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A new structure of photonic crystal fiber with high sensitivity, high nonlinearity, high birefringence and low confinement loss for liquid analyte sensing applications

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ABSTRACT

This paper proposes the design and optimization of microstructure optical fiber for liquid sensing applications. A number of propagation characteristics have been compared between two formations of hexagonal cladding of our proposed PCF structure. The core of the proposed PCF structure is designed with two rows of supplementary elliptical air holes. We investigate the performance of the designed PCFs for Ethanol as a liquid sample to be sensed. Numerical analysis is carried out by employing the full vectorial Finite Element Method (FEM) to examine the modal birefringence, confinement loss, relative sensitivity and nonlinear coefficient of the proposed PCF structure.

1. Introduction

Photonic Crystal Fiber (PCF) is a new class of optical waveguides has received a tremendous attention since the last decade [1]. PCF offers remarkable characteristics such as design flexibility, geometric versatility and exceptional guiding mechanism which tend to better performance compared to conventional optical fiber [2]. Due to having the well-known optical guiding properties such as high birefringence, low confinement loss, high nonlinearity, the endlessly single mode, flexible chromatic dispersion, large effective mode area and a small bending loss PCFs show a great potentiality in developing different optical functional devices [3–10]. However, in recent years, PCFs have been attracted a great deal of attention to the researchers for sensing applications [11].

Conventional optical sensors are commercially available [12], while PCF based sensors are still in development stage [11]. However, researchers are working for interfacing PCF based sensors in industrial safety purposes and environmental monitoring issues. PCF technology allows us to achieve exceptional propagation properties of fiber through changing the air hole shape, size and their position [13]. Various research studies of PCF based sensors have been reported to improve the performance of PCF with better propagation properties by changing different geometric parameters. Hollow-core Photonic Band Gap (PBG) PCFs are convenient for gas sensing applications. In contrast, for the liquid sensing applications, index guided PCFs are suitable. The sensing mechanism of index guided PCF is based on the evanescent interaction between guided electro-magnetic light mode and a sample (liquids or gasses), similar to that in traditional optical fiber sensors [12]. Recently, the concept of filling the PCF holes with different materials (gasses and liquids) opened a route for chemical and biological sensing [14,15]. There are several number of published papers which have investigated and developed the evanescent field sensing approach of PCF. Monro et al. [16] have introduced a PCF structure for evanescent field sensing whereby both core and cladding are microstructured. Cordeiro et al. [17] have demonstrated that the PCF structure in which both core and cladding are microstructured helps to increase electromagnetic power interaction with the sample to be sensed. Using this type of structure, the authors have stated in the articles [18–25] that their proposed PCF structures show higher relative sensitivity with low confinement loss for liquid and gas sensing applications. The authors in [3] have demonstrated that their proposed PCF structure for liquid sensor is simple and cost effective.

In some especial fiber optic sensors maintaining the state of polarization in fiber is crucial. Traditional Single Mode Fibers (SMFs) cannot maintain the polarization state of the electromagnetic field for many reasons, as stated in [26]. However, the polarization condition can be retained through the application of modal birefringence. High birefringent PCFs are highly intensive to temperature, which is an important feature for different sensing applications [11]. The articles [27–29] show that elliptical holes are responsible to achieve birefringence in PCF. The authors of the articles [28,29] demonstrated that their designed PCFs can achieve the birefringence up to the order of 10^{-2}. However, these PCFs show poor light confinement and high propagation loss. To

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overcome the limitations of poor mode of confinement, the article [31] proposed a PCF structure for liquid sensing applications which show good confinement of light. In the research article [30] authors have proposed a nonlinear PCF structure for gas sensing applications which shows high sensitivity with high birefringence, but the nonlinearity of the PCF is comparatively low.

In this study, we have proposed a PCF structure for liquid sensing applications in which both core and cladding are microstructured. The core holes are infiltrated with the targeted liquid. Generally, water or alcohol is treated as primary liquids; the numerical analysis has been done for Ethanol detection. In this PCF cladding air holes are circular and the supplementary core holes are elliptical.

2. Design Principle

In this work, we have proposed and analyzed an index guided PCF structure with hexagonal arrangement of air holes in cladding. From the Fig. 1(a) and (b), we can easily understand the difference between conventional hexagonal cladding and 90^0 rotated hexagonal cladding respectively. In both proposed structures the diameter of each air hole in the cladding is $d = 1.9$ μm. The number of air hole rings in the cladding is set to $N = 4$. One of the special features of the proposed PCF structures is that the core region is designed with vertically arranged supplementary elliptical air holes, which is filled with the targeted sample (Ethanol). The enlarged cross sectional view of the core region is shown in Fig. 1(c). Size of each elliptical air hole on the lattice is $A = 0.47$ μm^2 and their ellipticity constant, $\eta = a/b = 0.6$, where, a and b are half minor axis and half major axis respectively. This arrangement of core results in higher birefringence. In this simulation, the center-to-center spacing (pitch) between two air holes in the cladding is set to $\Lambda = 2.4$ μm. In the core, two different pitches have been taken to design, where, $\Lambda_a = 0.65$ μm and $\Lambda_b = 1.20$ μm are horizontal pitch and vertical pitch respectively. The background material is pure silica and in the calculations, the refractive index of silica is determined by the following Sellmeier equation [32].

$$n(\lambda) = \sqrt{1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}} \quad (1)$$

where, n is the refractive index of silica, λ is the operating wavelength in μm, $B_{(i=1,\ 2,\ 3)}$ and $C_{(i=1,\ 2,\ 3)}$ are Sellmeier coefficients. Perfectly Matched Layer (PML) is used as a boundary condition and the thickness of PML is set to 10% of the radius of the proposed PCF for effective calculation of confinement loss [6].

3. Simulation and principle of operations

In this study, the full vectorial Finite Element Method (FEM) with Perfectly Matched Layer (PML) boundary condition is adopted for the analysis of the structure with a FEM based simulation software COMSOL Multiphysics 4.2. The modal analyses have been performed on the cross section in the x-y plane of the PCF structure as the wave is propagating in the z direction. The radiation through the proposed PCF is guided by the modified total internal reflection. The following equation with a magnetic field formulation can be derived from the Maxwell equations [33].

$$\nabla \times \left(\varepsilon_r^{-1} \nabla \times \vec{H}\right) - K_0^2 \mu_r \vec{H} = 0 \quad (2)$$

where, $\vec{H}$ is the magnetic field, ε_r and μ_r are the relative dielectric permittivity and magnetic permeability respectively. The symbol K_0 is the wave number in vacuum; where $K_0 = 2\pi/\lambda$, λ is the operating wavelength. The magnetic field of the modal solution can be expressed as $\vec{H} = \vec{h}(x, y)\exp(-j\beta z)$; where, $\vec{h}(x, y)$ is the field distribution on the transverse plane. The propagation constant β is represented as $\beta = n_{eff}K_0$. After obtaining the complex modal effective index (n_{eff}), the modal birefringence can be determined by the following equation.

$$B \equiv \left| n_{eff}^x - n_{eff}^y \right| \quad (3)$$

where, n_{eff}^x and n_{eff}^y are the effective refractive indices of the x and y polarized fundamental mode respectively. The finite air holes in the cladding part cause the leakage of light from core to exterior part which results in confinement losses. The confinement loss can be calculated from the imaginary part of the complex effective index n_{eff}^i, using the following equation [1].

$$L_c = \frac{40\pi . \mathrm{Im}\left[n_{eff}^i\right] \times 10^6}{\lambda . \ln(10)} \mathrm{dB/m} (i = x, y) \quad (4)$$

However, by using an infinite number of air holes the leakage of light can be omitted. But in practical the number of air holes is finite. The evanescent field interaction between light and the targeted sample can be measured by the relative sensitivity coefficient. According to the Beer-Lambert law, light is attenuated by the intensity of the evanescent wave absorption [34].

$$I(\lambda) = I_0(\lambda)\exp[-r\alpha_m lc] \quad (5)$$

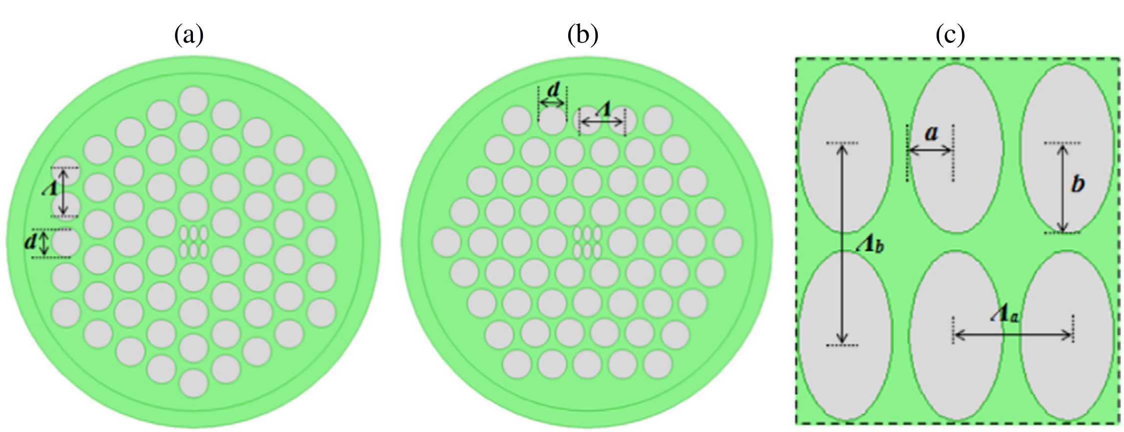

Fig. 1. Cross section of the proposed designs: (a) PCF_1: conventional hexagonal cladding (b) PCF_2: rotated hexagonal cladding (c) enlarged view of the core region.