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Folded cladding porous shaped photonic crystal fiber with high sensitivity in optical sensing applications: Design and analysis

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ABSTRACT

A micro structure folded cladding porous shaped with circular air hole photonic crystal fiber (FP-PCF) is proposed and numerically investigated in a broader wavelength range from 1.4 μm to 1.64 μm (E+S+C+L+U) for chemical sensing purposes. Employing finite element method (FEM) with anisotropic perfectly matched layer (PML) various properties of the proposed FP-PCF are numerically inquired. Filling the hole of core with aqueous analyte ethanol ($n = 1.354$) and tuning different geometric parameters of the fiber, the sensitivity order of 64.19% and the confinement loss of 2.07×10^{-5} dB/m are attained at 1.48 μm wavelength in S band. The investigated numerical simulation result strongly focuses on sensing purposes; because this fiber attained higher sensitivity with lower confinement loss over the operating wavelength. Measuring time of sensitivity, simultaneously confinement loss also inquired. It reflects that confinement loss is highly dependable on PML depth but not for sensitivity. Beside above properties numerical aperture (NA), nonlinearity, and effective area are also computed. This FP-PCF also performed as sensor for other alcohol series (methanol, propanol, butanol, pentanol). Optimized FP-PCF shows higher sensitivity and low confinement loss carrying high impact in the area of chemical as well as gas sensing purposes. Surely it is clear that install such type of sensor will flourish technology massively.

1. Introduction

Glancing to the scientific research in recent year is associated with optical fiber technology. It is exceedingly growing which dealing with photonic crystal fiber (PCF) sensor. It is vivid that, this research has a great impact to make the technology sustainable. PCF is a type of optical fiber where numerous air holes are arranged in longitudinal direction which arise some identical properties that does not lie in conventional optical fiber. These identical properties including endlessly single mode, high nonlinearity, large effective area, high birefringence and low confinement loss [1–4] are contributing a tremendous support to enriching optical communication as well as optical sensing.

High sensitivity and large effective area are attaining from this proposed structure PCF. High sensitivity is required for sensing application on the other hand; high nonlinearity is the prerequisite for super continuum generation (SC) [2,4–5]. Internet traffic growth rapidly as the users demanding rate as a result requires fiber with larger effective region. In the field of nonlinear fluorescence microscopy, optical metrology, tomography, telecommunications, flow cytometry etc.; SC is well renounced [5–9]. PCF has miscellaneous applications like optical sensing [2,4], optical amplification [10], and optical switching [11]. In the area of sensing using PCF are wider to wider. Recently it has been used as temperature sensor [11], pressure sensor [12], humidity sensor [13], bio-sensor [14] and more and more. Protein detection, diabetic's detection, virus detection, and cancer cell detection are highly notable in the medical as well as clinical and diagnosis area [15–17]. Progression of neuro-photonics added a new dimension in neuroscience [18]. These applications are varied based on hosting material, geometric diversity and light propagating mechanism.

The hosting material of the proposed microstructure circular folding PCF is pure silica. There is also a non silica fiber, such as telluride, graphene, chalcogenide glass optical fiber for their diversified applications [19,20]. PCF uses two mechanisms to propagate light based on the microstructure core and cladding types. These mechanisms are total internal reflection (TIR) and photonic band gap (PBG) effects. Total internal reflection is occurred when cladding region effective refractive index is comparatively less than the core of the fiber means $n_{eff(cladding)} < n_{eff(core)}$. On the other hand from the viewpoint of the brag fiber; it uses photonic bandgap effect mechanism for transmission the light through the fiber core [2]. The above properties are producing novel characteristics of a fiber.

The novel properties of photonic crystal P. Russel [21] invented PCF with air core for the first time. The structural shape was hexagonal. After that relentless research of researchers and technological revolution different designed structural PCF are found among them circular, elliptical,

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spiral, square, pentagonal, hexagonal, octagonal, decagonal [2,4,22–24] are popular most. Recently many design schemes , including symmetric or asymmetric structure have been proposed to attain high sensitivity, low confinement loss, large effective area, etc. [4]. As a consequence of developing the sensitivity purposes applications numerous PCF shape are found. In the year 2014, H. Ademgil [25] reported that a porous core hexagonal PCF attains the sensitivity response about 16% at the applied wavelength 1.55 μm. Looking forward to year 2015 S. Asaduzzaman et al. [26] proposed PCF performing chemical sensing capability approximately 35% at $\lambda = 1.55$ μm. In recent year 2016 S. Asaduzzaman et al. [27] proposed a hybrid structure PCF for sensing purposes and get sensitivity about 48% for ethanol at the wavelength 1.55 μm.

In this paper, we have an intense focus on a microstructure porous shaped folded cladding based PCF for sensing application. Successfully completing finer mesh analysis FEM has used to simulate this FP-PCF. Unwanted boundary reflection of electromagnetic (EM) wave is suppressed by the PML. The numerical simulation is done after completing the finer mesh analysis which provided much accuracy to gain approximate result. Other crucial properties like nonlinearity and effective area are also investigated. The investigation processes are run over the pumping wavelength band E + S + C + L + U. In the field of optical fiber communication these band are highly uses. Simulation result shows high sensitivity of 64.19% at the pumping wavelength 1.55 μm which lies in the range of S band. Beside this confinement loss, effective area and nonlinearity are also calculated. Higher nonlinearity is acquired at the wavelength 1.64 μm. Numerical results clearly supported that this PCF will be very effective in the area of sensing as well as communication.

2. Design of the proposed FP-PCF

Fig. 1 shows the end-faced of proposed FP-PCF. It is a PCF with microstructure porous shaped infiltrated with aqueous analysts ethanol ($n = 1.354$). Circular five layer air hole surrounded by the core acts as cladding region. The core region exists two layers microstructure holes where the radius of the core is homogenous. The core holes radius are $r_c = 0.18n$ μm. The hole to hole distance is called pitch and denoted by Λ. For the core the pitch is denoted by $\Lambda_c = 0.4n$ μm. For the cladding region five layers are hole diameter are $d_3 = 1.48n$ μm, $d_2 = d_4 = 1.05d_3$ μm, $d_1 = d_5 = 1.10d_3$ μm and pitch distance are $\Lambda_1 = 1.81n$ μm, $\Lambda_2 = \Lambda_3 = \Lambda_4 = \Lambda_5 = 0.98\Lambda_1$ μm. As the cladding region much air holes are existed and the core is infiltrated with chemical so the refractive index of core is greater than cladding region. As a result, the light propagating mechanism of this FP-PCF is TIR. The host material of the proposed PCF is silica which is highly uses to manufacture the optical fiber. Anisotropic perfectly matched layers are used to reduce undesirable electromagnetic reflection acting as absorbing boundary condition. The depth of PML boundary is 10% of the total cladding. Among various photonic crystal fibers manufacturing technique sol-gel technique is most suitable to make the fiber successfully. The numerical investigation is run over the parameter and shown details in below.

3. Numerical analysis

In this paper, different crucial parameters of PCF like sensitivity, confinement loss, effective area, and nonlinearity are investigated. The whole investigation process has done by the commercial software COMSOL Multiphysics version 4.2. The simulation process background framework is FEM which lies inside COMSOL.

The host material of the proposed PCF is pure silica. Silica has a refractive index dependency on wavelength followed by Sellmeier Eq. [5].

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

where $B_1 = 0.6961663$, $B_2 = 0.4079426$, $B_3 = 0.8974794$, $C_1 = 0.0684043$, $C_2 = 0.1162414$, C3 = 98.96161 and n (λ) is the refractive index for corresponding operating wavelength λ in μm.

A most powerful numerical simulation tool is full vectorial finite element method. This method has the greater efficiency for any kind of complex geometry structure to calculate. Various photonic waveguide devices are numerically analyzed by FEM [28,29]. FEM processes

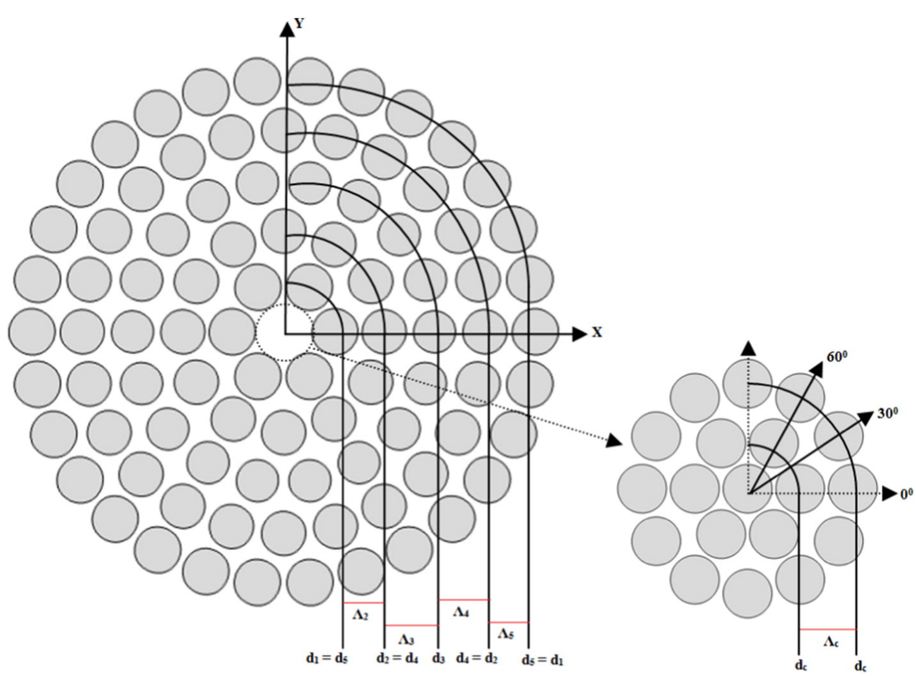

Fig. 1. Schematic of end-faced of proposed F-PCF.