several structures have been showing up lately based on the application of novel technologies to the optical devices. For instance, long period gratings (LPGs)[3] or tapered optical fibers[4], among others, are optical structures widely known due to their interesting capabilities. In addition, optical fibers present good properties such as electromagnetic immunity, light weight, low transmission losses in the communication windows, wide bandwidth and easiness to handle. This leads to a great variety of possibilities as far as sensing applications is concerned.

In this work, the analyses are focused on two specific optical fiber-based structures. The first one is the single-mode–multimode–single-mode (SMS) structure, which is commonly utilized in important fields such as optical communications and sensors. In optical communications, interesting devices such as wavelength filters have been developed[5], whereas in the optical sensors field it has been possible to measure magnitudes such as pressure or temperature[6,7].

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The basic physical principle of the SMS device is that light transmitted through the fundamental mode of the SMF segment is coupled to several modes into the MMF section and recoupled to the fundamental mode of the SMF at the end of the MMF segment[7]. Due to the phenomenon of multimodal interferometry (MMI) both transmission and attenuation bands are obtained in the optical spectrum. Particularly, the transmission bands obtained by the self-image effect exhibit minimum losses[8], and its central wavelength can be controlled as a function of the MMF segment dimensions, mainly the MMF segment length and diameter[7]. The MMF segment diameter is also responsible for the sensitivity of the device. It has been also proved that, by reducing the diameter, an improved sensitivity to refractive index can be obtained[7].

The second optical structure analyzed in this work is the cladding removed multimode optical fiber (CRMF). It is a really easy-to-handle optical structure that permits to access the evanescent field emerging from the inside of the fiber core. This can be taken in advantage to develop sensors by just functionalizing its surface adequately[9,10].

In this sense, there is also an increasing interest in developing optical structures coated with thin-films[11,12]. Two reasons justify the application of an additional coating. The first one is the ability to improve the performance of the same devices without coating[12]. As an example, it has been possible to obtain a 10-fold increase in long-period fiber grating refractometers[13]. The second reason is the possibility to use thin-films that are sensitive to chemical compounds or physical magnitudes[2,14]. Therefore, the presence of a thin-film can improve the sensitivity of the measurements done with optical devices.

The thin-films used in our laboratory pursue the objective of generating a specific type of electromagnetic resonances called lossy mode resonances, which characteristics and capabilities can be found elsewhere[9–11,14,15]. In this contribution, based on the interesting characteristics obtained with LMRs, high refractive index thin-films are deposited on either SMSs or CRMFs to obtain the desired phenomena to check their sensitivity afterwards: an increase in the wavelength shift of the resonances obtained by the interferometry, in the case of the SMS structure, and an LMR located in the middle of the desired wavelength range, in the case of the CRMF. Then, both devices are subjected to refractive index changes in the surrounding medium to check their sensing capability and they will be finally subjected to relative humidity on-off cycles. Results will show that the sensitivity of the LMR-based device is clearly higher than in the interferometer case.

2. EXPERIMENTAL SECTION

2.1. Optical monitoring set-up

In order to monitor the construction and further detection of the analyzed structures, the corresponding transmission configurations schematically shown in Figure 1 were prepared.

In the case of the SMS structure (Figure 1a), two standard SMF-28 pigtails from Telnet Inc. were spliced on both sides of a 20 mm-length coreless multimode fiber segment from POFC Inc., obtaining a 125 micron-diameter device. Then, a superluminiscent light emitting diode (SLED) broadband light source (83437A, Agilent Technologies) was connected on one side of the structure and the spectral response was monitored by an optical spectrum analyzer (OSA – 86140B, Agilent technologies) in the other side. The dimensions of the multimode segment permit to reduce the size of the device and, at the same time, obtain a set of attenuation bands in the infrared region that can be easily monitored when detecting their wavelength shift in a range from 1150 to 1650 nm[16].

For the CRMF structure (Figure 1b), a 200/250 μm (core/cladding diameter) cladding removable multimode optical fiber from Thorlabs Inc. (FT200EMT) was used. It was stripped, uncladded along 40 mm and then cleaned with ethanol, in order to remove the undesired covers. A halogen white light spectrum (ASBN-W-High power, Spectral Products Inc.) covering a wavelength range from 400 to 1800 nm, was launched into one end of the fiber. The other was connected through a bifurcated optical fiber (VIS-NIR with low OH^- content from Ocean Optics) to two spectrometers (a HR-4000 and a NIR-512), which permitted to monitor a wavelength range from 400 to 1700 nm.

2.2. Chemical materials and thin-film deposition

With the objective of depositing a high refractive index thin-film that increased the sensitivity of the presented devices, an LbL-assembly process was performed. To this purpose, a thin-film based on titanium (IV) oxide nanoparticles (TiO_2) and poly(sodium 4-styrenesulfonate) (PSS) was chosen, both adjusted at pH 2.0 in deionized water[17]. Moreover, when detecting the surrounding refractive index (SRI), several aqueous solutions of glycerol were used. All chemicals were purchased from Sigma Aldrich.

Regarding the LbL-assembly, substrates were first immersed in potassium hydroxide (KOH) 0.1 M for 5 minutes in order to chemically charge them. Then, they were immersed in the TiO_2 solution and then in the PSS solution, alternating acid ultrapure water rinses between them. A total amount of 15 bilayers were deposited for both optical structures.

To sense the SRI, several cuvettes containing increasing percentage of glycerol in water were prepared, from 0% to 100%, obtaining a wide range of refractive indices from 1.32 to 1.46.

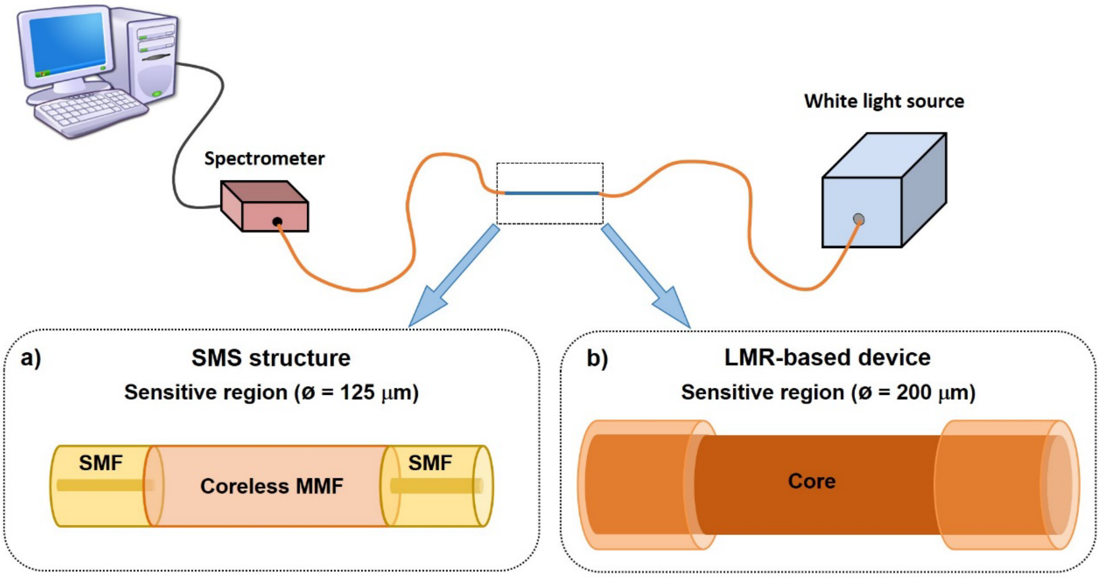

Figure 1. Experimental set-up designed for the optical characterization of both the thin-film deposition and the subsequent detection processes. (a) Single-mode – multimode – single-mode (SMS) fiber structure. (b) Cladding removed multimode optical fiber (CRMF).

3. RESULTS AND DISCUSSION

3.1. Surrounding medium refractive index measurements

Due to the deposition of the TiO_2/PSS thin-film, an increase in the wavelength shift of the spectrum is observed for both structures, although this influences in a different way depending on the used device. In the CRMF case, an LMR shows up in the spectrum, indicating that a mode is being coupled from the core of the structure to the deposited thin-film[17]. If adequately located in the spectrum at the desired wavelength range, it is possible to monitor the wavelength shift as a function of the SRI and, therefore, evaluate its sensitivity. However, in the SMS case, if the thin-film keeps on depositing until the LMR induces its maximum attenuation, the spectrum is totally lost[18]. So in order to obtain a good sensitive structure with the SMS device, there is a need for stopping the deposition before the LMR shows up. In spite of that, the sensitivity of the device will be clearly decreased[18] as it will be shown afterwards.

Thus, both SMS and CRMF deposited structures were subjected to increasing SRIs of 1.32, 1.34, 1.37, 1.40, 1.43 and 1.46 made from glycerol solutions in water. Figure 2a and 2b show the evolution of the spectra obtained for both devices when immersed in the subsequent refractive index solutions. The spectra for the SMS structure show transmission values whereas those for the CRMF structure show absorption values. A red-shift in wavelength as a function of the increasing SRI is registered for both cases. More specifically, for the SMS case (Figure 2a), the attenuation band located at 1577 nm shows a higher shift in wavelength than the rest, what means that is more sensitive. The following analyses will focus on the comparison between this last resonance and the LMR in Figure 2b.

First, the line-width of the resonances is analyzed. Any of the attenuation bands shown in the SMSs spectra (Figure 2a) has improved resolution if compared to the LMR in Figure 2b. Specifically, the SMS resonant band located at 1577 nm is around 10 nm width, whereas the LMR is several tens or even cents of nanometers width. Therefore, the SMS structure could be an option to take into account if a high resolution measurement is required.

Regarding the sensitivity, the opposite occurs. It can be observed how the CRMF is clearly more sensitive than the SMS structure, since the LMR produced shifts in wavelength more than even the most sensitive attenuation band in the interferometric device. These results are corroborated in Figure 3, where the wavelength shift of both resonances is plotted as a function of the increasing refractive index. In the SMS case, a wavelength shift of 20 nm from 1577 to 1597 nm is obtained, meaning 142 nm/RIU. On the opposite, the LMR shifts 134 nm from 457 to 591 nm, what means 955 nm/RIU and, therefore, almost a 7-fold sensitivity enhancement. Here is where it is demonstrated that, in the SMS case, the fact of stopping the deposition before the LMR shows up, involves a decrease in the sensitivity capability.

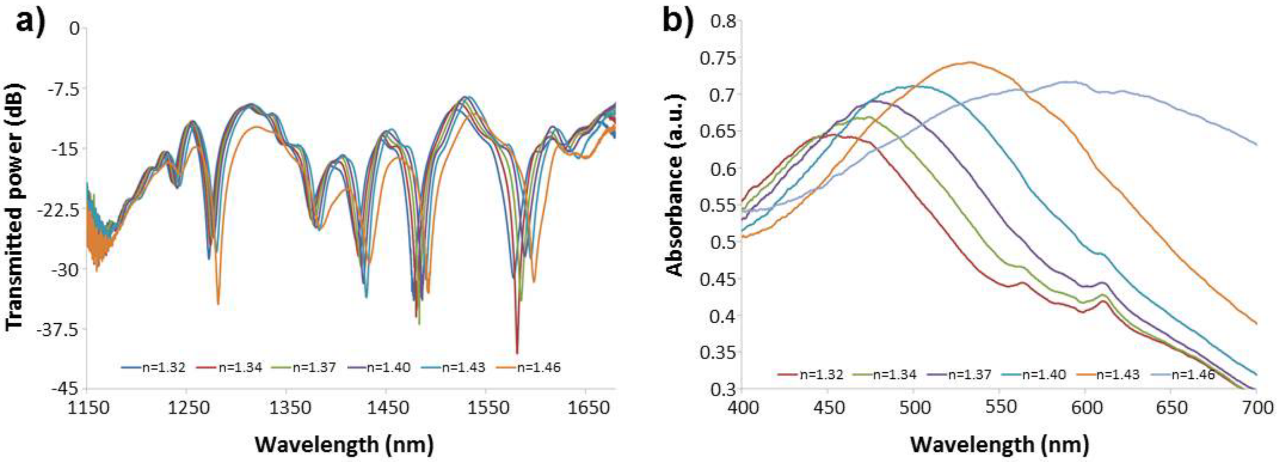

Figure 2. Spectral response of the SMS device (a) and the LMR-based device (b) as a function of the increasing surrounding refractive index variation.

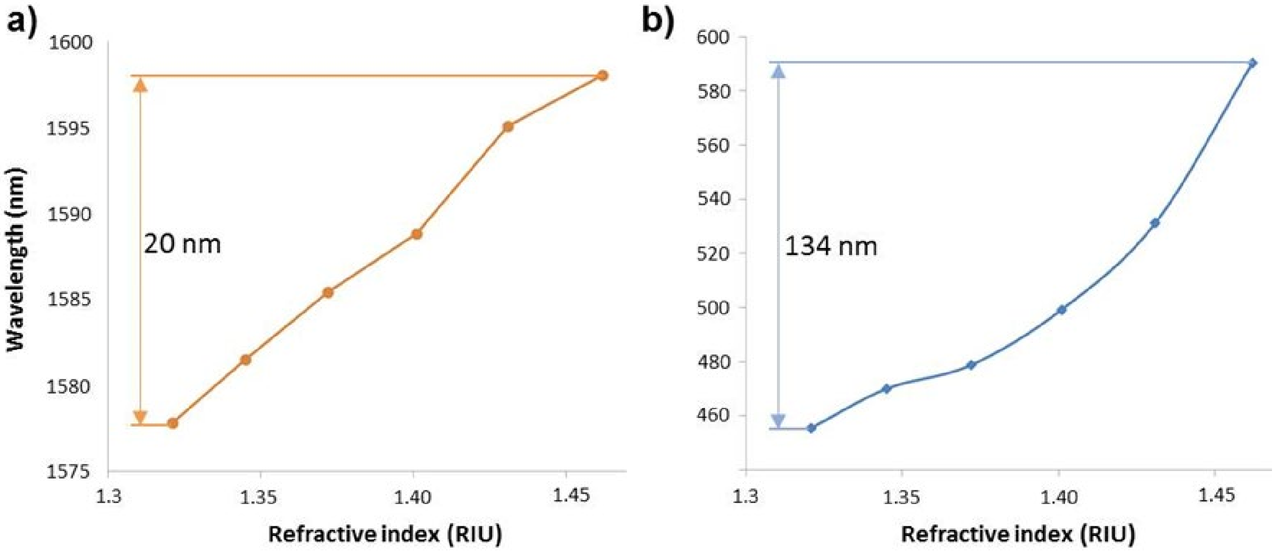

Figure 3. Wavelength shift of the SMS interferometric absorption band (a) and the LMR (b) as a function of the increasing surrounding refractive index variation.

3.2. Relative humidity measurements

Once the sensitivity of the analyzed devices to SRI was analyzed, they were subjected to relative humidity (RH) detection. To this purpose, substrates were introduced in a sealed chamber at a constant temperature of 23ºC while the humidity inside was varied between 40% and 90% for several times. Moreover, an electronic sensor was used, to obtain an actual humidity value and compare it with each optical device.

The temporal response of the SMS and LMR-based sensors as a function of the RH variation is plotted in Figures 4a and 4b, overlapped with the electronic sensor response in each one of the experiments. The response time is quite similar in every optical device, starting slightly slower than the electronic sensor but recovering faster. The repeatability of the measurements is also considerable, since the evolution is quite similar in each one of the cycles. Nevertheless, the sensitivity is something to highlight again. As it can be observed, there is a wavelength shift of 16 nm in the SMS device, what implies to have 0.3 nm/RH% of sensitivity value. In the LMR-based device case, there is a clearly increased wavelength shift of 205 nm, what means a sensitivity value of 3.54 nm/RH% and, therefore, a 10-fold improvement with respect to the interferometer.

The fact of dealing with a TiO_2/PSS thin-film is a good choice, since it has demonstrated to be quite sensitive to RH changes[19]. However, what produces the higher shift in wavelength is the fact of working with CRMFs, since the possibility of accessing the evanescent field of the structure to couple light into the thin-film makes it possible to generate an LMR that is highly sensitive to SRI variations[17]. Since the deposition of the thin-film on the SMS structure must be stopped before the LMR fades the interferometry pattern disappear, the sensitivity of the device is gently decreased for both SRI and humidity measurements[18].

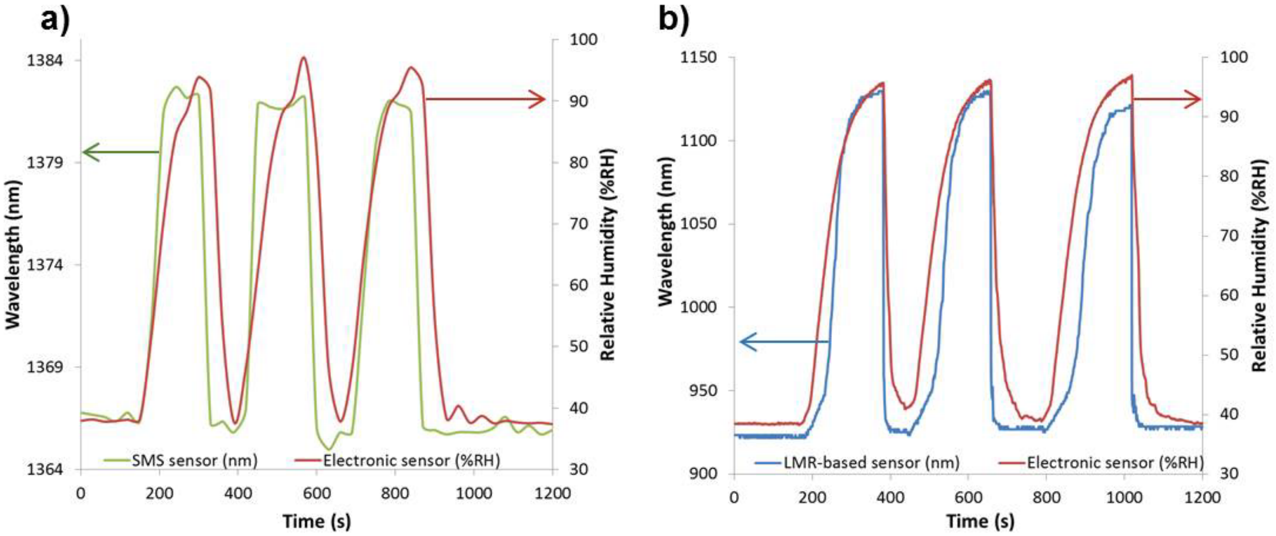

Figure 4. Dynamic performance of the SMS device (a) and the LMR-based device (b) when tested as relative humidity sensors from 40 to 90%.

CONCLUSIONS

A comparison between the sensitivities obtained by thin-film-coated single-mode – multimode – single-mode optical fiber devices (SMSs) and cladding removed multimode optical fibers (CRMFs) in terms of resolution and sensitivity of the resonant phenomena produced has been done for the first time.

The line-width of the SMS attenuation bands is as low as 8 nm, what is clearly better than the tens of nanometers registered by the LMR-based structure. Thus, SMS is a good option to discriminate between small changes in the magnitudes. However, the opposite occurs for sensitivity. When sensing surrounding refractive index changes, the LMR-based refractometer presents a sensitivity of 955 nm/RIU, meaning a 7-fold increase if compared with the SMS-based structure (142 nm/RIU). At the same time, when comparing the sensitivity to relative humidity changes, the LMR-based device shows values of 3.54 nm/RH%, whereas the SMS-based device only reaches 0.3 nm/RH% (a 10-fold improvement). Therefore, it has been proved that it is better to use an LMR-based device if a high sensitivity is needed.

ACKNOWLEDGMENTS

This work was supported by the Spanish Economy and Competitiveness Ministry project FEDER TEC2013-43679-R and by a Public University of Navarra pre-doctoral research grant. Authors would like to express their gratitude to Nadetech Innovations Inc. for the automation of the deposition processes.

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