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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 ($\Lambda$). 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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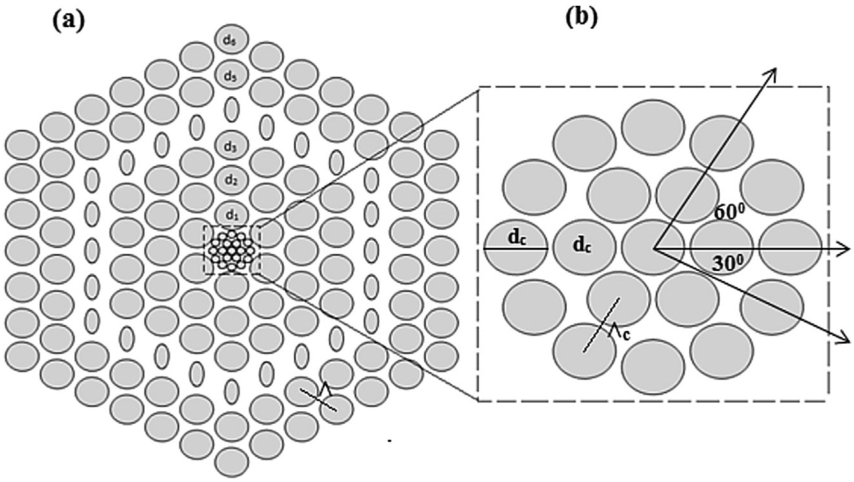


Fig. 1. (a) Cross sectional view of the proposed PCF (b) Geometrical view of holes in the core region.

## 3. Numerical analysis

The Commercial software COMSOL Multiphysics 4.2 version is used for this investigation study which is driven by finite-element method. FEM is chosen and applied here for its less computation time and complexity which all are reported in previously published literature. The FEM with completely circular anisotropic perfectly matched layer (PML) boundary condition is used to simulate the modal properties of proposed PCF fiber. Moreover finer mesh analysis is manipulated here and found number of vertex elements, boundary elements and elements are 588, 4891, 46286 respectively with minimum element quality of 0.6719. The finite number of air holes is divided into homogeneous subspaces of the PCF cross section, where Maxwell's equations are investigated by accounting for the adjacent subspaces. The following vectorial equation is calculated from the Maxwell's curl equations by utilizing the anisotropic PML [17].

$$\nabla \times \left([S]^{-1}\nabla \times \mathrm{E}\right) - K_0^2 n^2 [S]E = 0 \qquad (1)$$

where $K_0 = 2\pi/\lambda$ is the wave-number in the vacuum, λ is the wavelength, [s] is the PML matrix, $[s]^{-1}$ is an inverse matrix of [s], E denotes the electric field vector and n is the refractive index of medium.

In the simulation, the refractive index of the ethanol is fitted by the Sellmeier equation. Relationship between the wavelength and refractive index which is highly used to determine the refractive index (RI) of different crystal and it was first invented by Willhem Sellmeier in 1871. The equation is as follows

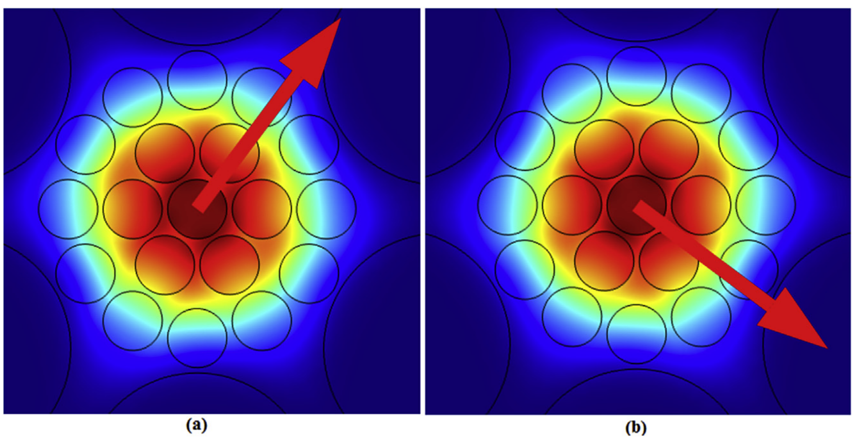


Fig. 2. Modal intensity distribution of the proposed PCF (a) along x-axis (b) along y-axis at activating wavelength λ = 1.55 μm for n = 1.354.

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

where, n and λ represent the refractive index and the wavelength respectively; $B_1$, $B_2$, $B_3$, $C_1$, $C_2$, $C_3$ are the coefficient of fiber background material silica.

The effective area $A_{eff}$ of the proposed PCF can be calculated by the following Equation (3) as follows

$$A_{eff} = \frac{\left(\int\int |E|^2 dxdy\right)^2}{\int\int |E|^4 dxdy} \quad (3)$$

where, E is the electric field in the medium.

Another crucial parameter of the PCF is nonlinearity which greatly depends on the nonlinear coefficient of the fiber background or hosting material. The nonlinearity in a PCF can be measured by the following Equation (4) as follows as

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} W^{-1} m^{-1} \quad (4)$$

here, $n_2$ is the nonlinear coefficient for silica.

Confinement loss is unavoidable in PCFs and arrives due to the finite extent of the periodic cladding. Finite number of air holes for different layer is ineluctably foreordained that the optical mode will leak from the core region into the outer air hole region which is commonly known as confinement loss or leakage loss. The confinement loss $L_c$ can be calculated from the imaginary part of the effective index $n_{eff}$, using the following Equation (5):

$$L_c = 8.686 k_0 I_m [n_{eff}] \quad (5)$$

where, $K_0 = 2\pi/\lambda$ is the wavelength of light, $I_m(n_{eff})$ is the imaginary part of the effective mode index.

V parameter is analyzed to ensure multi-mode fashion guidance. V-parameter can be investigated by the following Equation (6):

$$V = \frac{2\pi R}{\lambda}\sqrt{n_{co}^2 - n_{cl}^2} \geq 2.405 \quad (6)$$

where, R is the radius of the core, $n_{cl}$ and $n_{co}$ are the refractive indices of the fiber cladding and core respectively.

The relative sensitivity (r) coefficient at a particular wavelength gives an explicit idea on the interaction between the light and the material to be sensed. The relative sensitivity is calculated by the following Equation (7).

$$r = \frac{n_r}{Re[n_{eff}]} f \quad (7)$$

where, $n_r$ represents the refractive index of sensed material within the air holes and $n_{eff}$ is modal effective index. The f is the percentage ratio of the air hole power and the total power carried by that mode and expressed as Equation (8)

$$f = \frac{\int_{sample} R_e(E_x H_y - E_y H_x) dxdy}{\int_{total} R_e(E_x H_y - E_y H_x) dxdy} \times 100 \quad (8)$$

The ratio $f$ defines the percentage of energy presents in the holes.

here, $E_x$ and $H_x$ are transverse elective field and magnetic field, $E_y$ and $H_y$ are longitudinal electric field and magnetic field. The mode field pattern $E_x$, $H_x$, $E_y$, $H_y$ are calculated by solving Maxwell's equation with finite element method (FEM).

## 4. Result and numerical analysis

This section describes the numerical analysis of propagation characteristics in fundamental mode. The investigation study performs over a wide range of wavelengths ranging from 1400 to 1640 nm for E + S + C + L + U communication bands in a systematic way. The analysis of this study is given below step wise as follows.

In the beginning observation of the PCF is experienced with cladding area variation. Fig. 3 depicts the relative sensitivity variations for different cladding area. Area of the cladding region is varied for the alteration of the dielectric medium air holes. When the cladding area is 700 $\mu m^2$ the proposed PCF shows 62.24% sensitivity at a wavelength of 1.4 μm for Ethanol (n = 1.354). Besides 60.63% and 59.73% sensitivity is achieved for 800 $\mu m^2$ and 850 $\mu m^2$ cladding area respectively. So from Fig. 3, it is clearly visualized that lower cladding area enhances the sensitivity. It is also notified that response level of sensitivity for cladding region is absolutely inverse proportional to the cladding region. Cladding area has an impact on sensitivity which justifies Ref. [1] result.

Fig. 4 shows the sensitivity curve for the wavelength in the range of 1.4 μm—1.64 μm. For various diameters and pitch of core layers the sensitivity has been changed significantly. In this figure we may understand that the relative sensitivity increases with the wavelength and

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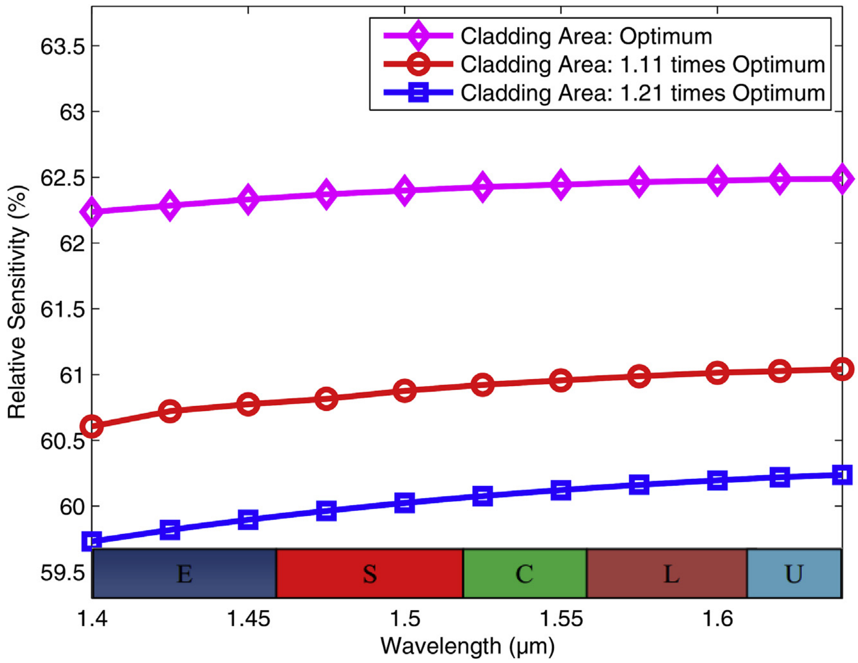


Fig. 3. The relative sensitivity versus wavelength for ethanol (n = 1.354) of proposed PCF varying cladding area 700 μm$^2$, 800 μm$^2$ and 850 μm$^2$.

core area. Fig. 4 also illustrates that core area 8 μm$^2$ shows higher sensitivity than 7 μm$^2$. So higher core area enhances the sensitivity which is vice versa compare with cladding area. Core area has a high impact on sensitivity which also justifies Ref. [1] result.

Fig. 5 shows the comparison of the sensitivity versus wavelength for ethanol (n = 1.354) of proposed PCF. The observation has been carried over the wavelength range from 1.40 μm to 1.64 μm by applying core area with circular, elliptical and square

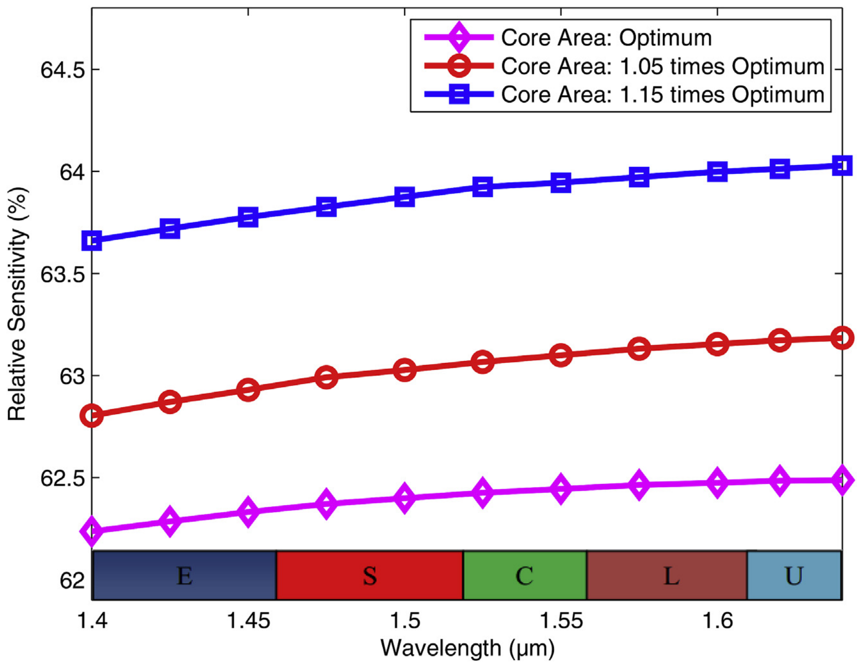


Fig. 4. The relative sensitivity versus wavelength for ethanol (n = 1.354) of proposed PCF varying various core area like as 7 μm$^2$ and 8 μm$^2$ and optimum.

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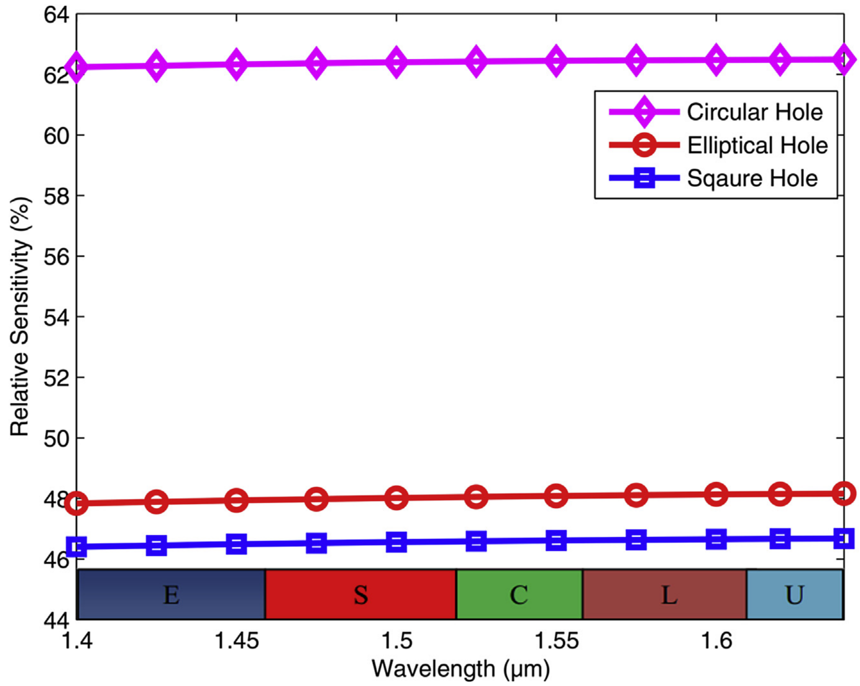


Fig. 5. The relative sensitivity versus wavelength for ethanol (n = 1.354) of proposed PCF that the core designed with circular, ellipse and square holes.

holes severally. For this reason it directly impacts on the sensitivity response of the fiber. Relative sensitivity response for square holes and elliptical holes are represented by blue and red curve respectively. Curves represent the relative sensitivity response of 46.79% and 48.06% for ethanol at the operating wavelength λ = 1.55 μm respectively. But it greatly remarks that circular holes in the core region shows higher sensitivity than elliptical and square hole. It gains the 62.19% for ethanol at λ = 1.55 μm which is 1.10 times better than previously reported article [18]. Sensitivity varies by the shape of air hole changes which also justifies Ref. [18] result.

From Fig. 6, it clearly illustrates that the geometrical properties are varied for different shape of air holes of the fourth layer in cladding like as elliptical, square and circular holes. In the cladding area, when the fourth layer air holes ring is ellipse then the relative sensitivity of 62.24% is attained, but for the circular and square air holes the proposed PCF has produced 59.73% sensitivity at a wavelength of 1.40 μm for ethanol (n = 1.354). So it is also nicely exhibited that elliptical air holes enhance sensitivity than circular or square shape air holes for this types of PCF.

Fig. 7 shows the relative sensitivity curve for ethanol (n = 1.354) of air-hole diameter and pitch variation from ±1% up to ±2%, along with the optimum sensitivity curve. Here air hole diameter −1% and −2% provide higher sensitivity than the optimum sensitivity curve on the other hand +1% and +2% provide lower sensitivity than an optimum sensitivity curve. When the air hole diameter and pitch are increasing +2% then it shows 62.19% sensitivity at a wavelength 1.40 μm whereas diameter and pitch are decreasing −2% then it shows the 62.28% sensitivity

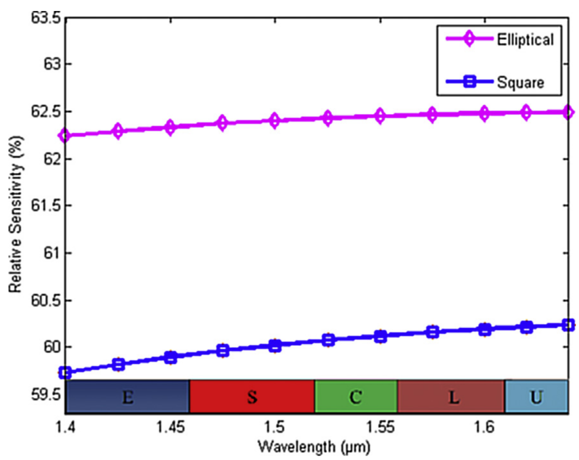


Fig. 6. The relative sensitivity versus wavelength for ethanol (n = 1.354) of proposed PCF varying different shape of air hole of the forth layer in cladding like as elliptical, square and circular.

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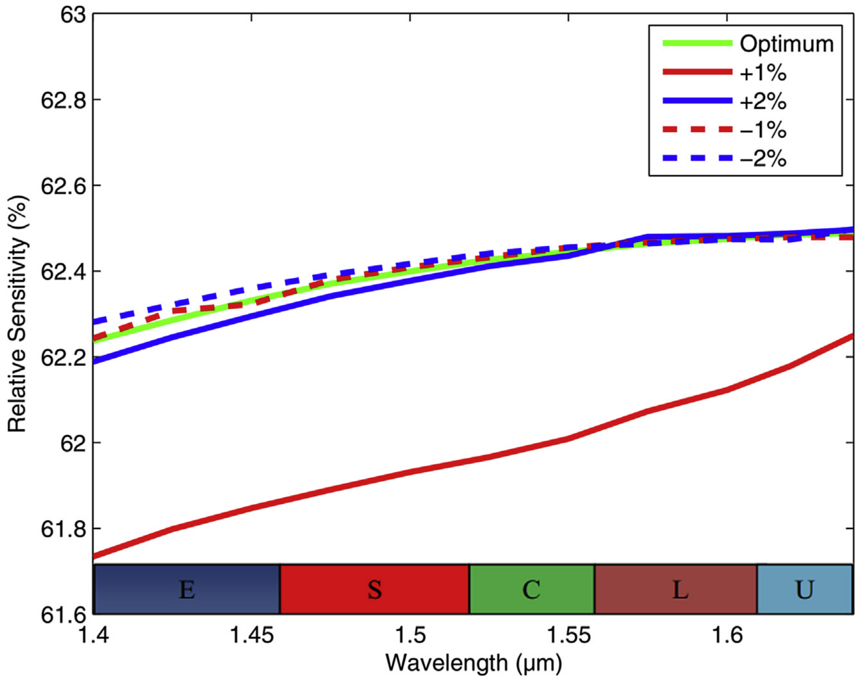


Fig. 7. The relative sensitivity curve for Ethanol (n = 1.354) of air-hole diameter and pitch variation from ±1% up to ±2%, along with the optimum sensitivity curve.

at the same wavelength. The optimum sensitivity is 62.24% at the wavelength 1.40 μm. So the change of sensitivity is negligible compare to the optimum. So after fabrication process the shape of air holes may be changed but the sensitivity of proposed PCF may not be varied as much.

Fig. 8 depicts the variation of V-parameter and wavelength of the proposed H-HPCF for optimal design. According to simulation, the proposed H-HPCF supports only multi-mode over the wavelength range 1400–1640 nm covering the band E + S + C + L + U. Beside this, it is carrying the information about slope of V-parameter which is downward. From this figure, it is easily notified that the proposed H-HPCF is multi-mode because its V-number is greater than 2.405. So the proposed PCF is less expensive to operate, install and maintain than single-mode cables.

The nonlinear coefficient and effective area as a function of wavelength at optimum parameters for the proposed PCF are shown in Fig. 9. The effective area is an assessment of the area covered by essential mode fiber; the width of the fundamental mode becomes greater whenever operating wavelength is increased. The effective area increases with operating wavelength and vice versa. The wavelength about 1550 nm, proposed PCF has effective mode area of about 6.8 $\mu m^2$ and nonlinear coefficient corresponds to this effective area is 18.4 $W^{-1}$ $km^{-1}$. The resulted nonlinearity of the proposed fiber is 7.08 times better than [18] at $\lambda = 1.55$ μm. The proposed structure exhibits a superior nonlinear coefficient and such high value of the nonlinear coefficient permits the structure is also suitable candidate for nonlinear optics applications. Table 1 shows the different numbers of guiding properties like frequency, propagation constant, total electric energy, total magnetic energy and wave number in the free space of the proposed H-HPCF.

Finally, a comparison is made between properties of the H-HPCF and some other fibers designed for sensitivity and confinement loss. Table 2 compares those fibers taking into confinement loss, relative sensitivity corresponds to the number of rings and different structural shape of the core and cladding that are used in PCF design, respectively. It clearly indicates that the designed fiber is good for lower confinement loss and higher sensing applications. Table 2 is clearly interpreted that the propose H-HPCF shows 2.62, 1.42, 1.33, 1.26 times superior sensitivity than [7,20,3] and [19] respectively along with comparatively lower confinement loss.

In this paper, the presented highly sensitive chemical sensor based on the hybrid hexagonal structure photonic crystal fiber is needed to fabricate before using as a

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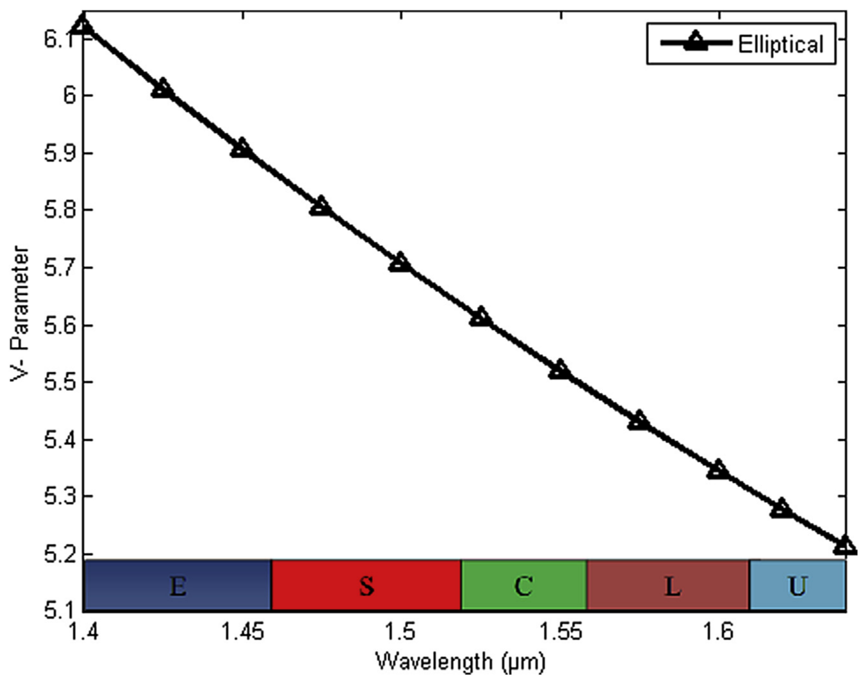


Fig. 8. Variation of V-parameter and wavelength of the proposed H-HPCF for optimum design parameter.

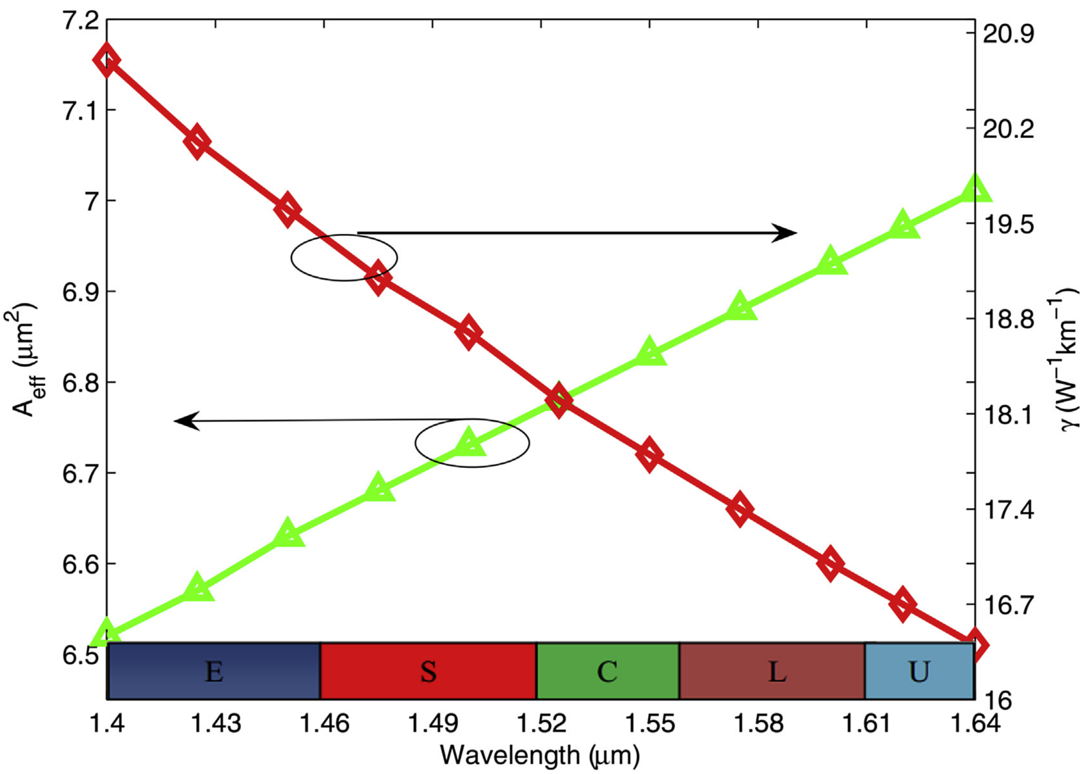


Fig. 9. Effective area and nonlinear coefficient as a function of wavelength including E + S + C + L + U band for optimum parameters of the proposed PCF.

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Table 1
Different guiding values of the optimum H-HPCF structure at λ = 1.55 μm.

| Investigation parameters | Ethanol |
|---|---|
| Frequency (Hz) | $1.9341 \times 10^{14}$ |
| Propagation constant (rad/m) | $5.4736 \times 10^{6}$ |
| Total electric energy (J) | $1.8157 \times 10^{-7}$ |
| Total magnetic energy (J) | $1.9081 \times 10^{-7}$ |
| Wave number in free space (rad/m) | $4.0537 \times 10^{6}$ |

Table 2
Comparison of simulated results and structural shape between proposed H-HPCF and prior PCFs at λ = 1.33 μm for Ethanol (n = 1.354).

| PCFs | Relative sensitivity (r %) | Con. loss (dB/m) | No. of ring | Structural shape | |
|---|---|---|---|---|---|
| | | | | Core | Cladding |
| Prior $PCF_1$ [7] | 23.75 | $2.40 \times 10^{-04}$ | 3 | Elliptical holes | Circular holes in octagonal |
| Prior $PCF_2$ [20] | 43.84 | $2.07 \times 10^{-06}$ | 4 | Circular holes | Circular holes in hexagonal |
| Prior $PCF_3$ [3] | 46.87 | $2.28 \times 10^{-14}$ | 5 | Circular holes | Circular holes in octagonal |
| Prior $PCF_4$ [19] | 49.17 | $2.75 \times 10^{-10}$ | 3 | Elliptical holes | Circular holes in circular |
| Proposed PCF | 62.19 | $5.56 \times 10^{-11}$ | 6 | Circular holes | Circular and elliptical in hexagonal |

sensor. Various methods have been developed for the fabrication of hybrid structure fibers, such as sol—gel casting, drilling, stack and draw, and extrusion [1]. Drilling techniques permit adjustment of both the holes size and spacing, but are generally limited to a small number of holes and restricted to circular shapes. Bise et al. [21] developed a Sol—gel technique to fabricate the PCFs with any structure, and they provide the independence to adjust air-hole size, shape, and spacing. In previous reported article based on micro core PCF [22—26] like the proposed H-HPCF, Sol—gel technique has been proposed as a good fabrication method. So for implementation of this type of PCF, the sol—gel casting method provides better design flexibility that will be essential for the proposed H-HPCF. Selective filling technique [27] is another well-known technique for filling chemical in the core region. So by this method we can easily fill chemical in our proposed H-HPCF. It is highly vivid that the proposed H-HPCF will provide a potential role in optical sensor as well as communication area of the optical field.

## 5. Conclusion

In this paper, the proposed Hybrid Hexagonal PCF (H-HPCF) is demonstrated good sensing characteristics of the proposed PCF for chemical sensing at the E + S + C + L + U communication bands. The proposed PCF is mainly highlighted the geometric arrangement of holes in the core region for which PCF displays higher sensitivity response of 62.24% for detecting Ethanol at the wavelength λ = 1.40 μm, which simplifies the fabrication process. The propagation characteristics of a Hybrid Hexagonal PCF (H-HPCF) have been numerically investigated using the FEM method. According to its remarkable guiding properties, we expect that the proposed H-HPCF will be helpful for sensing systems. The principal significance of the proposed structure can be easily manufactured by available commercial methods.

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## Declarations

All the authors have read the manuscript and approved this for submission as well as no competing interests.

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