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Fiber-Optic Lossy Mode Resonance Sensors

Francisco J. Arregui*, Ignacio Del Villar, Jesus M. Corres, Javier Goicoechea, Carlos R. Zamarreño, Cesar Elosua, Miguel Hernaez, Pedro J. Rivero, Abian B. Socorro, Aitor Urrutia, Pedro Sanchez, Pablo Zubiate, Diego Lopez, Nerea De Acha, Ignacio R. Matias

Universidad Publica de Navarra, Dpto IEE, Edif. Los Tejos, 31006 Pamplona, Spain

Abstract

In the last 4 years, experimental evidences about the potential use of optical sensors based on Lossy Mode Resonances (LMR) have been presented in the literature. These LMR sensors have some similarities with Surface Plasmon Resonance (SPR) sensors, the gold standard in label-free, real-time biomolecular interaction analysis. In these new LMR sensors, if the non-metallic nano-cladding of an optical waveguide fulfills the conditions explained in this work, coupling of light to the cladding modes happens at certain resonance wavelengths, which enables the use of LMR devices as refractometers and opens the door to diverse applications such as in biology and proteomics research. These highly sensitive refractometers have already shown sensitivities higher than 20,000 nm/RIU or 5x10-7 RIU and, given the youth of this field, it is expected to achieve even better values.

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Keywords: Lossy mode resonance, optical fiber, sensors, Layer-by-Layer

1. Introduction: the Lossy Mode Resonances

Thin films-coated optical waveguides has been a topic of high interest for decades and with the appearance of new techniques for fabricating micro and nanostructured films this interest has been renewed. Among the different types of these coated waveguides, metal-coated waveguides are having a special relevance due to their utilization as Surface Plasmon Resonance (SPR) devices. In fact, in the biomedical sensing field, SPR sensors are the dominant

* Corresponding author. Tel.: +34 948 16 92 73; fax: +34 948 16 97 20.
E-mail address: parregui@unavarra.es

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and can be considered the gold standard in real-time biomolecular analysis. The SPR devices are usually classified as label-free devices. In other words, these devices do not need additional tags, dyes or reagents for performing the optical measurement in opposition to what it happens in fluorometry or colorimetry. Basically, these SPR devices work as highly sensitive refractometers. Therefore, these devices measure changes in the refractive index that experiences an auxiliary material, previously deposited on the SPR device, which targets the parameter, compound or substance to be measured. Typical configurations are intended for the detection of proteins, nucleid acids, viruses or cells and these configurations are characterized in terms of their specificity, interactions, kinetics and binding strength to a counterpart. The most classical example is the binding reaction between antigen and antibody. For instance, a monolayer of an antibody can be attached to the surface of the SPR device. Once the device is subjected to the presence of the sample to be measured, the slight changes induced in the refractive index of this surface when the antigen binds to the antibody are measured by the SPR device. Due to this, it is easy to understand that the SPR devices have been the dominant devices in this field. This SPR phenomenon happens when a metallic thin film, typically 50 nm of gold, is sandwiched between two dielectrics, one of them can be an optical waveguide, for instance the optical fiber core, and the other dielectric can be the liquid of the sample to be measured. The metallic thin film is functionalized with the sensing monolayer that will be in contact with the sample. SPRs are described as surface electromagnetic waves that propagate in the direction parallel to the metal/dielectric interface. Since the wave is a surface wave, any change on the surface, such as the adsorption of antibodies to the functionalized metal surface, is translated to a sharp change in the optical spectrum of the device. This phenomenon can be monitored only for TM (transverse magnetic) or p-polarized light and the light which is not p-polarized will not contribute to the SPR and will increase the background intensity of the reflected light and will mask the SPR optical signal. In other words, the two basic limitations of SPR devices are: first, they utilization of noble metals, second, the need of optical polarizers to observe the SPR phenomenon.

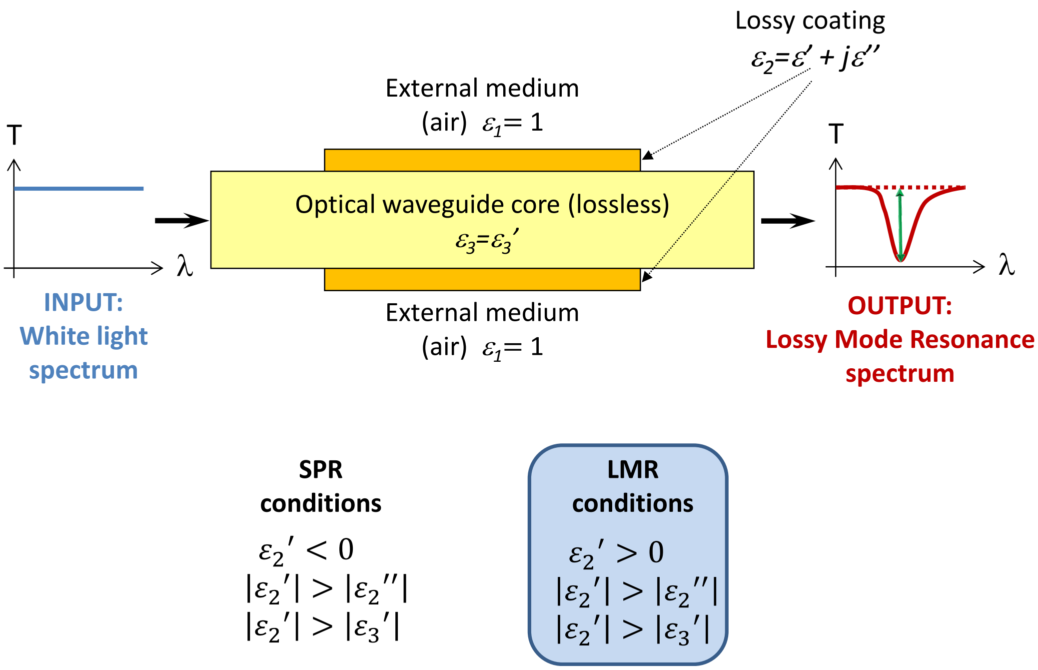

Fig. 1. Schematic of the waveguide coated with a thin film of an optical absorbing material that fulfills the conditions to generate LMRs

On the other hand, little attention has been paid in the literature to waveguides coated with thin films of optical absorbing materials or lossy materials. Some seminal works proved that the propagation of light in semiconductor cladded waveguides experiences some attenuation maxima for specific thickness values of the semiconductor cladding and, also, at certain wavelengths of incidence values [1]. This is due to a coupling between waveguide modes and a specific lossy mode of the semiconductor thin film [2]. These resonances, depending of the author, can be named as guided mode resonances [3] or Lossy Mode Resonances (LMRs) [4-7]. Since the first designation is very generic and the second one is more specific and descriptive, LMRs will be used henceforward. This phenomenon is not limited to semiconductor claddings but it can be also observed for dielectric claddings [8]. In fact, 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 permittivity of the materials surrounding the thin-film (waveguide and external medium as well). This is summarized in Fig. 1 where the conditions to be fulfilled for SPR as well as LMR are indicated.

2. Differences between SPR and LMRs

Apparently, from Fig. 1, it could be assumed that the differences between LMR and SPR are very subtle. From the point of view of fabrication, in order to generate LMRs, instead of using expensive noble metals, such as gold, many other materials can be used with the only condition of having moderate optical losses. From the point of view of optical performances the differences are more notable: LMRs can be observed for both TM (transverse magnetic) or TE (transverse electric) polarizations and, choosing carefully the material, the LMR for the TM mode, LMR_{TM},can fall in the same spectral band than the LMR_{TE} and then, the utilization of an optical polarizer, such as the SPR devices need, can be avoided. This simplifies enormously the fabrication of the sensor or even the experimental setup of the optical devices as is depicted in Fig. 2 where only an incandescent light source and an optical spectrometer are necessary to make the experiments.

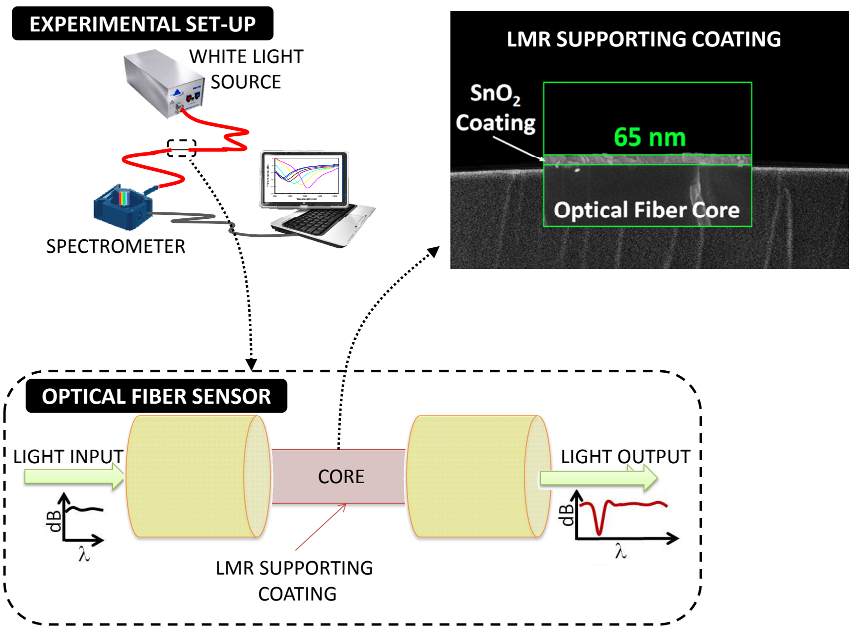

Fig. 2. Top-left, the simplified experimental set-up to observe LMRs in optical fiber; bottom, the optical fiber sensor based on LMR and top-right, SEM images of a LMR supporting layer.

There are also other remarkable advantages of LMRs. Their spectral position can be fine-tuned just by changing the thickness of the lossy coating. Even more, instead of having a unique optical resonance, several resonances can appear when the thickness or the lossy coating is increased and all these peaks can be used for sensing or other applications, see for instance Fig. 3. Just as an experimental proof of the high sensitivity of these LMR refractometers, the characterization of an ITO-coated optical fiber is shown in Fig. 4.

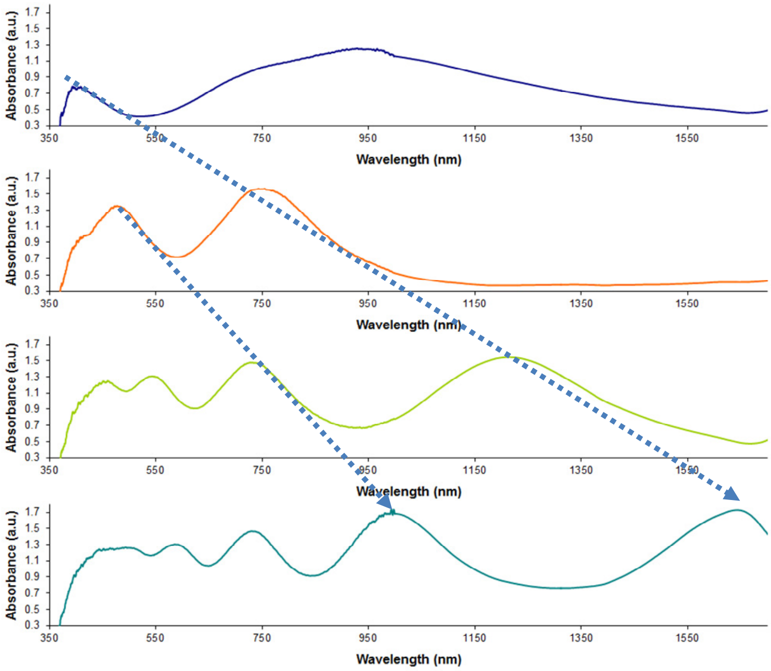

Fig. 3. Optical spectra of a LMR optical fiber device when the thickness of the supporting layer is increased. In this case, the supporting layer was a Layer-by-Layer assembled coating of [TiO_2/PSS], and the number of bilayers from top to bottom was 10, 30, 50 and 70. Details about the fabrication process of these coatings can be found in [9]

Surprisingly, in spite of all the cited advantages, it has been necessary to wait until 2010 to find works that make explicit use of LMRs for the fabrication of sensors [10-22]. Since them, refractometers [6, 7, 23], humidity sensors [24], pH [25], volatile organic compounds sensors [26, 27], antibody sensors [28] or aptasensors [29, 30] have been already presented in the literature and considering that a refractometer is an expandable platform for any other type of sensor, especially on biosensing, we can be witnessing the very beginning of a field of great impact in the future.

3. Conclusions

A very brief introduction about optical fiber Lossy Mode Resonance sensors has been presented. Although the development of these devices is still in its infancy, there are experimental evidences that choosing carefully the materials of the LMR supporting layers these refractometric devices achieve sensitivities higher than 20,000 nm/RIU or 5x10-7 RIU (refractive index unit) which already makes these devices highly competitive for sensing applications even at this stage of development.

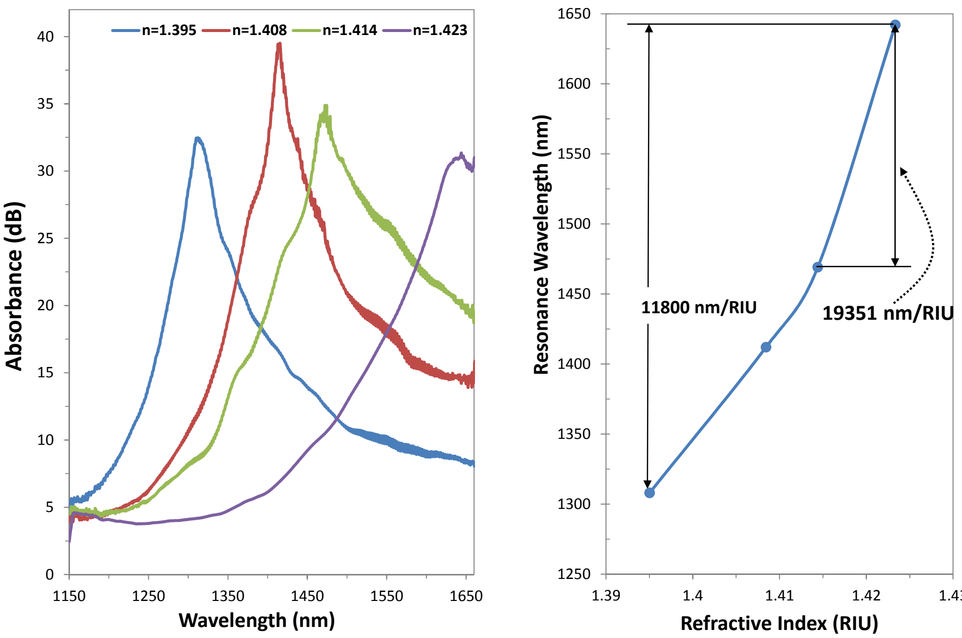

Fig. 4. (Left) Spectral response of a LMR optical fiber refractometer based on ITO thin film when the external refractive index changes from 1.395 to 1.423; (Right) Spectral position of the LMR band versus external refractive index.

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