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Design and numerical analysis: Effect of core and cladding area on hybrid hexagonal microstructure optical fiber in environment pollution sensing applications

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Abstract

This paper presents a micro-cored Hybrid Hexagonal shape photonic crystal fiber (PCF) for the higher sensitivity response in a wide range of wavelengths ranging from 1400 to 1640 nm. Numerical investigation is carried out by applying the full vectorial finite elements method (FV-FEM) with perfectly matched layer (PML) as an absorbing boundary condition regime. The proposed structure is suitable for highly sensible of standard multi-mode fiber (MMF) over E + S + C + L + U communication bands. Rigorous computational results are strongly evident that the proposed PCF acquires the highest relative sensitivity of about 62.24% at the controlling wavelength $\lambda = 1.40$ μm which will be applicable for monitoring environment in aspects of harmful and toxic chemical sensing. The proposed H-HPCF structure can be fabricated using a sol−gel technique method and is expected to be useful for wideband imaging and communicating applications too.

Keywords: Chemical sensor; Effective area; Environment monitoring; Finite element method (FEM); Multi-mode PCF

1. Introduction

In recent years, the research in Photonic Crystal Fibers (PCFs) field is one of the most acute and impetuous in the photonic spheres. Many remarkable properties of optical fibers with a high-index core region and surrounding silica or air photonic crystal cladding have been recently indicated. The geometrical structure of photonic crystal fibers and identical guiding properties has mentioned the potentiality to use in sensing applications. Optical fiber sensing has produced to the point that several types of physical parameters can be surveyed [1−3]. Photonic crystal fibers have been used for various purposes like chemical sensor, gas sensor, temperature sensor, pressure sensor and humidity sensor. These types of PCF

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sensors are carrying an important role in many commercial applications. PCF or microstructure optical fiber contains a microscopic array of air channels that run through the whole fiber and formulates a lower index cladding on a silica background [2,3]. PCFs are now not limited in silica as a background material or hosting material, many different materials like as Topas, Graphane, and Tellurite are used as background material to fabricate PCF reported in the research articles [4,5]. According to the light guiding properties, PCF can be divided into two categories. First one is photonic bandgap fiber (PBG) where the light is guided by photonic bandgap principle and another one is index guiding (IG) PCF where light can be conducted through the low index core by photonic crystal reflection cladding [6]. Both mechanisms offer an important platform in chemical and biological sensing [2,7]. PCF sensors have many advantages like high sensitivity, high safety and low cost than the electric sensor. Sensitivity of any sensor can be defined as the change of investigated output of the sensor per unit of observed parameter variation. But the sensor has a detection limit. The detection limit (LOD) of sensor depends on cross-sectional geometry and size [8]. Besides sensitivity, many different uniform properties like large effective area [9], nonlinearity [10,11], high birefringence [2,6], absolutely single polarization [12], and endlessly single mode [13] are found from PCF.

Varieties of procedures have been raised to improve the efficiency [1] for the sensing capability of index-guiding fibers. In this paper, the proposed PCF is designed by hybrid hexagonal structural manner that is suitable in compensating the higher sensitivity over a wide range of wavelengths from 1400 to 1640 nm. The proposed hybrid hexagonal photonic crystal fiber (H-HPCF) central air hole is surrounded with a high index ethanol because the ethanol is targeted chemical species for this work. It is widely used in the chemical industry perspective and polluted environment when emits as a waste. The proposed PCF also performs the broadband compensation at the E + S + C + L + U communication bands, which results in a development over the design proposed by Habib et al. [14]. The presented results are fundamental in the field of photonic bandgap guidance and create a new category in optical waveguide. Therefore, this is also becoming more interesting to the researchers for the large varieties of research areas. The proposed PCF architecture is more effective for appropriate sensing and optical communication systems. The proposed PCF is also micro structured core. So it will be capable to show high sensitivity compare to hollow core photonic crystal fibers [15]. Here, in this paper, for the first time we have introduced the effects of core and cladding area on optical guiding properties. It is highly comprehensive that the proposed hybrid hexagonal PCF is greatly applicable for monitoring hazardous chemicals found in environments. Chemical sensor based on photonic crystal fiber plays a vital role in environment monitoring [16]. So, such type of fiber will provide potential contribution in sensing applications.

2. Design approach of the proposed PCF

Fig. 1 depicts the transverse cross-sectional view of proposed chemical sensor based on hybrid hexagonal PCF that is holding six air-hole rings in the cladding area. The cladding area is constructed in combination with the circular and elliptical air holes. The background material of the proposed hybrid hexagonal PCF is pure silica with circular and elliptical air-holes. Silica is preferred here as a hosting material for its optical novelty and availability [1–3]. The cladding region of dielectric medium air-holes diameter of 1st, 2nd, 3rd, 5th and 6th rings are d_1, d_2, d_3, d_5 and d_6 respectively. Here, d_s and d_f are the minor axis and major axis lengths of the elliptical air-holes respectively. The elliptical air-holes ellipticity is represented by the ratio, $\eta = d_s/d_f$. The first, second, third, fifth and sixth rings was manufactured with 6, 12, 18, 30 and 36 circular air holes of the diameter $d_1 = d_2 = d_3 = d_5 = d_6 = 2.15$ μm. The distance between air-holes on the adjacent ring is defined as a pitch (Λ). Pitches in the cladding area are denoted by $\Lambda_1 = \Lambda_2 = \Lambda_3 = \Lambda_5 = \Lambda_6 = 2.60$ μm. Forth layer of the cladding is manufactured by 24 elliptical air holes, whose major axis and minor axis are 0.90 μm and 0.45 μm respectively with ellipticity $\eta = 0.50$.

The core is formed by the some tiny circular holes which have been arranged in porous form of the proposed Hybrid hexagonal PCF. Fig. 1(b) shows the geometrical view of holes in the core region. The diameter of each hole in core region is defined as $d_c = 0.55$ μm. The proposed PCF core contains two circular air hole rings which have created with 6 and 12 air holes respectively. To attain such type of architecture at core area holes are arrayed at an angle 60° for the 1st ring while holes on the 2nd rings are rotated at an angle of 30°. The refractive indices of the air hole and fiber silica are $n_a = 1$ and $n_s = 1.45$ respectively. Fig. 2 shows the mode profile of the *x*- and *y*-polarized mode for operating wavelength $\lambda = 1.55$ μm. The sensitivity characteristics have investigated filling ethanol ($n = 1.354$) at these circular holes in the core region.

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