Polarization in the lossy mode resonance sensor-based on directly drawn D-shape fiber

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Abstract—Standard fiber optic sensors based on D-shape fibers are typically fabricated from step-index fibers with a circular core. Such fibers do not maintain polarization, so unpolarized light is used in measurements. However, a new method based on the direct drawing of a modified preform has been developed, resulting in a fiber with an elliptical core. This innovative approach not only offers a fiber that maintains a polarized state but also opens up exciting possibilities for enhancing the performance of optical fiber sensors based on Lossy Mode Resonance.

Fiber-optic sensors (FOS) have gained recognition in many fields of engineering and science due to their exceptional sensitivity, high resistance to electromagnetic interference, and ability to transmit data over long distances. In recent years, new types of sensors with higher accuracy and a more comprehensive range of applications have been developed. One class of such sensors is those based on evanescent waves. Unlike optical fibers used in telecommunications, it is aimed at strong electromagnetic field interaction with the substance under study. Thus, changing the medium's optical properties affects the conditions for guiding light in the optical fiber [1]. For the light guided in the optical fiber to effectively interact with the external medium, the electromagnetic field located in the core must penetrate the medium under study [2]. Various approaches are used here. Among the most important are long-period gratings induced in the fiber core, tapered fibers, combinations of different fibers to obtain interferometric structures, photonic crystal fiber (PCF), anti-resonant fibers, and D-shape fibers [3]. In D-shape fibers, the interaction of light with the tested substance is possible thanks to moving the fiber core closer to the edge of the fiber by partially removing the cladding on one side. The D-shaped section is covered with a thin layer to increase measurement accuracy. For the metallic layer, a surface plasmon resonance (SPR) can be achieved [4], and for the dielectric layer, a lossy mode resonance (LMR) can be achieved [5, 6]. While SPR occurs only for transverse magnetic (TM) polarization, LMR can be observed for both TM and transverse electric (TE) polarized light. In addition, for selective detection of chemical or biological compounds, the fiber is covered with an additional thin immobilizing layer.

In this paper, we numerically and experimentally investigated the effect of polarization direction on the sensing properties of a D-shape fiber based on lossy mode resonance (LMR). We also examined whether using polarization-maintaining elliptical-core fibers for this purpose is reasonable.

The current standard for fabricating D-shape fibers is based on modifying an already drawn SMF fiber [7]. Fibers with a standard 125 μm diameter and circular core are ground, etched, or ablated to expose or reach the optical core. The problem with this approach is the low accuracy and repeatability of these processes, which results in different optical properties for each sensor. In consequence, each fiber requires separate calibration. In addition, the area of the fiber with the cladding removed covers only a tiny portion (10–50 mm) of the longer, unmodified SMF fiber. Therefore, regardless of the polarization coupled into such a fiber, there is unpolarized light in the sensing area and at the output of the fiber.

The disadvantages of fabrication reproducibility are eliminated by the recently presented method of directly drawing D-shape fiber from a modified preform [7]. In this method, the grinding process occurs on a macro scale where a standard silica preform with a circular core doped with germanium is processed. Then, the preform prepared this way is drawn on an optical tower. The result is hundreds of meters of nearly identical D-shaped fiber with high surface quality. As a result of the drawing, the fiber itself, as well as the core, is slightly deformed (Fig. 1). The shape change depends on several parameters, such as the glass viscosity and surface tension, the drawing process temperature, the preform delivery rate, and the fiber drawing rate. However, regardless of the combination of these parameters, the fiber core becomes elliptical, with the long axis of the ellipse perpendicular to the fiber's flat surface.

In the presented fiber, the birefringence resulting from the elliptical shape of the core is at the level of 1×10^{-4}. Thus, the fiber preserves the polarization state of the

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transmitted light over a distance of several tens of centimeters.

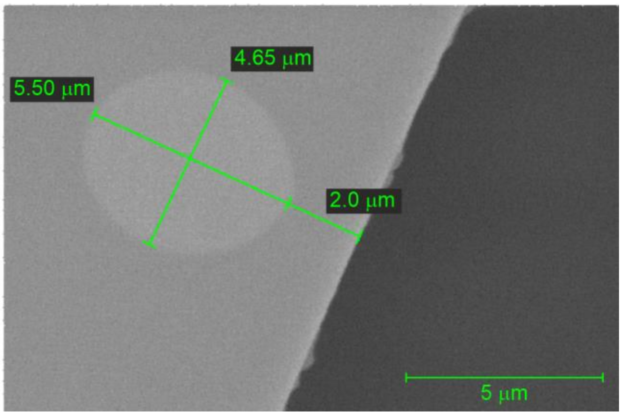

Fig. 1. SEM images of fabricated D-shape fibers.

The problem of the effect of polarization on the sensing properties of D-shape fibers was first investigated numerically using the FEM method implemented in the Comsol Multiphysics package. A fiber with a circular core that does not maintain polarization and one with an elliptical core that maintains polarization were considered. The size of both cores was chosen so that the fundamental mode had an identical effective mode area in both cases. Other parameters such as the properties of the dielectric layer (Si-N) and its thickness (250 nm), the distance of the edge of the core from the flat side of the fiber (2 um), the size of the fiber (125 um) and the length of the segment over which light interacts with the test substance (20 mm) were determined in the same way for both fibers. The test substance in both cases was water. This approach allowed us to eliminate potential other perturbations that could affect the sensing properties and focus only on the effect of the core's ellipticity and polarization.

In the simulations, both fibers were excited with light of a selected polarization parallel (horizontal) to the flat side of the D-shape fiber or perpendicular (vertical) (Fig. 2ab). In the case of the optical fiber with a circular core, due to the symmetry of the core, the light in the sensing section is unpolarized, and a transmittance curve with two pairs of two minima labeled D1–D4 is observed at the output of the fiber. One pair (D1, D2) is observed in the shorter wavelength range and the second pair (D3, D4) in the near-infrared range. The minima for each pair correspond to two different polarizations (Fig. 2c, 2d, red arrows). The distance between the minima in a given pair depends on the dielectric material and its thickness. However, overlapping minima make them wider with less relative depth, making signal analysis more difficult, which involves finding the central wavelength for a given local minimum. In the case of a D-shape optical fiber with an elliptical core along its length [7], excitation with the chosen polarization determines which polarization will interact with the test substance. The result is two different transmittance curves for two polarizations (Fig. 2e-h). An analysis of such a signal is easier and more accurate than for unpolarized light due to narrower and more dynamic minima.

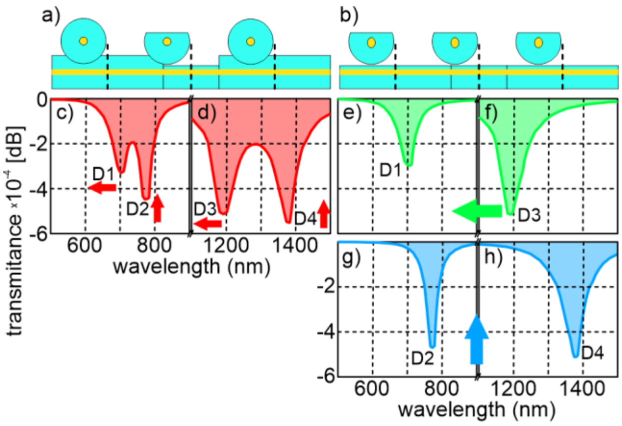

Fig. 2. Numerical analysis of the LMR sensor: a) scheme of the sensor with optical fiber with a circular core that does not maintain polarization, b) scheme of the sensor with a D-shape fiber with an elliptical core that maintains polarization, c, d) resonance dips for unpolarized light in the visible and near-infrared range, respectively, e, f) resonance dips for horizontal polarization and g, h) for vertical polarization. (The direction of polarization is shown by colored arrows)

To experimentally investigate the properties of the sensors built from the fabricated D-shaped fibers and based on the LMR phenomenon, they were covered over a 20-mm section with a dielectric layer of Si-N. Experiments were carried out for two different dielectric thicknesses of 200 and 250 µm. Broad-spectrum polarized white light from a supercontinuum source (Coheras SuperK) was launched into the fiber. The output signal was registered with a Thorlabs CCS175 spectrometer in a range of 500–1100 nm and Avantes, AvaSpec-NIR256-1.7 in a range of 900–1700 nm. Measurement results in air and water, presented in Fig. 3, show that for each polarization, there is one minimum in the visible light range and one in the near-infrared. In addition, the minima for vertical polarization are shifted to longer wavelengths relative to the minimum for horizontal polarization. The results obtained are consistent with those obtained for the numerical analysis. To check which polarization allows for a measurement with greater sensitivity, measurements were carried out at different refractive indices of the test substance. Various concentrations of DMSO in water from 0 to 100%, which results in a change in refractive index between 1.333 and 1.3725, were used in the experiment. The results in Fig. 4 and the sensitivity (S) determined based on them (Fig. 5) show that the measurement carried out using horizontal polarization (Fig. 4a, 5b) has nearly twice the sensitivity (S=670 nm/RIU) compared to the measurement for vertical polarization (S=360 nm/RIU) (Fig. 4b, 5a).

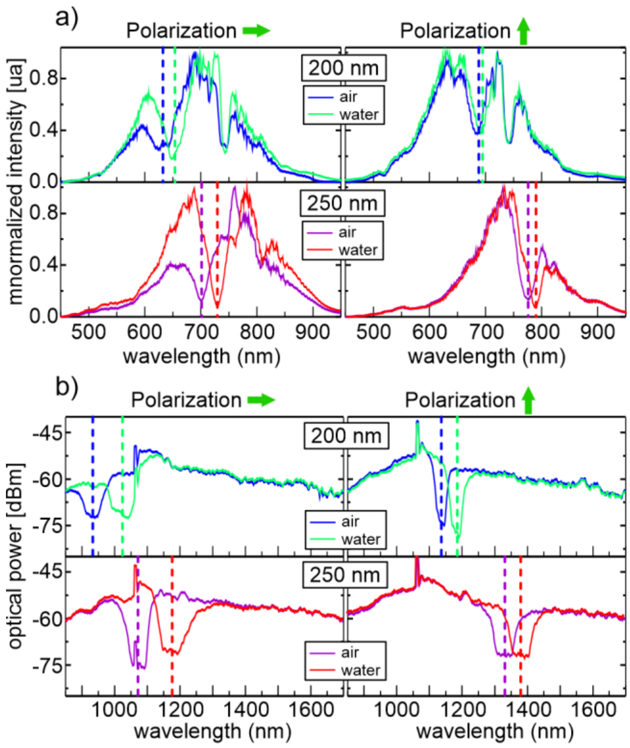

Fig. 3. Experimental results for the LMR sensor when excited with light in two orthogonal polarizations: a) in the visible light range, b) for light in the near IR range. (Green arrows show the direction of polarization)

Experimental results, confirmed by a numerical analysis, show higher sensitivity of sensors based on lossy mode resonance when polarization is parallel to the flat surface of the D-shape fiber. In addition, using a fiber with an elliptical core that maintains polarization makes it easier to analyze the signal since the intensity dips in the transmission curves are narrower and of higher contrast.

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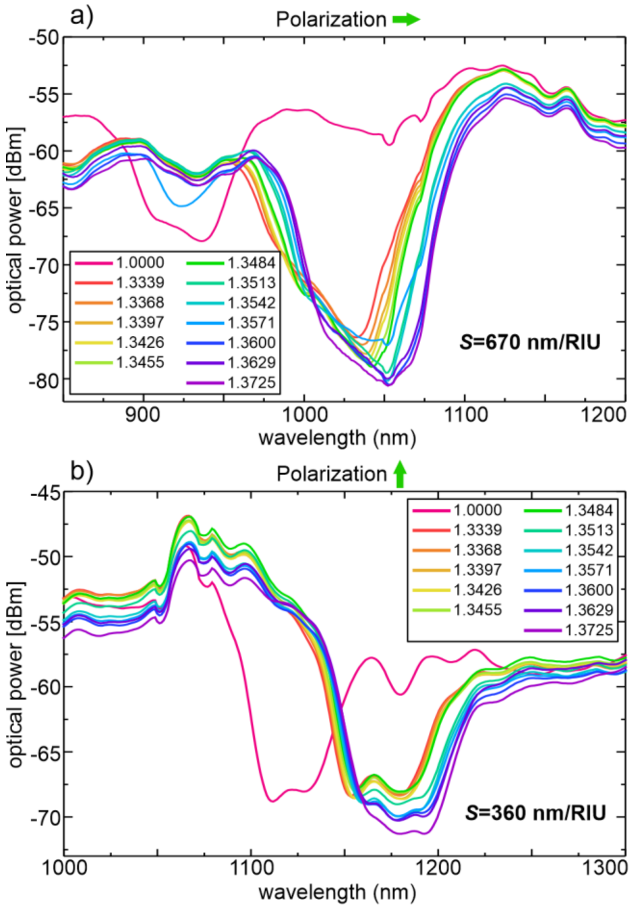

Fig. 4. The result of measuring the transmission of light in the LMR sensor at different refractive indices of the tested liquid for polarization: a) horizontal, parallel to the flat edge of the fiber, and b) vertical.

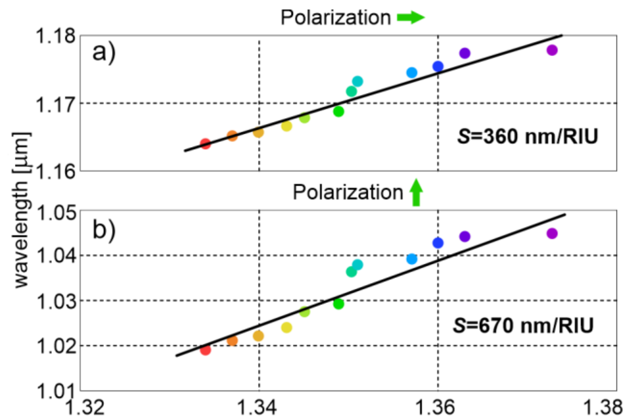

Fig. 5. Sensitivity of the LMR sensor for two different polarizations: a) vertical, and b) horizontal.

