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Design and analysis of decagonal photonic crystal fiber with elliptical air hole core for liquid sensing

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In this paper, a decagonal geometry has been designed for liquid sensing. The liquid analytes that are sensed are ethanol, benzene and water as they are the most used analytes in the chemical and biological industries. Firstly, a decagonal structure has been designed and n_{eff} and sensitivity of this structure has been calculated. Then, the core structure has been modified and decagonal, octagonal and hexagonal geometries have been constructed inside the core with circular holes. Lastly, these circular holes have been replaced by elliptical holes. All the designed layouts have been analyzed and compared. The sensitivity obtained is of the order 40-50 % and confinement loss of order $10^{-9}\,dB/m$ which shows that these structures can be used for sensing ethanol, water and benzene and are reliable. For benzene, water and ethanol, the decagonal structure with core comprised of decagonal geometry, has been made of elliptical holes (x as major axis), gives the best results. For this geometry, the n_{eff} values are 1.379, 1.317 and 1.313 for benzene, ethanol and water, respectively. The sensitivity values obtained are 51.94%, 46.95%, and 44.45% and confinement loss value is 8.19×10^{-10}, 1.03×10^{-9} and $1.069\times10^{-7}\,dB/m$, respectively.

Keywords : Photonic crystal fiber, Index guiding mechanism, Sensitivity, Confinement loss, Photonic band gap (PBG)

1 Introduction

PCF (Photonic Crystal Fiber) is one of the most interesting topics in research area in the field of optics. It consists of central defect with number of air holes arranged in periodic fashion, running along the entire length of fiber [1, 2]. It has got various advantages over the conventional optical fibers. Light is guided in the PCF by two different methods so accordingly they are classified as: i) Index guided PCF and ii) Photonic bandgap PCF. In the index guided PCF, light is guided by total internal reflection [3, 4] whereas in PBG (Photonic Band Gap) PCF the presence of periodically distributed air holes in the cladding generates photonic bandgap [5, 6]. PCF has unique properties like high non-linearity, ultra-flattened chromatic dispersion [7, 8], low confinement loss, small effective area [9, 10] *etc.* which makes it suitable for applications in diverse fields like biomedical, spectroscopy, pulse compression. Other advantages include their capability of usage under unfavorable environmental conditions such as high voltages, noise, nuclear radiation, strong electromagnetic fields, at high temperatures, in explosive or chemically corrosive media and others.

In the field of sensing, PCF is it's in youth stage. The PCF based sensors were first developed in 2000. Since then PCF have found immense growth in this area. PCF has become a very interesting choice for making fiber sensors because it has got various properties which makes it suitable for creating sensors [11]. Sensing in fiber is defined as the evanescent field interaction between samples filled in core with the light propagating in the fiber in a very well controlled manner [12].

PCF can be used for creating sensors by varying the size and location of holes in cladding and/or core. The variation in mode shape, birefringence, air filling ratio, non-linearity, dispersion gives PCF advantages over conventional optical fibers because they can reach values which are not imaginable by the latter. The presence of air hole in core provides a great opportunity of filling it with gas/liquids to check its interaction with the light propagating in the fiber [13].

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2 Structural and Theoretical Modeling

A decagonal microstructured PCF has been designed, where air holes which constitute the cladding, are arranged in a decagonal pattern with pitch (Λ) (hole to hole spacing) and is 1.23 µm and diameter of each hole (represented by d) is 0.75 µm. For decagonal geometry, vertices of adjoining air holes make an angle of 36˚. There are total 6 rings in the geometry. The core structure is varied by taking decagonal, octagonal and hexagonal geometries made up of (i) circular holes and (ii) elliptical holes. The holes in the core have diameter 0.32 µm and pitch 0.5 µm. When the circular holes are changed to elliptical for enhancing the sensitivity, the ellipticity is taken as 1.64. The designed architecture is shown in Fig. 1 (a, b, c) and Fig. 2 (a, b, c) (only core portion is shown).

The background material in the fiber is of silica which is filled by varying its refractive index using Sellemeier's equation[13].

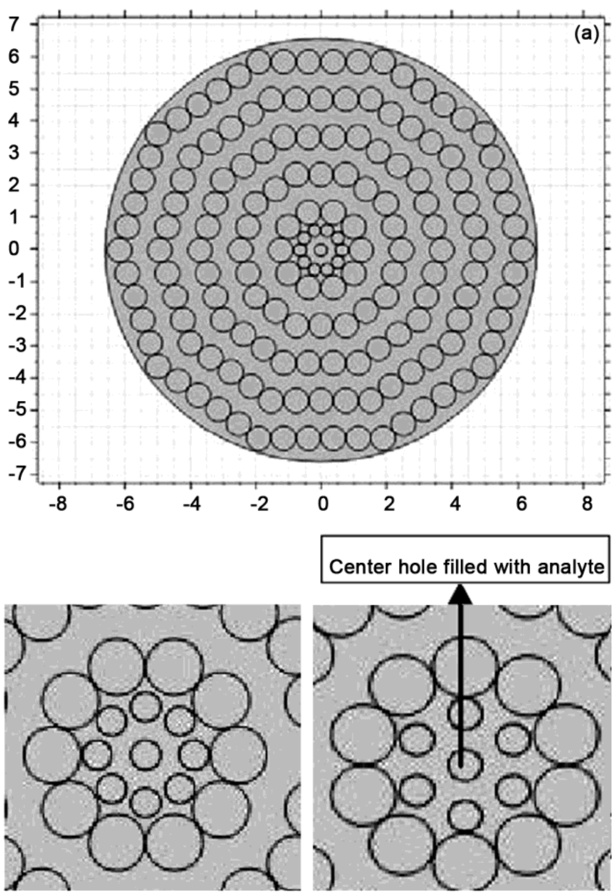

Fig. 1 — Design geometry with core made of circular holes arranged in pattern (a) Decagonal (b) Octagonal and (c) Hexagonal.

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

where $n(\lambda)$ is the refractive index of the material at the wavelength, B_1, B_2, B_3, C_1, C_2, C_3 are sellemeier's constants given in Table 1[13].

The holes present in the cladding are filled with air and the inner core is filled with liquid analyte whose sensitivity is to be determined. The liquid analytes that are tested are ethanol, water and benzene.

The designed PCF is simulated using software COMSOL Multiphysics and the values of sensitivity and confinement loss is observed over a wide range of wavelength. The values obtained for different analytes are compared with one another and analyzed.

3 Result And Numerical Analysis

The periodic arrangement of a finite number of air holes causes a reduction in optical confinement; hence light penetrates into the cladding region. This confinement loss is dependent on the structure and arrangement of air holes in the fiber. It is derived from the formula as given in Eq. (2)[3]:

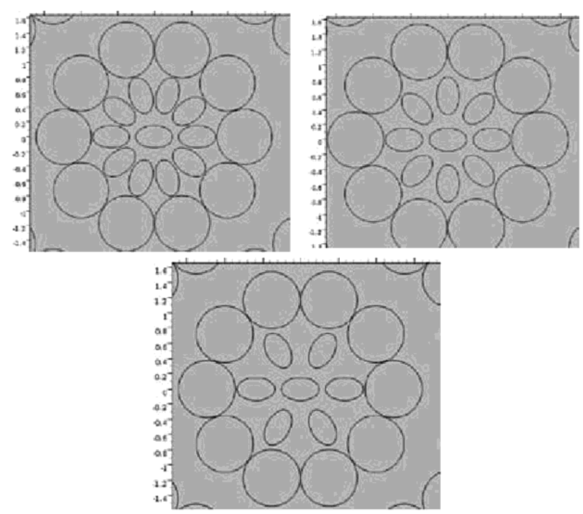

Fig. 2 — Design geometry with core made of elliptical holes arranged in pattern (a) Decagonal (b) Octagonal and (c) Hexagonal.

Table 1 — Sellemeier's coefficients of silica.

Constants	Value
B1	0.69617
C1	$4.6791*10^{-15}$
B2	0.40794
C2	$1.3512*10^{-14}$
B3	0.89747
C3	$9.793*10^{-11}$

$$\alpha_{loss} = \frac{40\pi}{\lambda l_n 10} I_m(n_{eff}) \times 10^6 \left(\frac{dB}{m}\right) \qquad \ldots(2)$$

$I_m(n_{eff})$ represent the imaginary part of the effective mode index and λ represents the wavelength of light.

Relative sensitivity coefficient which is a measure of interaction between light and analyte is given by the Eq. (3) [3]:

$$r = \frac{n_r}{n_{eff}} * f \qquad \ldots(3)$$

n_r is the refractive index of liquid analyte present in the core, n_{eff} is the effective mode index and ‘ f ’ is the percentage of the ratio of core power and total power in the fiber and is given by the Eq. (4):

$$f = \frac{\int_{sample} \mathrm{Re}(E_x H_y - E_y H_x)\,dxdy}{\int_{total} \mathrm{Re}(E_x H_y - E_y H_x)\,dxdy} * 100 \qquad \ldots(4)$$

where E_x, E_y are transverse and longitudinal electric field and H_x, H_y are transverse and longitudinal magnetic field, respectively.

The mode field pattern E_x, E_y, H_x, H_y and effective mode index are obtained by applying finite element method (FEM). Fine mesh size is used for computation. The Decagonal-PCF (D-PCF) supports fundamental as well as some higher modes but for further investigation, only the fundamental mode is considered shown in Fig. 3 and Fig. 4. The sensitivity and confinement loss of D-PCF fiber with varying core geometries is calculated using the above-mentioned formulas over a range of wavelength (1µm – 2µm).

It can be interpreted from the graph shown in Fig. 5 and Fig. 6 that core containing air holes in decagonal pattern gives highest sensitivity as more number of air holes increases the air filling fraction making the fiber more sensitive. When these circular holes are replaced by elliptical holes the sensitivity value further

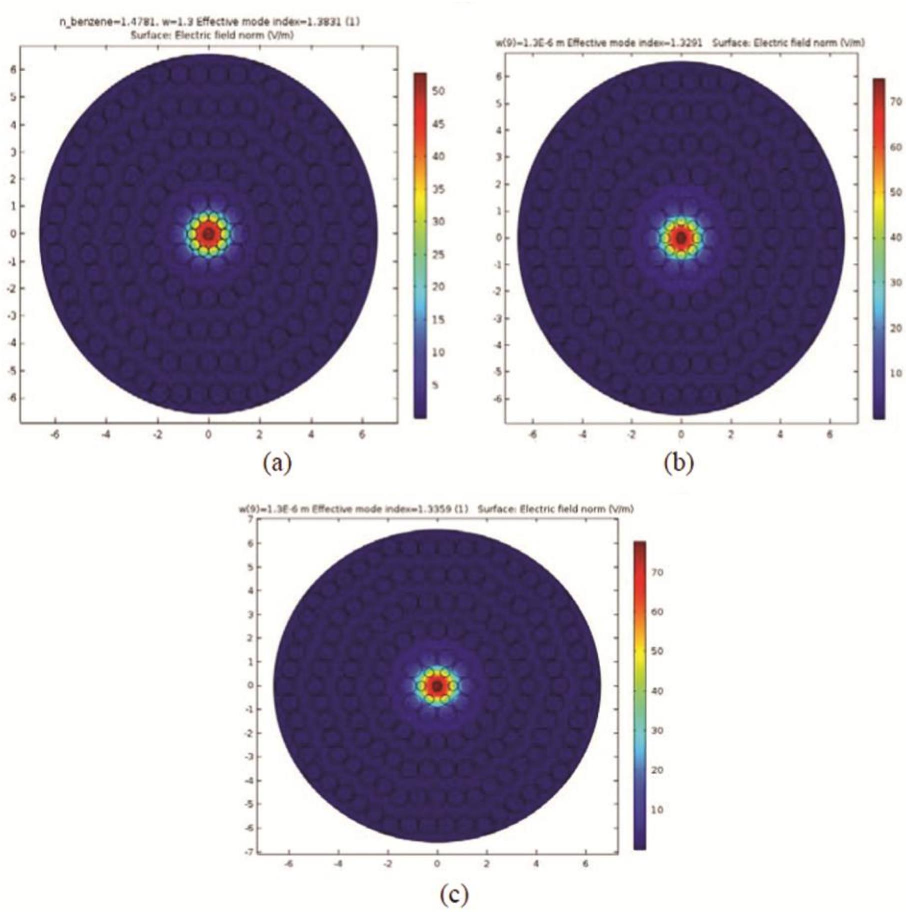

Fig. 3 — Snapshot of model analysis of geometry with core made of circular holes arranged in pattern (a) Decagonal (b) Octagonal and (c) Hexagonal.

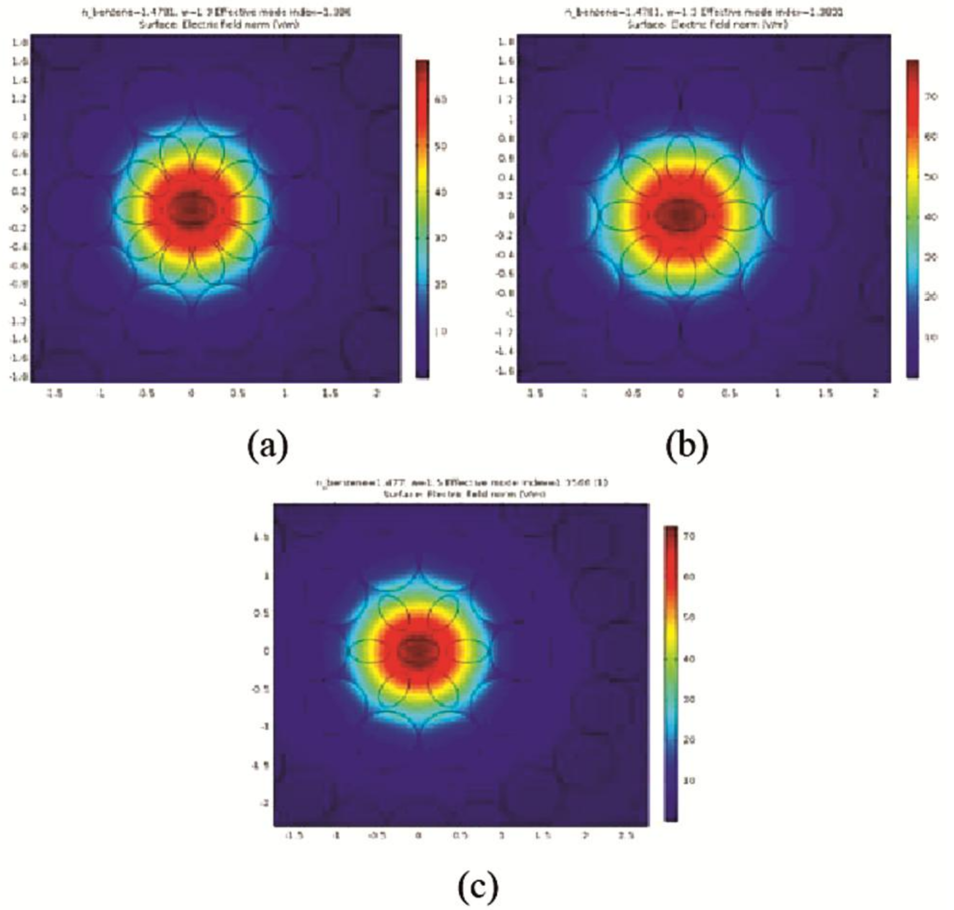

Fig. 4 — Snapshot of model analysis of geometry with core made of elliptical holes arranged in pattern (a) Decagonal (b) Octagonal and (c) Hexagonal.

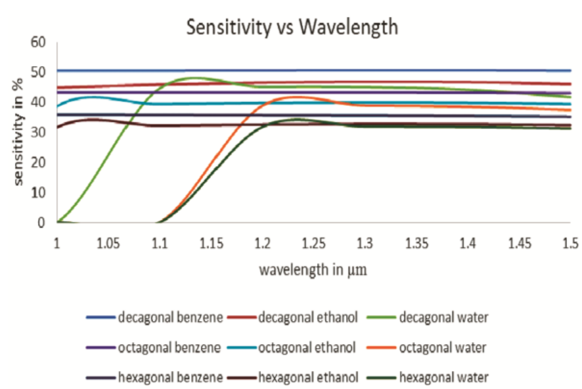

Fig. 5 — Sensitivity versus wavelength for geometry with core made of circular holes arranged in pattern (a) Decagonal (b) Octagonal and (c) Hexagonal.

increases as on distorting the symmetry of circular holes the ray gets diverted into ordinary and extra ordinary ray giving birefringence and thus increases sensitivity.

It can be seen from Fig. 7 and Fig. 8 that the confinement loss is almost negligible in the geometry

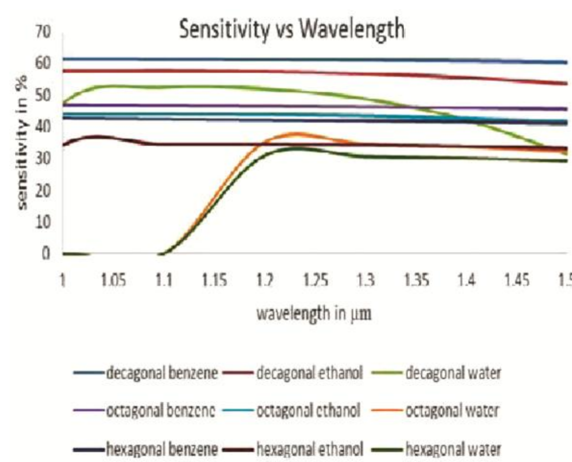

Fig. 6 — Sensitivity versus wavelength for geometry with core made of elliptical holes arranged in pattern (a) Decagonal (b) Octagonal and (c) Hexagonal.

having elliptical holes arranged in hexagonal, octagonal, or decagonal fashion in the core. Table 2 depicts comparison of reported result with previously reported results in the literature. The fabrication of the

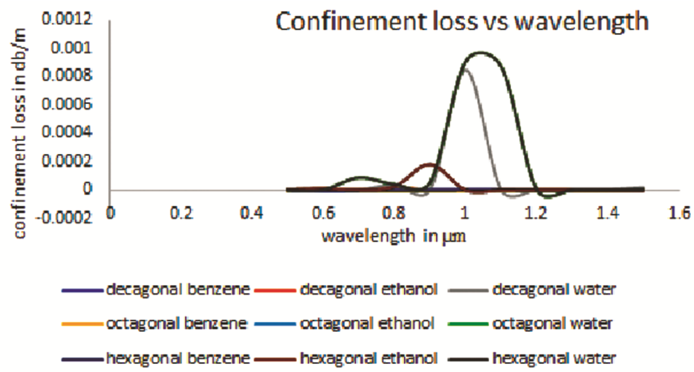

Fig. 7 — Confinement loss versus wavelength for geometry with core made of circular holes arranged in pattern (a) Decagonal (b) Octagonal and (c) Hexagonal.

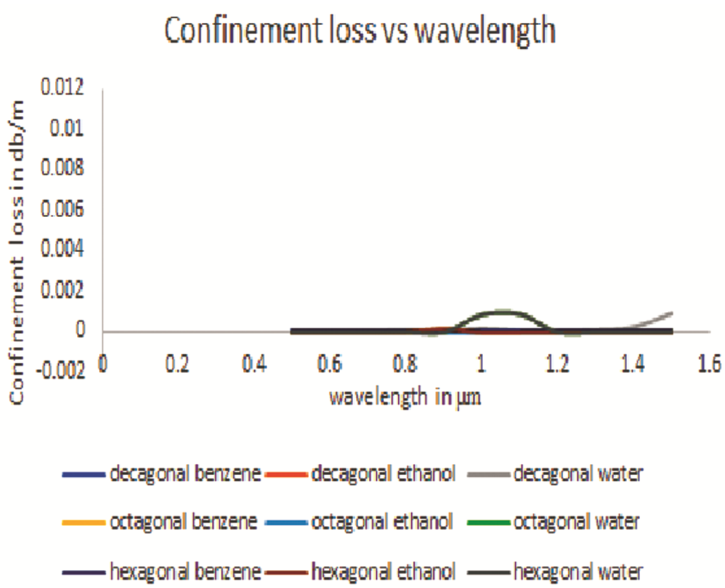

Fig. 8 — Confinement loss versus wavelength for geometry with core made of elliptical holes arranged in pattern (a) Decagonal (b) Octagonal and (c) Hexagonal.

Table 2 — Comparison of reported result with previously reported results in the literature.

	Geometry shape	Wavelength of analysis [µm]	Sensitivity			Confinement Loss (dB/m)		
			Water	Ethanol	Benzyne	Water	Ethanol	Benzyne
1.	Octagonal photonic crystal fiber (O-PCF) [1]	1.33	45.05%	46. 87%	47.35%	6.63622×10^{-15}	2.28217×10^{-14}	5.28542×10^{-14}
2.	A hexagonal PCF with micro structured core consisting of elliptical holes [2]	1.48	Not reported	43.84%	Not reported	Not reported	2.07 ×10−6	Not reported
3.	Microarray-core based circular photonic crystal fiber [4]	1.5	Not reported	29.25%	Not reported	Not reported	7.68 × 10–7	Not reported
4.	Proposed geometry in the paper	1.55	51.94%	46.95%	44.45%	8.19×10^{-10}	1.03×10^{-9}	$1.069\times10^{-7}\, dB/m$

proposed fiber can be done using latest technologies which include Sol-gel technique for fabrication and selective filling technique for filling liquids in the core[12]. Also the most versatile stack-and-draw method and lateral polishing technology can be used to fabricate the Decagonal Geometries[14]. For filling the analyte capillary force, focused ion beam milled micro channels can be applied to fill the air holes[15-16].Throughout this time many PCF sensors have been proposed and fabricated but it cannot be denied that the majority of the designed sensors are still at the proposal stage.

4 Conclusions

In the paper, the decagonal geometry has been analyzed for liquid sensing. The liquid analytes that are sensed are ethanol, benzene and water as they are the most used components in the chemical and biological industries. The geometry of core is varied to enhance the sensitivity. Firstly, the core structure is designed inscribing circular holes in decagonal, octagonal and hexagonal lattice. The results obtained shows that sensitivity is in the decreasing order for decagonal, octagonal and hexagonal. The decagonal geometry gives the best sensitivity because it covers maximum area making the light most confined in the core. Then, these circular holes are replaced by elliptical holes. The sensitivity values obtained shows that elliptical holes have higher sensitivity because of birefringence obtained. Hence, these structures open a new field of PCF based sensor. It is optimal for different liquid sensing applications. At present scenario it is clear that many PCF sensors having advanced sensitivity showing their potential in wide range of sensing application with their very small size, robustness, flexibility, immunity against harsh environment, and many more. So, we can hope that PCF-based sensors will overcome their current limitations soon and prove suitable in large scale applications in industry as well as daily life.

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