Sensing and Bio-Sensing Research 13 (2017) 55–62

Contents lists available at ScienceDirect

Sensing and Bio-Sensing Research

journal homepage: www.elsevier.com/locate/sbsr

Design of single mode spiral photonic crystal fiber for gas sensing applications

Md. Ibadul Islam [a], Kawsar Ahmed [a], Sayed Asaduzzaman [a,b], Bikash Kumar Paul [a,*], Touhid Bhuiyan [b], Shuvo Sen [a], Md. Shadidul Islam [a], Sawrab Chowdhury [a]

[a] Department of Information and Communication Technology (ICT), Mawlana Bhashani Science and Technology University (MBSTU), Santosh,1902 Tangail, Bangladesh
[b] Department of Software Engineering (SWE), Daffodil International University (DIU), Sukrabad, Dhaka 1207, Bangladesh

ARTICLE INFO

Article history:
Received 24 January 2017
Received in revised form 27 February 2017
Accepted 2 March 2017

Keywords:
Birefringence
Effective area
Gas sensor
Non-linear coefficient
Sensitivity
Spiral photonic crystal fiber

ABSTRACT

In this paper, a spiral shape photonic crystal fiber (S-PCF) has been suggested as a gas sensor for detecting toxic or colorless gases as well as monitoring the air pollution by metering gas condensate elements in production facilities. Our reported S-PCF is micro-structured where two layers porous core is encircled by a spiral shape cladding. The geometrical parameters have altered to optimize the parameters of the proposed structure. The numerical analysis of the proposed S-PCF is performed by utilizing finite element method (FEM). The relative sensitivity and birefringence of the proposed S-PCF are 55.10% and 7.23×10^{-3} respectively at the 1.33 μm wavelength that lies in the absorption line of toxic gases (methane and hydrogen fluoride). Besides, effective area, nonlinear coefficient and V parameters are also described briefly.

1. Introduction

The advancement of telecommunication and non-telecommunication sectors depends on modernizing variant of optical fiber which is renowned as photonic crystal fiber (PCF) [1]. It has guaranteed a revolutionary change in fiber optic communication. Day by day PCFs have become too much admired by researchers and forerunner due to its robustness and flexibility [2]. PCFs are formed by periodically or arbitrary arranged tiny air cavities which pass together with the whole length of fiber [3]. The propagation characteristics of light are separated PCF into two major categories. These are index guiding (IG) and photonic band gap (PBG) photonic crystal fiber [4]. In index guiding (IG) PCF, the optical field can be passed through the fiber core by moderated total internal reflection similarly in conventional optical fibers [5]. In addition, PBG fibers have consisted of large air core and light is confined via photonic band gap mechanism [6]. Narrow transmission spectral band and lack of precise control of waveguide parameters for maintaining the band gap effect are the principle restriction of PBG fiber. An index guided PCF is referred to subdue these limitations [5].

At first, hexagonal PCF structure is concocted by Knight et al. [7]. Nowadays, a lot of designs are possible due to the progress of fabrication technology. The square [8], hexagonal [9], octagonal [10], spiral [11], decagonal [12], circular [13], honeycomb cladding [14] and hybrid [15] modeled PCF is designed for obtain decent guiding properties. Recently, Silica [16], PMMA [17], Teflon [18], Topas [9] and Tellurite [13] are utilized as the background material to improve the performance of photonic crystal fiber. As a result, the promotion of fabrication technology enables PCF to procure of high relative sensitivity [5], low confinement loss [13], high numerical aperture [19], high nonlinearity [10], large mode area [20], highly birefringence [21], low bending loss [17], ultra-low material loss of THz wave guide [22], ultra-flat dispersion [8] and zero-flat dispersion [23] by altering the air hole diameters and pitch. The high power technology [24], medical diagnosis [25], drug testing [26], spectroscopy [27], super continuum generation [28] and sensing application [4] are the PCF based field for its unique attributes. The acceptance of PCF sensors can be raised due to its higher sensitivity and smaller size. PCF sensors are mainly divided into two sections. These are physical and biochemical sensors. The bend sensor, strain sensor, electric and magnetic field sensor, pressures sensor, temperature sensor, torsion/twist sensor, refractive index sensor, vibration sensor are the major types of physical sensor. On the other hand, gas sensor, molecular sensor, Rhoda mine sensor, DNA sensor, protein sensor, humidity and pH sensor and chemical sensor are highly used biochemical sensors [4].

Currently, gas sensors are used to observe the air quality of our environment and discerning of explosive, noxious and hydrocarbon gases [29]. In addition, industrial safety management purpose like oil and gas production systems are also required gas sensors to detect combustible or toxic gases leakage. The hydrogen sulfide (H_2S) and methane

* Corresponding author.
E-mail addresses: kawsar.ict@mbstu.ac.bd (K. Ahmed), bikash.k.paul@ieee.org (B.K. Paul).

http://dx.doi.org/10.1016/j.sbsr.2017.03.001

(CH_4) are the most significant noxious and flammable gases in oil rigs [6]. All existing technique for gas sensing is bulky, expensive and shortage of real-time data measurement. For this reason, the researchers are tried utmost to reduce the limitations of gas sensors.

Plenty of research articles have suggested, improving the efficiency and gas sensing capability of photonic crystal fibers. In the article [6], an evanescent-field gas sensor based PCF was proposed for gas condensate and air pollution monitoring that achieved the relative sensitivity of 13.23% with confinement loss of 3.77×10^{-6} dB/m at the 1.33 μm wavelength. But in 2015, Morshed et al. [30] reported a micro structured GeO_2 doped silica ring PCF and improved the sensitivity of 16.88% as well as reduced confinement loss of 1.765×10^{-8} dB/m at the same wavelength. In the article [31] proposed an index-guiding PCF for gas sensing application and obtained the sensitivity of 32.99% with confinement loss of 2.59×10^{-5} dB/m. By using a microstructure core photonic crystal fiber, Morshed et al. [5] enhanced the sensitivity of 42.27% and diminished confinement loss of 4.78×10^{-6} dB/m. In 2016, Asaduzzaman and Ahmed [32] proposed an E-PCF and procured the high relative sensitivity of 53.07% with birefringence in the order of 6.9×10^{-3} at 1.33 μm wavelength. Hasan et al. [33] suggested a hybrid photonic crystal fiber which revealed highly birefringence as well as high nonlinearity.

Now, in this research work, we have proposed and successfully investigated a simple spiral photonic crystal fiber (S-PCF) where micro structured core region is formed by circular air-hole. The proposed S-PCF provides highly relative sensitivity of 55.10% and ultra-high birefringence of 7.23×10^{-3} at the 1.33 μm wavelength. It (S-PCF) also shows large effective area (11.60 μm^2) which leads to confine more light into core vicinity that causes the high sensitivity coefficient. Moreover, the non-linear coefficient of 12.62 W^{-1} km^{-1} is gained at the same wavelength. The V-parameter represents that the proposed S-PCF acts as a single mode fiber over the entire utilized bands. As a result, the reported fiber is suitable for long distance communication applications.

2. Geometry of the proposed S-PCF

Fig. 1 depicts the cross sectional view of the proposed spiral photonic crystal fiber with the magnification of core region. The proposed PCF contains a cluster of circular air holes in the core region which are formed into a porous shape [5] and cladding is formed with spiral shape which also contains circular air holes. Spiral technique has great made attention due to their excellent modal confinement properties compared to conventional hexagonal PCFs [34]. In article [6], it was represented that the diameters of air holes located at innermost ring are responsible for high sensitivity as well as the diameters of outermost rings are accountable for lower confinement loss. Spiral symmetry consists of ten spiral arms, where each arm consists of nine circular air holes. The center to center distance between the two adjacent holes is called the pitch. The simplicity of the design demonstrated by $r_0 = \Lambda$ where r_0 is a distance of the first air hole in each spiral ring and Λ is the pitch of the lattice. Throughout the investigations, the value of Λ is defined as $0.68 * D_{core}$, where D_{core} is the diameter of core. The air-hole diameter at first two rings is denoted as $d_1 = 0.58 * \Lambda$ and third ring $d_2 = 0.72 * \Lambda$ and rest of the air holes diameter in the cladding region is defined as $d_3 = 0.94^*\Lambda$. The second air hole of each ring is placed from the center $r_1 = r_0 + (0.51 * \Lambda)$ distance. To ensure excellent light confinement, the diameters of the circular air holes located cladding of the proposed design are preferred as large as possible. The proposed PCF contains nine air holes in each spiral ring which are placed from the center at a distance $r_n = r_{n-1} + (0.51 * \Lambda)$ with an angular displacement, $\theta_n = (n * 360^\circ) / (2 * N)$ where N is the number of circular rings. For example, the angular distance of the first ring is defined as $\theta_1 = (360^\circ) / (2 * N)$. In the core region, small circular air holes are arranged by the optimized diameter of d_c which is depicted in the enlarged view of Fig. 1. Throughout the analysis, air filling ratio of core defined as $dc/\Lambda_c = 0.93$ is kept as large as possible. Due to select the core air-filling ratio by this way offers high birefringence. In addition, the value of dc/Λ_c should not be enhanced further to avoid overlapping among air holes. In such a situation, unrealistic fabrication may occur due to overlap among air holes. The pitch between adjacent circular air holes in the core region is denoted as $\Lambda_c = 0.41 * D_{core}$. Pure silica is used as the background material. The refractive index of silica changes with the wavelength according to the Sellmeier equation.

3. Synopsis of numerical method

To simulate the optical properties of this proposed S-PCF, a finite element method (FEM) is used for solving Maxwell's equation. It can

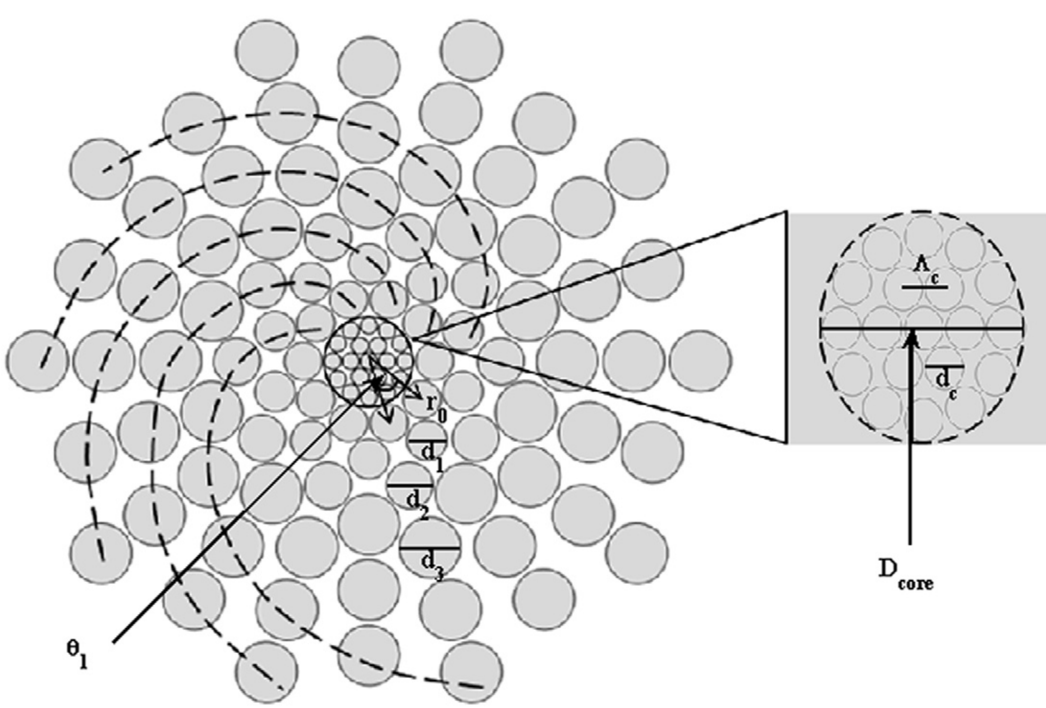

Fig. 1. Cross sectional view of the proposed S-PCF.