Design of High Sensitive Hybrid Honeycomb Photonic Crystal Fiber for Sensing C 8 H 8 O 3 /AsCl 3 /C 8 H 10 Analyte

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Abstract

A hybrid structured honey-comb photonic crystal fiber sensor is designed to detect the sensitivity of methyl salicylate ($C_8H_8O_3$), arsenic trichloride ($AsCl_3$), and ethylbenzene (C_8H_{10}) analytes. The cladding portion of the proposed structure consists of both circular and hexagonal holes in the form of a hexagon with a honeycomb arrangement. Moreover, the structure has a circular core with the chosen analyte. The design is investigated in the scope of wavelength ranging from 0.4 µm to 1.75 µm. The hybrid photonic crystal fiber sensor displays a sensitivity of 85.05%, 87.89%, 82.73% for methyl salicylate, arsenic trichloride, and ethylbenzene, respectively at 1.550 µm.

1. Introduction

In recent years, sensing of a high toxic analyte using Photonic Crystal Fibre (PCF) has gained interest among researchers due to the increasing demand for testing at the point of need of a particular analyte with improved sensitivity. Although various types of detection mechanisms, namely, electrochemical biosensors, acoustic sensors, optical sensors, magnetic sensor, micro-electro-mechanical systems-based sensor, radio frequency identification based capacitive sensor and thermometric sensors are available in the literature, they suffer from sensitivity and selectivity of the sensing due to the dimensional and temporal aspects of the sensing mechanism. Moreover, the sensor should detect the analyte in either of the gas, liquid, and solid forms. This motivated us to design a novel photonic crystal fiber sensor that allows the analyte and sensing materials to interact using the sensing mechanisms. The photonic crystal fiber is principally a fiber with an arrangement of air holes that achieves uniform features that are imaginary in standard optical fibers [1–4].

Photonic crystal fiber has an exceptional degree of changing the fundamental parameters of conventional fiber and thus demonstrating the wonderful structure adaptability. The auxiliary parameters limit the light in the core that influences the propagation features. Likewise, compact size, reduced cost, and resilience in perilous situations make PCF-based gadgets useful in different situations [6–11]. The optical fiber is known as waveguides that apply to light transference applications. In PCF, the center portion of the optical fiber is encircled by a layer called cladding that is depicted by a refractive index which is less concerning the centered core refractive index. The arrangement of core and cladding in PCF enables the total internal reflection for the propagation of light inside the waveguide [13–24].

The authors in [1] have made a detailed review of the design of PCF for sensing toxic and non-toxic gases. The importance of hollow-core PCF towards the detection of acetylene, methane, ammonia, nitrogen, oxygen, propane, ethane, carbon dioxide, toluene, acetone, hydrogen cyanide, hydrogen, carbon monoxide, and nitrous oxide has been discussed in detail. The fundamental limits in terms of the wavelength of operation, sensing principle, fiber length, response time, and detection limit have been formulated. The authors in [2] have designed hexagonal structured circular air holes with asymmetrical circular core regions. The core region consists of two different air holes to detect human mucosa and glucose analyte. These analyte display a sensitivity of 47.31% and 47.59% at the wavelength ranging between 0.6 μm and 1.3 μm. Moreover, the PCF structure displays a confinement loss of 6.54x10-4 dB/m with a birefringence of 0.0027.

For sensing ethanol, benzene, and water, the authors in [3, 36] have designed a five-layered heptagonal cladding with circular air hole PCF that operates at 1 THz frequency range. The PCF consists of a three-layered circular rotated hexa-core with a confinement loss between 1.92 dB/m to 2.13 dB/m and sensitivity ranging between 66.78–69.20%. The authors in [4] have designed a circular cladding with rectangular slotted core-based PCF for sensing carbon dioxide gas. It exhibits a maximum sensitivity of 24%, confinement loss of $12x10^{-4}$ dB/m, non-linearity of 0.6 $W^{-1}m^{-1}$, and birefringence of 0.035. The authors in [5] have designed an index-guided PCF with a circular cladding region and having an arrangement of the hexagon for detecting temperature and strain. The PCF consists of a hollow core with an elliptical structure at the outermost region of the core. The center of the PCF has two different elliptical rings that are arranged on the upper and lower side so that the PCF exhibits high birefringence of $1.5x10^{-2}$ for a wavelength of 1550 nm.

The authors in [9] have designed a three-layered nano solid core PCF to identify liquid glycerol, ethanol, and toluene analyte in wavelength ranging between 1.4 μm and 1.65 μm. The cladding consists of a five-layered circular structure with circular holes. The sensitivity of the structure ranges between 6.165–65.16% for a confinement loss of 9.2×10^{-6} dB/m and an effective area of 3.07 μm^2. The authors in [12] designed PCF using circular structured core and cladding air hole to detect formalin. The sensitivity of the PCF varies between 22–29% for the wavelength between 600 nm to 1600 nm. The authors in [25] have made a detailed analysis of the hybrid structured circular and elliptical air holes with the hexagonal arrangement in the cladding region. In this PCF, the inner three layers and the outer two layers of the cladding are made of the circular ring and the middle layer is made of elliptical rings. The core part of the PCF consists of circular rings that are arranged in porous form for sensing ethanol analyte. The hybrid PCF provides a sensitivity of 62.19% with a confinement loss of $5.56x10^{-11}$ at the wavelength of 1330 nm.

The authors in [26] have designed non-linear PCF with hexagonal cladding that consists of five layers of homogeneous circular air holes. The hollow core consists of a single hexagonal structure and the design is capable of detecting benzene, chloroform, ethanol, and water at the wavelength of 1.55 μm. The confinement loss in the structure is found to be 10^{-10} dB/m. The non-linearity of the structure varies between 29 W^{-1} km^{-1} to 33 W^{-1} km^{-1} with an efficiency between 88.93–97.89%. The authors in [30] have designed a two-layered PCF with gold-coated nano-film-based biosensor using the principle of surface plasma resonance. Both the core and cladding part of the biosensor follows a circular air hole with fused silica as the base material. The biosensor provides a birefringence of $1.9x10^{2}$ with improved sensitivity.

Although various photonic crystal fiber-based sensors have been suggested in the literature, the structural arrangement is commonly homogeneous that limits the operating wavelength and the type of analyte to be sensed [27–29]. On a very basic level, the structural arrangement of core and cladding in PCF resolve the operating wavelength, sensitivity, absorbance, birefringence, number of modes, dispersing, confinement loss, non-linearity, effective area, and polarization [31–36]. Hence, this paper proposes a hybrid arrangement of circular and hexagonal holes in the arrangement of honeycomb. Moreover, the proposed hybrid PCF provides the detection of methyl salicylate, arsenic trichloride, and ethylbenzene with improved sensitivity. In this structure, the hollow core is made circular and it is filled with the above liquids and the cladding consists of silica substrate with air holes.

The remainder of the paper is planned as follows: The requirement for the detection of methyl salicylate, arsenic trichloride, and ethylbenzene has been detailed in Section 2. Section 3 describes the strategy of the hybrid honey-comb photonic crystal fiber sensor. Results and discussion is described in Section IV and Section V concludes the major findings of the manuscript.

2. Detection Of Methyl Salicylate, Arsenic Trichloride And Ethylbenzene Using Pcf

The principle in the detection of analytes (Methyl Salicylate, Arsenic Trichloride, and Ethyl Benzene) using photonic crystal fiber sensor is through the amount of light interaction with the sample under test. The extent of light-matter interaction to be sensed depends on the absorption factor at a specific wavelength and the design of the core and cladding of the photonic crystal fiber. The light-matter interaction can be formulated using Beer-Lambert law and the ratio of the amount of the light due to the sample under test ($A(f)$) and the amount of light with the absence of sample under test ($A_0(f)$) can be formulated as follows [14]:

$$\frac{A\left(f\right)}{A_0\left(f\right)}=e^{-S_r\alpha_m l_c}$$

1

where S_r refers to the relative sensitivity of analyte, α_m refers to absorption factor of the sample under test, l_c denotes the channel length and f denotes the operating frequency. The logarithmic ratio of $I(f)$ and $I_0(f)$ refers to the absorbance (A) of the target analyte and it can be formulated from Eq. (1) as follows:

$$A=\log\left(\frac{A\left(f\right)}{A_0\left(f\right)}\right)$$

2

$$A=-S_r\alpha_m l_c$$

3

The spectral absorbance defined in Eq. (3) resolves the transmittance of a particular wavelength through a photonic crystal fiber sensor for a given analyte and it depends on the structure of the photonic crystal fiber.

Need for the detection of Methyl Salicylate ($C_8H_8O_3$)

Methyl salicylate has been identified as a volatile organic compound that is released by plants that leads to fungal infection. Hence, early detection of methyl salicylate leads to the identification of plant infection. In the medical sector, methyl salicylate is used widely to treat minor body aches, joint, and muscle pains. However, the salicylate in methyl salicylate is harmful due to its dermal absorption and toxicity. The dialysis patients are highly infected due to the toxic behavior of salicylates. Although there are various electrochemical sensing methods for the detection of methyl salicylate, they suffer from limited shelf life and cross-sensitivity of other analytes. Hence, this study provides an alternate sensing method using photonic crystal fiber with improved sensitivity.

Need for the Detection of Arsenic Trichloride ($AsCl_3$)

Arsenic trichloride is an inorganic compound that is highly toxic, colorless, and found as an intermediate during the manufacturing of organoarsenic compounds. The critical requirement for the detection of arsenic trichloride is due to the presence of a various arsenic compound in water that leads to contamination. The World Health Organization (WHO) has provided guidelines regarding the amount of arsenic in water (10 µg L^{-1}). In literature, the presence of arsenic trichloride is detected by mass spectrometry, chromatography, and optical methods. However, the sensitivity of these methods varies based on the amount of arsenic traces found in seawater, river, and freshwater. This demands a simple and efficient method for the detection of arsenic trichloride using photonic crystal fiber.

Need for the Detection of Ethyl Benzene (C_8H_{10})

Ethylbenzene is an organic compound that is toxic, colorless, and highly flammable. It is found in biological fluids, petroleum products and primarily used in the making of styrene. Exposure to ethylbenzene in the air results in acute respiratory effects, irritation of eyes, dizziness, and urinary infections. In literature, gas chromatography has been widely used for the detection of ethylbenzene. However, the detection of gas chromatography is limited to volatile samples and cross-sensitivity to the complex mixture. Hence, this demand for sensing using high sensitive photonic crystal fiber.

3. Design Of The Proposed Hybrid Honey-comb Pcf

The light propagation within the proposed hybrid photonic crystal fiber follows the total internal reflection of light. In the photonic crystal fiber, the cladding zone includes various air gaps, while the core is loaded up with synthetic substances and therefore the refractive index of the center substance remains greater than the cladding. Here, silica is utilized in the photonic crystal fiber at the external cladding. In the proposed structure, a hybrid structure is formulated that consists of circular and hexagon air holes at the cladding. The hybrid honeycomb-based photonic crystal fiber has been displayed in Fig. 1. The cladding part of the photonic crystal fiber consists of a circular air hole surrounded by a hexagonal pattern. The number of hexagonal holes surrounding the circle hole equal to six. Moreover, the three regions of circular holes in cladding are structured in a hexagonal pattern beside hexagon holes. Arrangement of hexagonal hole alone in the cladding section form a homogeneous honeycomb structure and the design of hexagonal and circular hole in the cladding section form the proposed hybrid honey-comb photonic crystal fiber. The mode field distribution of the hybrid honey-comb photonic crystal fiber along x and y polarization has been displayed in Figure. 2 (a) and Figure. 2 (b), respectively.

The diameter of the hollow circular core (dc) area in which we introduce the analyte, namely, methyl salicylate (n = 1.538), arsenic trichloride (n = 1.6), ethylbenzene (n = 1.495) for the wavelength ranging between 400 nm to 1500 nm. The hexagonal and circular air holes are of diameter d1 equal to 2 μm and d equal to 1.5 μm, respectively. The pitch (Λ) in the cladding region equal to 1.9 μm. In the design, the arrangement of the hole from the middle part of photonic crystal fiber is given by θ_n and it equals to (n*360)/(2*N). Here, N refers to the number of round rings, and n refers to ring number. The angular pitch in the hybrid PCF has values equal to 2π/3, π/3, and π/6.

The sensing behavior of the photonic crystal fiber is characterized by sensitivity, birefringence, and effective area. These properties are analyzed by a limited component strategy using comsol multi-physics. The light analyte interaction in the proposed hybrid photonic crystal fiber is given by the ratio of the amount of signal power in the core to the total amount of signal power in the structure. The intensity of the light analyte interaction ($P_{H\text{-}PCF}$) is expressed as follows [36]:

$$P_{H-PCF} = \frac{\iint_{holes}(Ex*Hy - Ey*Hx)dxdy}{\iint_{total}(Ex*Hy - Ey*Hx)dxdy} * 100 \quad (4)$$

where Ex and Ey refer to electric fields and Hx, Hy denotes magnetic fields. The light analyte interaction is used to estimate the relative sensitivity (S_r) and it is given as the ratio of the product of refractive index of the core (n_r) and intensity to the real part of the effective mode index (n_{eff}). The relative sensitivity can be expressed as follows:

$$S_r = \frac{n_r * P_{H-PCF}}{\mathrm{Re}[\mathrm{n_{eff}}]}$$

5

Effective area (A_e) displays the proportion in which the energy in the electric field is distributed. A_e in a single-mode optical fiber decides how much energy the core can convey without causing non-linearity and signal losses (confinement) and effective area (A_e) is calculated as follows [4]:

$$A_e = \frac{\left(\iint |E|^2 dxdy\right)^2}{\iint |E|^4 dxdy}$$

6

where E is the electric component in which the light is transmitted. Birefringence (B) is the property of a material that depends upon the polarization and physical evenness of the core. The birefringence is given as follows:

$B=|nx-ny|$ (7)

where, n, y refers to the effective mode indices of x, y polarised methods of the engendered light.

4. Results And Discussion

The characteristics of the hybrid photonic crystal fiber, namely, the effective mode index, birefringence, relative sensitivity, and effective area are calculated using the finite element method. To overcome reflection in the proposed hybrid PCF, a perfectly matching layer is applied at the outermost part of the cladding. The wavelength dependency of methyl salicylate, arsenic trichloride, and ethylbenzene with reference to the actual mode index for x, y polarized modes has been displayed in Fig. 3. The analyte is applied at the core part of the hybrid PCF and the results display that effective mode index reduces with an increase in the wavelength of incident light. As compared to arsenic trichloride and methyl salicylate, the ethylbenzene displays a low effective mode index. At a wavelength of 400 nm, the effective mode index is maximum and found to be 1.59, 1.53, and 1.487 in methyl salicylate, arsenic trichloride, ethylbenzene, respectively. In Fig. 3, the dot and line display the actual mode index in x and y polarized mode.

Birefringence is calculated from the effective mode index of x, y polarized modes, and birefringence for methyl salicylate, arsenic trichloride, and ethylbenzene has been exhibited in Fig. 4, Fig. 5, and Fig. 6, respectively. As seen from the display the birefringence varies with a varying wavelength between 400 nm and 1750 nm. This variation in birefringence is due to the refractive index change at x and y polarized mode. Here, the sensing of the analyte improves with a larger birefringence profile. As seen in Fig. 4, the methyl salicylate is highly sensitive to wavelengths greater than 1400 nm. However, as seen in Fig. 5 and Fig. 6, the arsenic trichloride and ethylbenzene are sensitive to wavelengths in the range between 0.4 μm – 1 μm and 1.2 μm – 1.75 μm, respectively. The profile displays that the proposed hybrid PCF is a rightful candidate in sensing the methyl salicylate, arsenic trichloride, and ethylbenzene analyte.

Table 1
Comparison of various photonic crystal fiber sensor

Parameters	Senthil R et al. [9]	Zhou, C et al. [10]	Lu Y et al. [11]	Arif M.F.H et al. [12]	Hasan M.M et al. [13]	This Work
PCF structure	Circular pattern PCF	Hollow-core and hexagonal PCF	Hexagonal PCF with elliptical core	Hexagonal PCF with a hexagonal core	Heptagonal PCF	Hexagonal PCF with circular and hexagonal holes
Liquid	Ethanol, glycerol, and toluene	Water and ethanol	Water	Water and formaldehyde	Benzene, ethanol, and water	Methyl salicylate, Arsenic trichloride, Ethyl benzene
Wavelength range	1.4 to 1.65 μm	0.542 μnm	1.3 μm	0.6 to 1.6 μm	0.3 to 1.4 μm	0.4 to 1.75 μm
Relative sensitivity	65.16%, 61.65%, 64.05%	68.23%	41.36%	22–29%	63.24% 61.05% 60.03%	85.05%, 87.89%, 82.73%

The relative sensitivity and effective area of methyl salicylate, arsenic trichloride, and ethylbenzene analyte with reference to variation in wavelength are displayed in Fig. 7 and Fig. 8, respectively. From the profile, it is found that arsenic trichloride displays high sensitivity as compared to methyl salicylate ethylbenzene. The profile of the relative sensitivity curve displays an exponential decay pattern with an increase in the input signal wavelength. Alternatively, the effective area of ethylbenzene is high as compared to methyl salicylate and arsenic trichloride. The reason for a reduction in an effective area with an increase in the wavelength is that the proposed structure display reduction in the leaking of modes over the air holes. It can be inferred that for a wavelength of 1550 nm, sensitivity and effective area of methyl salicylate, arsenic trichloride, and ethylbenzene analyte corresponds to 85.05%, 87.89%, 82.73%, and $1.486*10^{-12}$, $1.417*10^{-12}$, $1.537*10^{-12}$, respectively. Moreover, the effectiveness of the proposed hybrid PCF with reference to the literature has been displayed in Table 1. As seen from the table and literature, no work has been reported to detect the toxic methyl salicylate, arsenic trichloride, and ethylbenzene analytes. As the proposed structure display high sensitivity, it can be used as an effective biosensor for early detection of plant diseases, water contamination, and medical applications.

5. Conclusion

A hybrid hexagonal-shaped honey-comb PCF sensor with a circular core is designed for sensing methyl salicylate, arsenic trichloride, and ethylbenzene analytes. The results display that very high sensitivity and effective area for a range of operating wavelengths is obtained using the hybrid PCF sensor. The proposed hybrid PCF sensor displays an effective area of $1.486*10^{-12}$, $1.417*10^{-12}$, $1.537*10^{-12}$ for methyl salicylate, arsenic trichloride, and ethylbenzene, respectively at 1550 nm. Moreover, due to the flammable and cross-sensitivity nature of the analytes using conventional sensing methods, the proposed hybrid PCF sensor proves to be an excellent point of need in various applications.

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Conflict of interest / Competing interests

The Authors confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Availability of data and material

The authors declare that any data related to this research will be made available on request.

Code availability

The authors declare that any code related to this research will be made available on request.

Authors' Contribution

All Authors are responsible for the correctness of the statements provided in the manuscript. The following contributions have been made by the Authors. Author 1 has made the conceptual design of the PCF sensor. The design of hybrid PCF sensor, interpretation of the results, and proofreading have been made by Author 2. The mathematical analysis of PCF sensor has been made by Author 3, the sensing of methyl salicylate and arsenic trichloride analyte has been made by Author 4, and the sensing of ethylbenzene analyte has been made by Author 5.

Ethics approval

The Authors declare that this research does not contain any studies with animal or human subjects.

Consent to participate

The authors declare that that this research does not contain any studies with humans or individual participants.

Consent for publication

The authors declare that that this research does not contain any studies with individuals or patients and hence no data is associated to be published.

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Figures

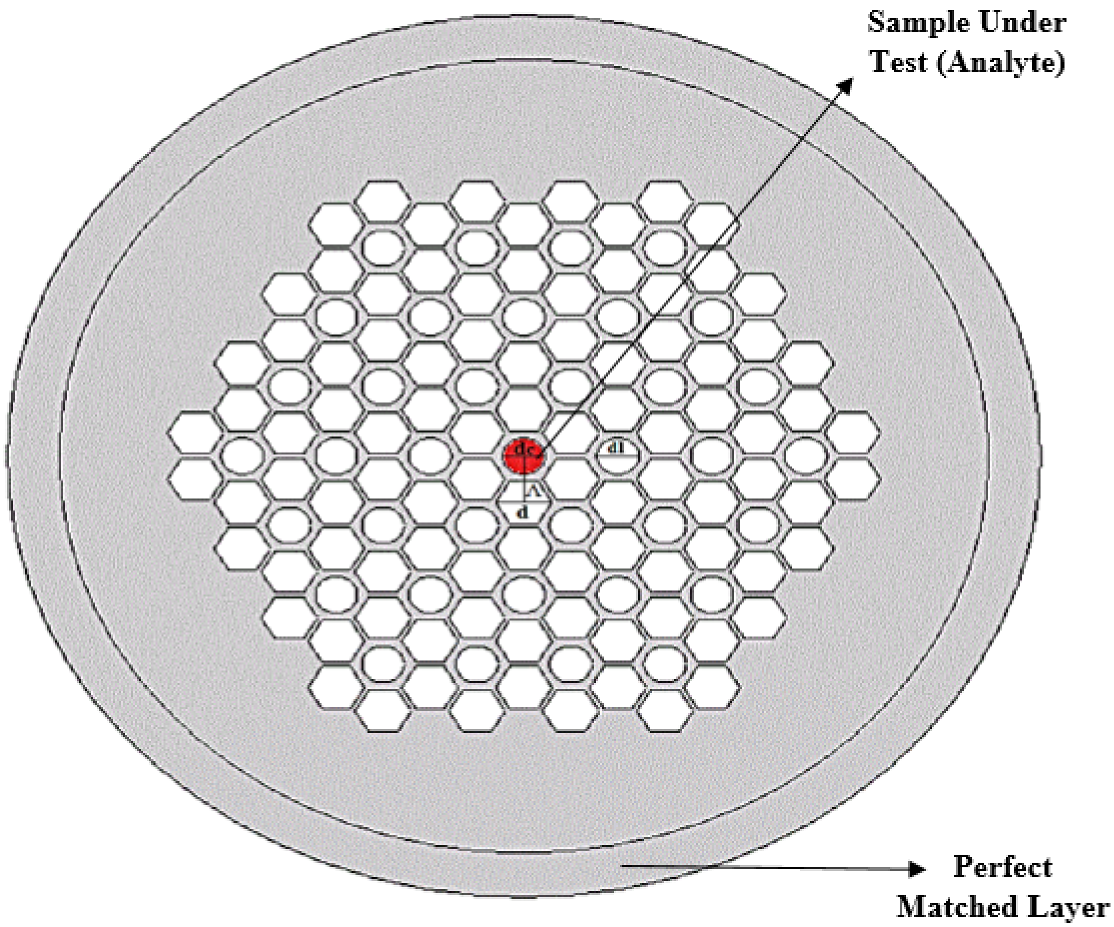


Figure 1

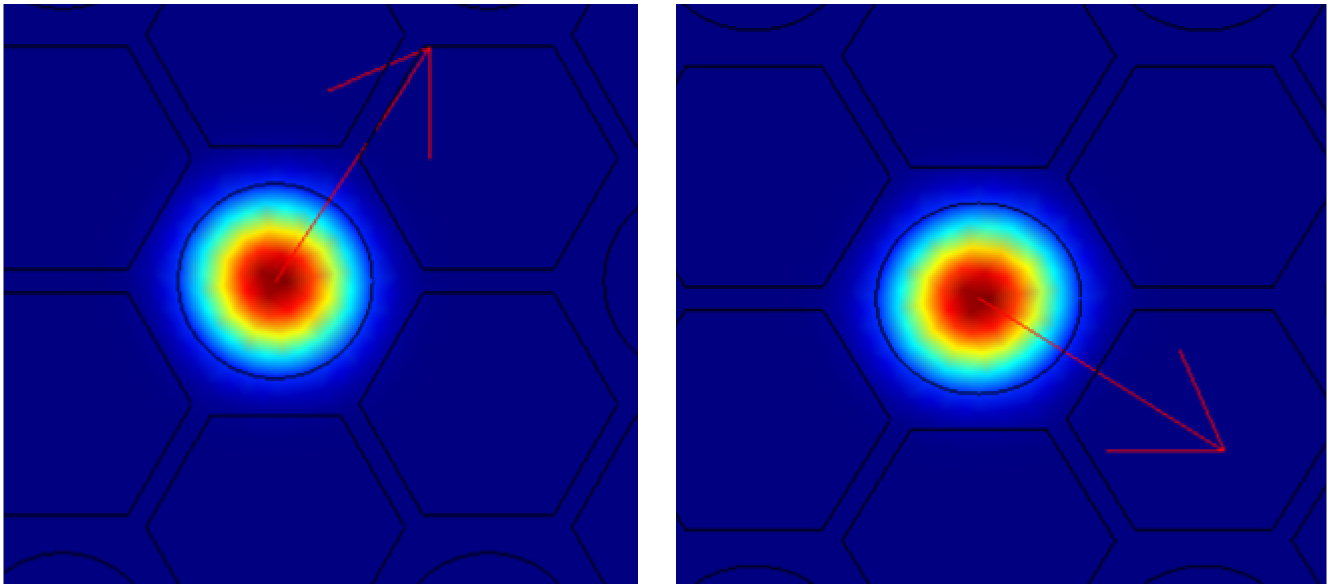
Cross-sectional observation of the hybrid honey-comb photonic crystal fiber

d – Diameter of cladding with a circular structure

d1 – Diameter of cladding with hexagonal structure

dc – Diameter of the core with a circular structure

Λ – Pitch



(a) (b)

Figure 2

Mode field distributions of the hybrid honey-comb photonic crystal fiber with

(a) X-polarization and (b) Y-polarization

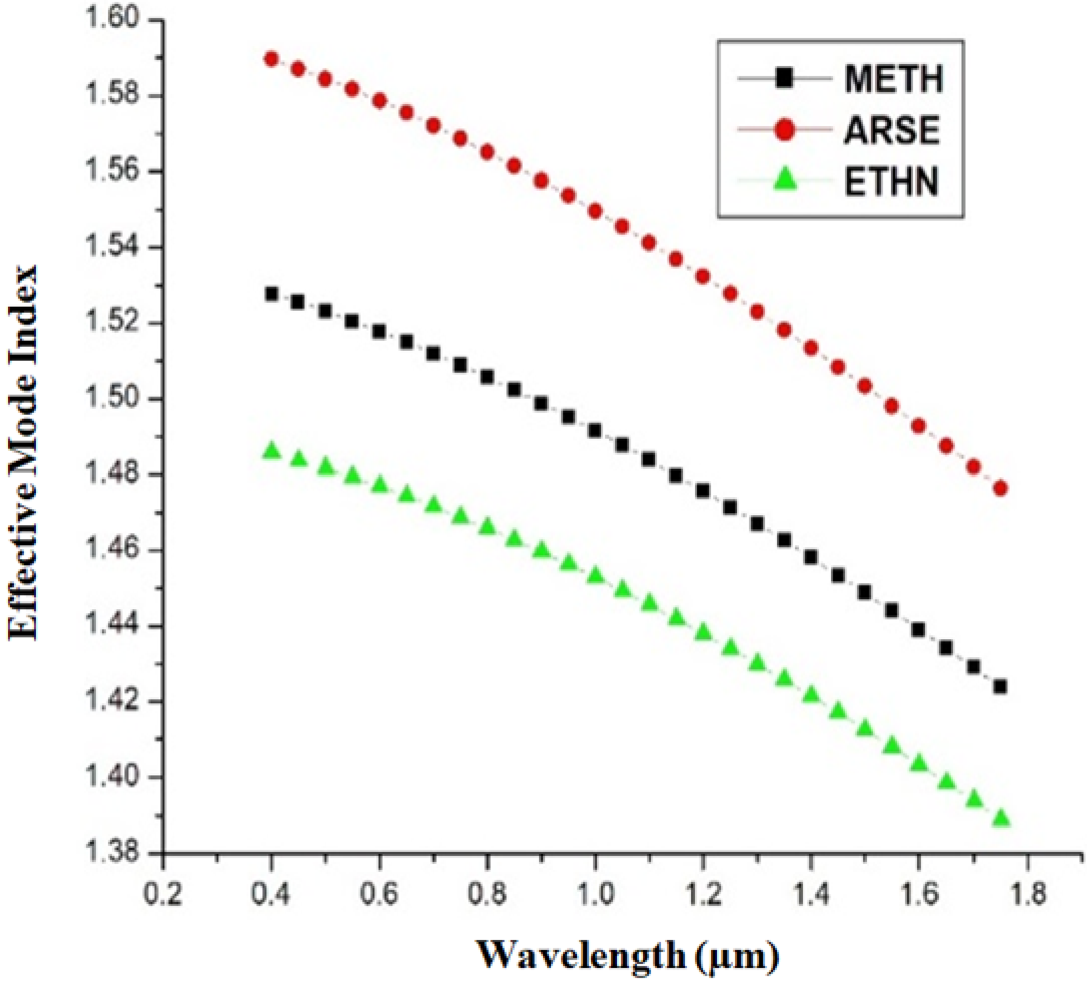


Figure 3

Effective mode index versus wavelength for hybrid honey-comb photonic crystal fiber (x (dotted) and y (line) polarized mode)

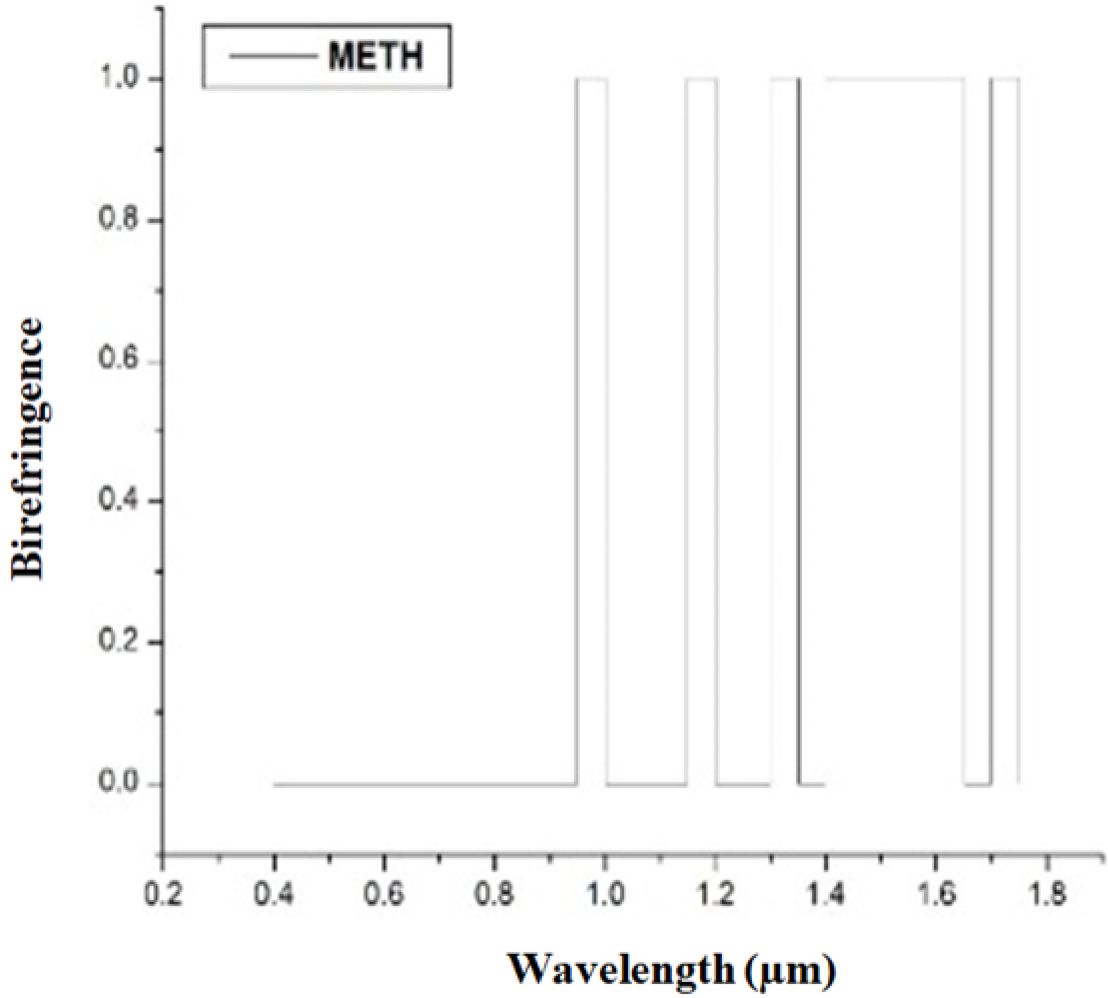


Figure 4

Birefringence versus wavelength for methyl salicylate (METH)

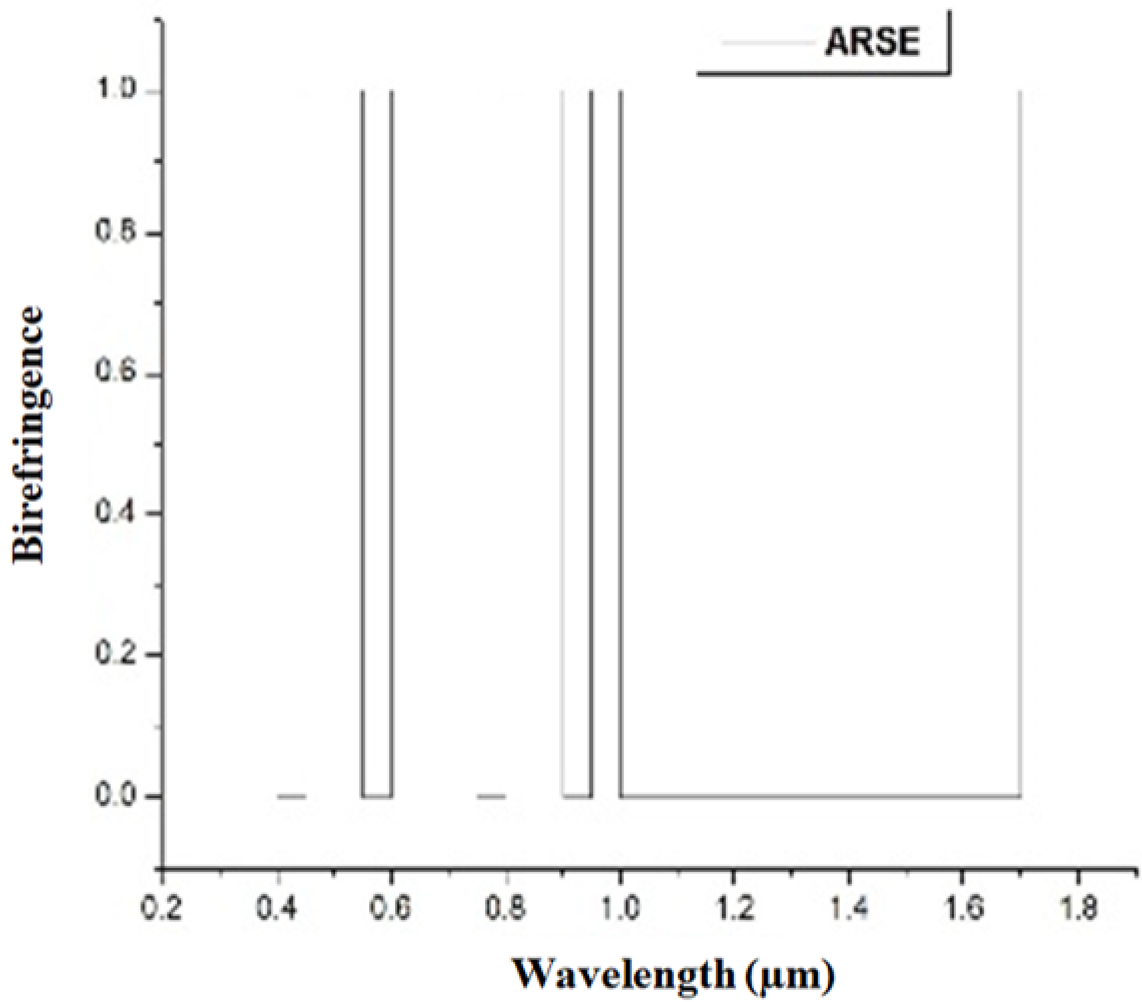


Figure 5

Birefringence versus wavelength for arsenic trichloride (ARSE)

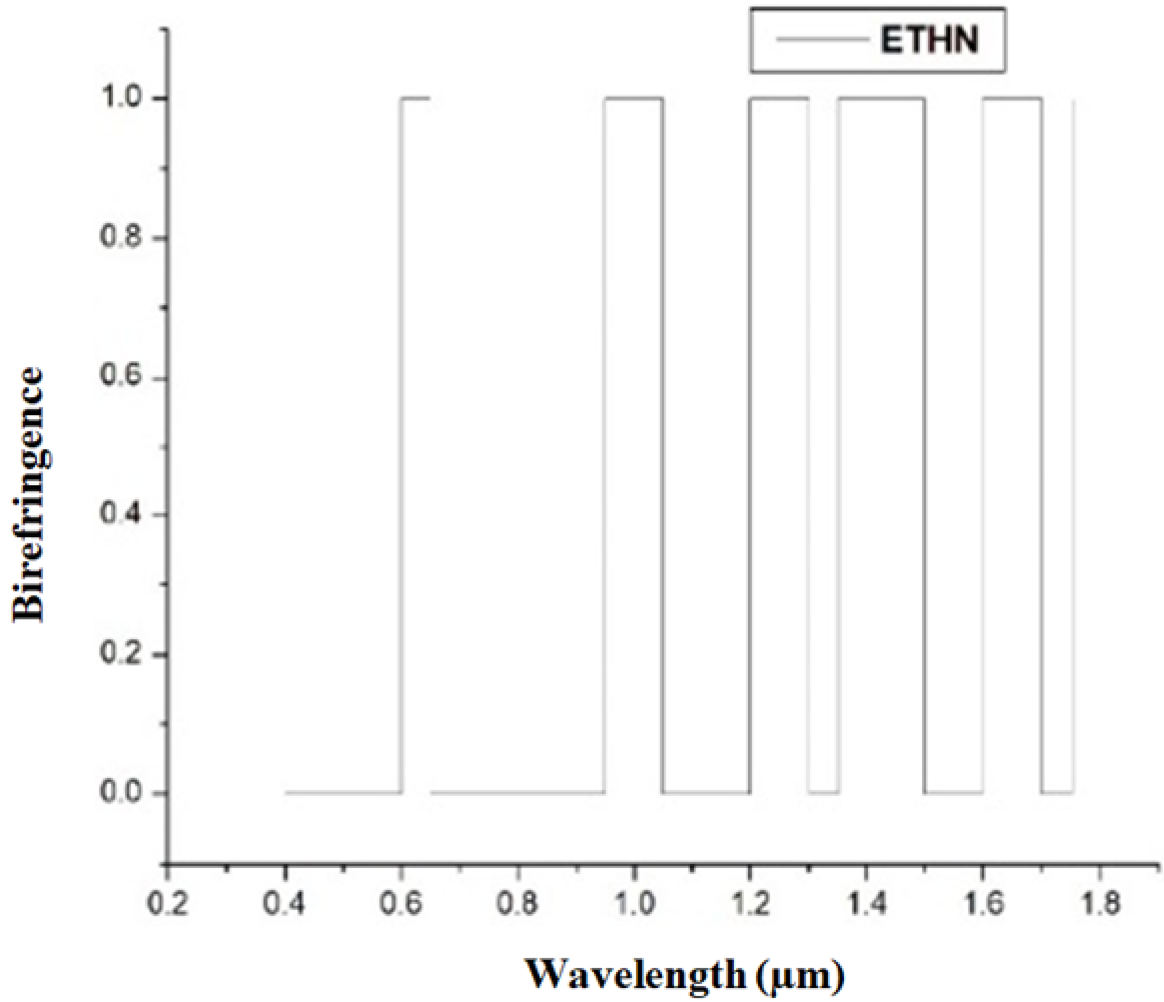


Figure 6

Birefringence versus wavelength for ethylbenzene (ETHN)

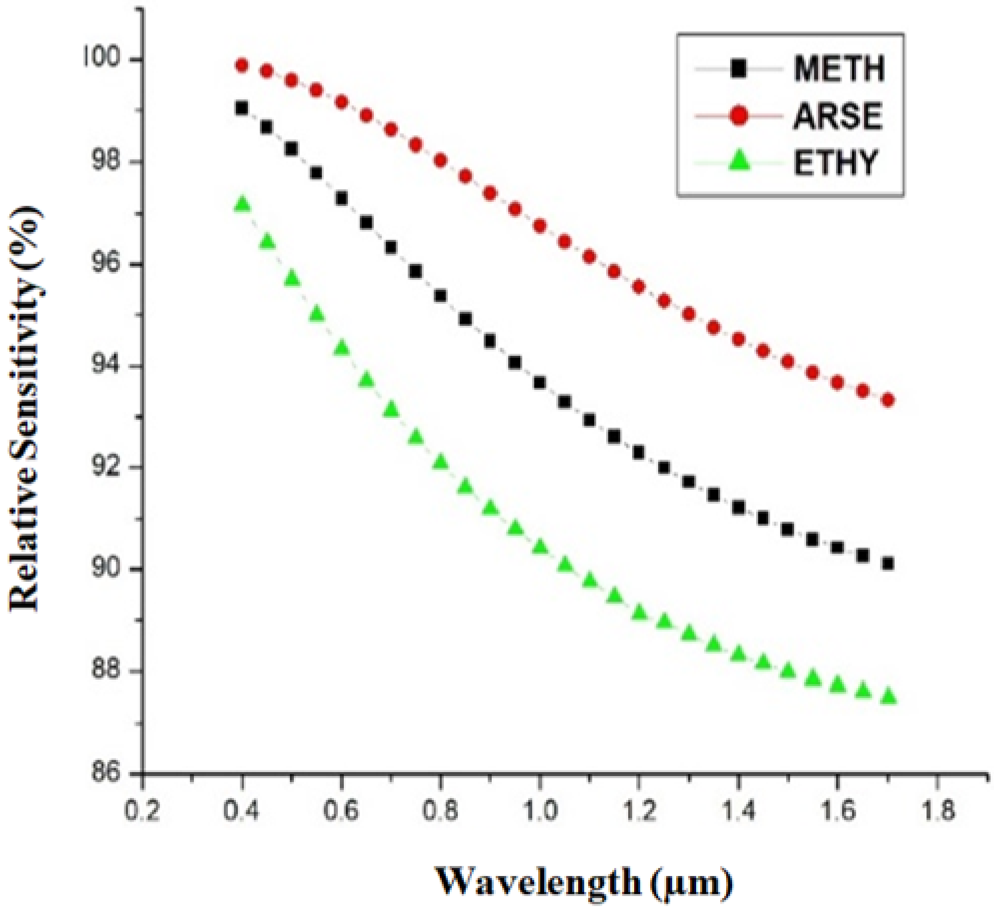


Figure 7

Relative sensitivity versus wavelength for methyl salicylate, arsenic trichloride, ethylbenzene

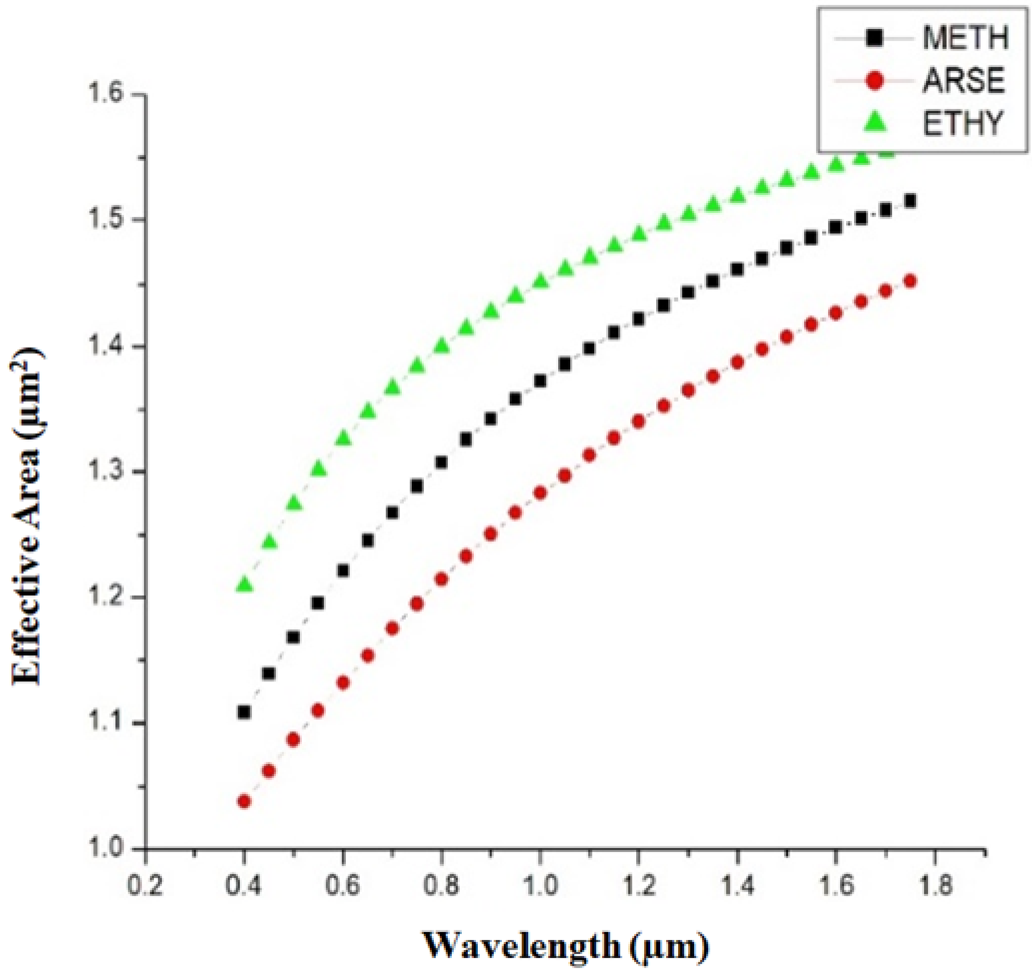


Figure 8

Effective mode area versus wavelength for methyl salicylate, arsenic trichloride, ethylbenzene