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# Proposal of a gas sensor with high sensitivity, birefringence and nonlinearity for air pollution monitoring

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ABSTRACT

Flammable or poisonous gasses in the air are capable of destroying a geographical area of causing a fire, fulmination, and venomous exposure. This paper presents a micro-cored photonic crystal fiber based gas sensor for detecting colorless or toxic gasses and monitoring air pollution by measuring gas condensate components in production facilities. The numerical investigation of the proposed PCF takes place using the finite element method (FEM). The geometrical parameters of proposed PCF are varied to optimize and observe the dependence of guiding properties on them. According to simulated results, the high relative sensitivity of 53.07% is obtained at 1.33 μm wavelength for optimum parameters. In addition, high birefringence of the order $6.9 \times 10^{-3}$; lower confinement loss of $3.21 \times 10^{-6}$ dB/m is also gained at the same wavelength. Moreover, nonlinear coefficient, effective area, splice loss, V parameters and beat length are reported briefly.



## 1. Introduction

Recently, due to the advancement of technology and for an extra degree of freedom photonic crystal fiber has drawn the attention of the researchers. Photonic crystal fiber (PCF) or holey fibers (HFs) or microstructure optical fiber contains a microscopic array of air channels that run through the entire fiber and formulates a lower index cladding on a silica background [1]. According to the guiding mechanism, PCF can be divided into two categories. One is photonic bandgap fiber (PBG) [2, 3] where the light is guided by photonic bandgap principle and another is index guiding (IG) PCF [4,5] where light can be guided through low index core by photonic crystal reflection cladding. Although the first fabricated PCF was hexagonal [6] but for encouraging technology, a lot of design flexibility is now possible. So to achieve better-guiding properties octagonal [7], decagonal [8], honeycomb cladding [9], circular [10] and hybrid [11] shaped PCF is designed nowadays. So far, high sensitivity [12], high birefringence [13], ultra-flattened dispersion [14], high nonlinear effect [15] can be accomplished by designing PCF because the advanced manufacturing technology allows PCF to tune by varying the air hole diameters and pitch. PCFs can be used for optical communication [16], nonlinear optics [17], high power technology [18], spectroscopy [19], supercontinuum generation [20], sensing application like - gas sensing [21] and chemical sensing [7] for its unique properties.

Microstructure core and cladding were first introduced by Cordeiro et al. [22] which shows that this type of PCF helps to increase energy into the holes which contain gas. An index-guiding PCF (IG-PCF) based gas sensor was proposed [23] which show a relative sensitivity of 13.23% and confinement loss of $3.77 \times 10^{-6}$. In 2015, M. Morshed et al. proposed a modified photonic crystal fiber [24] of [25] for gas sensing which shows better sensitivity and lowers confinement loss. The proposed PCF contains microstructure core instead of hollow core (of prior PCF) which improves the relative sensitivity of 42.27% with a lower confinement loss of $4.78 \times 10^{-6}$. Both the structures [23,25] demonstrate that by increasing the diameters of air holes placed in inner ring results in high relative sensitivity, whereas by increasing the air holes placed in outer ring results degraded confinement loss. A novel design of PCF was proposed in [26] where both core and cladding contains elliptical holes formed horizontally and vertically which shows high relative sensitivity, high birefringence and lower confinement loss simultaneously. The proposed PCF was used as a liquid analyte (water, ethanol and benzene) sensor.

A hybrid photonic crystal fiber was proposed in [27] which show birefringence of $3.79 \times 10^{-2}$ and high nonlinearity of 40.1 $W^{-1}\,km^{-1}$ at the wavelength of 1.55 μm. In [13], hybrid cladding PCF was proposed where the holes of the cladding wherein different shapes and used for dispersion, a nonlinear effect, birefringence and effective area. High birefringent PCFs can easily be realized for design flexibility and high Index contrast. There are lots of significant applications of high birefringent PCFs such as- fiber sensors, fiber filters, fiber communication etc. By depicting an asymmetric solid fiber core which is surrounded by air holes having double/triple defect core of PCF can be shaped for

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achieving high birefringence [28]. On the other hand, several papers show that ultrahigh birefringence can be gained by applying elliptical holes [28]. It is not easy to fabricate PCFs with elliptical holes accurately [29]. In addition, birefringence study in PCFs is growing interest day by day. The design of PCFs with high nonlinear coefficients due to its small effective area is more challenging [30]. Besides, in the field of telecommunication and supercontinuum applications nonlinearity with high birefringence derived a massive interest [31].

In this paper, a microstructure core based photonic crystal fiber is proposed that shows high birefringence, high relative sensitivity and lower confinement loss at the same time. The proposed PCF contains five rings of air holes in the cladding where the core contains elliptical air holes. The air holes of cladding are kept same to avoid design complexities. The proposed PCF shows 53.07% relative sensitivity as a gas sensor. Besides, the PCF shows high birefringence of $6.9 \times 10^{-3}$ and lower confinement loss of $3.21 \times 10^{-6}$, the high nonlinearity of $15.67\ W^{-1}km^{-1}$ at the wavelength of 1.33 μm. V parameters show the proposed PCF is a single mode fiber with a large effective area $3.88\ \mu m^2$ at the wavelength 1.33 μm. In addition, splice loss and beat length are also analyzed. A large number of analyses of the guiding and optical properties of PCF take place in this paper which makes our research unique one.

## 2. Geometries of the proposed E-PCF

Fig. 1 shows the transverse cross-sectional view of the proposed E-PCF. The cladding contains five rings of air holes in hexagonal manner. This method was introduced by [25] where the cladding was hexagonal with six missing holes in the edges of the outermost cladding. The diameters of two outermost ring and the three innermost rings were not same in the work. In our proposed E-PCF the diameters of all the five rings of cladding were kept same to match the proper fabrication tolerance and assumed as d. The concept of microstructure core was introduced by [24]. In [26] elliptical holes were used to get high birefringence. In the proposed E-PCF the core is organized with an array of 8 elliptical air holes which is horizontally arranged. The major and minor axis of the elliptical air holes is defined as $d_a$ and $d_b$ respectively. The hole to hole distance of two adjacent air holes is called pitch. The pitch between the holes of core and the holes of cladding is defined as $\Lambda_1$ and $\Lambda$ respectively. By article [25], the diameters of the innermost ring are responsible for high sensitivity and the diameters of outermost rings are responsible for lower confinement loss. In our proposed E-PCF the cladding air holes are optimized bigger to attain the low confinement loss and make the proper interaction of light through the core. All the parameters of both core and cladding were optimized by varying as a function of wavelength. By using perfectly matched layer (PML) boundary condition the optical properties and propagation characteristics of leaky mode can be measured. The PML is set 10% of the total diameter of the proposed E-PCF to meet the boundary condition.

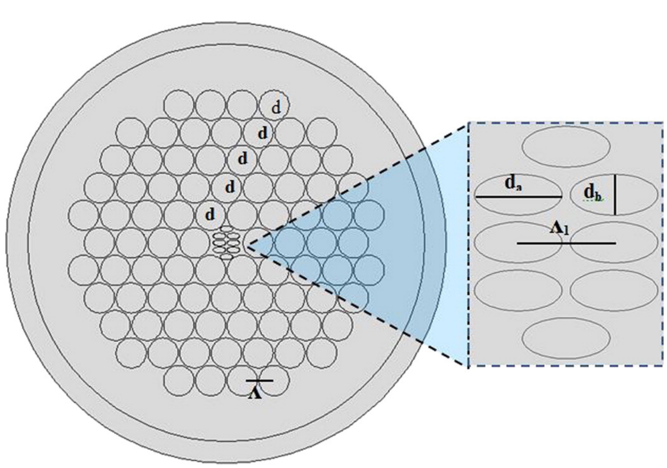


**Fig. 1.** Transverse cross section of the proposed E-PCF.

## 3. Synopsis of the simulation method

A finite element method (FEM) is used for solving Maxwell's Equation to simulate the guiding properties of the proposed PCF. It can solve very complex structures and can provide full vector analysis of different PCF structure [32].

To calculate the evanescent field by the gas samples the Beer-Lambert law can be used. The relationship between optical intensity and gas concentration can be determined as:

$$I(\lambda) = I_0(\lambda)\exp[-r\alpha_m l_c] \tag{1}$$

The absorbance of the sample can be defined as:

$$A = \log\left(\frac{I}{I_0}\right) = r\alpha_m l_c \tag{2}$$

Here, $\alpha_m$ is the absorption coefficient of the gas being detected; l is the length of the PCF; c is the gas concentration. Output light intensities with and without the presence of gas are I and $I_0$ respectively. Relative sensitivity r can be defined as:

$$r = \frac{n_s}{\mathrm{Re}[n_{eff}]} f \tag{3}$$

where $n_s$ is the refractive index of gas species considered 1; $\mathrm{Re}[n_{eff}]$ is the real part of the effective mode index. Here f is the fraction of total power and hole power which can be defined as:

$$f = \frac{\int_{holes} \mathrm{Re}(E_x H_y - E_y H_x)dxdy}{\int_{total} \mathrm{Re}(E_x H_y - E_y H_x)dxdy} \tag{4}$$

Here, $E_x$, $E_y$, $H_x$ and $H_y$ are the transverse electric and magnetic field. A circular perfectly matched layer (PML) is used to fulfill the boundary condition which avoids possible reflection at the boundary. By this term confinement loss or leakage loss can be calculated by the imaginary part of the effective refractive index. The confinement loss or leakage loss can be calculated by the following equation:

$$L_c = 8.868 \times K_0 I_m[n_{eff}](\mathrm{dB/m}) \tag{5}$$

where, $K_0$ is the wavenumber and $I_m\,[n_{eff}]$ is the imaginary part of the effective refractive index. The difference between refractive index of x-polarization and y-polarization is called the birefringence which can be defined as:

$$B = |n_x - n_y| \tag{6}$$

This property leads to periodic power exchange between two orthogonal components. This period is beat length which can be determined by:

$$L_B(\lambda) = \lambda / B(\lambda) \tag{7}$$

The single mode response can be determined by the V-parameter which is defined by:

$$V_{eff} = \frac{2\pi rf}{c}\sqrt{n_{co}^2 - n_{cl}^2} \le 2.405 \tag{8}$$

Here, $n_{co}$ and $n_{cl}$ are the refractive indexes of core and cladding. V-parameter ($V_{eff}$) of a PCF must be less than or equal 2.405 to be a