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Photonic Crystal Fibers for Liquid Sensing Applications: A Review

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Abstract--- **Till date, photonic researchers and scientists discovered rapid technological changes in the optical fibers, a new class of optical fiber i.e., Photonic Crystal Fibers (PCF) shows a great potential in replacing conventional optical fibers due to their numerous advantages such as adjustability to guide light in a desired direction etc. Filling of airholes with chemical analyte makes it suitable for liquid sensing applications. However, achieving a high sensitivity for liquid sensing is still a challenge. This article presents a detail theoretical investigation of some existing PCF designs based on different geometries and core structures for liquid chemical sensing applications. The investigation is done based on optical properties viz. relative sensitivity and confinement loss.**

Keywords--- **Photonics, PCF, refractive index, liquid sensing, water**

I. INTRODUCTION

Optical fiber communication technology continues as focused matter of interest for the optical scientists [1]. It was chosen as a mainstay of modern communication system as it offers more flexible and reliable optical channel than the free space channel. But the fixed rules for designing the fiber bounds its potentiality in different applications. The deficiency in adjustability to guide light in a given direction was one of the major restrictions to enlarge its capability over high-speed transmission. Since its invention in 1970s, optical fiber emerged into various forms, Photonic Crystal Fiber (PCF) new class of optical fiber [2] is one of them. It allows much enhanced adjustability to confine light in a desired direction.

Based on core structure the PCF is classified in two types hollow core based on photonic bandgap effect and high index PCF based on modified total internal reflection (m-TIR) [3]. High index PCF is also known as index guided fiber, it consists of a solid core and different periodic pattern of air holes in the cladding region. The overall refractive index of the cladding region is less than refractive index of solid core as the cladding part contains low refractive index air holes. In index guided PCF, guidance of light is done by m-TIR in a solid core, while Conventional optical fibers guide the light by total internal reflection (TIR) principle. The light sensing mechanism of solid core PCF or Index guided PCF based on the evanescent interaction between the analyte to be sensed and the optical field i.e., more the intercommunication between the light mode and analyte, greater will be sensitivity of the PCF. In hollow core PCFs, structures are designed to restrict propagation of light for some range of wavelength called photonic band gaps (PBG), here the light confinement is done in lower refractive index core than the cladding refractive index. PCFs based on m-TIR are desirable for liquid analyte sensing applications [3]. Another classification of PCF is done on the basis of geometry of the structure, On the basis of geometry, PCFs are divided into three broad categories: 1-Dimensional or 1-D photonic crystal, 2- Dimensional or 2-D photonic crystal and 3- Dimensional or 3-D photonic crystal.

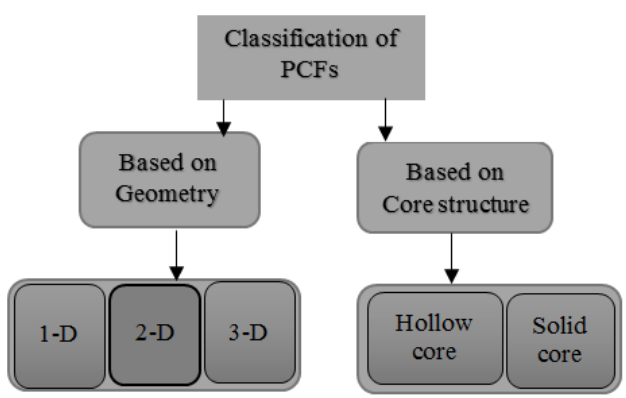

Fig.1 Classification of PCFs

PCF advances the performance of the fiber structure by improving the optical properties like dispersion, confinement loss, non-linearity and birefringence etc. Also, low weight, small diameter compatibility etc. makes PCF based devices and equipment practically desirable in many applications. Due to extraordinary optical properties this fiber can be utilized in multiple optical areas such as pulse transmission, four wave mixing, optical code division multiplexer, signal switcher etc. By filling the certain number of cavities or airholes with given analyte and confining light through it, the analyte is sensed by the intercommunication of light with the analyte, this property of PCF attracts researchers for certain applications including chemical sensing and bio-sensing.

A lot of PCFs has geometrical structures in their design. the cladding airholes are generally arranged in hexagonal, octagonal, circular, spiral etc. manner while, the shape of airholes is circular, elliptical, hexagonal, octagonal etc. Generally hexagonal shaped cladding structures are used in refractive index, evanescent sensors etc. Here the array of periodic holes forms a hexagonal pattern as expectation. The airholes can be solid or air, sometimes the pitch and diameters are different in a single PCF. Some biosensors and pressure sensors used circular structures. They have many airholes with different diameters. A central solid or hollow core can be greater or smaller than all other holes in the PCF. Because of their geometric patterns, octagonal shape structures have enormous fashionability in recent researches and used in food processing sensors and biosensors etc.

The PCF sensors are mainly designed to achieve higher sensitivity and it is totally depending on light -matter interaction. More the interaction of the sensing analyte (sample) with the light mode, the better is the sensitivity

Coefficient of relative sensitivity *r* at operating wavelength is defined as

$$r = \left(\frac{n_r}{n_e}\right) f \quad \text{……equation 1}$$

Here n_e guided mode effective refractive index, and n_r stands for refractive index of sensing material f is fraction of energy present in the airholes.

The fraction of total energy has been applied by the Poynting theorem of equation [4].

$$f = \frac{\int_{sample} Re(E_x H_y - E_y H_x)dxdy}{\int_{total} Re(E_x H_y - E_y H_x)dxdy} \text{x100} \quad \text{……equation 2}$$

While $E_x, E_y, H_x \; and \; H_y$ are transverse electric and magnetic fields [5].

Confinement loss is another vital factor along with the sensitivity to be considered in designing a PCF for sensing applications. The light mode is possible in the core area of the PCF sensor due to the finite number of airholes in the cladding layers. The loss of mode from core region towards cladding region is unavoidable and due to the extent of cladding confinement loss occurs. Hence for better performance of the PCF, relative sensitivity should be high and confinement loss should be as low as possible.

In recent times, many encouraging avengements have been reported in the area of liquid chemical sensing based on PCF, Ademgil improved the relative sensitivity up to 47% by using octagonal shaped PCF (O-PCF) over hexagonal shaped PCF (H-PCF) structure [6]. Asaduzzaman et al. achieved a sensitivity of 40.32% and 34.90% for sensing Ethanol and Methanol respectively by designing simple circular structure with core having tiny airholes are arranged in hexagonal form [7]. Arif et al. by using single hollow core instead of group of tiny airholes in the core enhanced the relative sensitivity up to 55.83% [8]. By proposing elliptical shaped air holes in the core region Arif et al. found a relative sensitivity of 53.35% [9]. In addition to sensitivity another important property i.e., confinement loss is considered while designing a PCF for sensing applications. Ademgil used octagonal PCF with supplementary air-holed core, decreased the confinement loss up to 10^{-9} dB/m [6]. Arif et al. achieved the low confinement loss of 8.72x 10^{-10} dB/m using ethanol as sensing analyte [8]. Islam et al. achieved confinement loss of 4.62 x 10^{-11} dB/m using spiral shaped PCF [10]. All these researches have confirmed PCF as a reliable and conceivable element in the field of liquid chemical sensing.

II. PCF FOR SENSING APPLICATIONS

Due to exceptional optical properties like single mode guidance and filling of airholes with analytes, PCF is widely used different practical applications. In modern days PCF are used exceptionally for Biochemical, biological and physical sensing applications. Biochemical sensing that are well-known to us are liquid gas, glucose, pH sensing etc. physical sensing involves refractive indices, vibration, pressure sensing etc. Biosensing applications is one of the important applications of PCF which consists of liquid, gas, chemical sensing in various fields like food quality control, environment pollution monitoring, glucose concentration detection etc. liquid chemical sensing is one of the important types of biosensing application.

Chemicals (liquid or gas) which are highly sensitive plays a salient part in many industrial applications especially for the detection of harmful and toxic chemicals to marsh the safety issues. Therefore, the detection of these chemicals

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become one of the major challenges to extreme the performance of the gas and liquid PCF sensors.

III. DIFFERENT PCF SENSOR STRUCTURES

Till date, many different PCF sensors structures based on geometry and core structure have been proposed for biosensing applications. In this article the theoretical analysis of five already proposed PCF structures in the field of liquid chemical sensing biosensing applications is done based on the optical properties viz. relative sensitivity and confinement loss.

Md. Faizul Huq Arif et al. [8] in 2016 proposed a H-PCF sensor which provides enhanced performance in terms of relative sensitivity and confinement loss for sensing different liquids (water, ethanol and benzyne). They have reported four different PCF structures, these structures are differentiated on the basis of diameters of cladding layer air holes. i.e., in structure 1 diameters of air holes for all the four layers are same, where d_1=d_2=d_3=d_4. In the investigation they have found that diameters of outer cladding layer have more impact on the confinement loss, structure 2 is designed with diameters d_1=d_2=d_3<d_4, another result shows that diameters of inner cladding layer improve the confinement ability i.e., relative sensitivity. Structure 3 is designed with optimized diameters d_2=d_3<$d_1 = d_4$. However, they have turned into structure 4 by replacing the supplementary tiny airholes of core with a single hollow core and achieved better performance at 1.33µm operating wavelength. They also compare the performance of the proposed structures 3 and 4 with previously reported octagonal shaped five ring structures for ethanol and benzyne, and performs better at the same operating wavelength. Although, diameters can be changed after fabrication but has not major effects on the results of the reported structure. Also, the techniques of selectively filling of air hole with analytes and issues related to fabrication are discussed. The process of fabrication of the micro holes is not an easy task but due to some technological advancements it is possible. Without destroying the fiber's probity microstructure airholes must be filled with analytes. Any kind of fabrication complexity can be removed by applying the sol-gel technique [15].

Shuvo Sen et al. [2] in 2017 reported a porous core hexagonal shaped PCF (P-HPCF) based optical sensor for lower band of wavelength (0.8 to 1.8µm), which provides better sensing performance in terms of confinement loss as well as relative sensitivity low for sensing liquid chemicals (water, ethanol and benzene). In the structure, the cladding region consists of five layers of circular air holes arranged in hexagonal shape and core locality is formed by using two layers of elliptical air holes. The numerical analysis of the PCF sensor is done by using FEM. Different values of both the investigating parameter are found by varying the diameters of the cladding airholes and core pitch (distance between the airholes). The guiding properties of the structure have been examined with different geometrical parameters and the investigation shows that at 1.33µm, the mode field is energetically confined in the core locality which increases the relative sensitivity of the P-HPCF. Also, the leakage loss is very low. The proposed P-HPCF shows optimum results when the structure is optimized based on the core and cladding air holes diameters and pitches. The optimization of structure has done using a simple method. First cladding region is optimized and other parameters are kept constant. After that core region is optimized. Finally, the optimization process is completed by optimizing the pitch values of the structure. The obtained optimum values of relative sensitivities are 57%, 57.18%, and 57.27% Additionally, the confinement loss of 2.15 x 10^{-10} dB/m, 1.11 x 10^{-11} dB/m and 1.97 x 10^{-11} dB/m for water, ethanol and benzene respectively.

Md Ibadul Islam et al. [10] in 2017 reported a spiral shaped PCF (S-PCF) based optical sensor. The structure contains ten arms with each arm consists of nine circular shaped air holes that forms spiral shape, and cluster of circular shaped airholes in the core region. The sensor was designed for liquid sensing applications. Water, ethanol and benzene are the liquids chemicals to be sensed. Due to their outstanding modal confinement properties, spiral structure PCF has great concentration over conventional hexagonal PCFs. To analyze the optical properties i.e., relative sensitivity and confinement loss, FEM method has been applied for solving the Maxwell's equations. The entire simulation is done for operating wavelength range of 1 to 1.8µm. Based on the investigation they analyzed that fundamental modes are confined strongly inside the circular core and analytes present in the core interacts strongly with the evanescent field [14] of light which increases the sensitivity as well as reduces confinement loss. At operating wavelength of 1.33µm, for the optimized geometrical parameters i.e., pitch and diameters of core and cladding airholes the S-PCF achieved high sensitivity of 72.95%, 74.55% and 75.14%, confinement loss of 1.85 x 10^{-10}dB/m, 4.62 x 10^{-11}dB/m and 6.35 x 10^{-11}dB/m for water, ethanol and benzene sensing analytes respectively. Apart from relative sensitivity and confinement loss, effective area, V-parameter and nonlinear coefficient are also examined. Finally, S-PCF is developed as a new advancement in the field of chemical-based sensing.

R. Malavika et al. [11] in 2019 proposed a spiral shaped PCF sensor for chemical (liquid) sensing applications, utilizing water, propane and propylene as a sensing analyte. The performance of the sensor is analyzed based on two fundamental optical properties i.e., sensitivity and confinement loss by changing the geometrical parameters for wide wavelength range of 800 to 1800nm (0.8 to 1.8µm). The reported spiral PCF consists of spiral cladding and micro core having elliptical shaped airholes, elliptical airholes are much more challenging for design and fabrication purpose than circular holes. The spiral cladding consists of ten arms with each arm containing nine circulars shaped airholes and eight horizontally arranged elliptical airholes forms the core. Fabrication methods to draw elliptical airholes is discussed in the reported article and founds that sol-gel fabrication method offers flexibility in design. Based on the investigation it is proved that reported spiral PCF with minimum loss is highly recommended for liquid chemical sensing applications.

Md. Jayed Bin et al. [12] in 2020 reported a PCF sensor structure using water as liquid sensing analyte. To reduce the design and fabrication complexities circular airholes instead of elliptical airholes are used. The cladding part of structure is formed by using circular airholes in hexagonal arrangement due to its characteristics to cover whole region without any spaces and the core region is formed by using circular airholes of two different diameters. The variation of diameters of core airholes has greater impact on the optical properties of the sensor. Using wide wavelength range 1.3 to 2µm, the performance analysis of the sensor is carried out by changing the diameters of core airholes investigating two main optical factors. Numerical investigation is done by using FEM. Based on the investigation it is found that the value of performance is worse when using same diameters of core airholes. Thus, by altering the diameter of one type of core airhole while fixing other, the performance of optical properties i.e., relative sensitivity and confinement loss is improved. The procedure and different methods of filling of airholes with analytes is also discussed in the paper. Finally, it is discovered that using different diameters of circular core airholes the performance is improved and can replace elliptical airholes to avoid fabrication complexity.

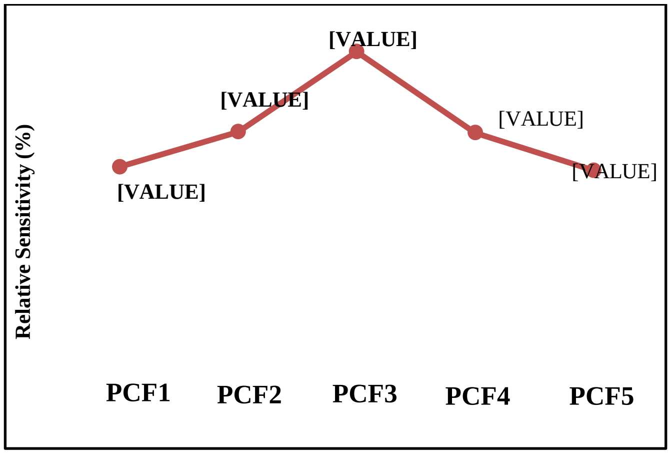
IV. COMPARISON

The comparison of the five different PCF structures is done based on results in terms of optical properties i.e., relative sensitivity and confinement loss operating in different wavelength ranges using liquid chemical sensing analytes [13]. Numerical analysis of all the PCF sensor structures is done by using FEM and simulation is performed by using COMSOL Multiphysics software by respective authors of related papers**.**

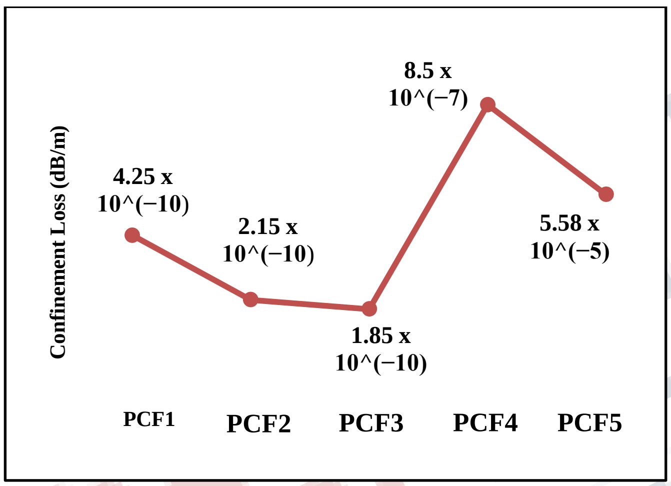
Based on the comparison it is found that the S-PCF structure proposed by Md Ibadul Islam et al. (PCF3) in 2017 performs better as compared to other structures and achieved higher relative sensitivity of 72.95% as shown in fig.1, while lower confinement loss of 1.85 x 10^{-10} shown in fig.2 as compared to other PCF structures using water as sensing analyte at an operating wavelength of 1.33 µm. Also, high relative sensitivity 74.55% and confinement loss of 4.62 x 10^{-11}dB/m is found using ethanol as sensing analyte.

Table1: Comparison in terms of relative sensitivity and confinement loss using different liquid sensing analytes at operating wavelengths

Authors and PCF structures	Year	Relative sensitivity in %	Confinement loss in dB/m	Operating wavelength (µm)
Md. Faizul Huq Arif et al. (PCF1)	2016	50 for water 55.83 for ethanol and 59.07 for benzyne	4.25 x 10^{-10} for water 8.72 x 10^{-10} for ethanol 2.56 x 10^{-10} for benzyne	1.33
Shuvo Sen et al. (PCF2)	2017	57 for water 57.18 for ethanol 57.27 for benzene	2.15 x 10^{-10} for water 1.11 x 10^{-11} for ethanol 1.97 x 10^{-11} for benzene	1.33
Md Ibadul Islam et al. (PCF3)	2017	72.95 for water 74.55 for ethanol 75.14 for benzene	1.85 x 10^{-10} for water 4.62 x 10^{-11} for ethanol 6.35 x 10^{-11} for benzene	1.33
R. Malavika et al. (PCF4)	2019	56.8 for water 58.3 for propane 62.7 for propylene	8.5 x 10^{-7} for water 7.2 x 10^{-8} for propane 6.5 x 10^{-8} for propylene	1.55
Md. Jayed Bin et al. (PCF5)	2020	49.13 for water	5.58 x 10^{-5} for water	1.3



(a)



(b)

Fig.2 Comparison of (a)relative sensitivities and (b)confinement loss of all the five PCF structures using water as sensing analyte.

Due to extraordinary light confinement property and better sensing results makes S-PCF a prominent structure for the liquid sensing applications. The performance of S-PCF can be further improved by parametric modifications in the geometry of the spiral structure.

V. Conclusion

In this study, the performance of some various types of PCF sensor structures for liquid sensing applications has been investigated theoretically. The study shows a clear understanding how a particular geometry of structure and shapes, diameters and pitches of airholes of core and cladding influences the optical properties of the PCF. Among all the structures, spiral PCF due to its extraordinary modal confinement properties provides a great potential for liquid sensing applications. Also, with some geometrical modifications' new different spiral structures with increased performance can be designed for liquid chemical sensing applications as well as for other biosensing applications like environment pollution monitoring, food quality control, gas sensing applications etc.

REFERENCES

[1] Atiqullah, S.M., Palit, A., Reja, M.I., Akhtar, J., Fatema, S. and Absar, R., 2019. Detection of harmful food additives using highly sensitive photonic crystal fiber. *Sensing and Bio-Sensing Research*, *23*, p.100275.

[2] Sen, S., Chowdhury, S., Ahmed, K. and Asaduzzaman, S., 2017. Design of a porous cored hexagonal photonic crystal fiber based optical sensor with high relative sensitivity for lower operating wavelength. Photonic Sensors, 7(1), pp.55-65.

[3] Cerqueira Jr, S.A., do Nascimento Jr, A.R., Bonomini, I.A.M., Franco, M.A.R., Serrão, V.A. and Cordeiro, C.M.B., 2015. Strong power transfer between photonic bandgaps of hybrid photonic crystal fibers. *Optical Fiber Technology*, *22*, pp.36-41.

[4] Singh, S. and Kaur, V., 2017, July. Photonic crystal fiber sensor based on sensing ring for different blood components: design and analysis.In *2017 Ninth International Conference on Ubiquitous and Future Networks (ICUFN)* (pp. 399-403). IEEE.

[5] Arif, M.F.H. and Biddut, M.J.H., 2017. Enhancement of relative sensitivity of photonic crystal fiber with high birefringence and low confinement loss. *Optik*, *131*, pp.697-704.

[6] Ademgil, H., 2014. Highly sensitive octagonal photonic crystal fiber-based sensor. Optik, 125(20), pp.6274-6278.

[7] Ahmed, Sayed Asaduzzaman. "Design of a porous cored hexagonal photonic crystal fiber based optical sensor with high relative sensitivity for lower operating wavelength" , Photonic Sensors, 2017

[8] Arif, M.F.H., Ahmed, K., Asaduzzaman, S. and Azad, M.A.K., 2016. Design and optimization of photonic crystal fiber for liquid sensing applications. Photonic Sensors, 6(3), pp.279-288

[9] Arif, M.F.H. and Biddut, M.J.H., 2017. A new structure of photonic crystal fiber with high sensitivity, high nonlinearity, high birefringence and low confinement loss for liquid analyte sensing applications. Sensing and Bio-Sensing Research, 12, pp.8-14.

[10] Islam, M.I., Ahmed, K., Islam, M.S., Paul, B.K., Sen, S., Chowdhury, S., Asaduzzaman, S., Bahar, A.N. and Miah, M.B.A., 2017. Single-mode spiral shape fiber based liquid sensor with ultra-high sensitivity and ultra-low loss: Design and analysis. Karbala International Journal of Modern Science, 3(3), pp.131-142.

[11] Malavika, R. and Prabu, K., 2019. Design optimization of a highly sensitive spiral photonic crystal fiber for liquid and chemical sensing applications. Optical Fiber Technology, 51, pp.36-40.

[12] Leon, M.J.B.M. and Kabir, M.A., 2020. Design of a liquid sensing photonic crystal fiber with high sensitivity, bireferingence & low confinement loss. Sensing and Bio-Sensing Research, p.100335.

[13] Optical and Wireless Technologies" , Springer Science and Business Media LLC, 2020.

[14] Monir Morshed, Md. Imran Hassan, Tusher Kanti Roy, Muhammad Shahin Uddin, S. M. Abdur Razzak. "Microstructure core photonic crystal fiber for gas sensing applications" , Applied Optics, 2015.

[15] M. Suganthy, Bikash Kumar Paul, Kawsar Ahmed, Md. Ibadul Islam, Md. Asaduzzaman Jabin, Ali Newaz Bahar, M.S. Mani Rajan. "Analysis of optical sensitivity of Analytes in aqua solutions" , Optik, 2018.