Alcohol Sensing Over O+E+S+C+L+U Transmission Band Based on Porous Cored Octagonal Photonic Crystal Fiber

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Abstract: A micro structure porous cored octagonal photonic crystal fiber (P-OPCF) has been proposed to sense aqueous analysts (alcohol series) over a wavelength range of 0.80 μm to 2.0 μm. By implementing a full vectorial finite element method (FEM), the numerical simulation on the proposed O-PCF has been analyzed. Numerical investigation shows that high sensitivity can be gained by changing the structural parameters. The obtained result shows the sensitivities of 66.78%, 67.66%, 68.34%, 68.72%, and 69.09%, and the confinement losses of 2.42×10⁻¹⁰ dB/m, 3.28×10⁻¹¹ dB/m, 1.21×10⁻⁶ dB/m, 4.79×10⁻¹⁰ dB/m, and 4.99×10⁻⁹ dB/m at the 1.33 μm wavelength for methanol, ethanol, propanol, butanol, and pentanol, respectively can satisfy the condition of much legibility to install an optical system. The effects of the varying core and cladding diameters, pitch distance, operating wavelength, and effective refractive index are also reported here. It reflects that a significant sensitivity and low confinement loss can be achieved by the proposed P-OPCF. The proposed P-OPCF also covers the wavelength band (O+E+S+C+L+U). The investigation also exhibits that the sensitivity increases when the wavelength increases like SO-band<SΕ-band <SS-band <SC-band <SL-band <SU-band. This research observation has much pellucidity which has remarkable impact on the field of optical fiber sensor.

Keywords: Porous cored OPCF; alcohol sensor; sensitivity; confinement loss; transmission band

1. Introduction

A massive technological change emerges through the innovative invention of researchers. As an optical medium, photonic crystal has some identical properties [1‒11]. The photonic crystal fibers are enormously used in the optical fiber technology due to its idiosyncratic properties. In 1996, Knight et al. firstly proposed the photonic crystal fiber for its novel competence [11]. The photonic crystal fiber is a fiber in which artificial frequent capillaries occur. Optical characteristics are mainly controlled by the number and size or magnitude of microstructure capillaries of air holes [12] and various structural diversities. Photonic crystal fibers (PCF) are becoming more and more
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popular for its better guiding properties, robustness, and flexibility.

Some identical properties are seen like as nonlinearity [1, 2], high birefringence [3, 4], high sensitivity [5, 6], low confinement loss [7, 8], improved effective area, and endlessly single mode [9–11]. For these reasons, PCF has drawn a great attraction among researchers. At the beginning time, PCF has limited applications areas. Now PCF is used in fields of THz telecommunications [13], nonlinear optics [14], bio sensing [15], chemical sensing [16, 17], spectroscopy [18], optical chromatography [19], and fuel adulteration detection [20]. In medical science, it is becoming more and more popular for bio-photonics [21] and neuro-photonics [22]. It is also used in the fields of cancer cell detection, HIV viral load detection [23], protein detection [24], diabetes detection [25], etc. Different types of PCF are used for numerous applications for their superb guiding capability.

As a novel method, optical indexed guiding PCF is well rebounded [26]. Depending on the light guiding mechanism process, a crystal fiber PCF can be categorized into two classes. One is the photonic band gap fiber which uses the photonic band gap (PBG) effect for guiding light through that fiber thus it is called PBG-PCF. The other one uses common optical properties total internal reflection (TIR) thus it is called TIR-PCF. PCFs are formed by the crystal which is made of silica glass. The main reason for choosing silica glass as a background material is its paramount property which provides momentous amenities. Recently, graphene [27], chalconide glass with polymer [28], telluride, and topus [29] are also used to fabricate PCF.

The first proposal of PCF came from Yeh et al. in 1978 [30]. But a photonic crystal fiber was designed using two-dimensional (2D) photonic crystals by Russel [31]. This fiber consisted of single air core, which was reported in Optical Fiber Conference at San Jose, CA in 1996 [32]. As a consequence in 1997, endlessly single mode fiber was invented. Highly birefringent PCF (HB-PCF) opened a new horizon in 2000. Later Bragg fiber, PCF laser, and PCF with ultra-flatted dispersion were invented. Recently, gas and liquid filled PCF created a new diversity in different application areas.

In 2014, Ademgil proposed an octagonal PCF sensor for chemical sensing [26]. At operating the 1.00 μm wavelength, it shows approximately 47 % sensitivity for aqueous analytes. In 2015, Ahmed et al. designed an O-PCF which gives the indication of relatively high sensitivity [33].

In this paper, we propound a design and numerical analysis of microstructure circular porous core PCF with high sensitivity and low confinement for chemical sensing applications covering the O+S+C+L+U wavelength band. A five-layer octagonal air hole lattice array which acts as a cladding encompasses the core region. For electromagnetic computation, an anisotropic perfectly match layer (PML) plays a vital role in sensing performance. PML is also used in the proposed PCF to attenuate unwanted reflection of light wave [33]. Here PML acts as an absorbing layer. Variations of geometrical properties (parameters) are also examined to analyze the effects of guiding properties on P-OPCF.

2. Geometries of the proposed PCF

The transverse cross sectional view of the proposed P-OPCF is shown in Fig. 1(a). There are five rings in the designed structure in the cladding part, and each ring gives a view of an octagonal that’s why it can be called as OPCF. For the first ring (the first layer) of the cladding, it contains 8 air holes. The number of air holes gets increased geometrically where the nearest next level number ring has 8 air holes more than the previous level of the ring. For the five rings, it can be represented as $8n$ where $n$ is the number of levels, and the first ring is $n=1$ and will increase by 1 for each level until it touches the ring number five where total number of air hole is $8n=8\times5=40$. Each air hole has the same
diameter where $d=1.75$ $\mu$m. The distance between two adjacent air holes of two conjugative rings is called pitch and denoted by $A_1$.

![Transverse cross-sectional view of the proposed P-OPCF](image)

The pivotal part of the proposed PCF contains a small area with two circular rings in porous shape which is known as core. Six holes filled with aqueous analysts are required to design the inner circle of the core where the outer circle has twelve holes filled. The core diameter $d_c$ processes a very small area where $d_c=0.57$ $\mu$m and each hole is filled with aqueous analysts that has the same diameter. The pitch of the core ($A_1$) is equal to $A_1=0.61$ $\mu$m, and the two adjacent air holes are filled with aqueous analysts both in the same circle and between two circles. For two-layer circular porous core, the first layer has 6 holes in total which makes an angle of $60^\circ$, and the second layer has 12 holes which makes an angle of $30^\circ$. According to the sequence for three layers having 6, 12, and 18 holes, they make angles of $60^\circ$, $30^\circ$, and $20^\circ$, respectively. The four-layer porous core makes angles of $60^\circ$, $30^\circ$, $20^\circ$, and $15^\circ$ for consequence layers, respectively.

The core cladding geometric structure is surrounded by anisotropic PML. Hence, we use a 10% of the PML size additive with an overall cladding size. The key component of the back ground, core, and cladding is pure silica where Sellmeier equation [35] is followed to determine the refractive index for the defined wavelength range.

3. Numerical analysis

A finite element method (FEM) is used to simulate our proposed photonic crystal fiber. The FEM sub-divides a larger complicated design into a smaller and simpler one which produces a more approximate solution. To design the issue of a PCF sensor, two fundamental parameters are directly associated.

The background material of the proposed P-OPCF is silica. As for the theoretical and experimental aspects, the refractive index (RI) is varying with wavelength $\lambda$ for different materials. There is a relationship between the wavelength and RI of different transparent materials and liquids. Based on the relationship, an equation is derived which is highly used to determine RI of different crystals and liquids. This relationship was first found by Willhem Sellmeier in 1871. The equation is as follows:

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

where $n$ and $\lambda$ represent the refractive index and wavelength, respectively, and $B_1$, $B_2$, $B_3$, $C_1$, $C_2$, and $C_3$ are the coefficients of silica.

The effective refractive index can be calculated by

$$n_{\text{eff}} = \frac{n_r}{k_0} \quad (2)$$

where $B$ is the propagation constant, and $k_0 = 2\pi/\lambda$ is the free space wave number.

The sensitivity can be calculated by (3) which was reported in [33]:

$$r = \frac{n_r}{n_{\text{eff}}} f \quad (3)$$

where $n_r$ is the RI of using materials within the air holes, and $n_{\text{eff}}$ is the modal effective index. Here, $f$ represents the percentage ratio between air hole power and total power which can be calculated by

$$f = \left( \frac{\int_{\text{sample}} \text{Re}(E_x H_y - E_y H_x) \, dx \, dy}{\int_{\text{total}} \text{Re}(E_x H_y - E_y H_x) \, dx \, dy} \right) \times 100 \quad (4)$$
where $E_x$ and $E_y$ are transverse and longitudinal electric fields, respectively, and $H_x$ and $H_y$ are transverse and longitudinal magnetic fields, respectively.

Light in the PCF should be confined into the core region. Due to the material impurity or structure combined, some light passes the outer of the core region, and the losses of light energy are treated as confinement losses or leakage losses. The loss can be calculated by using

$$L_v = 8.68\kappa_0 \text{Im}[n_{\text{eff}}]$$  (5)

where $\text{Im}[n_{\text{eff}}]$ is the imaginary part of the effective refractive index. Using the discussed equation above and FEM, a numerical result analysis is attained.

4. Result analysis

To construct a prognostic computational model for real world continuity numerous software use FEM. The accuracy of the computational model is directly involved with a numerical analysis. Different well-known numerical methods such as FEM, boundary element method (BEM), finite difference method (FDM), finite volume method (FVM), and mesh-less method (MLM) are used in the numerical computation. Among these numerical methods, FEM provides the most accurate computation. Along with FEM, the finer mesh analysis is used to gain more accurate solutions. By using the finer mesh analysis, we get $42,294$ elements (DOF degree of Freedom). COMSOL Multiphysics 4.2 has been used to investigate for the mesh and numerical analysis. According to the simulation result, Fig. 2 shows wavelength verses effective RI of our proposed optimized P-OPCF. It shows that the curves go downward due to an increase in the wavelength. This means that if we decrease the wavelength we get much higher effective RI and vice versa. This figure also represents the confinement of more light due to $X$-polarization and $Y$-Polarization at wavelength $1.33 \, \mu\text{m}$ for ethanol ($n = 1.354$).

4. Result analysis

Our desired goal is to getting much sensitivity and lower confinement loss, so we have investigated the core region by setting two, three, and four layers. Figure 3 shows the relative sensitivity verses wavelength for two-, three-, and four-layer porous core PCFs where two-layer core PCF is shown too much higher relative sensitivity than others. In addition, the confinement loss of $3.28 \times 10^{-11}$ dB/m, $1.32 \times 10^{-10}$ dB/m, and $6.96 \times 10^{-11}$ dB/m for two, three, and four layers core respectively at the $1.33 \, \mu\text{m}$ wavelength for ethanol. Here the relative sensitivity of two-layer core is superior to others three- and four-layer core. Based on the above argument, we choose two-layer porous core O-PCF for the further investigation.
A fundamental factor confinement loss (CL) is a vital issue which should be remembered in mind at the fabrication time of PCF. To reduce the confinement loss of micro-structured P-OPCF is always desirable. For the confinement loss, some light energy encroaches into cladding area which must cause the main hindrance to the flow of informative light energy. Relative sensitivities of methanol, ethanol, propanol, butanol, and pentanol are 66.78%, 67.66%, 68.34%, 68.72%, and 69.09 %, respectively at the 1.33 µm operating wavelength. Figure 4 depicts the relative sensitivity performance for alcohol analytes as methanol< ethanol< propanol< butanol< pentanol, respectively. It also exhibits that the sensitivity goes upward with an increase in the wavelength. Figure 5 shows the confinement losses for aqueous analysts of alcohol series methanol, ethanol, propanol, butanol, and pentanol, which are 2.42×10^{-10} dB/m, 3.28×10^{-11} dB/m, 1.21×10^{-6} dB/m, 4.79×10^{-10} dB/m, and 4.99×10^{-9} dB/m, respectively at the same wavelength. Diameter/pitch (d/λ), known as the air filling ratio, is tuned by modifying the core hole diameter and core pitch distance. Figure 6 shows that relative sensitivity curves are upward where in core region air filling ratio is high. So the air filling ratio has strong positive bonding with the relative sensitivity. We have investigated the relative sensitivity and confinement loss by varying the cladding air holes diameter which is shown in Figs. 7 and 8, respectively. It recounts comparatively higher sensitivity at d/λ=0.931 and relatively lower sensitivity at d/λ= 0.808 over the wavelength range 0.2 µm to 2.0 µm. To avoid fabrication tolerance, d/λ= 0.931 is selected because that the maximum air filling ratio 0.94 is considerable for fabrication without any collapse [36].
occur. For this unexpected error, we have changed different parameters of the proposed P-OPCF. At the time of fabrication, by using the standard draw there may occur ±1% variations on their overall parameters of PCF [38]. For this reason, we inspect the behaviors of the proposed P-OPCF by tuning the structural parameters in range from –2% to +2%.

![Graph](image1)

**Fig. 7** Comparison of relative sensitivity with cladding air filling ratio \(d/\Lambda_1\) variations for \(n = 1.354\).

![Graph](image2)

**Fig. 8** Comparison of confinement loss with cladding air filling ratio \(d/\Lambda_1\) variations for \(n = 1.354\).

Figure 9 shows the inspection of wavelength verses the relative sensitivity, making –2%, –1%, +1%, and +2% variations with the optimum parameters. The simulation process goes down for a wider wavelength limit over 0.8 \(\mu\)m to 2.0 \(\mu\)m which does not make a great difference between the proposed P-OPCFs. By changing +2%, +1%, –1%, and –2% of overall parameters, the relative sensitivity as well as confinement loss is not affected greatly.

![Graph](image3)

**Fig. 9** Comparison of relative sensitivity with optimum structural parameters variations for \(n = 1.354\).

On the other hand, we have examined that wavelength \(\lambda\) verses relative sensitivity increases in the wide range of wavelength and vice versa, which is more convenience for the fiber sensor fabrication. The main obstruction is to fabricate such a complex photonic crystal fiber sensor. But the massive achievement occurs in different technological sectors. By the progression of the technological achievement, numerous fabrication techniques such as stack and draw process [38], extrusion [39], drilling [40], sol gel casting [41], and die cast process [42] have been proposed. The stack and draw process is generally preferable for honey comb and triangular lattices. It has some limitations to construct the circular pattern. Different background materials are recently used to fabricate PCF. Some of these materials are fragile. For material fragility, the drilling technique is not allowed. Extrusion is another well-known fabrication technique for soft glass nevertheless wastage of material. For design flexibility and adaptive large scale manufacturing capability, the sol gel technique helps fabricate different micro-structure PCFs. So with the help of sol gel technique, the proposed P-OPCF can be fabricated easily without any damages.
5. Conclusions

A two-layer microstructure porous cored with octagonal cladding structure inclusion with perfectly match layer (PML) has been simulated using the finite element method. In the field of electromagnetic study, the finite element method has a leading impact on analyzing and calculating the complex geometry. This study of octagonal microstructure two-layer porous core has been proposed in favor of chemical sensing. The relative sensitivity and confinement loss have been analyzed by tuning different geometrical parameters of the proposed P-OPCF structure. The simulation is also employed to calculated sensitivity for two-, three-, and four-layer porous core. It shows that the proposed micro-cored two-layer structures reflect a higher level of sensitivity 67.66 % and a low confinement loss $3.28 \times 10^{-11}$ dB/m at the 1.33 μm for ethanol (RI=1.354). In fiber optics communication, wavelength band O+S+C+L is extensively used. Bearing with the wavelength band, the proposed fiber optic sensor can be applied in the wide range of wavelength (0.80 μm to 2.0 μm). Hence, it is vivid, and we confide that our designed P-OPCF will be very efficient for sensing application in the area of optical systems.

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