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Design and numerical analysis of microstructured-core octagonal photonic crystal fiber for sensing applications

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ABSTRACT

This paper presents an octagonal photonic crystal fiber (O-PCF) for liquid sensing, in which both core and cladding are microstructured. Some propagation characteristics of proposed structure have been investigated by using the full vectorial finite element method (FEM). Confinement loss and sensitivity are examined and compared with varying number of rings, core diameter, diameter of air holes in cladding ring and pitch. It is found that sensitivity is increased for the increment pitch value, air filling ratio, core diameter, inner ring diameter as well as number of rings. At the same time confinement loss is significantly decreased. It is also found that the increment of pitch by keeping the same air filling ratio increases the sensitivity and loss. Investigating the effects of different parameters, an O-PCF structure is designed which has a significantly higher relative sensitivity and lower confinement loss.

1. Introduction

Larger application areas of Photonic Crystal Fiber (PCF) technologies have attracted much attention in recent years. PCFs have started a new era overcoming many limitations of conventional optical fiber. In the history of optical technology, PCFs have added new epoch through designing freedom [1]. For enormous optical applications, PCFs have been appointed as one of the most fascinating structures [2–3]. Fibers can be categorized in two parts according to guiding mechanism of light. One is effective index guidance PCF that is solid cored and in the cladding area air holes are randomly or periodically [4–5] arranged. In index guiding PCFs air holes at cladding area have a lower effective refractive index compare to a solid core. Another one is photonic-band-gap (PBG) guidance PCF that is capable to control the light guidance for any frequency band. Here light confinement has occurred in the lower indexes core region compare to cladding. A sophisticated device that converts the light rays into electrical signals which can detect the change and response of ambient condition or can measure the intensity of electromagnetic waves called an optical sensor.

PCF technology allows for the accurate tuning of the propagation properties of fiber through changing of air hole shape, size and their positions. Various guiding properties of PCF can be achieved by changing geometry parameters [6]. At PCF, sensing is the interaction between passing light and analyte which are alterable by varying the frequency, intensity, wavelength, phase and polarization state of light etc. [7]. In this respect, PCFs can be designed for sensing applications in environment, biomedical and industry sectors. Better guiding properties have already been achieved by applying different geometric shape lattice structures such as Hexagonal [8], Octagonal [9], Decagonal [10], Elliptical [11] and Circular honey comb cladding [12]. A photonic crystal fiber demonstrates its potentiality for sensing applications due to its unique geometrical structure.

The evanescent wave based PCF sensors are increasing rapidly in chemical and biomedical applications for their attractive features. Besides sensing applications, PCFs are also designed for their extraordinary performance in dispersion [1], birefringence [13], guiding of light in air [14], and nonlinear effect enhancement [15,16] compare to conventional fibers. Higher sensitivity and smaller size have mainly increased the popularity of PCF sensors. However, hollow core PBG PCFs with low relative refractive index gas or chemical at the core region [17–18], are desirable in sensing [17–19]. But the complexity of the manufacturing process is responsible for decrement of PBG PCF applications and increment of index guiding PCF applications in sensing. The evanescent field of PCFs is commonly involved in gas sensing with different index materials [20–24], chemical and bio sensing [25–26]. On the other hand, they are also used as bacteria and remote sensors.

Sensitivity and confinement loss are two key guiding properties of PCF chemical sensors. Several papers have been published to gain sensitivity at a maximum and confinement loss at a minimum satisfactory level in chemical or gas sensing applications. 13.23% sensitivity has been gained by increasing inner ring air hole diameter and also reduced confinement loss to 3.77×10^{-6} dB/m at $\lambda = 1.33$ μm [27]. But M. Morshed et al. [28] improved sensitivity 13.94% compared to [29]. After that, they also gained sensitivity 20.10% for simple PCF structure

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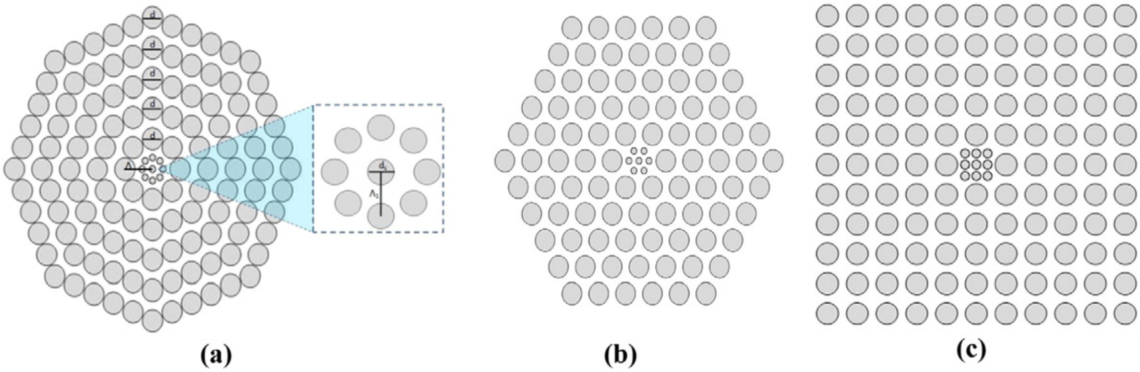

Fig. 1. Designing views of different PCFs geometrical formation (a) O-PCF (b) H-PCF and (c) S-PCF with structural parameters: diameter of air holes in core (d_c), Pitch in core (^$_1$), diameter of air holes in cladding (d) and Pitch in cladding (^).

and proved the benefits of modified PCF structure [30]. An index guiding nanostructure PCF has been proposed by S. Olyaee et al. [31] and achieved lower dispersion, confinement loss and nonlinear effect simultaneously. The article [32] improved sensing capacity by developing a new concept for evanescent sensing application in which both core and cladding are microstructured. The article [33] presented that Octagonal PCF shows smaller loss and the higher relative sensitivity coefficient compared with the Hexagonal PCF structure, in which both core and cladding are microstructured and also improved sensitivity by 47% compared to [32] for three analytes like Water, Ethanol and Benzyne. In this paper, it is proposed that an O-PCF structure with high relative sensitivity and low confinement loss compare to [33] as well as two other structures like H-PCF, S-PCF and investigated the effects of different parameter variations on propagation properties over a wide wavelength range.

2. Geometries of proposed O-PCF

The cross sectional views of the proposed O-PCF, S-PCF and H-PCF have been shown in Fig. 1. The figure clearly depicts the whole geometrical structure of the PCF. The proposed structures of the PCF are in square, hexagonal and octagonal shapes. So the vertices of the adjoining air holes contain 45° and 60° angles to form octagonal and hexagonal structures respectively. The hole to hole space (pitch) in cladding has been denoted by Λ for all types of fibers and operations. The diameters of air holes in each ring of cladding are denoted by d. Pure silica has been utilized as the background material for all types of fibers and refractive index is selected using Sellmeier equation [34]. The microstructure core of O-PCF and S-PCF contains 8 holes and H-PCF contains 6 holes. In addition, all fibers have a center air hole. In perspective to all shaping fibers, the diameter of the supplementary air holes in the core region is d_c and the pitch among the supplementary air holes at the core is Λ_1. Various analytes with refractive index like Water (n = 1.33), Ethanol (n = 1.354) and Benzyne (n = 1.366) [35] are filled in the supplementary air holes in the core region. Modal intensity distribution of proposed O-PCF, H-PCF and S-PCF has been shown in Fig. 2 respectively.

3. Synopsis of numerical method

For electromagnetic simulation, the Finite Element Method (FEM) has been utilized for the proposed PCF. Using the Finite Element Method (FEM) two key properties such as sensitivity and confinement loss have been investigated.

The guided light penetrates into the cladding region from the core due to finite number of air holes and it is known as confinement loss. The confinement loss L_c can be calculated through the imaginary part of the refractive index n_{eff} [36]:

$$L_c = \frac{40\pi.\mathrm{IM}[n_{eff}] \times 10^6}{\lambda.\ \ln(10)} (\mathrm{dB/m}) \tag{1}$$

where, Im $[n_{eff}]$ is known as the imaginary part of the refractive index and λ is the wavelength of light. The interaction between light and the analyte can be measured by the relative sensitivity coefficient and it can be obtained through the following equation [28]:

$$r = \frac{n_r}{n_{eff}} f \tag{2}$$

where, the refractive index of sensed material within the air holes is represented by n_r and the modal effective index is n_{eff}. The ratio of air hole power and the total power percentage can be calculated through

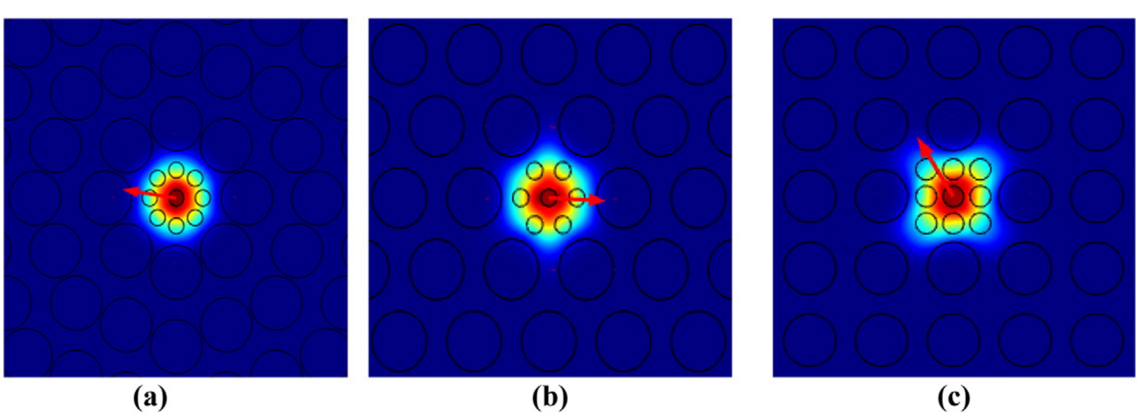

Fig. 2. Modal intensity distribution of proposed (a) O-PCF, (b) H-PCF and (c) S-PCF for ^ = 2.4 μm, d = 1.75 μm, ^$_1$ = 0.9 μm, d_c = 0.63 μm, and n = 1.33 at the wavelength of 1.33 μm.