Comparision of Different Photonic Crystal Fiber Structure: A Review

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Abstract. Photonic Crystal Fiber (PCF) is the category of optical fiber; the assets of this PCF is grounded on a photonic crystal. This PCF is of two types, and they are named as solid core PCF and Hollow-core PCF. Here, in this paper a survey is proposed for different shape PCF. These different shapes PCF uses different background material like silica, Zeonex, and TOPAS. Using this different shape PCF with different background material the sensitivity and confinement loss are compared. This paper can enhance research work in the field of fiber optics.

Index Terms — Photonic Crystal Fiber, Solid core, Hollow core, Zeonex, TOPAS, sensitivity and confinement loss

1. Introduction
The Photonic Crystal (PhC) is made of dielectric material and they are arranged in a periodic fashion which alters the propagation characteristics [1-5]. The PhCs are used for the variety of purposes in the form of waveguide structures, resonators and fibres, that are designed mainly on an One Dimensional (1D) and the Two Dimensional (2D) fashion. 1D is an appropriate for sensing applications but has poor light confinement [6-9]. This PCF has a range of applications, this PCF is used as sensors [10-20]. According to the properties of the PhC, an optical fiber also comes under the type of PCF. In conception, consistently structured fibers like PCFs, taken in a cross-section micro structured from an enormous substances, nearly everyone set occasionally above a great deal of the side view, frequently as a "cladding" environs a center (core) where an illumination is half-done.

The solid core and hollow core are the two types of the PCF. In solid core N1>N2 and it is high index solid core. The length and the pitch, adjust the high guiding characteristics of PCF. The possible pattern features of solid core fibers are endlessly SMF at all wavelength, large mode area at short wavelength, and high non-linearity multiple cores in one character. In hollow-core PCF N1<N2 and it has a high index core. Here the air core is hollow, this PCF hollow-core act as defects and creates a region through which light propagates. The key optical property of this hollow-core is the model index is 1. Many papers were written in this PCF and this field plays a major role in engineering. Different PCF sensors are available like Sensible, rectangular hollow-core, octagonal, and star-shaped photonic crystal and thus along.

2. Review Of Existing PCF
PCF is used in several applications like bio-sensing, bio-medical, chemical sensing, and gas sensing. For chemical sensing different PCFs were used in recent years [21-24]. Hither, in this survey all the PCF was in hexagonal. Most of the PCF uses silica, TOPAS, and Zeonex material as background material. In this study we are primarily focused on sensitivity and confinement, loss for different PCFs.

2.1 Sensible photonic crystals
The sensible photonic crystal is designed based on an altered hexagonal structure for assessing the sensitivity of the lesser Refractive index (RI) of chemicals such as Ethanol, water and, benzene [25].
Using this PCF, the sensitivity of ethanol, water and benzene was determined and their values are 53.22%, 48.19%, and 55.56% respectively. It measures some parameters like confinement loss, spot size, beam divergence and, non-linearity. Sol-gel technique can be used for PCF fabrication; using this technique the hole shape, size and distance can be adjusted independently. In PCF the air hole diameter is denoted as d, the term pitch defines the distance between the holes and the air hole can be revolved. To analyze different liquid the air holes are filled with ethyl alcohol, benzene and, water. Here COMSOL Multiphysics software was utilized. An imaginary part of the effective index neff term is used to calculate the confinement loss. Here, the sensitivity increases with the increase in an outer ring diameter value.

PCF found applications in fiber-optic communications, laser mode fibres, nonlinear devices, high-force spread, and responsive gas detector devices. Further particular varieties of PCF contains the Photonic-Band-Gap (PBG). It prohibits the certain frequencies acts as a reflector. The air holes are used in form of cross-section in hollow fibre. The light was guided by modification of the air holes in the high index core. The concentric rings of a multilayer film are formed by the PBG. Since, the light is well guided by the structural changes the PCF also taken into an account as a subclass of micro structured fibres irrespective of the Refractive Index (RI) term.

In this method the background is coated with silica, the outer rings are called air holes. The core defect was placed at the mid of the fiber structure. The production process of this method is possible by existing fabrication technology.

2.2 Rectangular hollow core PhC
A rectangular hollow-core PCF (HC-PCF) was planned and the analyst was placed in the core. The air holes are used in the centre region and circular holes are placed in the cladding region. The light guiding features are carried out with the help of Finite Element Method (FEM) by satisfying the boundary conditions (Perfectly Matched Layer) [26]. The FEM is used to estimate the high sensitivity output, increased birefringence, reduced confinement loss numerical aperture and null dispersion loss of for various chemicals. This sensor is used in terahertz applications.

2.3 Octagonal PhC
In order to sense the liquid an octagonal photonic crystal fiber (O-PCF) was used in this paper, here, center and outer coat were micro-structured. The propagation characteristics were analyzed by FEM [27]. Here confinement loss and sensitivity were analyzed. In this O-PCF the sensitivity of 46.3% was achieved.

2.4 Multiple sensing ring PCF sensor
In this method, the chemical was detected. The FEM analysis was used and the silicon is used as a background material. The light travels inside the ring structure to get interacts with the components. The interaction of the light with the various substances based on the RI term of each [28]. Based on the proper selection of air ratios, pitch, diameter of air holes and operating wavelength the confinement loss can be lowered. Results show that three rings have lower RI compared to four rings. The relative sensitivity increases as wavelength increases due to identical intensity spread in the ring for different sensing materials. The decrease in RI liquid has a lower sensitivity and high range of RI liquid has increased sensitivity. The silica width in 3 rings is larger compared to 4 rings so, the sensitivity is good in 4 rings. As silica width is large in 3 rings, the light dispersion to nearby ring is less in 3 rings so confinement loss is less in 3 rings compared to 4 rings. This method was manufactured using advanced extrusion, stack-draw, and drilling techniques.

Several detecting ring structure in the center part was used for sensing chemical and biochemical purposes. The multiple rings increase the sensitivity to 95.40% and 93.13% and the least amount confinement loss is 7.108x10^-8 and 2.47x10^-8 dB/km for four and three-ring model respectively. The sensing ring was filled with diverse sensing liquid. The PCF probe needs some dislocation once filling the
sensing liquid, this problem can be overcome by this proposed method. The applications of this method are food safety, gas detection, bio-sensing, bio-imaging, and drug detection.

2.5 star shape photonic crystal
A star shape photonic crystal fiber (CS-PCF) was proposed for Terahertz (THz) spectrum has low loss circular structure. Here, the background is coated with TOPAS material. It produces low scattering loss of about 1.235x10^-15 dB/km. The core has 6 air holes and a centre hole. The distance between the nearby air hole of the core was represented as ˄co, the distance for the nearby air hole of cladding was ˄cl. The radius of the cladding air hole is dcl. The air filling factor (AFF) of cladding was dcl / ˄cl = 0.85. To avoid reflection which transmits light a circular PML was employed around cladding [29]. This CS-PCF shown remarkable guiding act in a short and long-distance communication.

2.6 orthogonal photonic crystal fiber
An orthogonal photonic crystal fiber was proposed for the detection of ethanol. Here, hexagonal lattice and elliptical holes are present to detect liquid. The Pure silica gel was used as background material [30]. The sensing liquid ie., Ethanol was placed in the core. The hole in the cladding was in round and their diameter was d = 1.75μm. The center to center neighboring hole distance was called patch and this distance was 2.4μm. Here, the core was in elliptical shape and the elliptical constant value is 0.54. Software used here was COMSOL Multiphysics 5.1. To measure material dispersion sellmeier relation was used. Sensitivity can be find out by the Beer-Lambert law. As the wavelength increases from 1.33 to 2.3μm the light will disperse from core to cladding and an effective index will decrease. For elliptical core the relative sensitivity rises as wavelength goes up, since effective index falls out.

The neff of the outer part was lower than the core for better sensitivity, which creates RI between inside part and cladding which leads to powerful confinement in the center part. As the ellipticity increases, then the sensitivity decreases and confinement loss were increased and birefringence decreases. Confinement loss and sensitivity were analyzed mathematically by the Finite Element Method (FEM). Here, it was found that elliptical holes in the center region produce less confinement loss and more sensitivity for the wavelength of 1.33μm. The sensitivity and confinement loss of this method was 57.91% and 1.6x10^-03db/m respectively.

2.7 PCF for the Purpose of liquid sensing
A Hexagonal (H-PCF) with good sensitivity for fluid has been achieved the material used for the background is silicon. Material dispersion is measured by sellmeier equation. Here, four different analyses were made. The simulation was done in the wavelength range from 0.6μm to 1.6μm. Software used here is COMSOL Multiphysics 4.2. The convergence error for PCF3 is 3.55x10^-5 % and for PCF4 is 3.50x10^-5% [32]. For PCF1, PCF2 and PCF3 the effective index is inversely proportional to wavelength. PCF1 shows a higher effective index. The sensitivity value of PCF1 and PCF2 has no change. For PCF3 the sensitivity increases in a wide range for an raise in diameter of external holes at the wavelength of 1.33μm. This is because as inner hole increases the diameter moves closer to the core region and evanescent field penetrates. The sensitivity of Ethanol and water is measured by PCF3 and the sensitivity is 48.50% and 47.78%, respectively, and the confinement loss for Ethanol and water were 1.28x10^-10dB/m and 5.37x10^-11dB/m respectively. For much more sensitivity PCF4 was developed using single hollow channel insert of supplementary tiny holes. Sensitivity of water, Ethanol and benzyne for PCF4 were 50%, 55.83% and 59.07% respectively and the confinement loss was 4.25x10^-10 dB/m, 8.72x10^-10 dB/m and 2.55x10^-10 dB/m

The sensitivity was improved by increasing the inner diameter of the cladding. Numerical analysis was done by FEM. Moreover, placing single channel insert of multiple channels were increases sensitivity at low confinement loss. Here different liquids such as water, ethanol and benzyne were analyzed and compared. The fabrication was done by nano fabrication techniques.

2.8 Quasi photonic crystal fiber
In quasi-photonic crystal fiber (Q-PCF) design is a kind of microstructured with an expected birefringence, sensitivity and the reduced confinement loss. It is used in chemical sensing application for Terahertz range. Numerical analysis was carried out by Full Vector Finite Element Method (FV-FEM) [32]. For increasing key parameters Anisotropic Perfectly Matched Layer (A-PML) was employed. Sensitivity of Ethanol, benzene and water were 78.8%, 77.8% and 69.7% respectively. The key terms like NA, power fraction and other losses are also analyzed. Here, porous core with circular shaped air holes was used. Cladding air hole has a diameter of d_{cl} = 303.95μm, pitch was 0.94μm. The outer boundary was surrounded by A-PML. The background is coated by TOPAS. Software used here was COMSOL Multiphysics 4.2. For sensitivity calculation Beer-Lambert law was used. In this proposed method water had low sensitivity and ethanol had high sensitivity. Numerical Aperture of 0.57 was achieved when frequency of 0.8THz was used. This method is used in Optical coherence tomography (OCT) and medical image applications.

2.9 Circular-Pattern photonic crystal fiber

Here, the core and cladding were in porous shape. Sensitivity, confinement loss, non-linearity and effective area were computed here [33]. The confinement loss was triggered by leakage of light. There were three rings in the core and five rings in the cladding. Different liquids like glycerol, ethanol and toluene were filled in the core. The sensitivity and confinement losses were analyzed by FEM. Pitch. The confinement loss depends on the pitch and air holes. In an interior and shield the vertices of neighboring six air holes of the first layer are 60° angle. The residual 2 to 5 air holes are 30°, 20°, 15° and 12° angles and there are 12, 18, 24 and 30 number of air holes respectively. The hole in the core had a radius of 0.18μm. Light propagates by total internal reflection; the cladding had number of air holes and the core was packed with different chemical the RI of core is more comparable with cladding. Perfectly matched layer (PML) removes unwanted reflections. Software used here was COMSOL Multiphysics 5.1.

Here, three core material was taken distinctly for the same design. Here, two performance are analyzed first, ethanol and glycerol, then ethanol and toluene. Ethanol was common because of its high sensitivity. Ethanol is taken in the core material. On comparing with an ethanol and glycerol, glycerol had less confinement loss which depends on the structure of PCF. Reduced confinement loss for glycerol and Toluene is achieved when compared with an ethanol. Sensitivity of glycerol is 65.16% and the effective area is 2.81μm². The sensitivity of toluene is 64.05% and the Effective area was 3.07μm². So, the sensitivity and Effective area were increased using CP-PCF because of high effective area. More data can be transmitted with high speed so it is used in telecommunication data. In this method, liquids like toluene and glycerol were used to analyze CP-PCF properties for detecting applications. This sensing property of this material can be used to sense bio-sensing, bio-medical protein identification analysis and telecom etc.

2.10 Terahertz detection of alcohol

Ethanol is detected in Terahertz range in the order of 1 THz. Detecting ethanol is precisely same as alcohol. Here, zeonex based PCF is analyzed [34]. The zeonex is used as background for PCF. Analyzes was done by FEM and the software used was COMSOL. The sensitivity and confinement loss were achieved in the order of 68.87% and 7.79x10⁻¹² at 1THz respectively. The PCF was hexagonal shape. During numerical analysis the length of air holes was kept constant and the width was varied. The total fiber diameter was 3.2mm. The air filling fraction at cladding was 0.94μm. Sensitivity is measured by the Beer-Lambert law.

The Fabrication of this method was easy because it is suitable with the existing fabrication method. For elliptical shaped air holes monomer polymerization method was used. For symmetrical air holes 3D printed dies were used. The core power fraction was good at 1THz frequency. Sensitivity was good for x-polarization compared with y-polarization. High sensitivity ethanol was used in the bio-medical and in food industry. This paper opens a window to future researchers on Terahertz sensors.

3. Comparisons Of Different PCF
| S.No | Name of the Fiber | Background Material | Sensitivity | Confinement loss |
|------|-------------------|---------------------|-------------|------------------|
| 1    | Hexagonal structure [25] | Silica | Sensitivity of ethanol, water and benzene were 53.22%, 48.19% and 55.56% respectively | The confinement loss was analyzed from the complex effective index $n_{\text{eff}}$ presented in the imaginary part of the value. |
| 2    | Rectangular HC-PhC [26] | Zeonex | Greater Sensitivity | Low Confinement loss |
| 3    | Octagonal photonic crystal [27] | Pure Silica | Sensitivity of 46.3% was achieved | Low Confinement loss |
| 4    | Multiple sensing ring PCF [28] | | Sensitivity of 95.40% and 93.13% | Minimum confinement loss is $7.108\times10^{-9}$ and $2.47\times10^{-8}$ dB/km for four and three ring patterns respectively. |
| 5    | CS-PCF [29] | TOPAS | Sensitivity is good | Low Confinement loss |
| 6    | Orthogonal photonic crystal fiber [30] | Pure silica gel | Sensitivity is good | Confinement loss of this method is 0.0016, 57.91% |
| 7    | Hexagonal photonic crystal fiber (H-PCF) [31] | Silica | Sensitivity of water, Ethanol and benzene for PCF4 were 50%, 55.83% and 59.07% respectively | Confinement loss was $4.25\times10^{-10}$ dB/m, $8.72\times10^{-10}$ dB/m and $2.55\times10^{-10}$ dB/m |
| 8    | Quasi-photonic crystal fiber (Q-PCF) [32] | TOPAS | Sensitivity of Ethanol, benzene and water were 78.8%, 77.8% and 69.7% respectively | Low Confinement loss |
| 9    | Circular-Pattern photonic crystal fiber [33] | Silica | The sensitivity of toluene was 64.05% and the sensitivity of glycose was 65.16% | Confinement loss can be acquired with the help of the pitch and diameter of air holes. |
| 10   | Terahertz Alcohol PCF sensor [34] | Zeonex | The sensitivity was achieved in the order of 68.87% | Confinement loss was $7.79\times10^{-12}$ at 1THz respectively. |
4. Conclusion
In this paper, a comprehensive survey has been done in recent research on PCF structures. Different structures such as hexagonal, rectangular hollow core, octagonal, star shaped photonic crystal, Quasi-photonic crystal fiber and Circular-Pattern photonic etc., are compared. The background material used in this paper for analysis are silica, TOPAS and Zieonex. The main focus is to find out the sensitivity and the confinement loss. This PCF is used in different applications such as bio-sensing, bio-medical, chemical sensing, and gas sensing.

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