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Photonic Crystal Fiber for Sensing Application

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Abstract: The concern for Sensing Application using photonic crystal had become an elevation in diverse field. Enhanced precision in sensing became an anticipation of users. Photonic crystal fibers are considered to be eccentric than optical fiber sensors due to its geometric structures. By proposing novelty in geometric structures of PCF can increase the sensitivity range as per the required application. In this paper we made a review on different sensors like physical , Curvature, Displacement, Electric and magnetic field, Refractive Index , Bio chemical, Biomedical which are used for sensing applications .

Keywords: Photonic Crystal Fiber, Biochemical PCF Fiber, Biomedical Sensors, Hollow and Dual core.

I. INTRODUCTION

Philip Russell introduced Photonic Crystal Fiber during the period of 1996. Initially it was defined as solid core. Later during the year of 1998 he introduced hollow core. Photonic crystals are designed with core surrounded by cladding air holes; they are termed as solid core photonic crystal filter. When both core and cladding are structured by air holes they are known as hollow core Photonic crystal fiber [1].

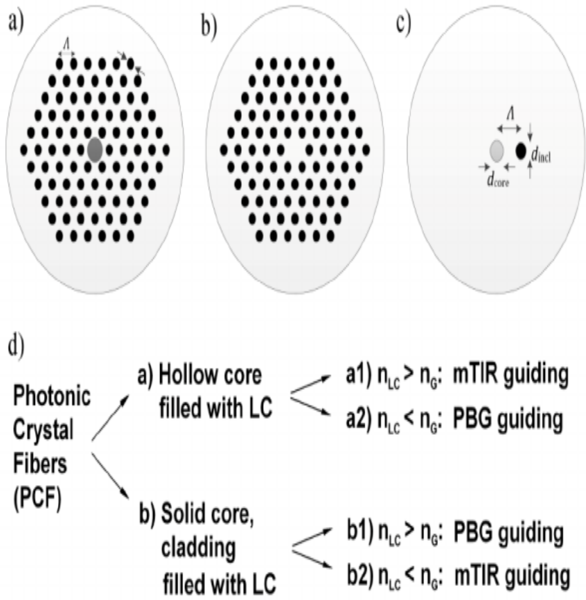

Fig 1. Solid core and hollow core

The above diagram states the basic structure that states hollow core and solid core. These structures can be designed based on the required geometrical structures like oval, spherical, honeycomb, hexagonal, orthogonal, hexagonal and so on.

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The following figure 2, figure 3, figure 4 shows PCF structures in the form of hexagonal , octagonal, honeycomb structures. PCF follow the properties of photonic crystals which are made by nanostructures. The main advantage of PCF that an optical fiber is light confinement. The Operation is given by their propagation mode. Higher index guiding fibers

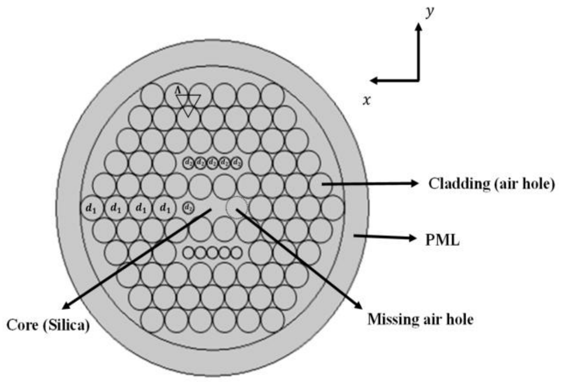

Fig 2. Hexagonal PCF structure

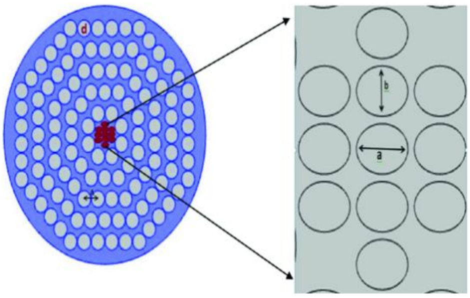

Fig 3. Octagonal PCF structure

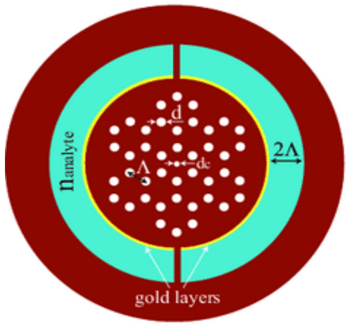

Fig 4. Honeycomb PCF structure

guides in solid core by total Internal Reflection principle. Wherein lower by photonic bandgap effect. There are many categories in photonic crystal fiber. They are, Photonic bandgap fiber which confines light through bandgap effect. Herewith, Holey fiber is also PCF which uses air holes in the cross section. Next type of PCF is hole assisted, which guides through conventional higher core modified. Along with this kind of PCF, Bragg fiber PCF is formed by concentric rings of multilayer film.

The development of PCF initially started during the year 1997, which proposed single mode PCF with the application of mode filtering, sensors and interferometer. In 1999 PCF with photonic bandgap air core was introduced with waveguide structure. Highly birefringent PCF was introduced during the year 2000 which consists of different air hole diameter with asymmetric core design or two orthogonal axes. Also during this same year Super continuum generation in PCF was generated due to Zero dispersion wavelength and high non-linearity. These were mainly used in laser sound spectroscopy, pulse compression. In 2000 Fabrication of Bragg fiber was introduced for extensive application in fiber lasers and optical sensors. Also double cladding was introduced in the same year with ytterbium doping. During the year 2002 0Ultra-flattened dispersion was introduced. In year 2003 Bragg fiber with air core and silica came into existence. Novel chalcogenide PCF introduced to exhibit an extreme high refractive index coefficient at 2004. Later, kagome lattice PCF was developed in 2005 which has higher contribution to gas sensing.

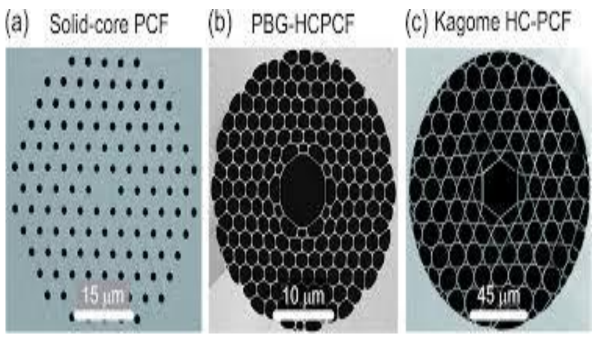

Fig 5. Difference between structures in Solid core PCF, Bandgap effect and Kagome HC-PCF

In 2006, Hybrid PCF was introduced which is doper with germanium. Silicon double Inversion established in 2007 to withstand room temperature. During the year 2009 to 2015 Multicore fiber properties, Nano displacement sensor , equiangular spiral photonic crystal fiber and Yb doping came into existence. Many other structures were used along with these categories of PCF for better sensitivity [2]. PCF has desired properties for sensitivity or any other application. Dispersion Property which also includes group velocity, material, waveguide and chromatic dispersion. Wherein, loss mechanism is another property which comprises of confinement loss and bending loss. V-Parameter, Effective area, Numerical Aperture, Spot size, Non- linearity co-efficient is also other properties of PCF. The Fabrication technologies used in PCF are Stack and draw process, Extrusion and filling technology, Sol-gel technique for fabricating irregular shaped PCF. There exits many application on PCF in various field like Sensing Application, Medical Application, Communication Application, Laser Technology, Optical interconnection, Multi structured fiber. In this paper we review on sensing application of Photonic crystal fiber.

II. SENSING APPLICATIONS

In-spite of developing sensing application in PCF, Many scientific groups started research on PCF for its unique characteristics. The main attraction towards PCF is its varying locations, size in cladding or core holes. PCF has capacity to propagate light in air. Wherein PCF has also additional capacity to insert gas or liquid into air holes which becomes the main reason to interact with the sample to be sensed. In this, sensing applications of PCF in diverse field are explained. Based on parameter PCF sensing are divided to Physical sensors [3], Biochemical sensors and Biomedical sensors.

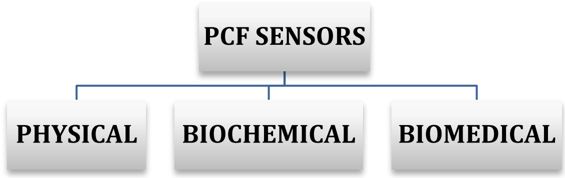

Fig 6. Major types of PCF sensors

A. Physical Sensors

Physical sensors are beneficial because of its flexibility nature and its internal structure to fill analyte for interaction with light. Physical sensors are mainly meant for measuring some desired parameters like pressure, torsion, refractive index, electric field, Magnetic field, temperature, Displacement, Stress, Strain for various applications in health monitoring , bio-medical sensing, civil structure monitoring, remote sensing , in-order to find the fault in the initial state and to prevent accidents or abnormal conditions.

B. Biochemical sensors

Some sensors are used to detect chemicals which are in the form of gas, vapour or liquid. They are used chemical industries to sense various chemicals to detect leakages and density of chemicals. In medical field blood components and harmful substance in body are sensed. Food components are also sensed to identify harmful additives.

C. Biomedical Sensors

There is more need for sensing in medical field. Blood sensing , DNA hybridisation, to detect disease, to detect antibodies and antigens, to detect pathogens, to detect glucose. Different structures are introduced to increase the sensitivity range. PCF structures are used to sense because of its reliable structures.

III. DIFFERENT TYPES OF SENSORS

In this section we will discuss about various types of sensors with its result and its applications.

A. Temperature Sensor

PCF type are widely used in the fields of biomedicine to monitor medical incubation and dialysis machines. Agricultural field uses to monitor soil and water for plant growth. Food, beverage industries sense meat processing, fermentation process and temperature of storage room is sensed. Birefringence is comparatively low as decrease in the temperature. A methods implements filled ethanol in air holes of PCF. Through this ,the varies 45 to 75 ◦ C and L = 5.05 cm [4], which have higher application on detection.

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Sensitivity 31.66 pm /°C and displacement range of -528.57 pm/µm, respectively [5].This is achieved through the structure of coated strip. Towards designed hybrid structure senses both temperature and displacement simultaneously. A novel fiber in-line Michelson interferometer been proposed to achieve −0.05 rad/ °C at 20 °C to 90 °C [6] in-order to lower measuring error phase- shift, tracking demodulation method used. Sensitivity 14.31 pm/°C using silica cavity [7] at 100–800 °C.

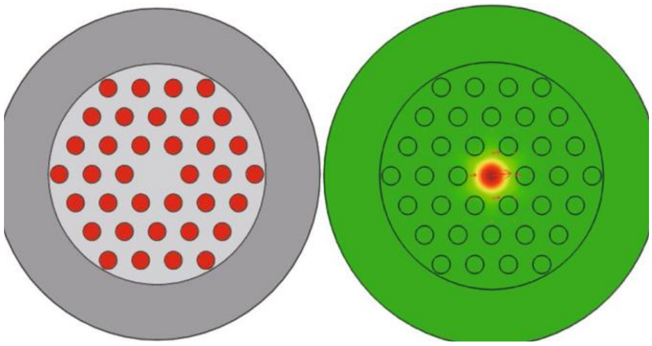

Fig 7. A simple design structure to sense temperature

To detect environmental conditions 0 °C to 360 °C, two dimensional photonic crystal ring resonator proposed [8]. Silicon rods are in form of Hexagonal rods surrounded by air. Detection range is relied on change in refractive index. 92.3 pm/°C. This is suitable for nanotechnology. When PCF is infilterd with liquid crystal, periodical alteration occur due to electro-optic effect as voltage is applied externally. 15°C to 58°C [9] is the sensitivity range obtained using this sensor. Liquid crystal consists high thermos- optic coefficient used for biochemical application for cell culture. Graphene oxide is coated with PCF and cascaded in two spherical structures. This sensor depends on Mach- Zehnder interferometer. Graphene Oxide is used as it has the property of hydrophilic which changes the refractive index. Temperature sensitivity and humidity sensitivity value found in this research work 0.063 nm/◦C and 0.086 nm/◦C at 10◦C to 70◦C. Detection are 0.128 nm/% RH and 0.159 nm/%RH from 30% to 70% [10]. Novel fluorescein luminescence is introduced to sense wide range of sensing. With the detection limit at the level 0.24 mW and wavelength presented is 490nm [11]. Dual elliptical core photonic crystal fiber is introduced for wide sensitivity in short range. Thermo –optic co-efficient of silica and chloroform are used to analyse the temperature. Obtained result through proposed method 42.99 nm/_C for distance 1.41 cm [12]. Isopropanal filled with photonic crystal fiber long period grating used in high thermos optic coefficient. Detected value 1.356 nm/_C [13] .

B. Alcohol sensor

Alcohol may be in the form of liquid or vapour. Its sensitivity are achieved through different structures in Photonic crystal fibers. Octagonal structure is proposed with micro structure porous core to sense aqueous analysts with wavelength range of 0.80 $^{-1}$m to 2.0 $^{-1}$m. FVFEM is used for numerical analysis. In this work ethanol, methanol, propanol, butanol, and pentanol these solutions are sensed with the sensitivity value of 67.66%,66.78%, 68.34%, 68.72%, and 69.09% with confinement loss of 2.42 × 10^{-10} dB / m,3.28×10^{-11} dB/m, 1.21×10^{-6} dB/m, 4.79×10^{-10} dB/m, and 4.99×10^{-9} dB/m. Wavelength at 1.33 m^{-1} [14] .When alcohol is the form of vapour it is sensed through change in colour during light incident. Cellulose film with colloidal array are embedded inside in three dimentional and they are fabricated with poly methacrylate as their refractive index are increased, redshift in reflection of incident light. This changes the color from blue to green visually [15]. Quasi-fiber sensor is proposed for alcohol sensing. FEM implemented for NA at 0.80 μm to 2.8 μm wavelength. At the outer boundary scattering boundary condition is implemented to attain sensitivity from 60%~98%, Numerical Aperture of 0.68[16], this type of sensor is used in medical imaging. Zeonex based photonic crystal is modeled to identify the ethanol content in food and beverage. The obtained sensitivity 68.87% and confinement loss at 1 THz are 7.79 × 10−12 cm−1 [17].

C. Analyte Sensing

Analyte is a substance which is in the form of liquid. The substance to be sensed by a photonic crystal fiber is given by an analyte. Octagonal photonic crystal fiber proposed with perfectly matched layer. For sensing wavelength upto 2.2 µm starting from 0.6 µm, The achieved sensitivity for Ethanol, Benzyne andwater, are given by 56.75% ,58.86% and 52.07% at λ = 1.33 µm. CL 1.55×10^{-13} dB/m, 5.05×10^{-13} dB/m and 7.50×10^{-13} dB/m ,EA of 4.91 μm^2, 5.11 μm^2 and 5.31 μm^2[18].Another square cored introduced to achieve the sensitivity and 56.25%, 58.36%,51.65%, for above with the confinement loss of 1.31×10-12 dB/m, 3.13×10-13 dB/m, 6.64×10-13 dB/m [19].An innovative photonic crystal fiber is introduced with the principle that implements a single mode gets spliced into multimode fiber in either sides. This type of PCF consists of empty core which is surrounded by elliptical plasma rods. E - band is with dispersion of 1360-1460 nm and U-band dispersion of 1360-1460 nm [20]. In this type of model arrangement different core is for pentanol designed to attain higher sensitivity. Ethanol sensitivity coefficient is given by 32%-42%. Water sensitivity co-efficient is givent b1 8% - 25% [21]. In this same model the PCF uses three different structures. They are given by X-Model ,Z- Model and V-Model.

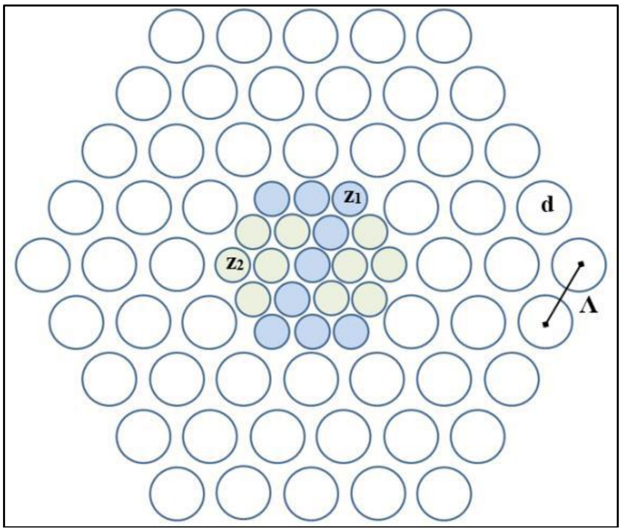

Fig 9. Z-Model PCF

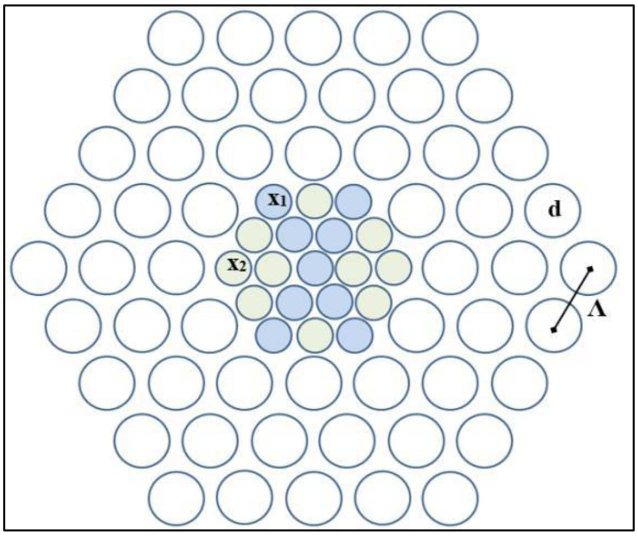

Fig 10. X-Model PCF

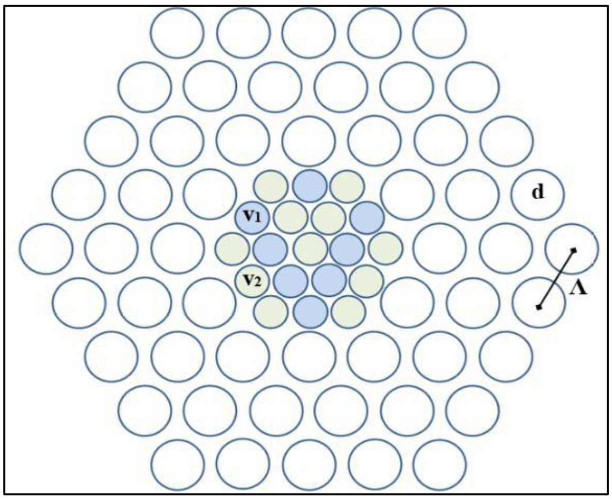

Fig 11. V-Model PCF

D. Blood Sensing

Blood is an important component for survival. From normal condition to pandemic condition sensing of blood plays a vital role for finding the problem state. Through sensing of blood detection of glucose, hemoglobin, antigen, antibody, pathogens are also identified. Glucose in salaiva is sensed through haemoglobin directly through Matrix assisted pulsed laser evaporation technique. In this paper haemoglobin in the blood is been immobilized to get the glucose concentration. The obtained glucose concentration is 0.1 mmol/L [22].In this paper PCF are used with hollow core structure in PCF to sense epidermis blood. The proposed system gives sensitivity of 674.603 RIU^{-1} [23] by the model HC19-1550 PCF. There are many components in blood with varied sensitivity. In this paper HC photonic crystal fiber is used to identify the components like water, plasma, WBC, hemoglobin and red blood cells in blood. There is very less confinement loss. Here the frequency used is 2THz.Finally the obtained result through this structure 89.14%,90.48%, 91.25% (WBCs), 92.41% for hemoglobin (HB), 93.50% [24]. Same work includes Zeonex as fiber material for high sensititivity. The Fabrication of the material is done through 3D printing technique. The sensitivity range obtained are given by 55.82%, 58.047%, 62.721%, 65.054% and 66.469%.Also the obtained confinement losses are given by (dB/Km) 8.1343 × 10^{-11}, 4.8787 × 10^{-10}, 1.8134 × 10^{-09},2.5928 × 10^{-08}, and 4.890 × 10^{-08} [25].These kind of sensor are used in the form of nanosized biosensor to obtain maximum performance. D-shape elliptical DC Photonic crystal fiber is introduced to obtain sensitivity 4.62 nm/gL^{-1} and 5.1 nm/gL^{-1} [26]. Following diagram explains above Description. This structure also provides air holes structure

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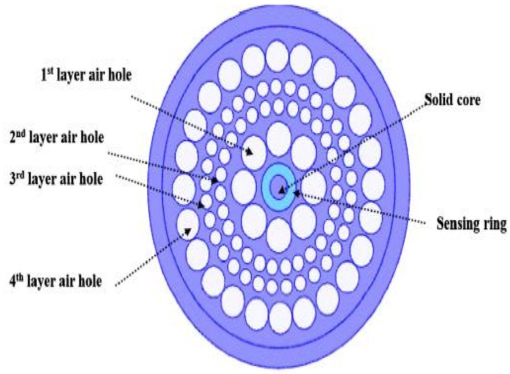

Fig 12. SC-PCF Ring structure

Figure states 5 different layers used for analysing the sensitivity.

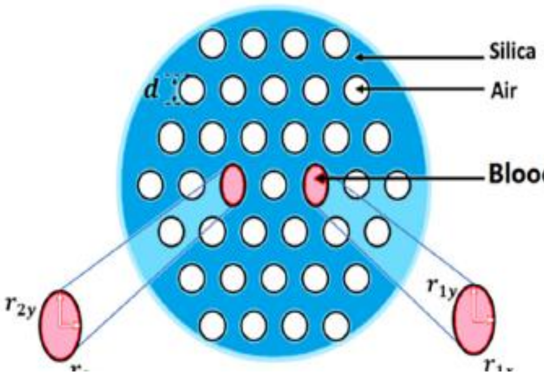

Fig 13. Cross Sectional view of Dual core PCF structure for blood sensing

The above diagram states the structure of Dual core PCF. The diagram clearly explains about presence of blood in air hole.

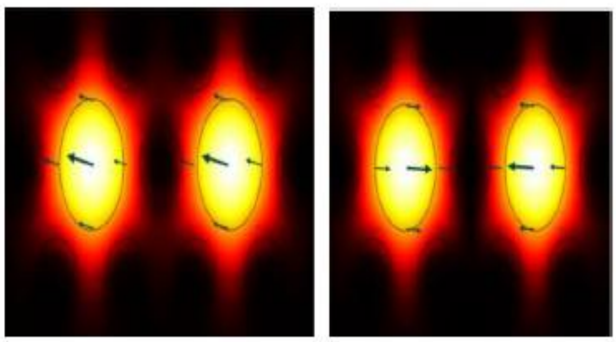
Fig 14. Mode field distribution

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The above diagram explains about the distribution of modes clearly in both polarisations.

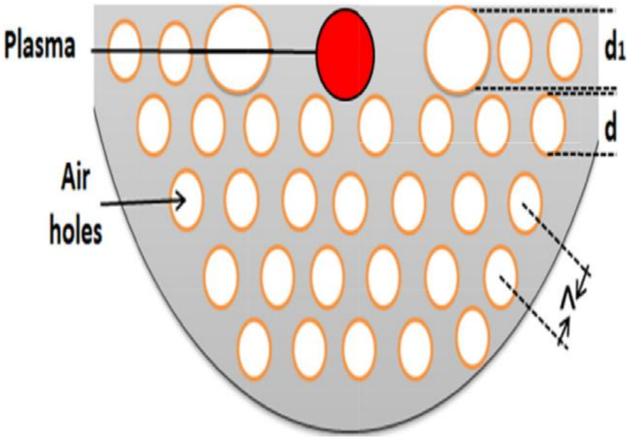

Fig 15. D-shape Structure

These types are used in finding variation in biosamples. Another research paper which explains symmetric photonic crystal fiber for sensing blood which is provided in elliptical core. This structure is based on different polarization and coupling principle. The obtained result through this structure is given by 13.5 nm/g/dL X-polarized mode and 5.96 nm/g/dL Y-polarized mode with 5 cm fiber [27]. For sensing blood constituents in the wavelength from the range of 1530-1565nm; PC based ring resonator enabled. For Cytop (polymer), Biotin–Streptavidin, Albumin, Ethanol, Bovine Serum Glucosesolution(40gm per 100ml), Hemoglobin, Blood Plasma, Poly-acrylamide [28].Along with Finite Difference Time Domain method, EM Equation Propagation and photonic Bands in simulation tools; used for modelling PCRR signals. Through this design the obtained sensitivity is given by 343nm/RIU. This result is achieved by the little change in refractive index [29]. By implementing FVEIM and TMM blood glucose level identified and through D-shaped photonic crystal fiber (DPCF) doped with gold nanoparticles the same parameter can be identified .These are embedded with titanium dioxide which act as an important material for detection 0.83 nm/(g/L) and hemoglobin content 160 g/L [30]. Another biosensor with dual-core for sensing. Based on Effective RI sample of blood are determined . For the purpose of numerical analysis FV finite element method is used. Attained value are 8.013 nm/g/dL in X-polarized mode and 7.68 nm/g/dL Y-polarized mode under length 3.7cm,3.2cm [31].

E. Chemical sensor

Chemicals are substance used as mixture in other substance or solvent. It also detects substance and preserve materials We will discuss about PCF based sensors. A proposed D shape is introduced to detect methane, based on Sagnac interferometer. Two ultra-large air holes taken along with methane sensitive film in horizontal way to minimize response time. Methane is in form of gas and its obtained sensitivity is given by 36.64 nm% [32] with the range of 0–3.5%. These type of sensors are mainly used for sensing methane gas. Formalin detection is performed using Kretschmann configuration .In this work graphene and MoS2 are used for detection purpose. The proposed biosensor obtained sensitivity is 85.375% [33]. Detection of bane chemicals are performed in this work. As a fiber material Zeonex is used and performance of sensor analyzed at terahertz mode. Sensitivity obtained is 94.4% [34] at 1.8 THz frequency with CL 1.71 × 10−14 cm^{-1} .Sulphuric Acid detection is performed through Comsol software for analysing the sensitivity. At λ =1.5mm and confinement loss of 1.422×10^{-17} dB/km.Finally the attained sensitivity is 63.4% [35]. photonic crystal fibers with Glass hollow core (HC-PCF) which are modified chemically. Silanol groups are in inner surface of HC-PCF with (3-aminopropyl) triethoxysilane (APTES) [36].

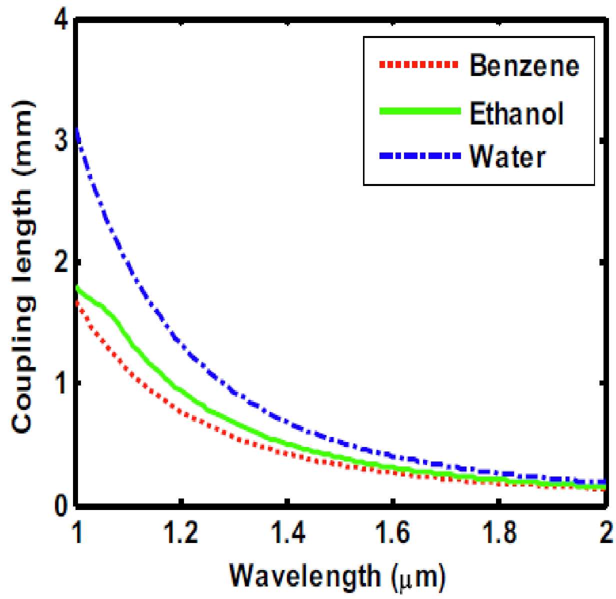

Fig 16. Wavelength measurement

Through the inference from above diagram, there is clear execution in wavelength measurement of Benzene, Ethanol and water.

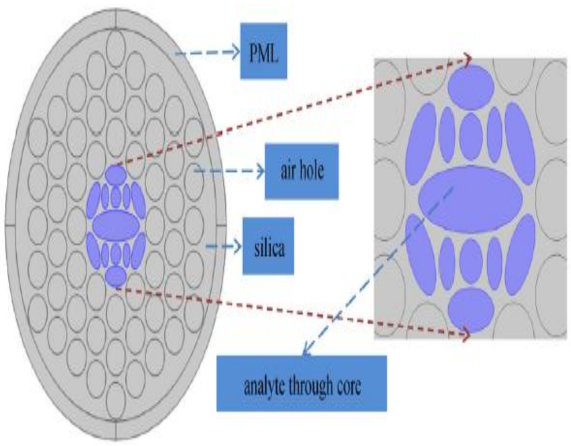

Fig 17. PCF structure used for sensing Sulphuric acid

Microporous core structured PCF chemical sensor introduced which are inbuilt with claddingporous shape . The obtained NA is from NA 0.35 to 0.36 and Aeff from 5.50 to5.66 μm^2 [37].

In a biochemical sensing Mid-infrared waveband plays a vital role. Silica glass fiber used less because of its high transmission loss nature. Silica glass fiber are used for refractive index testing. For sensing and sampling dual-channel integrated with fluorine-doped tin oxide and fiber sensor proposed for high sensitivity. These structure are error tolerant and useful to detect multiple physical quantities along with biochemical sensing simultaneously [38]. Using COMSOL Multiphysics dual core designed to determine Benzene, ethanol and water are sensed here through PCF separation in its cores.The wavelength used here is 1.55 mm. And the final sensitivity obtained is given by 9615 nm/RIU (refractive index unit) [39]. Photonic crystal fiber (RH-CPCF) with hexacore in rotated structure is introduced along with cladding of circular shape in five layers and two layer core are designed. To obtain result PMLB mode of propagation used. Finally at end stimulating sensitivity for Benzene ,Water ,Ethanol are given by 77.16% ,73.20%, 76.44%, with confinement loss of, 3.07×10^{-06} dB/m ,2.84×10^{-02} dB/m, 2.33×10^{-03} dB/m [40] for wavelength 1 THz. Another work which uses spiral photonic crystal fiber along elliptical air-holed placed for liquid sensing. Achieved result 58.3% 62.7%,56.8% of substance propane, propylene, water, with confinement loss of, $7.2\times^{10-8}$, 6.5×10^{-8}dB/m,8.5×10^{-7}. Fig 14 explains the structure and analyte used in this work. For the purpose of methane sensing twin-core proposed in which side holes polished with methane sensitive film. This structure is mainly introduced for sensing and monitoring environmental gas. The detection limit is given by 4.60 nm/% and 435 ppm [42]. Along with temperature compensation highly sensitive methane sensor is proposed to eliminate cross sensitive effect through matrix demodulation method. Methane sensitivity 20.07 nm/% with maximum range value 3.5% [43]. In this section we saw various structures and results for sensing chemical. Comparing to other sensors chemical sensors requires additional layers of core and cladding to withstand the

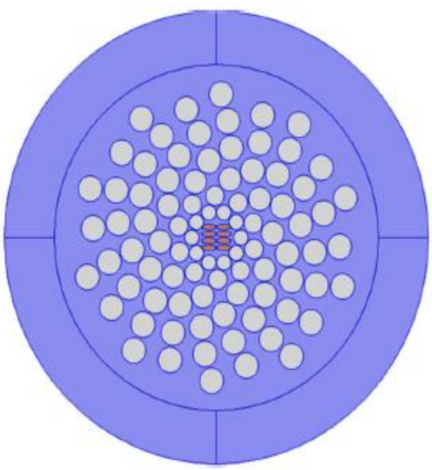

Fig 18. PCF structure with analyte filled

chemical intensitity. Eventhough chemicals are hazardous there is in need of its value for various processing. Hence sensitivity range of chemical and its concentration are essential. The following diagram gives the inference about different layers inside a PCF for sensitivity purpose. This sensitivity is attained through hexagonal air holes.For identification purpose, some of the airholes are structured with separate colour.

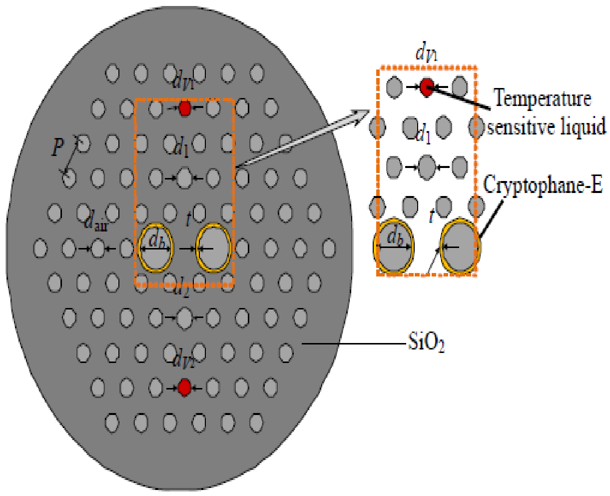

Fig 19. Different layers inside PCF

F. Current Sensing

Current used in various fields for working and avoiding interruption became important to continue the performance. Such type sensed for proper discharge. CPCF was designed with air holes in circular polarization. Air filling ratio,specific rotation structured by 4.5 μm, 0.42 and 2.9×10^{-4} rad/μm, [44] respectively. Air hole diameter fluctuation given by ±10% with higher value to $|S3| = 0.9664$ in SSBF. It has circular-polarization that maintains over long period in addition to sensing coil through current measurement as it has decreased error. Also it is low cost with increased accuracy.

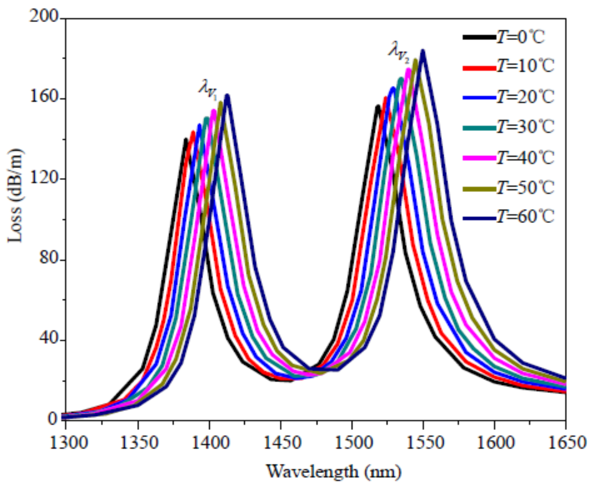

Fig 20. Wavelength Measurement

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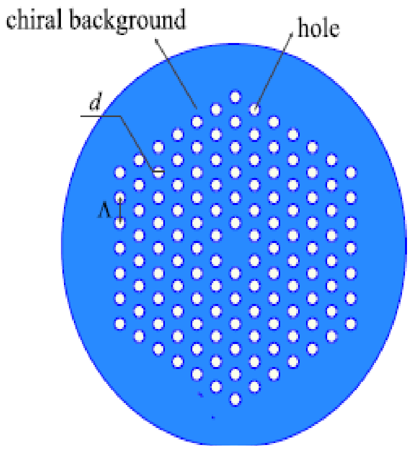

Fig 21. PCF structure with chiral background

G. Curvature Sensing

In this work, SM fiber taper structure used along loop ring down curvature sensor technique is proposed. Five SMF tapers are used in this work. Curvature is sensed by the ring-down time altered by the bending loss with different curvature. Through concerned work sensitivity is 44.1 µm and 65.4 µm waist diameters 0.725 $\mu s/m^{-1}$ and 0.328 $\mu s/m^{-1}$[45].

H. Food Sensing

Food is an essential for survival, wherein its qualitity is important to stay as safer zone. Some additives are added in food which may become harmful, when level gets exceeded than stipulated range. Hence sensing of food additives plays a vital role. In this paper Hollow Core Photonic Crystal Fiber used to sense Sacchari,Butyl Acetate, Sorbitol,which are harmful food agents. Hexagonal airholes designed at inner cladding for increased sensitivity. Circular airholes are structured. Obtained sensitivity in chemicals are 87.37% , 88.75% and 86.72% [46] with operating wavelength 1.33 µm. Ethanol also sensed through this structure. Vectorial Finite Element Method used.

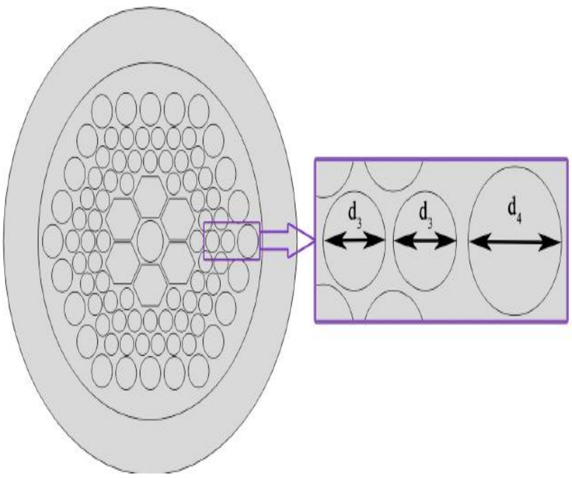

Fig 22. PCF structure hexagonal and circular air holes

I. Gas Sensing

Some Gases are colourless and sensing this material is difficult as its spreading is more. In this paper five hexagonal cladding is used with circular shaped core. The obtained sensitivity through this work 56.65% with CL 2.31×10^{-5} dB/m, wavelength 1.33^{-1}m, EA 6.44 $^{-1}m^2$ [47]. Experiment under Hydrogen Sulphide gas sensed. Graphene structure utilized for better sensing. Air holes in PCF are triangle shape with SOI layer at inner surface. Attained sensitivity through this work is given 1.2 × 104 nm/RIU upto 1.87×10^{-6} RIU range in detection [48]. Gas sensitive film introduced for increased sensitivity. Hollow core photonic crystal with group indexed band-gap. For Numerical analysis PWM and FEM utilized. Obtained sensitivity through this work is given by 0.794 nm/% [49]. This structure is used for detection of mixed gas also. Spiral shaped Photonic crystal fiber is used here for the detection of toxic and colorless gases. This sensor is mainly used for monitoring air pollution. Two layers of porous core are been micro structured and cladding is structured with spiral shape. NA undergone and sensitive range 55.10% attained [50]. The absorbed toxic gases through this work are methane and hydrogen fluoride. Dual Fabry-Pérot interferometric carbon monoxide gas sensor introduced. Membrane is coated at one end of optical fiber for increased sensitivity. Single mode fiber is used in another end. These layers are formed by airholes combination. This work is meant for sensing carbon monoxide with the value 0.3473 dB m/ppm[51] , 68 s and 106 s are the response and recovery time. This sensor is considered as more advantageous because of its low cost, high sensitivity and compact size. Ambient oxygen, carbon dioxide, nitrogen gases and vapours acetone, 1,1,1-trichloroethane, toluene, are sensed here by implementing hollow core photonic crystal fiber. These types are applied for environmental sensing. Methane and hydrogen fluoride are sensed in this work . The obtained sensitivity and birefringence through the spiral structure are of 57.61% and 7.53×10^{-3} also with 4.1° divergence and wavelength from 1 µm to 1.8 µm [52]. The following structures describes the coating and layers in proposed PCF.

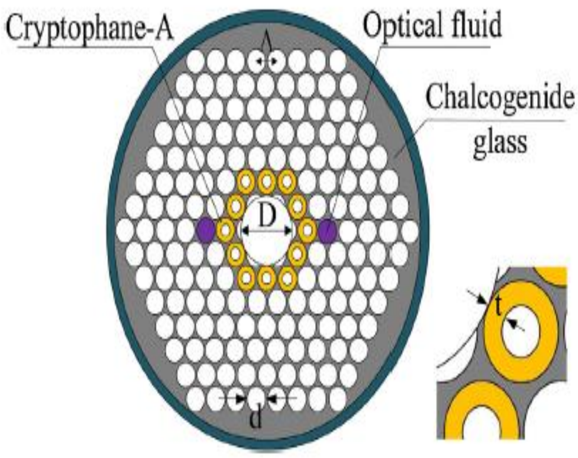

Fig 23. PCF structure explaining its layers

Another research work which works on photon energies that corresponds polar materials that reaches terahertz regime to sense toxic gases. Rotational transitions create weak dipole moment that limits gas at lower concentration.

High sensitive detection of gas are achieved through cavity defect stage along resonance on absorption of required characteristic. Hydrogen cyanide of 2 ppm concentration Under 1 atm AP [53]. Circular based gas sensor are analysed. Spiral porous Core region is suggested for high light interaction. Achieved sensitivity are represented as 72.04% with the wavelength of 1.33 µm [54]. In this work toxic gases can be sensed between the wavelength of 1 µm to 1.8 µm. Similar to chemical sensing gas sensing are also challenging as its characteristics are like highly toxic capacity, colourless, odourless. Gases becomes an omnipresent hence we need to identify its intensity and the type of gas. Gas sensors are mainly in used in industries and for environmental purpose to monitor air pollution. To avoid accidents of gas spilling in industries sensors are essential. Hence different structures are introduced to attain better sensitivity.

J. H. Glucose sensing

Glucose is present in blood, water and many other substances. Glucose is essential but usage in correct density is required. In this section there is a discussion about glucose sensing. Using COMSOL multi physics software silver nanowires are designed with photonic crystal fiber. The attained sensitivity through this work is 19009.17nm/RIU and detected amount of glucose in water is 44.25mg/dL [55]. The diameter used here 90–120nm . In this new work 146699.26 nm/RIU [56] is obtained through its refractive index. Urea, Albumin in glucose are analysed using the PCF structure implemented with glucose sensor.This has tighter confinement. Another PCF design got higher refractive index and spectral sensitivity of 19135.70 nm/RIU [57]. Air hole designed in such a way that it supports liquid core. In the second layer six cores are present to exit the air hole. This structure is mainly used in real time application. Even though sensors are available users always expect a compact size. In this work the design explains about A compact glucose sensor is designed. For the same PCF is fiber inserted in Sagnac loop interferometer . Spectral sensitivity attained are given by of 22 130 nm/RIU with the range 0.76 mg/dL of glucose in water, which is lower than 70 mg/dL [58]. It is highly efficient for glucose detection in hypoglycemia patients. New glucose sensor in a tapered structure is introduced that are coated with graphene oxide and gold nanoparticles. The taper region is used for exposing evanescent waves at the cladding boundary with graphene oxide . Gold Nano particles and Graphene Oxide are used for its good absorbance capability. Its absorbance wavelengths are given by 230 nm and 519 nm. The analysis are done through UV–vis spectrophotometer and TEM. The attained value through this structure are 1.06 nm/mM [59]. Blood samples of humans are sensed. Coupling is done between silica mode and analyte mode and reported sensitivity is 8333 nm/[*RIU*] in variation 10 g/l to 20 g/l with resonance wavelength [60].Thus we saw different results and structures in glucose sensing among various field including blood samples. Additives in glucose that is toxic in characteristics are added. To overcome this issue, obtaining higher sensitivity is essential and hence different stuctures are implemented.

K. Humidity sensing

Humidity necessary to sustain suitable condition. In this section exhibits some sensing structures on humidity. PCF coated with car-boxy methyl cellulose for responsive parameter. Bragg grating used for actuating mechanical strain in response to changes. Achieved range is 5%–40% and measurement uncertainty over this relative humidity range is ± 2% (k = 1) [61].Interferometric sensor are spliced into standard single mode fibers, poly(allylamine hydrochloride) and (acrylic acid) ,polymeric nanocoating are deposited on well-established layer-by-layer nano assembly technique. Nano layer modified by humidity as detectable shift is observed in interference pattern. For spectrum analysis Fast Fourier Transform are used response. The resolved humidity through this work is given by 0.074% and relative humidity is operated at 20–95% RH [62]. Finally the response time is obtained as 0.3. Through a different new inline mode Mach–Zehnder interferometer with coating of graphene quantum dots and polyvinyl alcohol for sensing . The sensitivity gained through this work is 343.7 nm/RIU [63].One dimentional photonic crystal fiber is calculated both theoretically and experimentally to detect environmental sensitivity. Multilayer porous thin films are deposited on fiber which are the sensing elements. Humidity detection level is from 11 to 84%RH [64].

L. Liquid Sensing

Liquids are of many forms. Under this section, there is a discussion about different liquid sensors. To detect liquid analytes. Photonic Crystal Fiber with Finite Element Method is used For wavelength (0.6 µm−1.6 µm) [65]. It has lower confinement loss.Wherein with the structure of A solid core for identifying chemicals in liquid form . The wavelength range between 1.4 and 1.65 µm are synthesized. The filled amount are glycerol (n = 1.4722), ethanol (n = 1.354), and toluene (n = 1.4968), By applying various parameters in structures of PCF 65.16%, 61.65%, and 64.05% [66] of sensitivity are attained as a result. Comparatively Confinement loss is minimum through this structures also effective area is analysed here.

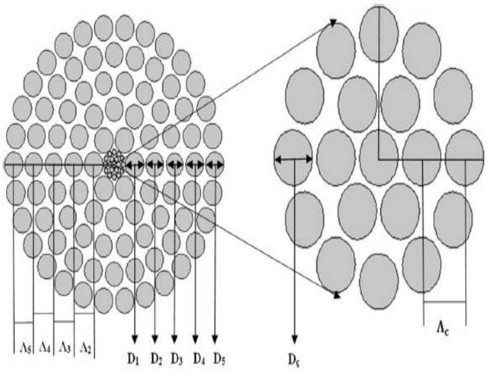

Fig 24. PCF structure with increased number of core and cladding air holes for increased sensitivity

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For attaining high sensitivity,high birefringence and low confinement loss in liquid sensinge through Photonic Crystal Fiber, full Finite Element Method for elliptical holes are choosed in the core region. The wavelengths (1.3 μm–2 μm) are assigned here. 49.13% [67] is the sensitivity obtained and the birefringence is 0.008. These are suggested for bio-sensing applications. Mach–Zehnder modal for sensing concentration of Fe in water. The core and cladding are recombined. The sensitivity detected is sensitivity was 42.446 nm/RIU [68].

M. Magnetic Field Sensing

Magnetic have capacity to attract metallic substance. For sensing magnetic materials these sensors Multimode-single mode-multimode combination is introduced in Magnetic fluid-filled optical fiber Mach-Zehnder interferometer, fabricated through splicing Magnetic fluid-filled capillary tube is sealed within a microstructure. The change in refractive index is due to variation in Magnetic field. Through this 0.12306 nm/mT [69] value is attained. By tuning the structure highest response is 5000 pm/Oe and resolution 11.33 Oe [70] .These type of sensors are mainly used in nanofluidic technology. Magnetic field are also based ferrosoferric oxide to increase sensitivity. There is need to detect magnetic field from 100 Oe to 160 Oe. Attained sensitivity in X and Y polarization given by 83268.46 nm/RIU and 83188.25 nm/RIU [71]. The accuracy is comparatively high with lost cost. 2D photonic-crystal is used with nanocavity infiltrated along with magnetic fluid. To increase the sensitivity air holes which are infiltered are also used in huge number. Around 12 infiltrated airholes are implemented in this structure. Refractive index sensitivity for the structure is provided by 146.97 nm/refractive index unit [72]. Another D- shaped photonic crystal fiber and Ethanol inserted structure is introduced. Along with magnetic field, temperature also sensed through this work. Magnetic sensitivity is obtained by this structure is 0.21 nm/Oe and temperature −1.25 nm/°C [73]. Square lattice dual core photonic crystal fiber is implemented to attain the sensitivity of sensitivity of 799.07 pm/Oe [74]. The structure consists of two cores in which mode coupling is performed. This sensor is used in health monitoring instruments and it is a portable device. Sagnac interferometer based polarization maintaining photonic crystal fiber is used which is a refractive index sensitive structure. Possessing low refractive index, the water-based nanoparticles uses $Fe3O4$. In this structure magnetic field it attained in opposite direction. Result obtained through this work is R-squares are 0.98113, 0.98415 respectively for detected range 410-600 Oe [75].

N. Fuel Sensing

Fuel is essential thing for performing some works like transports and working in generators. If there is adulteration in fuel then it may lead to other functional problem in parameter used. Hence sensing fuel plays vital role to identify adulteration . In this work dual core photonic crystal fiber which consists of single analyte channel is given for detection of petrol adulteration. Using finite element method ,sensing Probes analyzed. Petrol is sensed in circular analyte which is infiltered . Through simulation 20,161.2 nm/RIU is observed [76]. With the help of this work along with the Fuel

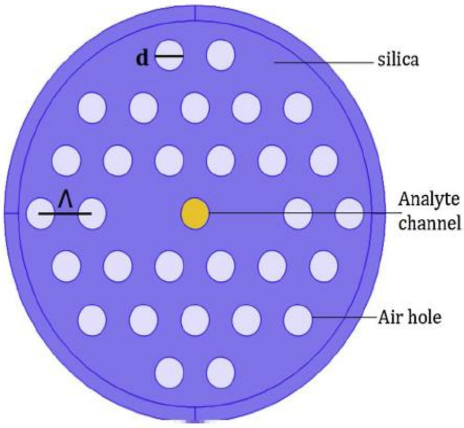

Fig 25. PCF structure used for fuel sensing

adulteration sensing, It can also be used for sensing environmental pollution, to increase the life time of engine.

O. Pressure

These have physical quantity for observing environmental condition at required application areas, monitoring industrial processes in harsh climate. Interact with human and other animal medical diagnosis purpose, measure human body fluid pressure, under water pressure. Along with this temperature can also be sensed. Pressure measurements are needed for industrial applications at tough environments like power plants, , oil ,gas exploitations are complex in some applications as high temperature and corrosive materials or interference due to electromagnetics, these are overcome my pressure sensors. Measurements of hydrostatic pressure are also done through this sensor. In this section, there is a discussion about its applications and different structures and materials used to increase sensitivity of pressure. modulation and polarisation type used to execute high-birefringence fiber.. Sensitivity obtained through this work is is 2.05×10^{-6} [77] RIU/MPa in pressure 0–100 MPa, and temperature sensitivity is 7.27 ×10 − 10 RIU/°C upto 0–100 °C. Results show that 0.145 dB/MPa at 0–44 MPa of pressure value.These sensors are used in Ocean bottom holes. Polarization is maintained by using SM fiber. 2 Orthogonal modes used inthe PM-PCF are excited by splice point. Wavelength-pressure coefficient 4.15 nm/MPa, temperature coefficient 1.4 pm/◦C [78] . Another novel asymmetric double-core fiber which provides hydraulic pressure is introduced with 10-cm and 2.867-cm of sensing range from 0 to 900 MPa and sensitivity 0.3 mm/MPa [79]. Double fiber core with and two side air holes are used for ensuring asymmetric pressure-induced phase change for guiding light in two fiber cores. Using novel hybrid-dual core photonic crystal fiber at a length 6 cm has sensing range from 0 to1000 Mpa and sensitivity -11.6 pm/Mpa [80]. Two-dimensional hexagonal photonic crystal ring resonator structure designed for sensing both pressure and temperature based on effective RI .This nano type sensor is designed to detect pressure upto 6 GPa and temperature 540 °C maximum [81] .

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In this work finite-difference time domain method used for functional analysis of dynamic range, sensitivity, transmission efficiency , and quality factor. This sensor is used for bio sensing applications.It is advantageous because of its compact size.

P. Refractive Index

Based on Refractive index value the other sensors are diagnosed for its sensitivity .With variation in RI shows detecting range in sensor. Through this section,A multi-core micro nano fiber proposed for lower valued solutions. The mode field distribution are tapered multi-core fiber. At length of 16.20 mm, 5815.50 nm/RIU [82] is obtained. Measurement error is 0.5 %. Diameter is less than 4.864 μm with sensing rangec10000 nm/RIU. This kind of sensors are useful for detecting temperature also it can be used for sensing salinity in seawater . D-shaped with gold belt introduced. There is broad measurement range under 1. 9 $\times 10^{-5}$ RIU [83].With simple structure Mach–Zehnder interferometer demonstrated through fabrication and welding of a dual-waist photonic crystal fiber. Fusion technology and taper in core are performed here. The measured sensitivity through this work is of 263.5 nm/RIU [84].The impregnation on anodic aluminum oxide films is introduced to sense water-ethanol and water-glycerol of $\Delta\lambda/\Delta n$ = 142 nm/RIU [85] . Liquid mixtures are identified in this work. Through infiltration method different kinds of liquid mixtures are sensed. By presenting a carbon nanotubes deposited photonic crystal fiber along Mach-Zehnder interferometer configuration RI sensing. CNTs deposited on PCF surface for enhancing interaction of evanescent waves. Sensitivity 19.4 dB/ RIU within range 1.33 to 1.38 and 24.2 dB/ RIU under 1.38 to 1.42 [86]. Conventional graded-index multimode optical fiber uses. NaCl solution to get 70 nm/RIU at 1.333 to 1.345 [87] range.Better contact with surface and sensing element. Chemicals and biological sensing can be sensed through this work 2D photonic crystal worked with air-slot width-modulated line-defect microcavity with waveguide. Though simulation sensitivity of 400 nm/RIU [88] with detection limit 2.98 × 10^{-5} RIU is attained. Another D-shaped near-infrared spectrum suitable for detection of biomedical and biochemical analytes with different indexes. The active metal used here is Gold and a layer of molybdenum disulphide is coated for oxidation resident. Along with this graphene also deposited. Through this simulation simulation the sensitivity attained 14,933.34 nm/RIU with figure of merit, effective RI resolution of 401.05 RIU−1 and 6.69 × 10−6 RIU [89].Similar D-Shape structure with silica as coating material provides wavelength sensitivity 66666.67 nm/RIU, AS = -1488.82 RIU-1 ,of NA = 1.36 to 1.39, Resolution = 9.66 × 10-4 RIU [90]. This sensors are proposed for the analyte sensing in biochemical and biomedical applications. Mach-Zehnder interferometer with Cladding etched for high sensitivity is proposed along with splicing for increased refractive index. MZI with 35 mm PCF are 211.53 nm/RIU and 359.37 nm/RIU [91]. These biosensor is used for sensing higher spectral density. Amplitude sensitivity 11,412 RIU−1 , when refractive index varied from 1.44 to 1.45 [92]. Coupling is easier through this design. The simulation concludes analyte RI is 1.425–1.45 and 1.45–1.46, with average sensitivity 60,611 and 28,000 nm/RIU respectively, and detection limit 1.58×10−6 and 2.86×10−6 RIU [93]. An elliptical cavity for detection unit in a 2D hexagonal hole-type photonic crystal is notable for large detection range n = 1 to over 2 [94]. Sensing is divided into two distinct detection space in a different spectra. The design structures are analysed through the topology by FDTD and PWE methods. D-shaped infrared spectrum is proposed for analytes and liquids detection with different refractive indices ranging upto 1.40.Gold and graphene are coated to increase the sensitivity 33,500 nm RIU−1 with resolution 2.98 × 10-5 RIU [95]. Hollow core fiber is cost effective, analysed through full vectorial finite element method .This design exhibits sensitivities 10560 nm/RIU, 6400 nm/RIU , 12,400 nm/RIU for, gold silver,copper with resolution of 1.61 × 0−6 RIU [96].

Q. Salinity Sensing

Salinity is increased amount of salt content. Under this section its sensing provided. Seawater said to be highly saline. Sensing is difficult because sensors used corrode due to its high salt content and long-time survival possibility less because of high salt water content. Providing supply for working of sensor also difficult. Cavity photonic crystal resonator proposed for sea water salinity concentration detection . Computed value 544 nm/RIU with quality factor 3860. figure of merit 1.234 × 103 RIU−1 and detection limit 8.1 × 10−5 RIU [97]. Transmission characteristics of device attained through finite-difference time-domain. Result is 37,500 nm/RIU and 7.5 nm/% . Maximum resolutions 66 × 10−06 RIU and 1.33 × 10−02% with linearity 0.9924 at 2.20 cm length [98].This result is obtained through Sagnac Interferometer based fiber. When saline water infiltrated in one of cladding air hole, that offers high confinement loss. In this work along silica Phase matching condition used for power transmission in core. Numerical calculation is done through Finite Element Method. The observed result is given as5405 nm/RIU -x-polarization and 5675 nm/RIU y-polarization over 0.0037 RIU limit [99]. This gives 10^{-3} birefringence

R. Strain Sensor

Some of the strain sensor based three interferometric kind fiber explained. Hi-Bi PCF ,PMF and standard used. This type achieves sensitivity 0.893 pm/με ,26.85 pm/με,1.809 pm/με. for 7 cm and 23.9 cm [100].They are used for measuring hazardous environments and monitoring heath under complex structures. Under cascaded multimode fiber fusion spliced single mode fiber in either ends.. Through this work observed value ~−14.89 pm/με [101]. Ultra- long period fiber grating sensor introduced for simultaneous measurement. Fabricated done by splicing multimode fiber. Through strong refractive index, uncertainty values of the SMS-ULPFG structure are 3.26 με and 0.23 °C over the ranges of 0–1000 με and 26–118 °C.[102]. Through study of polarization modulation, high-birefringence fiber selected for fluid medium pressure measurement.

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Results show pressure 2.05 ×10 − 6 RIU/MPa in the pressure range of 0–100 MPa, and temperature 7.27 ×10 − 10 RIU/°C at range of 0–100 °C. Results project pressure sensitivity 0.145 dB/MPa under 0–44 MPa [103] Spliced twin-core fiber with fiber tapers are weak and T-shaped. Roles are splitting and combining modes. Proposed extinction ratio of 20 dB is achieved. When stress to 841.5 με, wavelength of 3.31 pm/με and 6.11 pm/με are achieved. Intensity sensitivities of 7.5×10−3 dB/με and 9.9×10−3 dB/με [104]. These sensors are used for Practical applications. For a Mach–Zehnder interferometric ,Designed with hollow-core photonic bandgap fiber to detect intrusion. result shows NR in HC-PBG is about 3.6 – 5.3 dB increased than SMF upto frequency range 2 kHz. Measurements on HC-1550 is concentrated. The input signal frequencies are from 500 Hz to 2 kHz [105] . Through the way of phase generated carrier,signal information are extracted. These types are used for monitoring in borders . Micro-strain sensor taperd with a single mode fiber base photonic crystal fiber – single mode fiber structure is used . Fabrication process and sensing done by Intermittent cooling method for increased sensitivity with value 5.46*pm/με* [106].This provides more fessibility.

S. DNA Hybridization

Sensing DNA is difficult task because of its minimized structure. Such hybridization performed and viewed. In-line Michelson interferometer introduced with combination of tuneable mode coupler and opto fluidic channel. Guided light changes refractive index in optic fluid channel. Through binding of methylated DNA and 5-methylcytosine (5-mC) monoclonal antibody are identified. This work shows detection 5nM [107].Transformation from ssDNA into dsDNA, performed here. Amplitude with wavelength, 6.82 RIU-1 94.59 nm/RIU [108]. This sensor classifies gold and analyte for performing Hybridization.

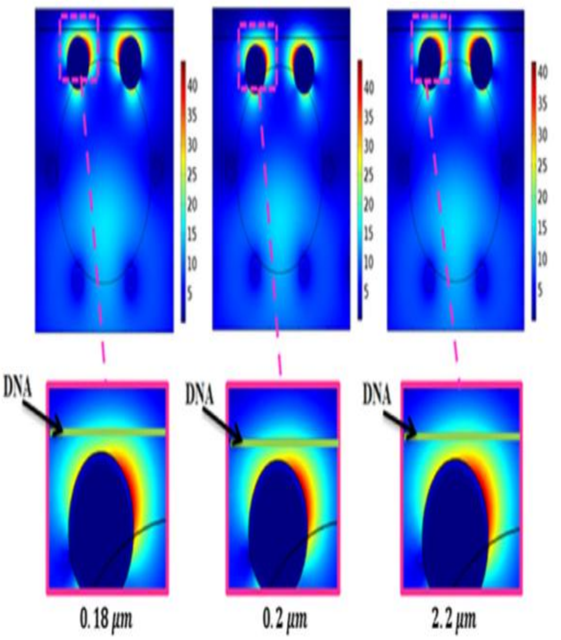

Fig 26. DNA Hybridization performance

IV. CONCLUSION

Photonic crystal fibers are known from the year of 1996. As years pass on the necessity of Photonic crystal fiber are increased due its unique application in sensing field. In this paper we made a review on different sensors like physical, Curvature, Displacement, Electric and magnetic field, Refractive Index, Bio chemical, Biomedical which are used for sensing applications in Photonic crystal fiber. Different structure that are used in Photonic Crystal Fiber are analysed along with its sensitive range. Among all type of sensors, Sensing of Chemicals, Salinity in seawater and Blood component detection is comparatively a challenging task. As world grows upon civilization, new diseases also grow along. It became an essential to find the disease to avoid a pandemic situation. Testing Glucose in blood are performed level within a minutes. Similarly the testing of Disease should be done faster. To attain this we have to use different structures in future .

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