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Microarray-core based circular photonic crystal fiber for high chemical sensing capacity with low confinement loss

SAYED ASADUZZAMAN, KAWSAR AHMED

Department of Information and Communication Technology,
Mawlana Bhashani Science and Technology University,
Santosh, Tangail-1902, Bangladesh

*Corresponding author: samonna25@gmail.com

In this article, a circular photonic crystal fiber based chemical sensor has been presented where core region is designed with an array of elliptical holes. The proposed structure is numerically investigated by using a full vectorial finite element method. From the numerical results, it is observed that introducing an array of elliptical holes helps to obtain the high relative sensitivity and realizes a low confinement loss. In addition, the increase in the value of the diameter of holes in the innermost ring enhances the relative sensitivity. Moreover, the increase in the value of the diameter of holes in the outermost ring reduces the confinement loss. In this work, we have considered an industrially valuable chemical ethanol. Simulation results disclose that the highest relative sensitivity of proposed photonic crystal fiber is 29.25% for ethanol and the confinement loss is 7.68×10^{-7} dB/m at the wavelength 1.5 μm.

Keywords: circular photonic crystal fiber, confinement loss, elliptical core, chemical sensor and relative sensitivity.

1. Introduction

The photonic crystal fiber (PCF) has drawn much attention due to its design flexibility compared with conventional optical fibers [1]. Recently, researchers are working relentlessly to develop the performance of PCF by improving its guiding properties. PCF has included a large dimension of research field in the modern world such as biomedical [2] and industrial sectors [3].

The guiding properties of a PCF vary depending on wavelength, phase and the polarization state of light [4]. Various geometrical parameters of PCF are also responsible for changing the guiding properties [5]. Different shapes of lattice structure of

PCF have already been proposed for better guiding properties such as hexagonal [6], octagonal [7], decagonal [8], elliptical [9], and circular honey comb cladding [10]. Estimation of the relative sensitivity of a PCF for chemical and gas sensing takes into account the evanescent wave [11].

Two key guiding properties of a PCF based sensor are the relative sensitivity and the confinement loss. A number of works have been done to enhance the relative sensitivity and degrade the confinement loss of PCF for chemical and gas detection applications. In [12] the relative sensitivity improved to 13.23% by increasing the diameter of the holes located in the innermost ring and the confinement losses reduced to 3.77×10^{-6} dB/m by increasing the diameter of holes located in the outermost ring at $\lambda = 1.33$ μm. In 2015, MORSHED *et al.* [13] designed a 3-ring hollow core hybrid structure PCF based gas sensor which improved the relative sensitivity. They showed that the relative sensitivity was 20.10% which was higher than the previous structures [14, 15]. In [16], there was proposed a chemical and gas sensor where both core and cladding are microstructured. In [17] it was demonstrated that the hexagonal shape of PCF, where both core and cladding contain elliptical holes, shows high sensitivity, high birefringence and low confinement loss. In [18], the central core area was designed with microstructured elliptical holes, which helps to get higher birefringence.

In this paper, we proposed a circular photonic crystal fiber (C-PCF) with an array of elliptical holes that can realize the high relative sensitivity of about 29.25% at the wavelength of 1.5 μm and low confinement loss of about 7.68×10^{-7} dB/m. The paper is organized as follows. Section 2 presents the geometric description of the proposed PCF. Section 3 shows the numerical analysis and the mathematical calculations of the relative sensitivity and the confinement loss. Section 4 presents numerical results and discussion. In Section 5 we describe the future works of PCF. The conclusion of this paper is provided in Section 6.

2. Geometrical description

The cross-sectional view of the proposed C-PCF is shown in Fig. 1 which contains three circular rings in the cladding and an array of elliptical holes in the microstructure core. The outermost ring contains 18 holes, the middle ring contains 8 holes, and the innermost ring contains 6 holes. Here, the diameter of the elliptical holes in the core region for the major and minor axis is determined as d_m and d_n. The center-to-center distance of the two adjacent holes is called a pitch. The pitch between the two adjacent elliptical holes at the core is presented by Λ_c. The diameters of holes in the first, second and third ring are denoted as d_1, d_2 and d_3, respectively. The pitches of the first and second ring are defined by Λ_1 and Λ_2, respectively. A perfectly matched layer (PML) is used outside the C-PCF to meet the boundary conditions and concentrate more light through the core. The depth of the PML is set 10% around the whole diameters of the proposed C-PCF. Elliptical holes are used to enhance the sensitivity in [19]. So we have

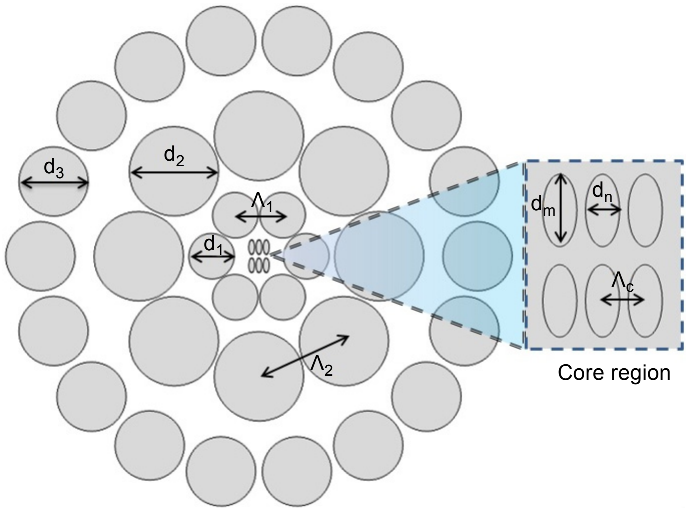

Fig. 1. Cross-sectional view of the proposed C-PCF (see text for explanation).

used elliptical holes in the core. The cladding is set in such a way that it reduces the confinement loss and guides more light through the core. The outer two rings of cladding holes are set bigger than the innermost holes because the outermost ring of holes is responsible for confinement loss [20].

3. Synopsis of the numerical method

A full vectorial finite element method (FEM) is utilized to examine the proposed PCF structure. By utilizing PML's boundary condition, propagation characteristics and optical properties of leaky modes in PCFs can be exactly assessed [21, 22]. The modal analysis has been done on the cross-section in the *x*-*y* plane of the PCF as the wave is spreading in the direction.

Utilizing Maxwell's equation, the vectorial mathematical statement is determined as

$$\nabla \times ([S]^{-1})\nabla \times E - K_0^2 n^2 [S]E = 0 \tag{1}$$

where $K_0 = 2\pi/\lambda$, is the wave number in the vacuum, λ is the operating wavelength, E is the electric field vector and S is the PML matrix. Leakage of light happens from the center to the outside lattice material because of the limited number of layers of holes. This leakage of light energy is known as confinement loss L_c which is calculated from the imaginary part of the effective refractive index n_{eff} using the following equation:

$$L_c = 8.868 K_0 \,\mathrm{Im}[n_{eff}] \quad [\mathrm{dB/m}] \tag{2}$$

Relative sensitivity coefficient r is the key parameter to measure the efficiency of a PCF. According to the modified Beer–Lambert law, the relative sensitivity coefficient can be defined as

$$r = \frac{n_r}{\mathrm{Re}[n_{\mathrm{eff}}]} f \tag{3}$$

where, n_r presents the refractive index of sensed material (in this paper we considered ethanol) within the holes, n_{eff} is the modal effective index, and f is the percentage ratio of the air hole power and the total power

$$f = \frac{\int_{\mathrm{sample}} \mathrm{Re}(E_x H_y - E_y H_x) \mathrm{d}x \mathrm{d}y}{\int_{\mathrm{total}} \mathrm{Re}(E_x H_y - E_y H_x) \mathrm{d}x \mathrm{d}y} \times 100\% \tag{4}$$

where E_x and H_x are transverse electric and magnetic field, respectively, E_y and H_y are longitudinal electric and magnetic field, respectively. Using FEM, the mode field pattern E_x, H_x, E_y, H_y and effective index n_{eff} are obtained. Pure silica was set as the background material of the proposed PCF. The refractive index of the silica varies depending on the wavelength with the Sellmeier equation.

4. Results and analysis

The guiding property (like sensitivity and confinement loss) of the proposed C-PCF has been analyzed in this section. The analysis takes place by changing geometrical parameters (such as the diameters of the holes, pitch value) to optimize the parameters. The whole analysis was done at a wider transmission band of wavelength between 0.8 and 2 μm. The wavelength range is used so that the proposed C-PCF can be used to sense not only ethanol but also other chemicals whose absorption line lies between 0.8 and 2 μm. In this research, we have considered an industrially valuable chemical ethanol which is a lower indexed chemical. The refractive index of ethanol is ($n_r = 1.354$ at the wavelength $\lambda = 1.33$ μm). Filling the core with the chemical to be sensed (ethanol) is a challenging part. The refractive index of ethanol changes with the wavelength slightly according to the change in wavelength. We can fill the core with ethanol by some modern techniques like selective filling technique [23] so that the proposed PCF can sense the chemical.

Figure 2 shows the mode field distribution of the proposed C-PCF. The figure depicts that the mode field is tightly confined to the core region for the fundamental mode of the effective refractive index. The variation of the effective refractive index of the fundamental mode is shown in Fig. 3. The refractive index decreases at a constant rate with the wavelength.

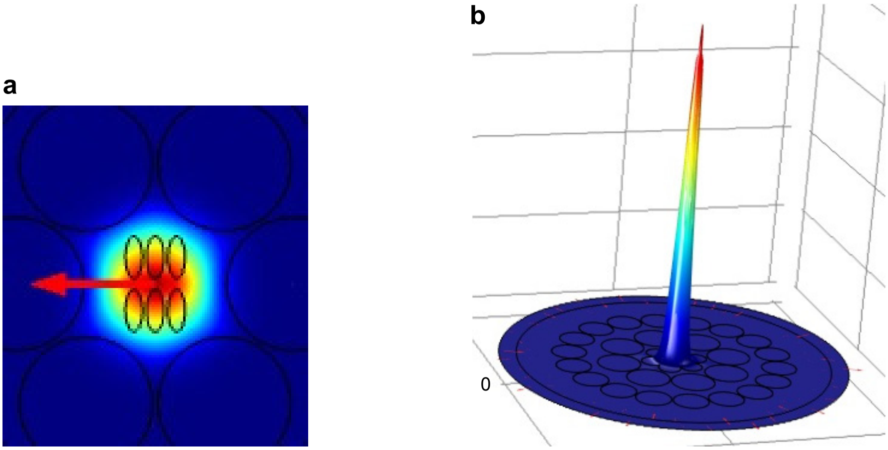

Fig. 2. Mode field distribution of the proposed C-PCF 2D (**a**) and 3D (**b**) view at the wavelength 1.33 μm.

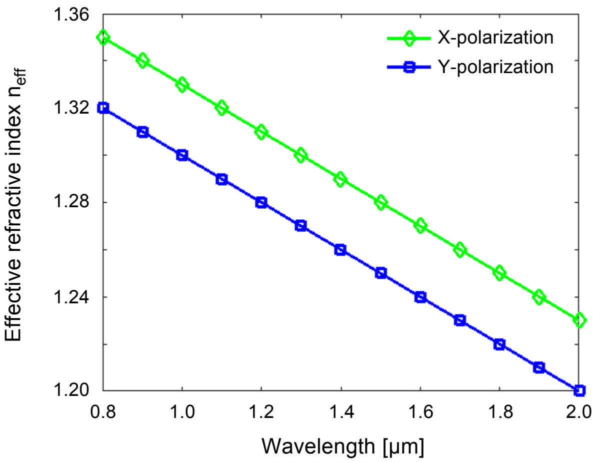

Fig. 3. Variation of effective refractive index n_{eff} of proposed C-PCF *X*- and *Y*-polarization depending on wavelength.

The comparison of relative sensitivity (%) and confinement loss (dB/m) depending on wavelength by varying the first ring diameter is shown in Fig. 4. Figure 4**a** clearly shows that the relative sensitivity is higher for d_1 = 1.25 μm. Figure 4**b** depicts that by varying the inner ring diameters, d_1 has a little impact on confinement loss although the relative sensitivity varies a lot.

Figure 5**a** illustrates that the relative sensitivity remains same for different diameters of the outer ring of holes but Fig. 5**b** shows that lower confinement loss can be gained for the largest diameter d_3 = 1.9 μm of holes of the outer ring. In this research, we have optimized all the parameters by varying the geometrical parameters, such that when

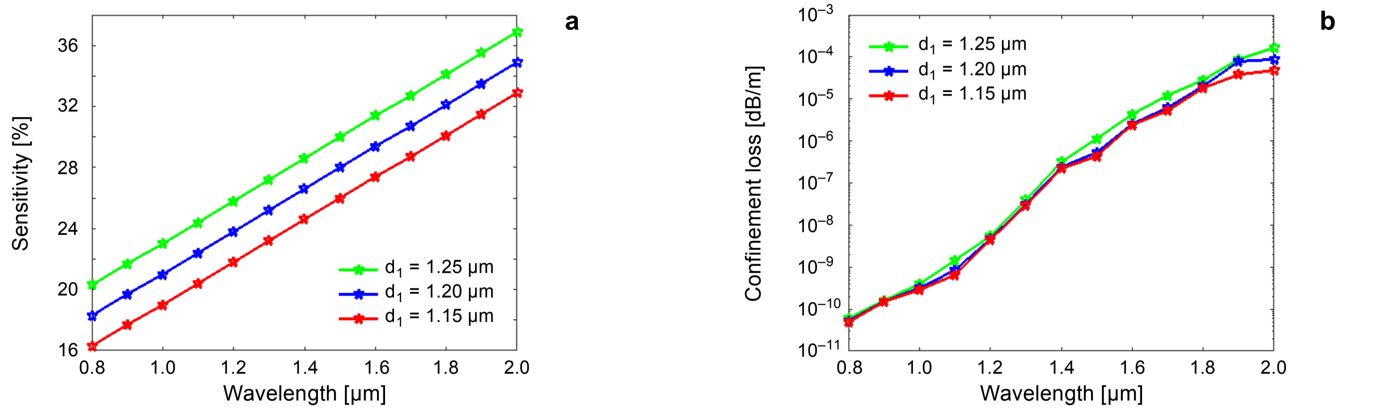

Fig. 4. Variation of the relative sensitivity (**a**) and confinement loss (**b**) for ethanol depending on wavelength for d_1 equal to 1.25, 1.20, and 1.15 μm when other optimized parameters were kept constant.

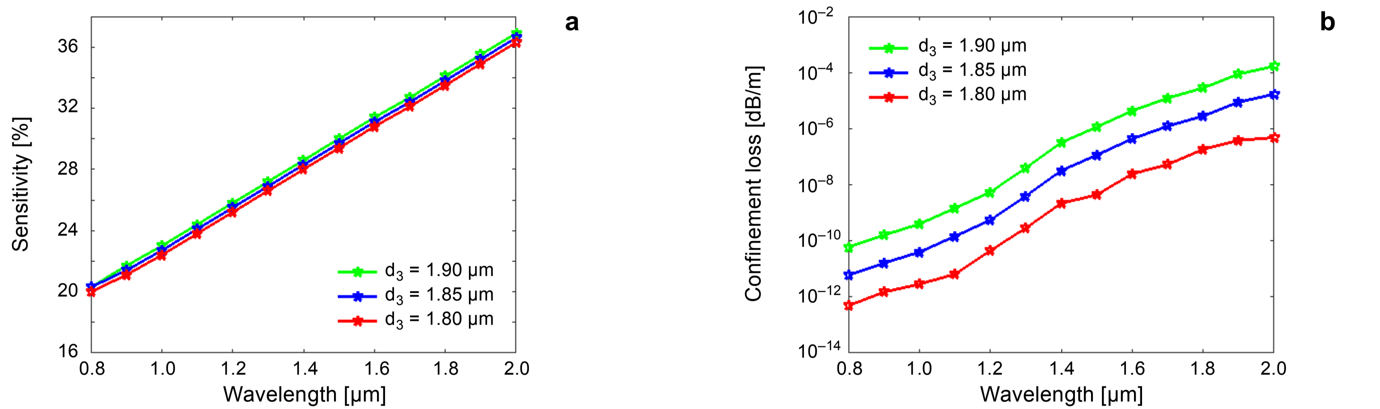

Fig. 5. Comparison of relative sensitivity (**a**) and confinement loss (**b**) for ethanol depending on wavelength among the outer rings of holes diameters for d_3 equal to 1.9, 1.85, and 1.80 μm when other optimized parameters are kept constant.

T a b l e. Comparison of simulated results and structure shapes among proposed C-PCF and prior PCF for ethanol at $\lambda = 1.5$ μm.

PCFs	Sensitivity	Confinement loss [dB/m]	No. of ring in cladding	Structural shape	
				Core	Cladding
Prior PCF [17]	25.01%	3.30×10^{-3}	3	hexagonal (elliptical holes)	hexagonal (elliptical holes)
Proposed C-PCF	29.25%	7.68×10^{-7}	2	array (elliptical holes)	circular (circular holes)

we varied the first ring diameters d_1, the other parameters like diameters of the second and third ring d_2 and d_3 were kept constant. Again when we varied the third ring diameters, the second ring and first ring were kept constant. In this process, we can select the optimum results like higher sensitivity and lower confinement loss and optimized the geometrical parameters d_1, d_2, and d_3.

The Table shows a comparative analysis of both optical properties and geometrical structure between the proposed C-PCF and prior PCF [17]. In the prior PCF three different chemicals have been analyzed (benzene, ethanol and water). For our research, we have compared our results with the values of ethanol of the prior PCF [17]. Our C-PCF shows higher sensitivity and lower confinement loss than the prior PCF.

The fabrication process of any PCF is an important issue. The proposed microstructured core C-PCF seems to be easy to fabricate for its structural simplicity. Due to the advancement of nanotechnology [23, 24], the fabrication of even more complex PCF structures is possible.

5. Future work

This proposed C-PCF may be difficult to fabricate. The holes of cladding are of different diameters. The core is formulated with elliptical holes. Proposed C-PCF can be fabricated by a sol-gel technique which enables to fabricate PCFs with different diameters of holes [24]. The fabrication of the elliptical hole based PCF is possible now-a-days [25]. Our proposed C-PCF is a dual shape mixing PCF (core is formed with an array of elliptical holes and cladding is circular). This kind of dual shape mixing PCF can be fabricated by the method proposed in [26]. To fill the core with the chemical is a great challenge. In [23] it is shown that the core can be filled with analytes for sensing application. By this mean, we greatly believe that our proposed C-PCF can be fabricated for sensing purposes without major difficulties.

6. Conclusion

We have designed a lattice of microstructured PCF with effective elliptical holes in the core region for chemical sensing applications. Simulation results show that the sensitivity of the proposed C-PCF significantly enhances, as compared to [17]. In this work, the sensitivity, confinement loss, and the effective refractive index were measured for ethanol sensing. It is expected that the proposed C-PCF will be able to sense all kinds of lower indexed chemicals. The proposed C-PCF can be a great potential in chemical and biological sensing.

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