Influence of the core shape on the quality of fiber sensors based on D-shape fiber

Rafal Kasztelanic,*[1,2] Grzegorz Stepniewski,[1] Dariusz Pysz,[2] and Ryszard Buczynski[1,2]

[1]*Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*
[2]*Photonics Materials Group, Lukasiewicz Research Network – Institute of Microelectronics and Photonics, al. Lotników 32/46, 02-668 Warsaw, Poland*

Received June 03, 2024; accepted September 24, 2024; published September 30, 2024

Abstract—Typical optical sensors based on D-shape fibers use standard step-index single-mode fibers (SMF) with a circular core. Multi-mode fibers, fibers with elliptical or rectangular cores, and photonic crystal fibers (PCF) are also used to achieve the best possible sensor performance. However, since the presented sensors differ not only in geometry but, most importantly, in the materials and core sizes, it is difficult to compare their properties directly. In this paper, we numerically analyzed the influence of the shape and size of the core on the sensing performance, with all other relevant parameters being equal.

Optical fiber sensors (OFS) have recently attracted the attention of scientific communities and industry. They are primarily used for monitoring large infrastructures and are last used as chemical sensors and biosensors. OFSs are based on a variety of optical fibers, from the most popular standard single-mode silica glass fiber (SMF) [1] to highly structured optical fibers made of special materials [2]. For chemical and biological measurements, the light guided in the fiber must interact with an external medium, for instance, through an evanescent field. In addition, the measurement conditions should be chosen so that any change in the medium's optical properties would modify the conditions for guiding the light in the fiber. Several solutions meet these requirements. Among the most important are fibers with a long-wavelength grating induced in the core, fiber tapers, fiber interferometric systems [3], and fibers with part of the cladding removed. The latter includes D-shape optical fibers [4]. To increase measurement accuracy and enable selective detection of chemical or biological compounds, the D-shaped section of the sensor is additionally coated with a thin layer of metal or dielectric, plus an immobilizing layer [5]. In this case, the effect of Surface Plasmon Resonance (SPR) [6] or Loss Mode Resonance (LMR) [7] can be achieved, in which resonance wavelength changes with changes in optical properties on the surface of the thin film.

Typically, the basis of a D-shape OFS is a standard single-mode step-index optical fiber with a circular core, in which part of the cladding is removed by mechanical, chemical, or laser ablation methods, but other fiber geometries are also used [8]. The D-shape fiber can also be fabricated by drawing a modified preform directly on an optical tower [9]. In this case, the fiber core naturally, due to the thermodynamics of the drawing process, becomes elliptical with the long axis perpendicular to the flat edge of the fiber (Fig. 1a). Elliptical cores, rectangular cores, and various core shapes in PCF are also used to achieve the best possible sensing properties. However, since the presented sensors differ not only in geometry but also in the materials used, sizes, and fabrication methods, it is difficult to compare their properties directly.

This paper numerically analyzed how the shape and size of three different cores affect the parameters of the Lossy Mode Resonance sensor: an elliptical core (Fig. 1a) [9], a rectangular core, and a nanostructured square core guiding a top-hat fundamental mode (Fig. 1b) [10]. It was assumed that all sensor parameters except the shape and size of the D-shape fiber core were identical to enable comparison. The main objective of this comparison is to see if the intended (elliptical core, rectangular nanostructured top-hat) or resulting from fabrication processes [9] deformation of the D-shape fiber core significantly affects the sensing parameters.

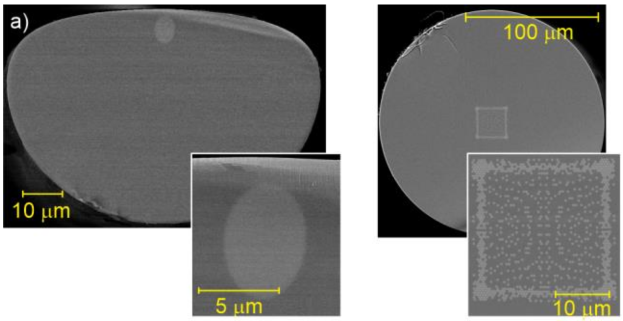

Fig. 1. Examples of optical fibers with: a) elliptical core [8] and b) top-hat nanostructured core [10].

The analysis assumes that the fiber cladding is made of silica and the core is made of silica doped with germanium at a level of 2% (mol) (Fig. 2a). Their refractive indices (RI) follow those proposed by Fleming *et al.* [11]. The core, regardless of its size or shape, is distant from the flat surface of the fiber by $g = 2$ μm. On

---

[*] E-mail: kasztel@igf.fuw.edu.pl

the flat surface is a layer of ITO (RI based on [12]) with a constant thickness of h =240 nm. Three types of cores were considered in the analysis: an elliptical core (Fig. 2b–d), a rectangular core (Fig. 2e–g), and a nanostructured square core guiding a top-hat fundamental mode (Fig. 2h). For the elliptical and rectangular core, the variable parameters were the size of the core and the ratio (r) of the horizontal to the vertical size, equal to 3/2 (Fig. 2be), 1 (Fig. 2cf) and 2/3 (Fig. 2dg), respectively. The diameter of the core in a circular core fiber and the side of a square core were the same and were 5, 8, and 11 µm. The fibers with an 8 µm core are single-mode, similar to the standard SMF-28 fiber. The fibers with a 5 µm core are also single-mode, but the guided modes have a larger effective mode area than those with an 8 µm core. On the other hand, fibers with an 11 µm core guide 2–3 modes, while the analysis carried out was for the fundamental mode. The sizes of the elliptical and rectangular cores were chosen so that the areas of the cores, regardless of the r parameter, were the same. The core size was changed for the D-shape optical fibers with a nanostructured core (top-hat). However, each core size was independently optimized to guide the top-hat-shape fundamental mode. It should be noted that only those with a core of 8, 10, and 12 µm of this type of fiber were single-mode. The test medium was a DMSO (RI based on [13]) solution in water with concentrations ranging from 0 to 50%.

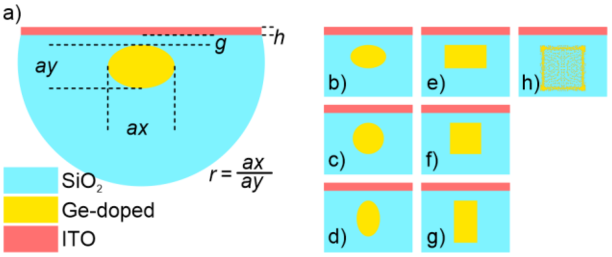

Fig. 2. Fibers used in the analysis: a) definition of basic geometric dimensions, b-d) elliptical-core fibers, e-g) rectangular-core fibers, h) top-hat nanostructured-core fiber.

The analysis studied how different D-shape fibers' transmittance changes as a wavelength function. The fiber shows polarization properties since the core is not always symmetrical, and the cladding is asymmetrical. Therefore, two distinct minima from two different polarizations can be identified on the transmittance curve (Fig. 3).

The most important parameter determining the properties of a D-shape fiber-based sensor is its sensitivity (S), defined as:

$$S = \frac{\Delta\lambda_{LMR}}{\Delta n}. \quad (1)$$

Sensitivity was calculated independently for both polarizations. The other parameters of interest in analyzing the signal captured by the sensor are the depth of the transmittance dip D and the width w of these dips (Fig. 4).

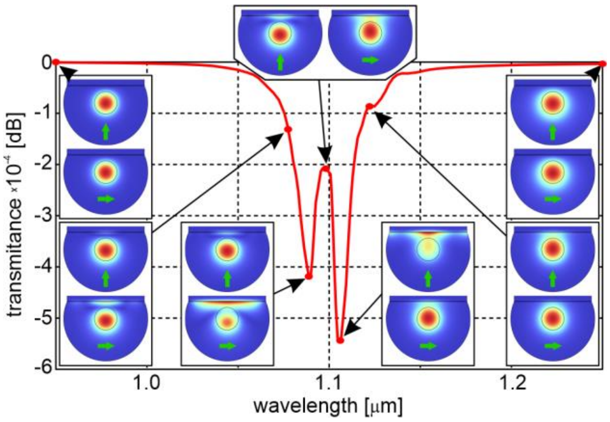

Fig. 3. Fundamental modes for D-shape fiber with circular core. Red dots indicate the wavelength for which the modes are shown. Green arrows indicate the direction of polarization.

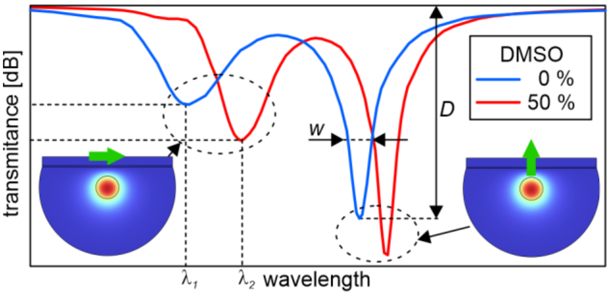

Fig. 4. Example of the transmittance of a D-shape fiber with a circular core for two different solutions of DMSO in water. The green arrow indicates the direction of polarization.

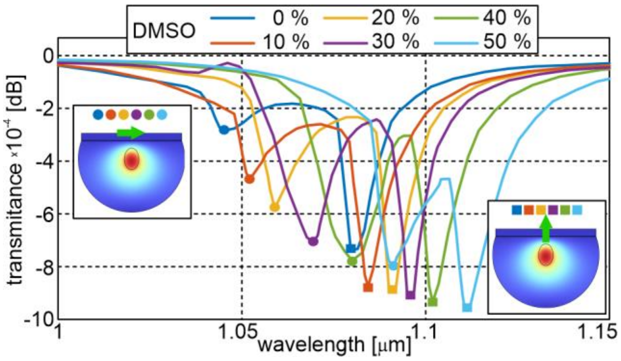

Fig. 5. Transmittance for different concentrations of DMSO solution. Circles and squares indicate minima for horizontal and vertical polarization, respectively.

The procedure for determining the sensitivity, using an elliptical fiber with ratio r=2/3 as an example, is shown in Fig. 5 and Fig. 6. In the first step, the transmittance curves for the fiber at different concentrations of DMSO solution were calculated (Fig. 5). Then the positions of the transmittance minima for horizontal polarization (circles in Fig. 5) and vertical polarization (squares in Fig. 5) were determined. In the next step, the obtained values were applied to a figure showing the dependence of the lossy mode resonance wavelength (λ_{LMR}) on the refractive index of the liquid under test (n_d) (Fig. 6). The linear regression finally determined the sensitivity coefficient s. The results for elliptical and rectangular core D-shape fibers are summarized in Tab. 1. The results for the nanostructured top-hat fibers are shown in Tab. 2.

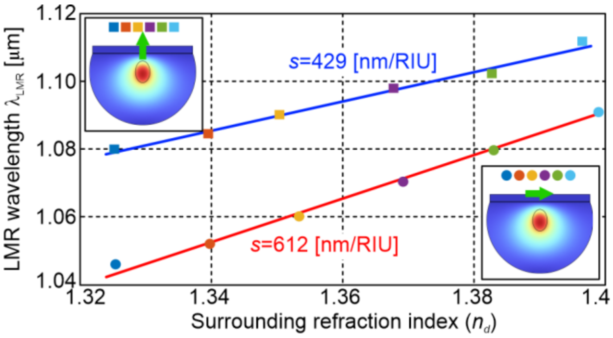

Fig. 6. Evolution of the LMR wavelengths from the refractive index surrounding the fiber. Linear regression determines the sensitivity of D-shape fiber.

Tab. 1. Sensitivity of the D-shape fiber. Results in nm/RIU. (Arrows indicate the direction of polarization).

		Elliptical			Rectangular		
		Size [µm]			Size [µm]		
	ratio	5	8	11	5	8	11
→	3/2	696	696	752	696	710	752
	1	682	735	752	670	724	752
	2/3	612	724	752	626	724	752
↑	3/2	388	415	430	388	388	430
	1	429	415	430	415	388	430
	2/3	429	402	430	443	388	430

Tab. 2. Sensitivity of the nanostructured top-hat-core D-shape fiber. Results in nm/RIU. (Arrows indicate the direction of polarization).

	Size [µm]						
	8	10	12	14	16	18	20
→	718	700	700	700	691	691	674
↑	404	396	396	396	388	388	379

The results show that regardless of size, shape, and ratio, higher sensitivity was observed in D-shaped fibers for horizontal polarization. However, for horizontal polarization, the minimum depth (D) was smaller, and their width (w) was larger, potentially making signal analysis difficult. For fibers with elliptical and rectangular cores, sensitivity also increased with the core size, reaching the highest values for 11 µm cores. Of note, however, is that this was not a single-mode fiber, which can result in incorrect measurements. The depth of the minima D also decreased with the size of the cores. For horizontal polarization, for a small core of 5 µm, fibers with cores with a ratio r=3/2 had a higher sensitivity. The opposite relationship was observed for fibers with a core of 8 µm, where fibers with a ratio r=2/3 showed the highest sensitivity. For vertical polarization, differences in sensitivity depending on the ratio were observed for fibers with a core of 5 µm. For larger fibers, sensitivity changed little or not at all. Importantly, no significant differences were observed between elliptical and rectangular cores. Only in the case of vertical polarization, elliptical fibers with an 8 µm core had a higher sensitivity of about 10% than rectangular-core fibers. For nanostructured fibers with a top-hat core, the highest sensitivity was observed for a fiber with an 8 µm core. Then, the sensitivity started to decrease as the core size increased.

We analyzed the effect of the shape and size of the D-shape fiber core on the sensitivity of a sensor based on such a fiber. The analysis showed a higher sensitivity for horizontal polarization than vertical polarization and no significant dependence on core shape. Regarding single-mode operation, it is better to use a fiber with the largest possible core and a ratio equal to or less than 1. The results also show that the core deformation in fibers fabricated by the direct drawing method of D-shape optical fibers, with cores of the order of 8 um, is advantageous.

Acknowledgments: TECHMATSTRATEG-III/0042/2019 NCBiR, Poland.

References

[1] D. Jauregui-Vazquez, J. P. Korterik, C. E. Osornio-Martinez, J. M. Estudillo-Ayala, H. L. Offerhaus, J. A. Alvarez-Chavez, Opt. Comm. **522**, 128659 (2022). https://doi.org/10.1016/j.optcom.2022.128659.

[2] H. H. Liu, D. J. Hu, Q. Z. Sun, L. Wei, K. W. Li, C. Liao, B. Li, C. Zhao, X. Dong, Y. Tang, Y. Xiao, G. Keiser, P. Shum, Opto-Electron Sci. **2**, 220025 (2023). https://www.oejournal.org/article/id/64099b4299d8812a5f85c9d3

[3] K. Gasior, T. Martynkien, P. Mergo, W. Urbanczyk, Sensors and Actuators B: Chemical **257**, 602 (2018). https://doi.org/10.1016/j.snb.2017.10.084.

[4] Y. Ying, G. Si, F. Luan, K. Xu, Y. Qi, H. Li, Opt. & Laser Techn. **90**, 149 (2017). https://www.sciencedirect.com/science/article/abs/pii/S0030399216310301?via%3Dihub

[5] J. Homola, *Surface Plasmon Resonance Based Sensors* (Berlin, Springer 2006).

[6] K. Gasior, T. Martynkien., M. Napiorkowski, K. Zolnacz, P. Mergo, W. Urbanczyk, J. Opt. **19**, 025001 (2017). https://iopscience.iop.org/article/10.1088/2040-8986/19/2/025001.

[7] Q. Wang, W. M. Zhao, Opt. Lasers in Engineering **100**, 47 (2018). https://www.sciencedirect.com/science/article/pii/S0143816617302026

[8] K. Gasior, T. Martynkien, G. Wojcik, P. Mergo, W. Urbanczyk, Opto-Electronics Review **24**(4), 209 (2016). https://doi.org/10.1515/oere-2016-0025.

[9] G. Stepniewski, A. Filipkowski, D. Pysz, J. Warszewski, R. Buczynski, M. Smietana, R. Kasztelanic, Measurement **222**, 113642 (2023). www.sciencedirect.com/science/article/pii/S026322412301206X

[10] R. Kasztelanic, H. T. Nguyen, D. Pysz, H. Thienpont, T. Omatsu, R. Buczynski, Adv. Science **11**, 2402886 (2024). https://onlinelibrary.wiley.com/doi/epdf/10.1002/advs.202402886.

[11] J.W. Fleming, Dispersion in GeO2-SiO2 glasses, Appl. Opt. **23**, 4486–4493 (1984), https://doi.org/10.1364/AO.23.004486

[12] T.A. König, P.A. Ledin, J. Kerszulis, M.A. Mahmoud, M.A. El-Sayed, J.R. Reynolds, V.V. Tsukruk., ACS Nano **8**, 6182-6192 (2014). https://pubs.acs.org/doi/10.1021/nn501601e

[13] I.Z. Kozma, P. Krok, E. Riedle, J. Opt. Soc. Am. B **22**, 1479-1485 (2005). https://opg.optica.org/josab/abstract.cfm?uri=josab-22-7-1479