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B.Elizabeth Caroline

IFET College of Engineering

Mohamed Nizar (✉ nizar.shabu@gmail.com)

IFET College of Engineering

Prabu Krishnan

NITK Surathkal: National Institute of Technology Karnataka

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Photonic Crystal Fiber Sensor for the detection of Different Hazardous Gases

B.Elizabeth Caroline¹, S.MOHAMED NIZAR^{2*}, PRABU KRISHNAN³

¹Department of Electronics and Communication Engineering, IFET College of Engineering, Villupuram, Tamilnadu, India, Email: carolinebritto96@gmail.com, Tel: *(91) 9489462260 (E.C);

²Department of Electronics and Communication Engineering, IFET College of Engineering, Villupuram, Tamilnadu, India, Email: nizar.shabu@gmail.com, Tel: *(91) 7094647170 (M.N);

³Department of Electronics and Communication Engineering, National Institute of Technology Karnataka, Surathkal, India. Email: prabuk@nitk.edu.in, Tel: *(91) 9884888408 (P.K);

* Corresponding Author

Abstract- Three different Photonic Crystal Fiber (PCF) gas sensors are designed to detect five different gases for a wide range of wavelengths. The three unique configurations are designed based on four outer Elliptical cores PCF (4E-PCF), four outer Circular cores (4C-PCF) PCF, and different Eight Elliptical cores PCF (8E-PCF) to analyze and sense the light interface with applied gases. For three proposed gas sensors, the sensing parameters for five different hazardous gases, such as relative sensitivity, effective area, birefringence and dispersion, are acquired. The five different gases considered for the sensor investigation are Sulfur trioxide [SO₃] (20°C), Tetrachlorosilane [SiCl₄], Tetrachloromethane [CCl₄], Turpentine [C₁₀H₁₆], Tin Terra chloride [SnCl₄]. Among the three designs, 8E-PCF yields a maximum sensitivity of 75.75%, an effective area of 2.45μm², and a birefringence of 0.0421 for SnCl₄ gas.

Keywords: Photonic Crystal Fiber (PCF), four outer Elliptical cores PCF (4E-PCF), four outer Circular cores (4C-PCF) PCF, and different Eight Elliptical cores PCF (8E-PCF), Sensitivity.

1. Introduction

PCF is generous with optical fibre. The PCF consists of a core surrounded by cladding, and includes a range of micro-structured air holes that run along the length of the fibre. The light in the PCF is propagated through the hollow core region via total internal reflection. Due to its unique design structure, the PCF produces outstanding results in multiple applications. Some PCF applications include: biochemical, strain sensor, temperature sensor, pressure sensor, vibration sensor [1-5]. PCF-based sensors are essential due to their high relative sensitivity, small size, flexibility, and robustness. PCF properties can be improved by changing the shape

and location of the air holes, as well as the core diameter and pitch (distance between two consecutive air holes). These properties were difficult to detect using conventional optical fibre. [6]. The presence of air holes in both the core and the PCF cladding allows directed light to pass through them and allows analytics (gases) to be inserted into the air holes, facilitating the finite interaction of the light with the sample. As a result, new sensing applications emerge. [7].

The high-performance PCF [8] was designed to detect liquids and gases. The relationship between the index-guided and the air-core was analyzed for sensing properties. Simulation results show that the sensitivity of the fiber increases as the core size increases, and the sensitivity decreases as the pitch decreases. Index PCF guidance [9] was proposed for the detection of methane gas. Sensitivity and containment loss were detected using the Finite Element Method (FEM). The sensitivity of the index ring with a hole in the centre of the fibre has been improved and the loss of containment has also been reduced. In order to increase the sensitivity, the gap in the inner ring was increased. Confinement loss was reduced by increasing the outer ring. In addition, the sensitivity was increased by a hexagonal hole. The relative sensitivity for methane at 1.33 μm wavelength was 13.23% and the confinement loss was 3.77×10^{-6} .

Two ring circular PCF [10] were analyzed for different wavelengths by different core and cladding diameters. A maximum sensitivity of 13.94 per cent was achieved for the wavelength of $\lambda=1.66\mu\text{m}$ and a confinement loss of approximately 2.74×10^{-4} dB/m was achieved. Detection of industrial gas [11] was proposed by the combination of PCF and Long-Period Grating (LPG). The PCF – LPG was also synchronized with the tunable Er-doped fibre ring laser. Decent sensitivity has been achieved efficiently by using Er-doped fibre. Hollow Core-PCF (HC-PCF) [12] was proposed to detect acetylene based on a ring fibre laser with a Sagnac loop filter. This design was operated at 1532.83, and 1 percent acetylene was applied at 1534.10 nm, and the sensitivity of 398 and 1905 PPMV was achieved. The PCF gas sensor detected toxic, colourless and harmful gas and was preferred mainly due to its compact size, light control capability and rapid response. The propagation of light can be controlled by a variety of structural parameters and core material. Harmful gas can be detected by different core-coating shapes and fibre background materials [13]. A circular PCF gas sensor [14] was proposed to detect toxic gas for wavelengths ranging from 1 μm to 1.8 μm . The spiral porous core region was designed to achieve

high sensitivity. The sensitivity of the sensor was 72.04% for a wavelength of 1.33 μm . Hexagonal hybrid Porous Core Photonic Crystal Fibre (HPC-PCF)[15] was designed to detect methane gas. Optical properties such as confinement loss, relative sensitivity, refractive index (RI), effective area, and non-linearity were studied using this method by varying the diameter of the air hole, pitch constant, and core porosity.. Using this method, 21.2% sensitivity and 0.000025 dB/m confinement loss were achieved. In order to detect hydrogen sulphide (H_2S) gas, a PCF Mach–Zehnder interferometer (MZI)[16] was proposed. The graphene quantum dots of 1 μm were coated on the surface of the sensing membrane. The sensitivity of this sensor was 26.62 ppm $^{-1}$, shown to be selective in the range 0 ~ 55 ppm.

H_2S (hydrogen sulphide) and CH_4 (methane) are flammable, toxic, and colourless gases found in oil rigs and refineries[17]. A hexagonal PCF for sensing these gases[18] was presented. The relative sensitivity is increased to 62.07 % and 67.07 % for the wavelength range of 1.1 μm –1.6 μm , respectively. According to the numerical results, using non-circular holes around the central ring holes, as well as a greater number of ring holes, improves sensitivity and confinement loss. Ammonia gas was detected in breath using PCF gas sensor. From the simulation results it was analyzed that the sensitivity of 63.18% was achieved. These types of sensors are used in medical field.

In this proposed work, PCF is used as a sensor for the detection of different gases, such as Sulfur trioxide [SO_3] (20°C), Tetra chloro silane [SiCl_4] (25°C), Tetra chloro methane [CCl_4] (25°C), Turpentine [$\text{C}_{10}\text{H}_{16}$] (25°C) and Tin Terra chloride [SnCl_4] (25°C). These gases are available in the industrial sector. They cause serious damage to the human being. Some of the causes of these gases are liver damage, central nervous system damage, eye damage, kidney damage and cancer. Suppose that long-term CCl_4 exposure causes death or coma.. In this research work, the hexagonal PCF structure with circular cladding and core holes is designed to investigate different gases and their relative sensitivity, effective area and birefringence. The proposed 8E PCF sensor is compared to the elliptical and circular core regions. In this paper, a hexagonal PCF sensor is used to test different industrial hazardous gases. The rest of the paper is ordered as follows. Section 2 presents a design methodology that explains the geometric synopsis of four circular core regions, four elliptical core regions and eight elliptical core regions. Session

3 deals with the numerical method, explaining the different parameters of the PCF design. Section 4 provides the results and discussions. Section 5 concludes the paper.

2. Design Methodology

The key feature of the proposed gas sensors is to change the structure of the core in three different methods, as shown in Figures 1 and 2. In the first method (4E-PCF), the core is designed with four elliptical holes around the circle. In the second design (4C-PCF), the sensor is designed with four circular holes around the centre circle, and in the third design (8E-PCF), the core consists of eight elliptical holes. This method uses two different sizes of the elliptical nucleus, and the small elliptical nucleus has a semi-axis of $0.3\mu\text{m}$ and a b-semi-axis of $0.12\mu\text{m}$. The large elliptical core has an a-semi-axis diameter of $0.33\mu\text{m}$ and a b-semi-axis of $0.5\mu\text{m}$, as shown in Table 1. For all three designs, the circular cladding has a diameter of $1\mu\text{m}$. The pitch is center to center between two air holes, and it is represented as Λ . The pitch for this design shall be $1.1\mu\text{m}$. The cladding consists of three layers, with two extra circles, one at the top of the core and the other at the bottom. In the proposed sensor structure, instead of using the typical hexagonal shaped cladding, the compact configuration of the air holes is attractive. In the cladding region, there are seven holes in the four faces and three holes in the two faces. This is done to reduce the size of the PCF sensor and to improve the sensing parameters of the proposed gas sensors. In addition, this arrangement gives zero confinement loss. The Perfectly Matched Layer (PML) of $0.5\mu\text{m}$ avoids light reflection during propagation.

Table I: Simulation Parameters

Proposed Methods	Core Shape	Core Diameter	Different Core Shapes Surrounds the centre hole	Centre Circle diameter	Background Material Used
4C-PCF [Figure 1a]	Circle	$1.3\mu\text{m}$	$0.28\mu\text{m}$	$0.5\mu\text{m}$	Core – Topaz with RI of 1.606 Cladding – Silica with RI of 1.45
4E-PCF [Figure 1b]	Elliptical	$1.3\mu\text{m}$	a semi-axis = $0.3\mu\text{m}$ b semi-axis = $0.5\mu\text{m}$	$0.5\mu\text{m}$	

8E-PCF [Figure 2]	Small Elliptical Core	1.3 μm	a semiaxis = 0.3 μm b semiaxis = 0.12 μm	0.52 μm 0.58	
	Large Elliptical Core		a semiaxis = 0.33 μm b semiaxis = 0.5 μm

Figure 1(a) Design of 4C-PCF and 1(b) Design of 4E-PCF

Figure 2: Design of 8E-PCF

To observe the detecting mechanisms, the core holes are filled with different analyte gases such as SO_3 (20°C), SiCl_4 (25°C), CCl_4 (25°C), $\text{C}_{10}\text{H}_{16}$ (25°C), and SnCl_4 (25°C), whose RI are 1.40965, 1.41156, 1.461, 1.472, and 1.5086 respectively.

3. Numerical Method

The most numerical approach for the design and development of photonic components and devices is the FEM with PML boundary conditions. Using the FEM method for the proposed three sensors, 4E-PCF, 4C-PCF and 8E-PCF, the sensing parameters such as sensitivity, n_{eff} , birefringence, effective area, Numerical Aperture and beat length are investigated. Confinement

loss or leakage loss occurs when optical power goes through a PCF waveguide and some of it accidentally distributes into the cladding region from the core due to a finite number of air holes. The following equation [19] can be used to calculate the confinement loss

$$L_c = 8.686k_0 \alpha I_m(n_{eff}) \times 10^6 \quad (1)$$

$$k_0 = \frac{2\pi}{\lambda}$$

L_c and k_0 is the confinement loss and the wave number in free space and the imaginary part of an effective mode index is represented by $I_m(n_{eff})$. The components of the gas absorb the energy of photons of light at a specific wavelength. The Beer-Lambert equation states that the amplitude of light changes as photon energy is absorbed by gas components.. The equation Eq.[20] defines the Beer-Lambert law.

$$I(\lambda) = I_0(\lambda) \exp(-r \theta_m L C) \quad (2)$$

where $I(\lambda)$ and $I_0(\lambda)$ are the input and output light intensities, θ_m is the gas absorption coefficient, L is the length of the fiber, λ is the wavelength and C is the gas concentration. Sensitivity is a measurement of sensor performance that indicates how the output changes in relation to the input. The Beer-Lambert law expresses relative sensitivity and is given by Eq. [21].

$$r = \frac{n_r}{n_{eff}} \times f \quad (3)$$

where n_r is RI, and n_{eff} is the effective RI of different gas. f is the percentage of energy present in holes with respect to optical power. According to Poynting's theorem, f can be expressed by the following equation [21]

$$f = \frac{\int_{\text{Sample}} \text{Re}(E_x H_y - E_y H_x) dx dy}{\int_{\text{total}} \text{Re}(E_x H_y - E_y H_x) dx dy} \times 100 \quad (4)$$

where H and E are transverse magnetic and electric fields, respectively. The following equation can express the absorption of the target sample

$$A = -\log_{10} \left(\frac{I_0}{I} \right) = r\alpha_m lc \quad (5)$$

where I and I_0 are input and output intensities accordingly, l is the fiber length, c is the analyte concentration, and α_m is the absorption coefficient. The basic mode of light propagates through the fibre and covers an area of the core called the effective area, which is different from the geometrical size of the core. The effective area (A_{eff}) is primarily determined by the operational wavelength of the light and the modal power coverage of the core region, both of which can be calculated using the following equ.[22]

$$A_{\text{eff}} = \frac{(\iint |E|^2 dx dy)^2}{\iint |E|^2 dx dy} \quad (6)$$

Where, E is the optical power, the RI difference between x and y polarization modes are known as birefringence. The equation[23] can be used to describe birefringence occurrences.

$$B = |n_x - n_y| \quad (7)$$

Where n_x is effective RI of x polarization and n_y is effective RI of y polarization. The birefringence feature causes a periodic power exchange between two orthogonal components, and this period is known as the beat length[24], which is given in the Eq (8)

$$L_B(\lambda) = \frac{\lambda}{B(\lambda)} \quad (8)$$

The numerical aperture (NA) is a critical metric that indicates the fiber's light gathering capacity. A PCF with a higher NA is predicted to perform better as a sensor because more light can be captured by the fibre and steered in the core. PCF's global parameters can be tweaked to modify the NA. The relationship of the equation [25],[26] determines the NA.

$$NA = \frac{1}{\sqrt{1 + \frac{\pi x A_{\text{eff}}}{\lambda^2}}} \quad (9)$$

4. Results and discussions

This paper analyses the gas sensor structures of 4E-PCF, 4C-PCF and 8E-PCF. The performance of the PCF is determined by various parameters, such as relative sensitivity, n_{eff} , A_{eff} , birefringence, NA and beat length.

4.1 Sensitivity

The relative sensitivity of three different designs is shown in figure 3. The five other toxic gases pass through the three different designs' core region. The resonance wavelengths and relative sensitivities are calculated as analyte RI functions.

Figure 3: Relative Sensitivity of (a) 4C-PCF (b) 4E-PCF (c) 8E-PCF

Figure 3 (a) represents relative sensitivity of 4C-PCF, whose sensitivity values at 1.3μm for the following RI 1.40965, 1.41156, 1.461, 1.472, and 1.5086 are 25.816%, 25.982%, 30.647%, 31.785%, and 35.824% the wavelength of 0.9μm to 1.3μm. The light confinement occurs only between 0.9μm to 1.3μm wavelength; above and below this frequency, the sensor will not confine the light. Figure 3 (b) represents the maximum sensitivity of 40.964%, 41.152%, 47.851%, 47.851%, 50.726% for the same RI sequence. It is noted that there is degradation in the performance of 4C-PCF due to the smaller size of the circular core holes compared to the elliptical core. The elliptical core modifies by increasing the number of core holes from four to

eight to achieve better results. Simultaneously, the center circle's size in the core is maintained in $0.5\mu\text{m}$ because of these two reasons, the sensitivity of the 8E-PCF is very high. The sensitivity of 8E-PCF for different gases at the wavelength of $1.3\mu\text{m}$ are 67.26%, 67.466%, 72.192%, 73.095%, 75.753%. Compared to 4C-PCF and 4E-PCF, the sensitivity of 8E-PCF is good.

4.2 Effective RI

Figure 4: n_{eff} of (a) 4C-PCF (b) 4E-PCF (c) 8E-PCF

The n_{eff} is drawn for the wavelength range of $0.9\mu\text{m}$ to $1.3\mu\text{m}$ and it is shown in figure 4. In all three cases, the effective mode index decreases as the wavelength is increased to its maximum value. From the graph it is clear that the effective refractive index is inversely proportional to the wavelength. The distribution of power in the different core for both x and y polarization is shown in Figure 5.

Figure 5: Different polarization mode of (a-b) 4C-PCF (c-d) 4E-PCF (e-f) 8E-PCF

It is found that there is a difference in the mode field through the core region. As a result, there is a difference in effective index between the polarization modes with respect to wavelength. The light confinement in all three methods can be seen in figure 5. The light confinement in the 8E-PCF gas sensor is more efficient than the other two methods.

4.3 Birefringence

The Birefringence for three methods is analyzed and shown in Figure 6. The circular core design 4C-PCF has different birefringence values for five other gases with the maximum birefringence value of 0.0387. For the elliptical core 4E-PCF, the birefringence region is less compared with the 4C-PCF design and its maximum birefringence value is only 0.0013, and finally for 8E-PCF the birefringence range is 0.0166 to 0.0421. Comparatively, the birefringence of 8E-PCF is high with a negligible confinement loss.

(c)

Figure 6: Birefringence of (a) 4C-PCF (b) 4E-PCF (c) 8E-PCF

The birefringence of three different core shapes is analyzed for five different gases. From this analysis it is understood that the gas with high refractive index produce good results i.e., the SnCl_4 gas produce good sensitivity for all the three design. The birefringence of the 8E-PCF gas sensor is high in the order of 0.0421 and is greater than that reported in [27, 28, and 29]. Birefringence is on the increase for two reasons. The first reason is that the RI of the material increases, the second reason is an increase in the core size of the birefringence and the third reason is the wavelength increases the refractive index difference between the x-polarized mode and y-polarized mode of light increases.

4.4 Effective Area (A_{eff})

(a)

(b)

(c)

Figure 7: Effective area of (a) 4C-PCF (b) 4E-PCF (c) 8E-PCF

Figure 7(a-c) demonstrated the different effective mode area of the core for different core design. The maximum A_{eff} of 0.636, 1.19 and 2.53 is achieved at 4C, 4E and 8E-PCF respectively for SnCl_4 gas which has high RI compare to other four gases. With increasing wavelength the A_{eff} is increasing this is because the optical power traveling through a PCF waveguide with a wider wavelength, which takes use of the core's larger area that provides better effective mode area. From the comparative graph it is clearly shown that the maximum A_{eff} value is achieved for 8E-PCF at higher RI gas.

4.5 Numerical Aperture

(a)

(b)

(c)

Figure 8: Numerical Aperture of (a) 4C-PCF (b) 4E-PCF (c) 8E-PCF

NA is the significant parameter of fiber, which depends on the effective area and wavelength. Figure 8 depicts the NA graph for three different designs. It is determined that the NA for the 4C-PCF and 4E-PCF designs is decreasing for all gases except SnCl₄. This is due to two factors. The first is that the RI of SnCl₄ is high in comparison to other gases. As the RI of gas increases the light confinement is good which in-turn increase the NA and the second reason is the number of elliptical holes in the core region is more in 8E-PCF gas sensor. From the equation of the NA, it is clearly understood that the NA is directly proportional to the wavelength.

4.6 Comparison of 4C, 4E, and 8E-PCF gas sensor design

Figure 9 shows a comparison of relative sensitivity, n_{eff} , A_{eff} , birefringence and NA in three different designs. Among five different gases SnCl₄ produces better results this is because as the RI of the material increases all the parameters gives good results for this reason only SnCl₄ is considered. The graph shows that the relative sensitivity of SnCl₄ is 75.753% for 8E-PCF, which is greater than the other two methods. Figure 9 shows that the n_{eff} decreases in all three directions as the wavelength increases. The birefringence value is high compared to the other two. Comparatively, 8E-PCF provides good results due to the core arrangement. As the number of core holes increases, various optical fiber parameters produce good results.

Table II: Comparison of 4C-PCF, 4E-PCF, and 8E-PCF Sensor Design

S	Types of	4C – PCF Gas Sensor	4E-PCF Gas Sensor	8E-PCF Gas Sensor
.				

N o	Gases	Sensitivity (%)	n_{eff}	Birefrin gence (B)	Effective Area (A_{eff})	Sensitivity (%)	n_{eff}	Birefrin gence (B)	Effective Area (A_{eff})	Sensitivity (%)	n_{eff}	Birefrin gence (B)	Effective Area (A_{eff})
1	SO ₃	25.816	1.5014	0.03	0.398	40.964	1.4727	0.0013	0.937	67.26	1.4367	0.0005	2.58
2	CCl ₄	25.982	1.5019	0.0301	0.402	41.152	1.4735	0.0013	0.943	67.466	1.4379	0.0009	2.58
3	SiCl ₄	30.647	1.516	0.0339	0.516	47.851	1.4945	0.0007	1.12	72.192	1.4692	0.0005	2.55
4	SnCl ₄	31.785	1.5194	0.0349	0.544	47.851	1.4997	0.0006	1.14	73.095	1.4765	0.0342	2.53
5	C ₁₀ H ₁₆	35.824	1.5319	0.0387	0.636	50.726	1.5184	0.0004	1.19	75.753	1.5015	0.0421	2.45

Table II provides sensitivity, n_{eff} , A_{eff} and birefringence values for three different sensor designs for 1.3 μ m wavelength. It is understood from the table II that the 8E-PCF gas sensor yields best results compared to the 4C and 4E-PCF gas sensors.

(a)

(b)

(c)

(d)

(e)

Figure 9: Comparison of three different designs for SnCl₄ gas

From the above analysis, it is inferred that the 8E-PCF gas sensor produces excellent results for the SnCl₄ gas whose RI is 1.5086. The parameters such as sensitivity, n_{eff} , Effective area, birefringence and numerical aperture produce best results for this sensor. Numerical Aperture is a dimensionless parameter, it decide the amount of light compilation. For broad scope of sensing application the NA should be high, the 8E-PCF gas sensor with Sncl₄ RI produce high NA of 0.424 which is high compared to other designs.

Considering above advantages the 8E-PCF gas sensor at 1.5086 RI is used to detect the beat length. The beat-length is an important argument for finding birefringent optical fibers. When the phase difference between two orthogonal polarization states varies 360°, it specifies the optical signal transmission length through the fiber[30]. This trait causes two orthogonal components to swap power on a regular basis. From the graph shown in figure 10, the beat length decreases as the wavelength increases. Beat length is significant because it is a key indicator of an optical fiber's ability to maintain polarization. A fiber with a short beat length will keep its polarization better than a fiber with a long beat length. The 8E-PCF gas sensor which uses Sncl₄ as RI produce very less beat length of 30.87, which is very less compared with other design.

Figure 10: Beat length with respect to Wavelength

4.7 Fabrication feasibility

The fabrication feasibility is a critical issue in the design of PCFs. The main challenge for designing the proposed guiding structure is the central area, where the core region is an ellipse air hole. Currently, fabrication procedures such as boring, sol-gel, passageway stacking, stacking, and attraction are widely used to make PCFs. However, recently, the sol-gel [31-37] technique is more effective in making sensor PCFs. A sol-gel technique for fabricating PCFs with varying structures was proposed, allowing the freedom to adjust the air-hole shape, size, and spacing. Although more versatile methods, such as stack and draw and extrusion, are efficient, they are limited to lower porosities or soft glasses only [38].

5. Conclusion

In this proposed work, the elliptical core Topaz-based PCF sensors have been thoroughly examined using COMSOL Multiphysics. We also discussed the design of the three different types of novel PCF-based 4C-PCF, 4E-PCF and 8E-PCF gas sensors operated in the frequency range from 0.9μm to 1.3μm and analysed the effects of sensitivity, n_{eff} , birefringence, Effective area, Numerical Aperture and beat length on sensing performance. The three proposed gas sensors, 4C-PCF, 4E-PCF and 8E-PCF, are compared. Among these designs, the simulation results of the 8E-PCF gas sensor produce a high relative sensitivity of 75.75%, a high birefringence of 0.0421 for SiCl₄ at 25°C, with a RI of 1.5086, the numerical aperture of 0.424 is achieved in 8E-PCF gas sensor and the A_{eff} of 2.55μm². Moreover the proposed method produces a low beat length, which is best suitable for the optical fiber sensor. The micro-structured 8E-PCF with the above properties is best suited for practical applications in optical

sensing, optical waveguides and numerous photonic devices. The 8E-PCF gas sensor can be manufactured using the current manufacturing technology. These PCF sensors are used to detect harmful gases that cause serious problems within industries, smart cities using the Internet of Things (IoT).

Table III: Comparison of the proposed 8C-PCF sensors with other designs.

S.No	Sensor type	Sensitivity (%)	NA	Birefringence
1	Index guided PCF [9]	13.23%	--	--
2	Two rings circular PCF [10]	13.94%	--	--
3	Circular PCF gas sensor [14]	72.04 %	--	--
4	Hexagonal hybrid porous core PCF [15]	21.2%	--	--
5	PCF Mach–Zehnder interferometer [16]	26.62 pm ppm ⁻¹	--	--
6	Rectangular Slotted Porous Core Photonic Crystal Fiber (RSPC-PCF) detect CO ₂ [39]	24%	0.27	0.035
7	Slotted core PCF [27]	48.26%	--	2.17x10 ⁻²
8	Zeonex based PCF for alcohol detection [29]	68.128%	--	0.176
9	Micro-cored PCF [24]	53.07%		6.9x10 ⁻³
10	Spiral Shape PCF Sensor [40]	57.61%	--	6.29 × 10 ⁻⁴
11	Index guiding PCF gas sensor [17]	Sensitivity was enhanced to 62.07% and 67.07%	--	--
12	Ammonia Measurement in human breath[18]	63.18%	--	--
13	Quasi – PCF gas sensor [38]	64.69%	0.185	--
14	8E-PCF (Proposed Method) SnCl ₄	75.75%	0.424	0.0421
15	8E-PCF - SO ₃	68.05%	0.410	0.0006
14	8E-PCF - CCl ₄	72.84%	4155	0.0005

15	8E-PCF - SiCl ₄	68.23%	0.417	0.0008
16	8E-PCF - C ₁₀ H ₁₆	73.25%	0.418	0.0402

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