Influence of Waist Length in Lossy Mode Resonances Generated with Coated Tapered Single Mode Optical Fibers

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***Abstract*—In this work, the generation of electromagnetic resonances due to the deposition of a nanocoating on a tapered single mode optical fiber is analyzed. Layer-by-layer technique is used to control the thickness of the nanocoating. According to the results that have been obtained, the depth of the resonance depends on the length of the waist region. Variations in the transmitted optical power of 40 dB are observed in just a few layers. This can be considered in the fabrication of both highly sensitive resonance-based sensors and optical filters.**

***Index Terms*—Layer-by-layer, lossy mode resonances, optical fiber nanosensor, tapered single mode fiber.**

I. INTRODUCTION

Several studies have been published related to tapered optical fibers, describing the propagation of light depending on the parameters of this structure (e.g. the waist diameter and length) [1-2], and trying to use it for sensing applications [3-4]. This work presents a study of lossy mode resonances (LMRs) induced by the deposition of nanocoatings on single mode optical fibers which have been tapered. The aim is to get more sensitive structures than those obtained without tapering [5].

In accordance with both the literature and the experiments done in the laboratory, there are two main groups of tapers: adiabatic and non-adiabatic. In the first group, the fundamental mode is propagated with losses lower than 1 dB and preserves the spectrum profile, whereas non-adiabatic tapers present higher losses and oscillations in the transmitted spectrum. In view of this, adiabatic tapers of minimum length constitute the main interest for this article [1,6].

In addition to this, electromagnetic resonances are innovative phenomena that occur when a nanocoating introduces losses to the propagation of light in an optical waveguide [7]. In general, they are all produced at the interface between a thin film with certain parameters and a light waveguide, where the propagation takes place. Depending on some conditions which affect essentially to its complex effective refractive index, these resonances are classified as Surface Plasmon Resonances (SPRs), Long Range Surface Exciton Polaritons (LRSEPs) and Guided Mode or Lossy Mode Resonances (LMRs) [8]. The last case, LMRs, occurs when the real part of the thin film permittivity is positive and its absolute value is higher than the absolute value of its own imaginary part and higher than the absolute value of the material surrounding the thin film (i.e. the optical waveguide and the surrounding medium in contact with the thin film) [8]. The resonance consists of coupling of light propagated through the waveguide to lossy modes guided in the thin film [7,9]. Hence the term used for this phenomenon is lossy mode resonance (LMR) [9].

When an optical fiber is covered by a thin film with these properties and light is propagating along it, there is a maximum coupling of light to the thin film region at specific wavelengths. Therefore, there are some wavelengths in which the propagation of light by the fiber is inhibited. These losses can be detected by an optical analyzer [9]. Furthermore, if the optical fiber is tapered, then losses are greater. This permits to improve the capacity of detecting greater power variations due to little changes in the thickness of the deposited nanostructure.

The main objective of this work is to measure the formation and behavior of so called LMR phenomena in tapered SMF fibers when varying its waist length, to establish whether this combination can be used for future sensors based on variations of coating thickness or refractive index. The measurement can be done either by analyzing power variation or resonance wavelength shift.

II. EXPERIMENTAL SET-UP

A. Materials and deposition

To carry out the construction of the nanostructure, Polyallylamine Hydrocloride (PAH), Neutral Red (NR) and Polyacrylic Acid (PAA) were used. All these substances were purchased from Sigma-Aldrich.

Two standard single mode optical fibers (SMF-28) were stripped, cleaned and tapered using a smooth flame and a

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micropositioning system from Nadetech S.L. until two adiabatic tapers of minimal length were formed [1]. Their waist lengths reached 5 and 20 mm, respectively, whereas their waist diameters and transition regions were 40 µm and 3 mm respectively. Once the substrates were obtained they were deposited sequentially, using the same polymeric solutions, to ensure that the properties of the materials were not going to change during the process. The layer-by-layer electrostatic self assembly method (LbL-ESA) was used to deposit these materials. The description of the deposition process can be found elsewhere [3,6]. Each deposited bilayer was composed by a polycation monolayer of PAH and NR and a polyanion monolayer of PAA. The total quantity of material deposited was 80 bilayers, so that the polymeric matrix was thick enough to monitorize the resonances that may appear during the construction. At the end of the experiments, the estimated effective refractive index of the structure immersed in water was 1.49 for each coating. This refractive index is higher than that of the optical fiber, so this condition permits the generation of an LMR [9].

B. *Monitoring the process*

In order to measure the resonances produced during the construction of the nanostructure, the set-up shown in Fig. 1 was prepared. First of all, a super luminescent emitting diode (SLED) light between 1150 and 1680 nm was used to launch light into the tapered fibers. The light modulated in the structures was detected by an optical spectrum analyzer.

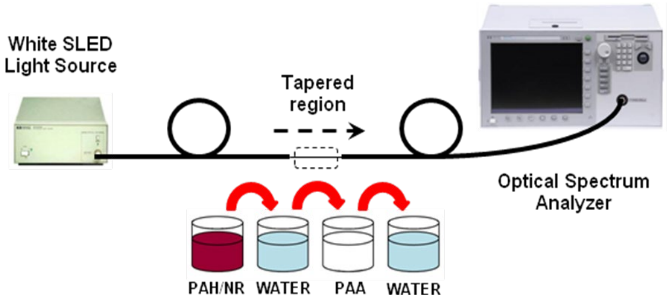

Fig. 1. Set-up of the construction and monitorization of the process.

Furthermore, to guarantee the repeatability of the characteristics of the deposited structure, the solutions were preserved from one experiment to the other. Moreover, by maintaining the same polyelectrolitic solutions, the LMRs appear at the same bilayer, which is interesting in order to compare results among different experiments. This idea is corroborated by comparing the experimental results with theoretical results in section III.

III. RESULTS AND DISCUSSION

After processing the data monitorized during the experiments, three main results are obtained. The first one is depicted in Fig. 2, where the electromagnetic spectrum of one of the two tapers is analyzed as a function of the number of bilayers deposited. According to [9], the generation of a LMR coincides with the moment when a lossy mode is guided in the nanocoating. In this case, an LMR starts being visible after the deposition of 35 bilayers at 1150 nm. While the construction takes place, the resonance presents a red-shift and its transmission decreases reaching -40 dB, which supposes twice the depth obtained with non-tapered optical fibers [5].

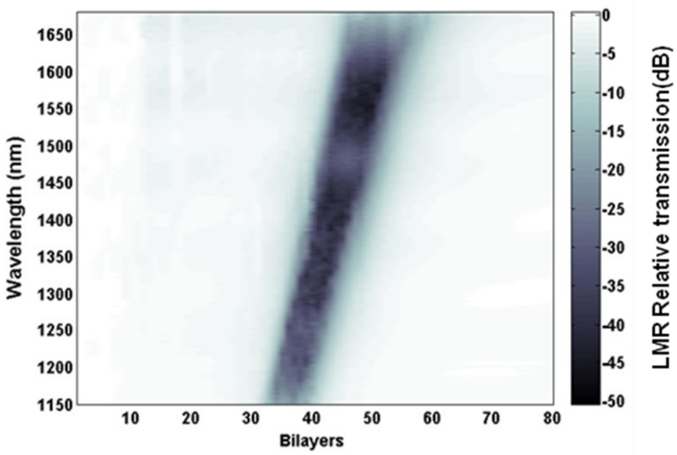

Fig. 2. Evolution of the relative power spectra while the nanocoating construction takes place. The gray-scale shows the depth reached by the LMR as a function of the number of bilayers.

The previous results can be analyzed for a specific wavelength of 1310 nm in Fig. 3. Fig. 3a shows the relative power evolution as a function of the deposited material for both the 5 mm - tapered fiber and the 20 mm - tapered fiber. Here, the two resonance profiles are compared in order to observe in a better way the behavior of these phenomena at the same time that the length of the taper waist increases.

The LMR is deeper when the taper waist is longer, which can be understood with the following explanation. When a non-tapered optical fiber propagates the light, the spectrum presents no resonances, because all the modes guided by the fiber are confined into the core and therefore, there are no power losses. After the tapering process, the core and the cladding diameter are reduced to a point that light is guided through the cladding in the tapered region. That is why light is coupled to the nanocoating in this region. Taking this into account, if the length of the tapered region increases, the longer it is, the more light will get out of the waveguide. The strong attenuation given by the resonance is obtained since the polymeric nanocoating sets the optimal conditions to permit coupling from the waveguide region to the nanocoated region [9]. This effect will be stronger when the taper waist increases, because there will be a longer region where light may be coupled from the cladding of the taper to the nanocoating.

To reinforce this hypothesis, Fig. 3b presents a theoretical simulation obtained with CAMFR software [10], which is based on the three-dimensional eigenmode expansion technique with perfectly matched layers.

A second characteristic observed both in theoretical and experimental results is that the resonances occur at the same range of bilayers. This highlights the importance of maintaining the same conditions when performing the layer-by-layer deposition.

Finally, there is one more aspect to take into account, which is the comparison of sensitivity among the different tapers (see Fig. 4) as a function of the excitation wavelength. As can be seen, the sensitivity curves are parallel and present low dependence on wavelength. The main aspect to comment here is that for the longer taper (L_w = 20 mm) the transmitted power change per bilayer is higher in comparison with that obtained with the shorter taper (L_w = 5 mm).

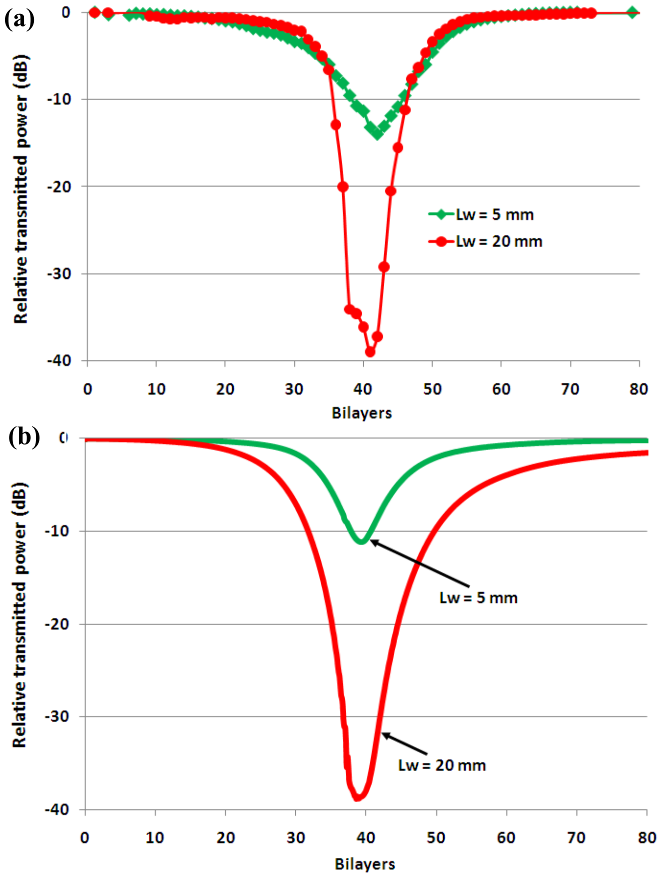

Fig. 3. (a) Comparison of resonance profiles for the two tapers analyzed at 1310 nm. The taper waist lengths are 5 and 20 mm. Both of them start to lose power from bilayer 30. (b) Theoretical simulation of the relative transmitted power for the same experiment.

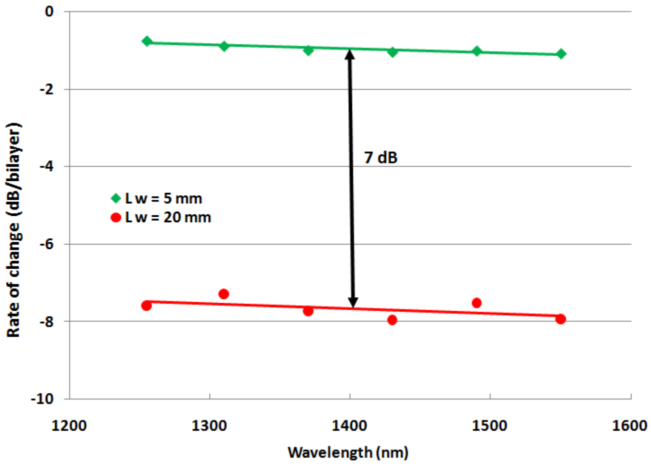

Fig. 4. Resonance evolution as a function of wavelength. The structures present no response depending on wavelength but great differences can be observed in the propagated power.

Concretely, the taper with L_w = 5 mm and 3 dB/bilayer can give enough sensitivity to detect certain phenomena, but if more sensitivity is required, the 8 dB/bilayer (20 mm length-waist) would be a better option.

IV. CONCLUSION

In summary, this work analyzes the behavior of lossy mode resonances (LMR) when they are induced by depositing a nanocoating on a tapered single mode optical fiber. The results show that for longer taper waists there is an increase in the registered losses, which implies higher sensitivity when power variations due to changes in nanocoating thickness are analyzed. This is a consequence of the interaction between the nanocoating and the evanescent field guided by the fiber in a longer region. In addition to this, it is important to reproduce the same conditions from an experiment to another, so that the deepest point of the resonance fixes at the same bilayer.

As has been proved, theoretical results correspond faithfully with experimental data, which may permit the design of innovative sensors with tunable sensitivity. This kind of structures can be used as detectors for nanofilm thickness changes, due to the extreme variation observed in their transmitted optical spectra, which can be applied for applications such as immunosensors or pH monitorization with a polymeric matrix which experiments swelling and deswelling with different pH values [5]. Moreover, these devices could be used as notch filters with different attenuation depending on the wavelength.

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