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Design of Highly Sensitive Photonic Crystal Fiber for Sensing Harmful Chemicals

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Abstract: *Highly sensitive Photonic Crystal Fiber (PCF) has been designed and investigated for sensing the most harmful chemicals that exist in the world. The proposed structure of PCF consists of a solid circular core in which the samples of the chemicals are to be filled, surrounded by a hexagonal air-hole ring. The outermost cladding region comprises circular air-holes arranged in a helical (spiral) manner. Moreover, the sensitivity ratio of the liquid samples is investigated with respect to the wavelength. Sensitivity is monitored by checking for different wavelengths that range from 0.4µm to 1.85µm. With this proposed structure, the relative sensitivity of the chemicals such as paraffin liquid (n=1.48), pyridine (n=1.51), and bromobenzene (n=1.56) are found to be 78.49%, 82.99%, and 89.34% respectively. The proposed PCF structure is used to detect chemicals and any liquids due to its high sensitivity, large effective mode area, and low confinement loss.*

Keywords: *Effective mode area, relative sensitivity, confinement loss, photonic crystal fiber, etc.*

I. INTRODUCTION

In recent days, electronic detectors are mostly replaced by optical sensor devices since electronic detectors are subject to some major limitations such as complex processes [1], high cost of manufacturing, tardier response time, and reliability in comparison with optical sensors. At present, optical-based physical sensors are widely used to detect and examine the tortuous environment and its circumstances such as torsion [2], stress [3], pressure [4], humidity [5], temperature [6], etc. and they are most significant in the field of robotics, health, and safety monitoring and wearable sensors. Thus, optical-based sensors are highly applicable for oil, gas, and chemical sensing applications [7] because of their assets of high sensitivity, reasonable cost, reliability, quick response, etc. In the last few years, photonic crystal fiber (PCF) plays an important role in the area of optical sensor applications.

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PCF is commonly recognized as a holey fiber with microstructured air-holes arranged periodically that runs throughout the length of the fiber. It highly attracts engineers and researchers to develop the optical-based devices and sensors due to its advantages such as microscopic structure, quick response, freedom of design, and capability of controlling light. An evanescent field of the PCF [8] has been regulated by altering the design specifications like pitch, air-hole diameter, air-filling fraction, number of rings, and air-hole structure, as a result, it will be applicable for many applications specifically in the field of sensors. air-hole structure, as a result, it will be applicable for many applications specifically in the field of sensors. Over the last few decades, PCF has been broadly examined in the area of optical sensors. In specific, it is widely used to sense highly sensitive gases and liquids that are toxic and inflammable to ensure safety in the industrial process. Thus, researchers focused on developing PCF based sensors for observing the safety of an environment. Many types of PCF based sensors were developed to achieve high sensitivity by modifying the various geometric parameters of the PCF. The performance metrics required for PCF to be a typical sensor can be boosted through either regular or irregular geometric structures such as square, kagome, elliptical, hexagonal, and honeycomb cladding. Many researchers are attempting to improve the efficiency of the PCF by changing the structure of the cladding and also by introducing various types of transparent materials. The attributes that are responsible to use PCF as a sensor are opto-thermal effect, fluorescence, absorbance, luminescence, reflectance, refractive index, and light scattering. Among these attributes, absorbance is widely used for sensing applications. In recent years, different types of PCF has been discussed in the literature that can be applied in various sensor application. Hexagonal shaped cladding with microstructured core has been reported to sense water with a sensitivity of 49.13% in 1.3 µm - 2 µm range of wavelength [9]. Similarly, the same sample of water is sensed with the PCF composed of hexagonal-shaped cladding and elliptical core which shows a sensitivity of 41.36% at a wavelength of 1.3 µm with high nonlinearity of about 74.75 $W^{-1}km^{-1}$ and low birefringence of about 0.00509 [10]. In another literature, sulphuric acid of high concentration has been sensed with high sensitivity of 63.4% at a wavelength of 1.5 µm using the PCF that comprises of hexagonal-shaped cladding and a microstructured core made of numerous elliptical holes which shows zero birefringences and very low confinement loss in the order of 10^{-17} at the same wavelength [11]. With the use of PCF circular-pattern of air-holes in both cladding and core, the three different liquids such as glycerol, ethanol, and toluene with a sensitivity of 65.16%, 61.65%, and 64.05% respectively have been sensed at the range of wavelength of 1.4 µm - 1.65 µm [12]. A novel quasi PCF has been developed to sense water, ethanol, and benzene with high sensitivity of 70.94%, 71.06%, and 72.19% respectively in the regime of terahertz [13].

Similarly, a spiral-shaped cladding PCF with a microstructured core made of elliptical holes has been reported to sense the liquids such as water, propane, and propylene with a sensitivity of 56.8%, 58.3%, and 62.7% respectively at a communication wavelength of 1.55 µm [14]. In one of the literature, rhombic core PCF has been discussed to sense the samples of any liquid with a high sensitivity of 74.85% at a communication wavelength of 1.55 µm [15]. In this paper, a PCF with a ring of hexagonal air-holes around the core covered by helically arranged air-holes has been proposed to sense the most harmful liquids such as paraffin liquid, pyridine, and bromobenzene. The structure of the research paper is as follows: In section-2, the details of the proposed structure of the PCF have been discussed. In section-3, the performance metrics of the proposed PCF has been presented. The results and graphs obtained through an investigation are described in section-3 and section-4 concludes the major results of the analysis.

II. PROPOSED DESIGN OF THE PCF

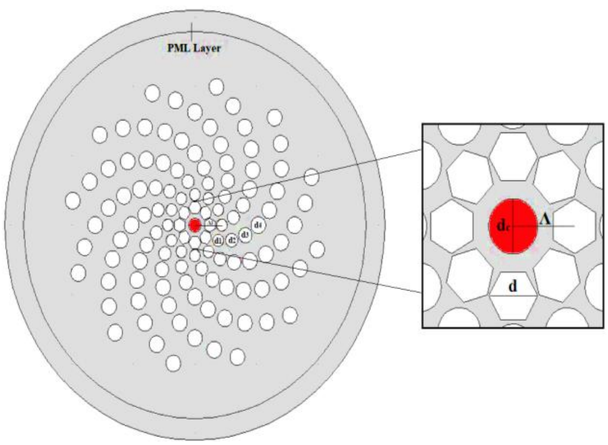

Fig. 1.Geometrical structure of the proposed PCF

Figure.1 depicts the proposed structure of the PCF for sensing harmful chemicals. The diameter of the circular core in which the harmful chemical sample is to be filled is d_c = 1.5µm. The inner layer of the cladding consists of air-holes of hexagonal shape with a diameter of d=2µm and the pitch value is Λ=2.5 µm. In the literature, we have come to know that the sensitivity increases by increasing the diameter of the air-holes closer to the core area [16]. As a result, the diameter of the air-holes in the inner layer of the cladding was selected as maximum as possible without being overlaid. The air-holes in the outer layers of the cladding in the structure of PCF are arranged in a helical (spiral) manner [17]. The outer helical layer of the cladding is made of 10 arms each with 9 circular air- holes. In the design, the first air-hole in the helical arm is spaced at a distance of Λ_1 = 4.4 µm from the core. The remaining 8 air-holes of the helical arm are spaced at a distance from the core which is deduced as $r_n = r_{n-1} + (0.45*\Lambda_1)$ [18], where n is the corresponding ring number. The air-holes in the helical arm are displaced obliquely from the center by employing the formula $\theta_n = (n*360)/(2*N)$, where N denotes the number of spiral arms. The diameter of the first circular air-hole in the spiral arm is given as $0.4*\Lambda_1$. The second air-hole diameter of the spiral arm is deduced as $0.45*\Lambda_1$, the third air-hole diameter of the spiral arm is $0.5*\Lambda_1$ and the fourth air-hole diameter is $0.55*\Lambda_1$. The diameter of the remaining circular air-holes of the spiral arm is fixed as $0.55*\Lambda_1$.

III. PERFORMANCE METRICS OF PCF SENSOR

The structure of PCF was developed with a perfectly matched layer (PML) by employing the finite element method (FEM) [19]. Here, the performance metrics [20] such as effective mode area, relative sensitivity, confinement loss, and birefringence. The most important metric for a PCF to be used as a sensor to calculate relative sensitivity. It is nothing but the sensing capacity of the fiber and it is obtained as given in equation 1 [21],

$$r = \frac{n}{|n_{eff}|} * f \tag{1}$$

Where n & n_{eff} is the index of refraction of the sample liquid and effective mode index respectively, and f denotes the sensitivity ratio which is computed as given in equation 2 [22],

$$f = \frac{\iint_{holes}(Ex*Hy-Ey*Hx)\,dx\,dy}{\iint_{total}(Ex*Hy-Ey*Hx)\,dx\,dy} \times 100 \tag{2}$$

Where E_x, E_y, H_x, and H_y are x & y-components of the electric field and magnetic field respectively. The numerical calculation of an area in which the mode of the fiber or waveguide encloses in the transverse dimensions is called as effective mode area (modal field distribution) and it is obtained as given in equation 3 [23],

$$A_{eff} = \frac{\left(\iint |E|^2\,dx\,dy\right)^2}{\iint |E|^4\,dx\,dy} \tag{3}$$

Where E denotes the component of the electric field of the fundamental mode of light propagated. An ability of controlling the polarization is obtained through the fiber Birefringence. The stability and accuracy of the system can be improved by achieving high birefringence and it is calculated as given in equation 4 [24],

$$B = |n_x - n_y| \tag{4}$$

Where n_x and n_y are the x and y polarized mode indices of the propagated light. Confinement loss or leakage loss arises due to the leakage in the propagation mode and also due to the irregular arrangement of air-holes [25] and it is computed as given in equation 5,

$$L_c = 8.686k_o \times Im[n_{eff}] \tag{5}$$

where k_o is the wavenumber and it is computed as $k_o = {}^{2\pi}/_{\lambda}$.

An imaginary part of the mode index is denoted as Im[n_{eff}] and it is computed by employing PML conditions around the structure of PCF.

IV. RESULT AND DISCUSSIONS

The variation of the effective mode index (n_{eff}) of both x-polarized and y-polarized modes with respect to wavelength is shown in figure 2(a) & (b). From the graph, it is clear that both x and y polarized mode indices decrease on increasing the wavelength. At 1.55 µm wavelength, the n_{eff} of the three liquids such as paraffin liquid, pyridine, and bromobenzene is found to be 1.436753 (x) & 1.436765 (y), 1.460392 (x & y), and 1.502665 (x) & 1.502666 (y) respectively. Now, let us discuss the effective mode area (A_{eff}) that decides the absorbance of the sample liquid. The variation of the A_{eff} with respect to the wavelength is shown in figure 3. From the graph, it infers that A_{eff} increases on increasing the wavelength. At 1.55 µm wavelength, the A_{eff} of the three liquids is 2.82 µm^2 (paraffin liquid), 2.70 µm^2 (pyridine) and 2.70 µm^2 (bromobenzene).

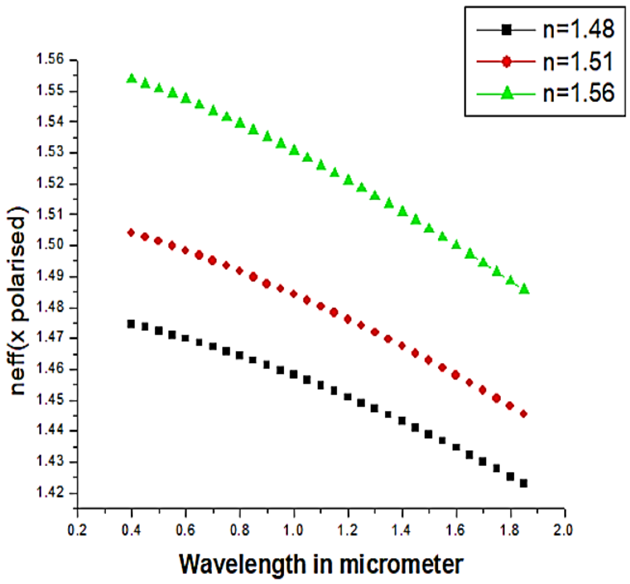

Fig .2. (a) Effective mode index(X-polarised) vs Wavelength

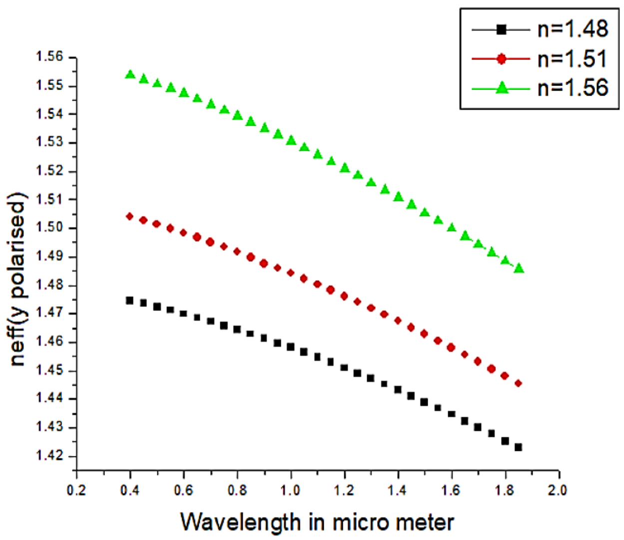

Fig.2.(b) Effective mode index(Y-polarised) vs Wavelength

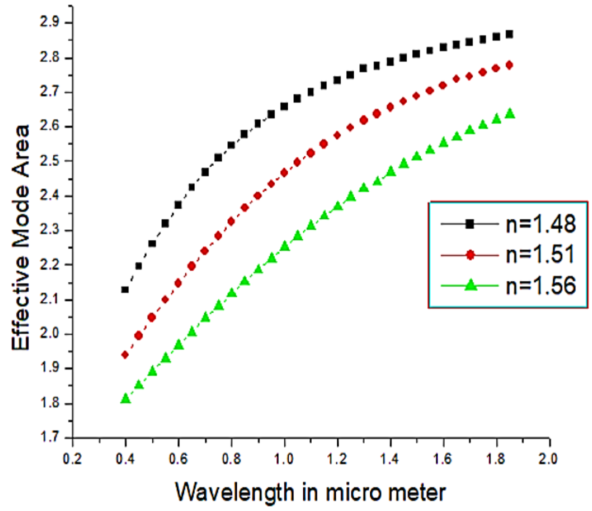

Fig.3.Effective mode area vs Wavelength

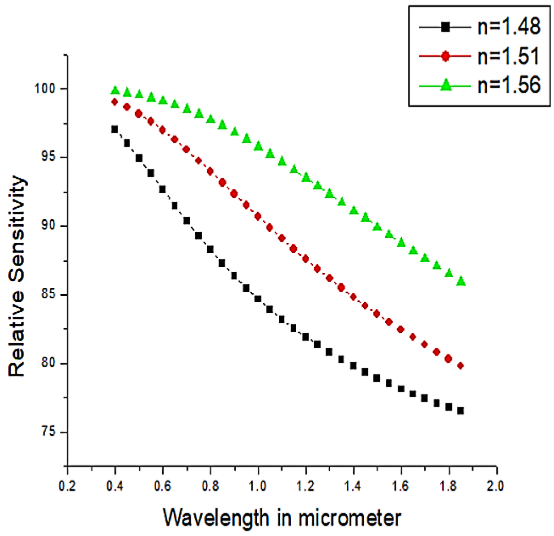

Fig.4: Relative sensitivity vs wavelength

The sensing capacity of the PCF has been observed by computing an important metric known as relative sensitivity. The variation of relative sensitivity with respect to wavelength is shown in figure 4. From the graph, it is noticed that the sensing capacity of the proposed PCF reduces on increasing the wavelength. It exhibits a very high sensitivity for lower wavelengths when compared to higher wavelengths. At 1.55 µm wavelength, the PCF senses bromobenzene and pyridine with high sensitivity of 89.34% and 82.99% respectively.

Whereas, the sensitivity of the paraffin liquid is about 78.49% at the same wavelength. In the wavelength range of 0.4 - 1.85 µm, the fiber shows the high sensitivity in the case of bromobenzene and pyridine (i.e.) ≥ 80%. But, in the case of paraffin liquid and pyridine, it exhibits a high sensitivity in the wavelength range of 0.4 - 1.2 µm. The comparison of the variation of effective mode area and sensitivity with respect to wavelength for each liquid shown figure 5 (a), (b) & (c). It is clear from the graph that for high sensitivity, the mode area of the propagated mode must be less.

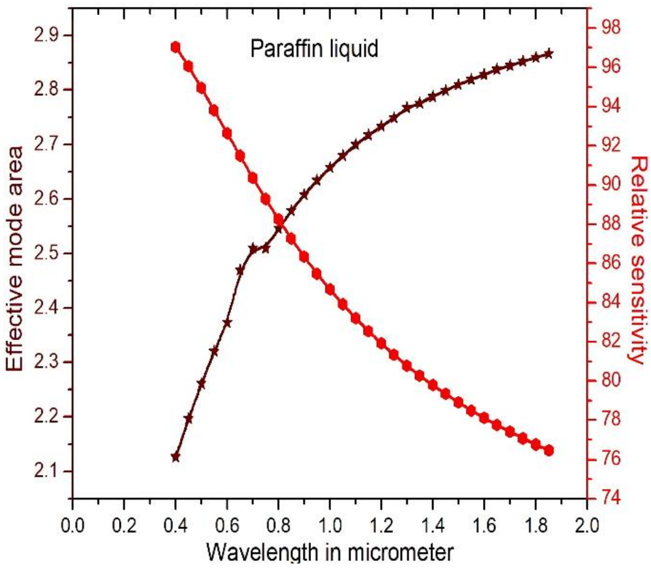

Fig.5(a)

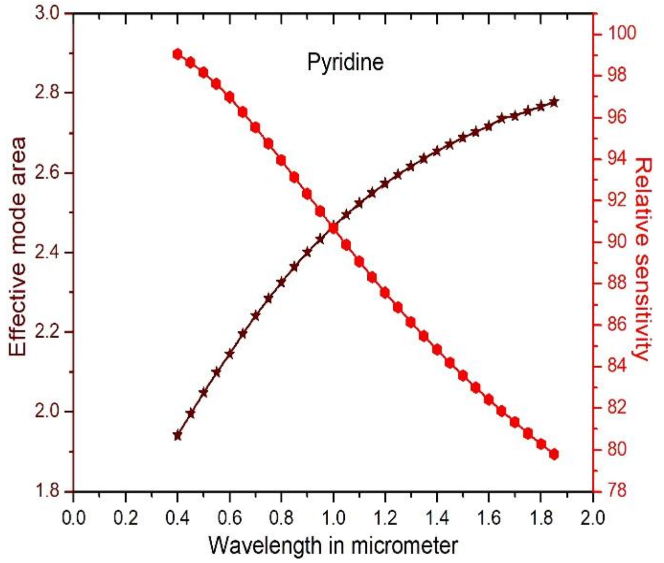

Fig.5(b)

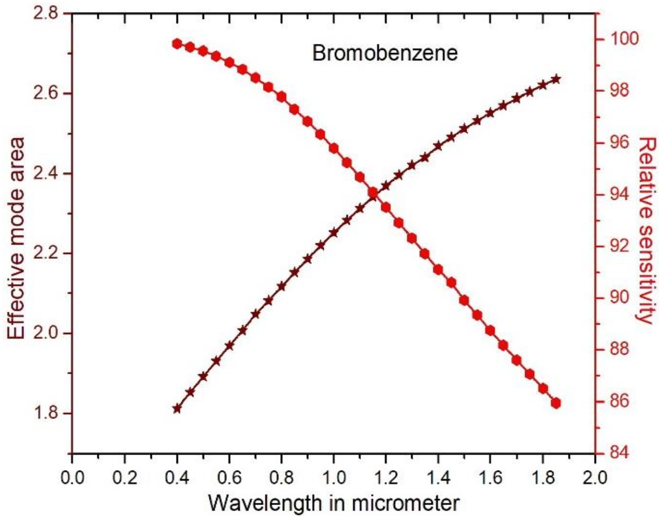

Fig.5(c)

Fig.5: Comparison of the variation of effective mode area and relative sensitivity of (a) paraffin liquid, (b) pyridine, and (c) bromobenzene

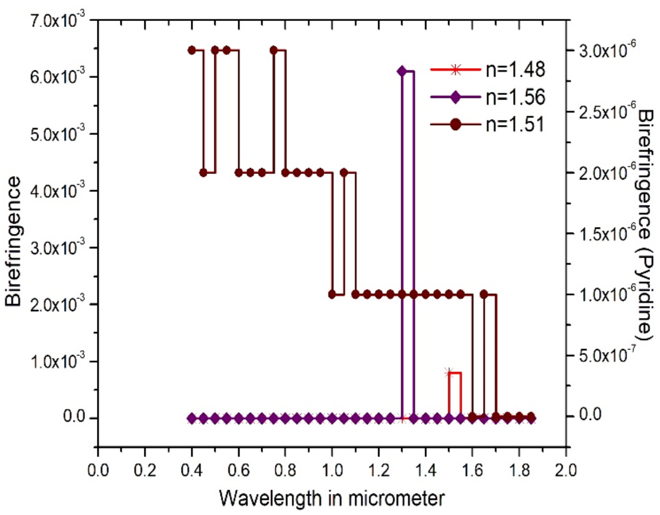

Fig.6 Birefringence vs wavelength

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Parameters	[9]	[10]	[11]	[12]	[13]	[14]	[15]	Proposed work
PCF structure	Hexagonal cladding with microstructured core	Hexagonal cladding with elliptical core	Hexagonal cladding with elliptical holes in the core	Circular pattern of air-holes in both cladding & core	Quasi PCF	Spiral cladding with elliptical holes in the core	Hexagonal cladding with rhombic core	Circular core covered by hexagonal air-hole ring surrounded by spiral cladding
Liquid sample	Water	Water	Sulphuric acid	glycerol, ethanol, and toluene	Water, ethanol, and benzene	Water, propane, & Propylene	Any liquid	Paraffin liquid, pyridine, & bromonbenzene
Wavelength range (µm)	1.3 - 2	1.3	1.5	1.4 - 1.65	Terahertz regime	1.55	1.55	1.55
Relative sensitivity (%)	49.13	41.36	63.4	65.16, 61.65, & 64.05 respectively	70.94, 71.06, & 72.19 respectively	56.8, 58.3, & 62.7 respectively	74.85	78.49, 82.99, & 89.34 respectively

Table.1: Comparison of proposed work with the literature

Now, another parameter birefringence varies with respect to wavelength as shown in figure.6. From the graph, it infers the value of birefringence for paraffin liquid, and bromobenzene is almost equal in the wavelength range of 0.4 µm - 1.85 µm. Whereas, its value for pyridine is too high for most of the wavelengths. At 1.55 µm wavelength, the value of the birefringence of three liquids is found to be $1.2\text{x}10^{-5}$ (paraffin liquid), 0 (pyridine), and $1\text{x}10^{-6}$ (bromobenzene). Confinement loss for all the three liquids is obtained as zero (i.e) it ensures that there is no leakage of modes propagated.

V. CONCLUSION

The results achieved in the proposed work has been compared with the literature work in Table 1. From the table, it is clear that the proposed PCF has a high sensing capacity for the liquids with refractive index ≥ 1.45. Thus, the proposed structure is efficient to sense the harmful chemicals with refractive index ≥ 1.45. From the results, it is proved that the proposed structure is highly applicable for sensing harmful liquids with minimum confinement loss for a broad wavelength range of 0.4 µm - 1.85 µm. The relative sensitivity obtained for the proposed structure is 78.49%, 82.99%, 89.34% for paraffin liquid (n=1.48), pyridine (n=1.51), and bromobenzene (n=1.56) respectively at the communication wavelength.

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