Chapter 1

Introduction and Motivation

Chapter 1 briefly introduces photonic crystals and its type. Further in this chapter, we have discussed optical fiber and it different types. A broad view on photonic crystal fiber with their different types based on light guidance mechanisms and various applications has been discussed further. Additionally, we have described the finite element method (FEM) for simulation and COMSOL Multiphysics software for designing the photonic crystal fiber sensor structure, along with the principle and properties of different theoretical approaches. The fabrication process through the stack and draw method has been detailed explained. In the last literature review, the objectives and the motivation behind this thesis have been described.

Chapter 1: Introduction and Motivation

1.1 History of Photonic Crystals

Photonics is fundamentally described as the science of light. The word photonics originated from the Greek word "Phos" which means light. In 1887, Lord Rayleigh started the study of one-dimensional photonic crystals as periodic multilayer stacks of dielectric but at that time, no one used the term photonic crystal for this structure[1]. After a century, in 1987, two researchers Eli Yablonovitch[2] and Sajeev John[3], published their research papers on photonic crystals. This was the beginning of the photonic crystals field, and after 1987, a wide range of research papers based on photonic crystals began to grow exponentially. The fabrication process of PCs was complicated in the initial stage. Hence, they were mainly studied theoretically, where they can be built at a small centimeter scale. In 1996, a three-dimensional photonic band gap based photonic crystal was demonstrated by Yablonovite in a microwave regime[4]. After this 3-D photonic band gap crystal structure, Thomas Krauss proposed a 2-D photonic crystal structure in an optical wavelength regime[5]. Using 2-D photonic crystal, the first photonic crystal fiber was developed by Phillips Russell in 1998 that overcome the limitations of optical fiber[6].

1.2 Photonic crystals

Photonic crystals (PCs) are the optical medium with periodic modulation of refractive index. It has at least two different refractive index materials arranged in a periodic manner throughout its length. It has a natural structure as well as an artificial structure. This refractive index contrast creates a forbidden gap known as a photonic band gap (PBG) structure. This photonic band gap prohibits the optical mode of a specific range of frequencies[2]. Due to its unique design, this PC has achieved a milestone in different fields, such as computing, communication, and signal processing.

A wide range of applications in the telecommunication field are sensors, filters, mirrors, optical cavities, super prism, etc.[7]**.** There are three types of photonic crystal structure depending upon the unique arrangement of periodic materials named as (i) One dimensional (1-D) photonic crystals (ii) Two dimensional (2-D) photonic crystals (iii) Three dimensional (3-D) photonic crystals.

1.2.1 One-dimensional (1-D) photonic crystals

One-dimensional PCs are compact structures using the concept of the photonic crystal in which a periodic stack of two alternative dielectric layers along one direction is depicted in figure 1.1. Several successive reflections and transmissions occur when a light ray propagates at every face. With a proper choice of material and thickness of the layer, transmitted light is out of phase while the reflected light rays are in phase, and hence we get constructive interference due to reflected light for a range of wavelengths[8]. The most famous example of a 1-D photonic crystal is the Bragg mirror, based on the phenomenon of the photonic band gap, which arises due to the interference of electromagnetic waves within the photonic crystal. When a light incident on the Bragg mirror due to the PBG effect, light of a certain frequency highly reflects from it, and hence it is also termed as the stop band of the Bragg reflector[9].

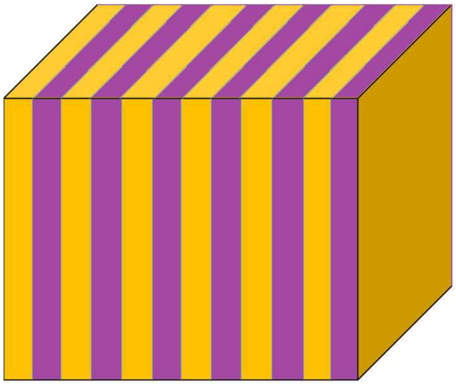


Figure 1.1 Periodic structure of one dimensional photonic crystal

A number of examples of one-dimensional PCs are available in nature such as the morpho butterfly, peacock feather, and Wing of the male Sasakia Charonda butterfly[10].

1.2.2 Two-dimensional (2-D) photonic crystal

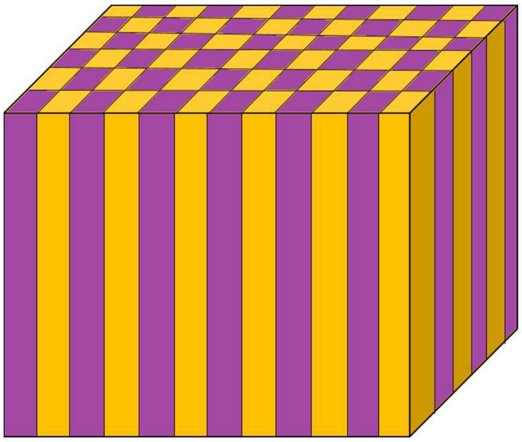


Figure 1.2 Periodic structure of a two-dimensional photonic crystal

Figure 1.2 shows that in the 2-D photonic crystal structure, low refractive index and high refractive index contrast are arranged periodically in two dimensions while it remains homogenous along the third dimension[11]. A few examples of 2-D photonic crystals are square and triangular lattice mentioned in figure 1.3.

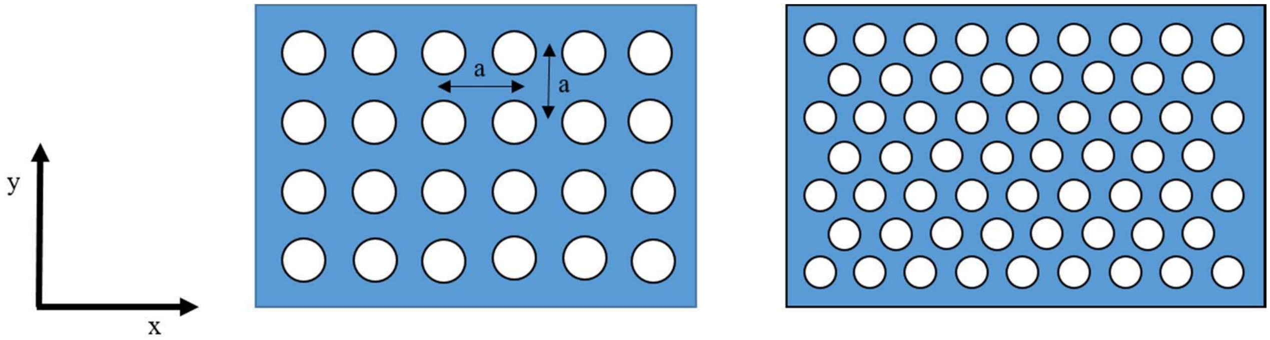


Figure 1.3 Cross-section view of square lattice and triangular lattice photonic crystal

In these structures, the cylindrical rods of air holes are of the same length, run along the z – direction, and are symmetrically arranged along the xy – plane of the high dielectric constant medium. The spacing between cylindrical air holes (lattice parameter *a*) and their specific size are chosen carefully to create the photonic band gap that prohibits the propagation of a particular frequency band. The tuning of the size and spacing of cylindrical air holes opens a door for several applications in the field of optics, such as optical filters[12], optical waveguides[13], photonic sensors[14] etc.

1.2.3 Three-dimensional (3-D) photonic crystal

In the 3-D photonic crystal, a periodic pattern of dielectric materials is extended up to the three spatial directions depicted in figure 1.4. It consists of a regular arrangement of unit cells with periodic refractive index variation throughout the crystal structure[15]. We may achieve many optical properties with the manipulation of shape, size and unit cell arrangement. For example, by creating photonic bandgap cavities by confining light inside the crystal structure, we can have many applications, such as optical filters, lasers, and integrated circuits.

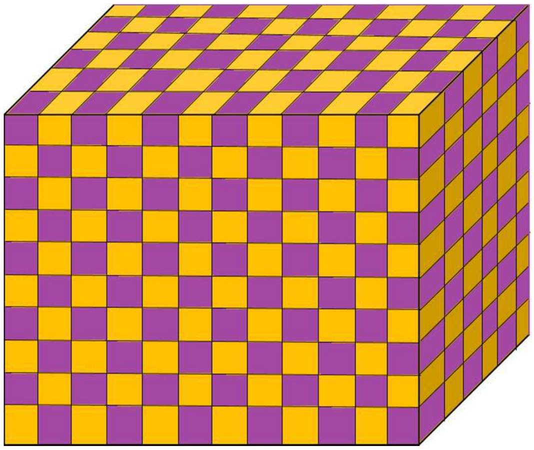


Figure 1.4 Periodic structure of a two-dimensional photonic crystal

The first 3-D photonic crystal was experimentally realized by Yablonovitch, having a face-centered cubic (fcc) structure with a band gap in the microwave regime[16]**.** A number of 3-D PCs structures like woodpile structures, face-centered lattice, and body-centered lattice are now available that manipulate light in three directions to provide the optimistic idea for the fabrication of photonic devices with improved and enhanced functionality.

Woodpile structure based 3-D photonic crystal has diamond symmetry, and it could be fabricated by stacking layer by layer of pre-patterned dielectric rods with alternate orthogonal ordination[17]. Fabrication of 3-D photonic crystal structure is difficult with currently available technologies and has not widely progressed compared to 2-D photonic crystal structure**.**

1.2.4 Natural photonic crystal

Form the last two decades, photonic crystal have been a prime research subject. It is seen that whatever scientists are trying to find, our mother nature created the same a million years ago. In nature, many objects, animals, and living creatures are examples of natural photonic crystals. Since all the natural photonic crystals are not the same, they may have different functionality[10].

Opal is a stone that has the features of photonic crystals. It is the best example of a natural photonic crystal in which spherical particles are arranged in the cubic structure and found in different colors like brown, red, pearly, or orange. Milky white opal is the most expensive stone with rainbow color reflections. Wings of butterflies are also a creation of photonic crystals. It has a periodic structure of deep and iridescent hints of green and blue color. Other examples of natural photonic crystals are sea mouse (Aphrodite), Edelweiss flower, feathers of peacocks and wild ducks[18]**.**

1.3 Photonic sensors

Sensors are the system or a device to detect and sense a physical, chemical, biological measurands capturing all the information and reproduce them in the electric form and make it useful in daily life application. Photonic sensors are device which are designed in such a way that it gather all the information from the measurand through photonic technologies.

Photonic sensors consist of mainly three parts. (i) Optical transducer (ii) Optical channel (iii) Optoelectronic unit. In the first part (optical transducer), the measurand modulates the light. Optical channel works as a bridge between optical transducer and optoelectronic unit. In the last part (optoelectronic unit) light is detected, modulate, process and converted into electrical signal[19].

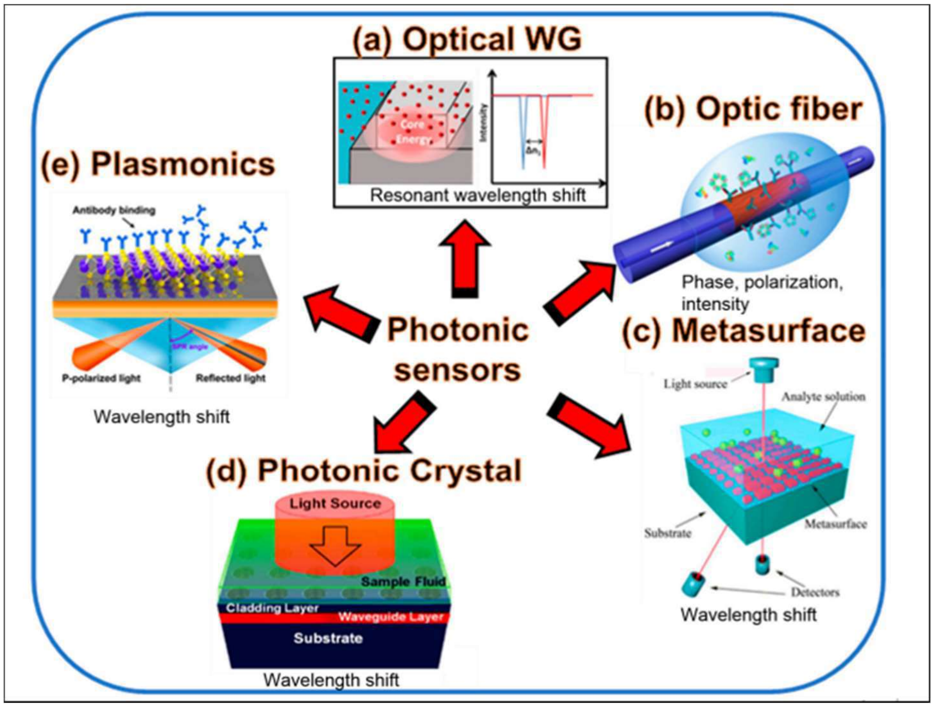


Figure 1.5 Photonic sensor application as **(a)** Optical waveguide sensor **(b)** Optical fiber sensor **(c)** Metasurface sensor **(d)** Photonic crystal fiber sensor (e) Plasmonic sensor.**[20]**

Figure 1.5 represents that photonic sensors has a vast categories of sensors such as optical fiber sensors (OFS), optical waveguide sensors, photonic crystal fiber (PCF) sensor, meta surface sensors, ,integrated optical sensor, image sensors when photonic sensors are attached with optical fiber, optical waveguide, photonic crystal fiber, meta surface, integrated optic, hybrid or image based technologies, respectively[20]**.** In this thesis we will study about optical fiber sensor and photonic crystal fiber sensors.

1.4 Optical fiber

In order to study optical fiber sensor, first we will have a brief description about optical fiber and its type. Optical fiber is optically transparent and basically composed of two co-axial cylinders of different materials, such as glass or silica. The central cylindrical part is called the core of the optical fiber, through which light is guided with a proper guidance mechanism. Cladding is the next cylindrical layer surrounding the optical fiber's core. These two sections are differentiated based on their refractive index (RI).

The core part material has a higher refractive index (n_{core}) than that refractive index of cladding material ($n_{cladding}$), i.e. ($n_{core} > n_{cladding}$) and due to this refractive index variation, light can easily be guided through the core of optical fiber due to the total internal reflection (TIR) phenomenon. Figure 1.6 represents the structure of the optical fiber.

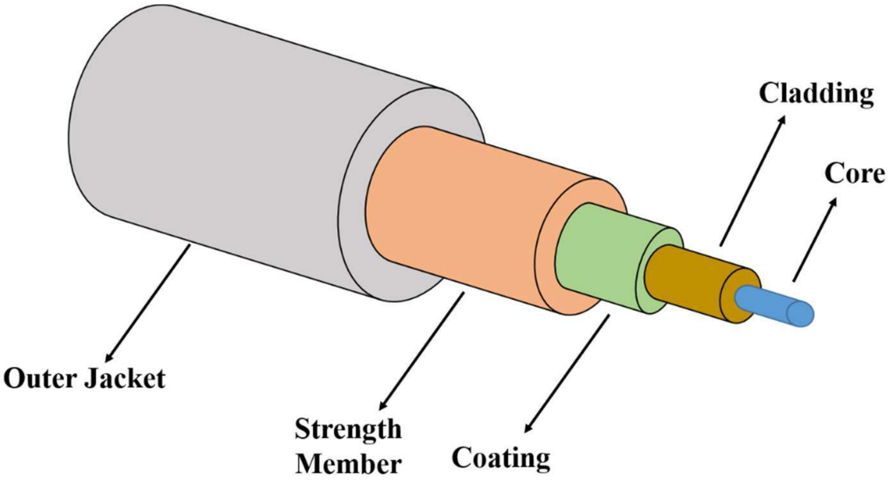
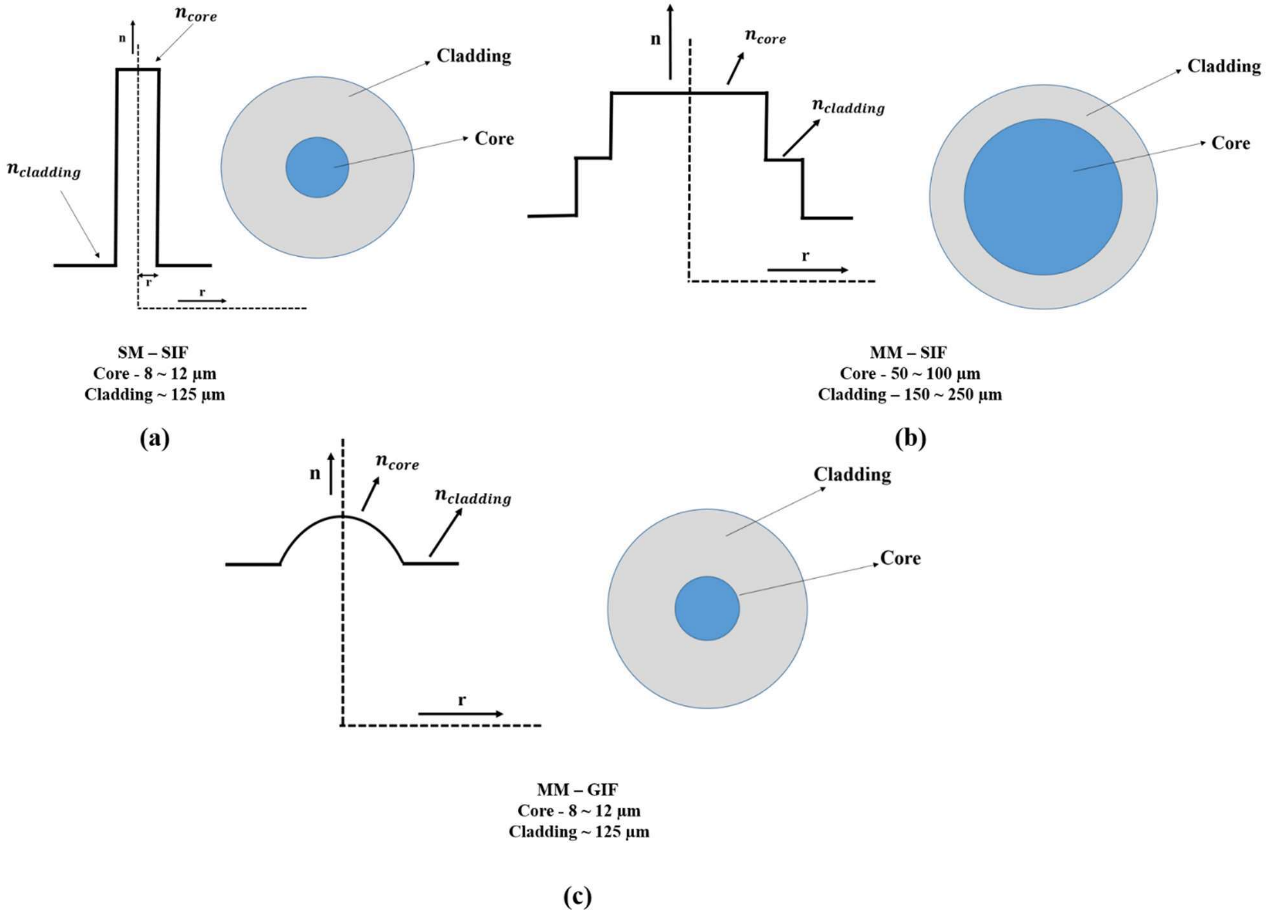


Figure 1. 6 Schematic representation of optical fiber

Classification of optical fiber can be performed in terms of different parameters. Depending on the number of modes propagating inside the fiber core, there are two types of optical fiber: (i) Single mode fiber (SMF) and (ii) Multimode fiber (MMF). Based on the refractive index profile, optical fibers are classified as (i) Step index fiber (SIF) and (ii) Graded index fiber (GIF). Thus we classify three types of optical fibers: (i) Single mode step index fiber (SI - SMF), (ii) Multimode step index fiber (MM – SIF) (iii) Multimode graded-index fiber (MM - GIF). Figure 1.7 represents the cross section view of all three types of optical fiber.



SM – SIF
Core - 8 ~ 12 µm
Cladding ~ 125 µm

(a)

MM – SIF
Core - 50 ~ 100 µm
Cladding – 150 ~ 250 µm

(b)

MM – GIF
Core - 8 ~ 12 µm
Cladding ~ 125 µm

(c)

Figure 1.7 Cross section view of **(a)** single mode step index fiber **(b)** multimode step index fiber **(c)** multimode graded index fiber

1.4.1 Optical fiber sensors

Photonic sensors which are based on the optical fiber technology are referred as optical fiber sensors. In starting age of the development of optical fiber, the primary use of optical fiber was for communication, and this technology overcame electronic communication technology.

After some time, this technique has developed rapid growth in the field of sensing due to excellent performance, lightweight property, compact size, and high immunity over electromagnetic interference[21].

The system configuration for an optical fiber sensor has a light source (LED or Laser) in the input terminal, the optical fiber sensing head, and then the output terminal has a detector to detect and analyze the output signal. Optical fiber utilizes the total internal reflection phenomenon for guiding the light through the fiber. While changing the physical environment (pressure, temperature, force, etc.) at the outer portion of the optical fiber, the optical property of the wave (intensity, phase, polarization, wavelength, etc.) changes, and the output signal is received at the detector[22]. Optical fiber sensors are designed and manufactured for different physical, chemical, and biochemical sensing types based on daily life applications.

1.4.2 Merits and Demerits of optical fiber technology

Optical fiber technology has several advantages, such as broad communication capacity[23], long range data transmission with low loss, highly immune electromagnetic interference, light weight with small diameter size[24], different types of sensors, and high-temperature operation[25]. But along with the merits, it also has some demerits limiting the use of optical fiber. Two significant restrictions of optical fiber are (i) the finite core and cladding diameter size of either step index fiber or multimode fiber due to limited free engineering for different applications. (ii) Different material selection in the core and cladding portion limits the matching of chemical, optical, and thermal properties. Apart from these two significant demerits, dispersion, which limits the communication for linear light guidance, non – linear guidance of light, and lack of high power communication are also the limitations of conventional optical fibers[26].

Due to these limitations, further review and research were conducted on optical fiber technology to modify its structure and material composition in the core and cladding portion. After around three decades, a new concept was introduced in the optical fiber field to take this technology to a new height.

1.5 Photonic crystal fiber

Photonic crystal fiber (PCF) is a new class of fiber in the class of photonic sensors that became a primary tool in the optical fiber research field after 1996. This photonic crystal fiber has unique properties and overcomes the limitations of conventional optical fiber. This PCF is quietly different from conventional optical in the manner of the same materials in the core and cladding regions. It has a single background material throughout the fiber structure, along with a finite number of air holes arranged in a periodic manner throughout the cladding portion over the entire length of the fiber. Due to these air holes in cladding, this fiber is known as micro-structured optical fiber (MOF). The core of PCF is either a solid core or a hollow core. The PCF has pure silica or fused silica in the background material and low refractive index air holes in the cladding portion [27].

In contrast with optical fiber, photonic crystal fiber has superiority due to a maximum number of geometrical variations with the help of air holes in the cladding region. In the modeling and fabrication process, a few parameters like air hole size and distance between centers of two air holes (pitch) are needed to look perfect to obtain the best results [28]. In this section, we will discuss a detailed classification of photonic crystal fiber with some unique optical properties.

1.5.1 Classification of photonic crystal fiber

The geometry of photonic crystal fiber has single material in the background with a finite number of air holes in the cladding region arranged periodically. Based on the core structure, PCF can be classified into two categories (i) Solid – Core PCF (SC – PCF) and (ii) Hollow Core PCF (HC – PCF) [27].

1.5.1.1 Solid–Core photonic crystal fiber

In Solid – Core PCF structure, the cladding portion is surrounded with finite air holes through the entire fiber length, while the core is solid and made up of single material. Here, air holes in the cladding portion provide a low refractive index atmosphere while the core is of high refractive index material such as pure silica or fused silica. This core–cladding arrangement that raises the proper condition for total internal reflection for light guidance through the PCF displayed in figure 1.8. Light guiding through the core of SC – PCF has been depicted in figure 1.9. This type of total internal reflection is modified total internal reflection (M – TIR) [29]. The first solid-core PCF was reported in 1996 [30].

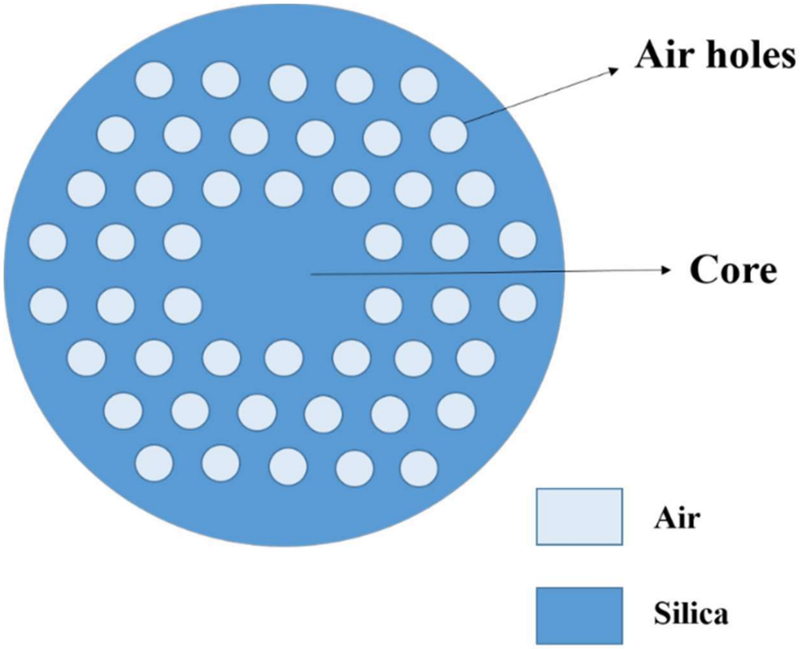


Figure 1. 8 Cross – section view of solid core PCF.

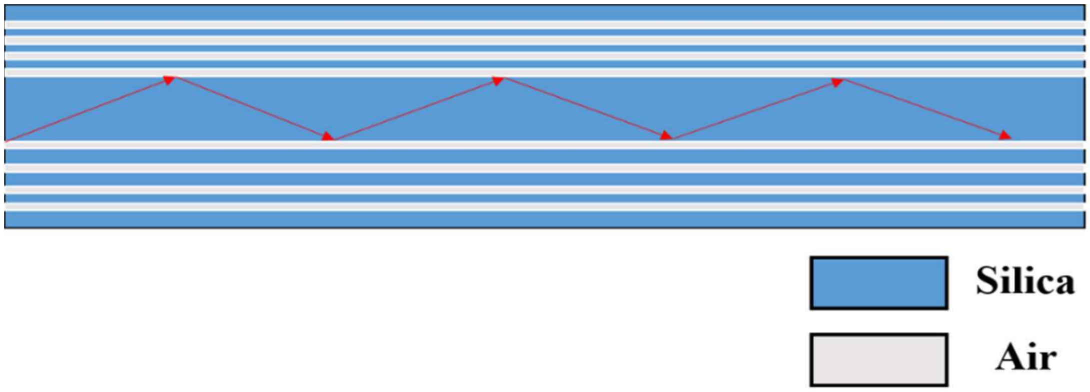


Figure 1. 9 Light guidance through solid core PCF.

Due to the flexible design of PCF, there is easy single-mode guidance with high birefringence and large–mode area in PCF. These extraordinary properties of PCF make it usable for applications such as supercontinuum – generation [31], spectroscopy [32], fiber laser [33], and sensing technique [34]. The last application is the topic of our thesis and will be discussed in later chapters.

1.5.1.2 Hollow–Core photonic crystal fiber

A 2-D configured hollow-core photonic crystal fiber (HC – PCF) has the micro-structured air holes in the cladding portion arranged regularly with a hollow core. Since the refractive index of the cladding region is high compared to the refractive index of the core, light guidance in this type of PCF is impossible with a total internal reflection mechanism due to this negative core- cladding refractive index profile. The light guidance mechanism is explained in hollow-core PCF based on the photonic band gap (PBG) concept in which light of a specific frequency range is prohibited from propagating through the fiber length but reflects [29]. This PBG phenomenon is analogous to solid-state physics electronic band structure phenomenon. In 1999, the first research paper was reported on hollow-core photonic crystal fiber based on photonic bandgap [35]. Based on the photonic band concept, this HC – PCF generates many applications like a laser–induced particle guidance [36], gas – based nonlinear optics [37], high power transmission [38], and sensing application [39]. Figure 1.10 illustrates the hollow core PCF cross-section view and light propagation through it.

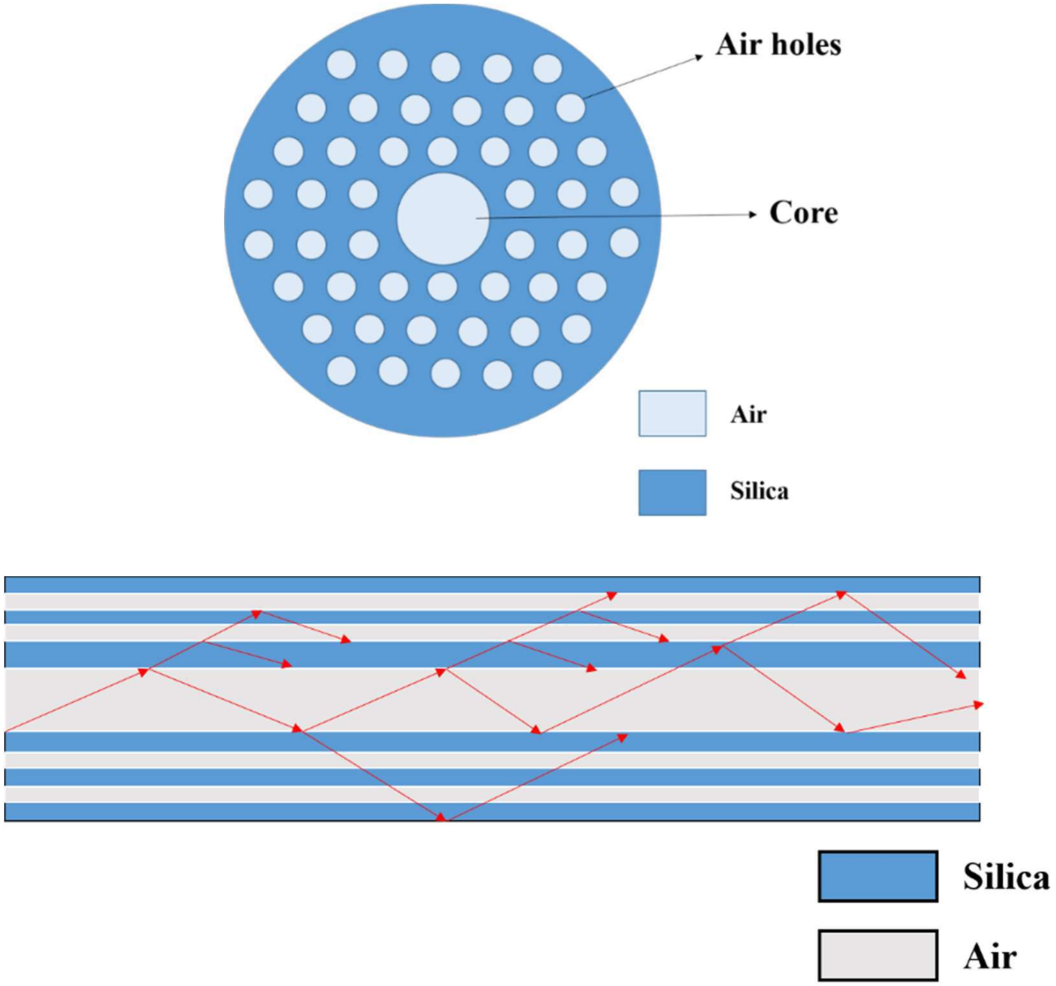


Figure 1. 10 Cross – section view and light guidance through hollow-core PCF

1.6 Photonic crystal fiber sensor

Photonic crystal fiber has acquired a new mile stone in different scientific fields due to its excellent properties, such as variable size and location of air holes in cladding regions with solid or hollow cores. Using PCF as a sensor, the following setup is arranged. The light source is LED or Laser at the input terminal, a photonic crystal fiber sensing head, and optical fiber at both sides of PCF followed by an optical spectrum analyzer (OSA) to analyze the output wave [40].

Based on the sensing mechanism of analyte sensing, PCF has two categories:

(i) External Sensing Mechanism

(ii) Internal Sensing Mechanism

Based on application, the PCF is categorized into three sections:

(i) Physical Sensor

(ii) Chemical Sensor

(iii) Bio Sensor

A detailed explanation will be discussed in a later section based on these types of sensor applications and sensing mechanisms.

1.6.1 Sensing mechanism-based PCF sensors

PCF sensor is categorized into two parts based on its sensing mechanism. A detailed explanation is given below -

1.6.1.1 Internal sensing mechanism based PCF sensor

In this type of PCF sensing mechanism, we keep the unknown analyte (which we need to detect) inside the micro-structured air holes. A sample in the form of liquid is filled inside the microchannel air holes with a suitable pressure difference on both sides of PCF, displayed in figure 1.11. This procedure of sensing an analyte is typical because we need to clean the air holes every time we change the analyte [41]. This distinct procedure limits the PCF sensing approach. Still, this type of PCF sensor is compatible with the magnetic field or electric field sensing applications where the filled analyte is not needed to replace every time.

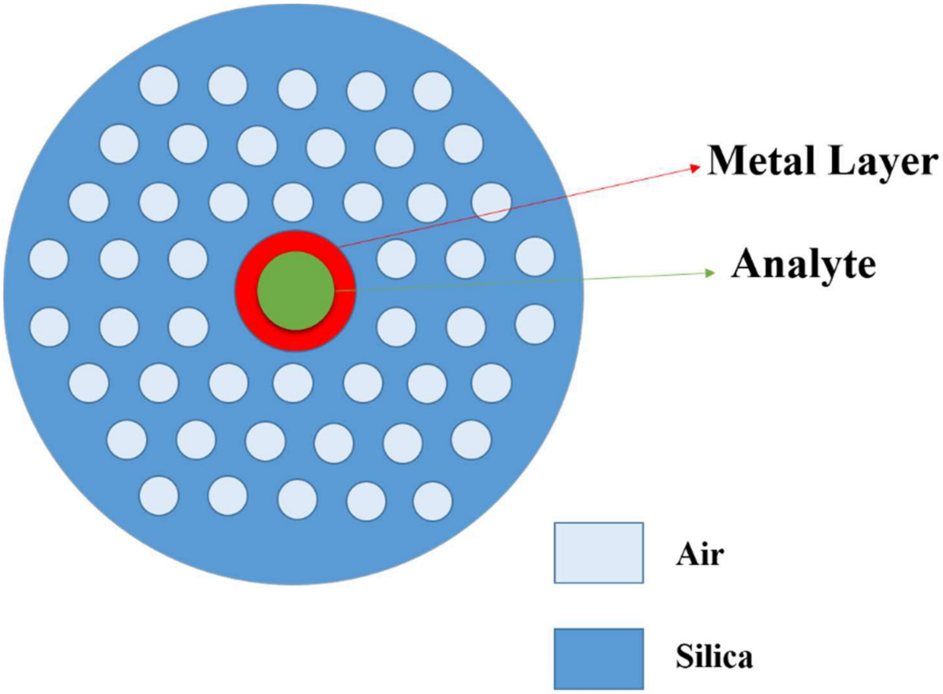


Figure 1. 11 Cross – Section view of internal sensing-based PCF sensor.

1.6.1.2 External sensing mechanism based PCF sensor

In this mechanism, the analyte is placed exterior to the PCF head, or the PCF can be immersed inside the analyte sample for detection, depicted in Figure 1.12. This sensing method is very convenient compared to the internal sensing approach in a different manner and cleaning process after analyte detection. The PCF with this approach provides high sensitivity [42].

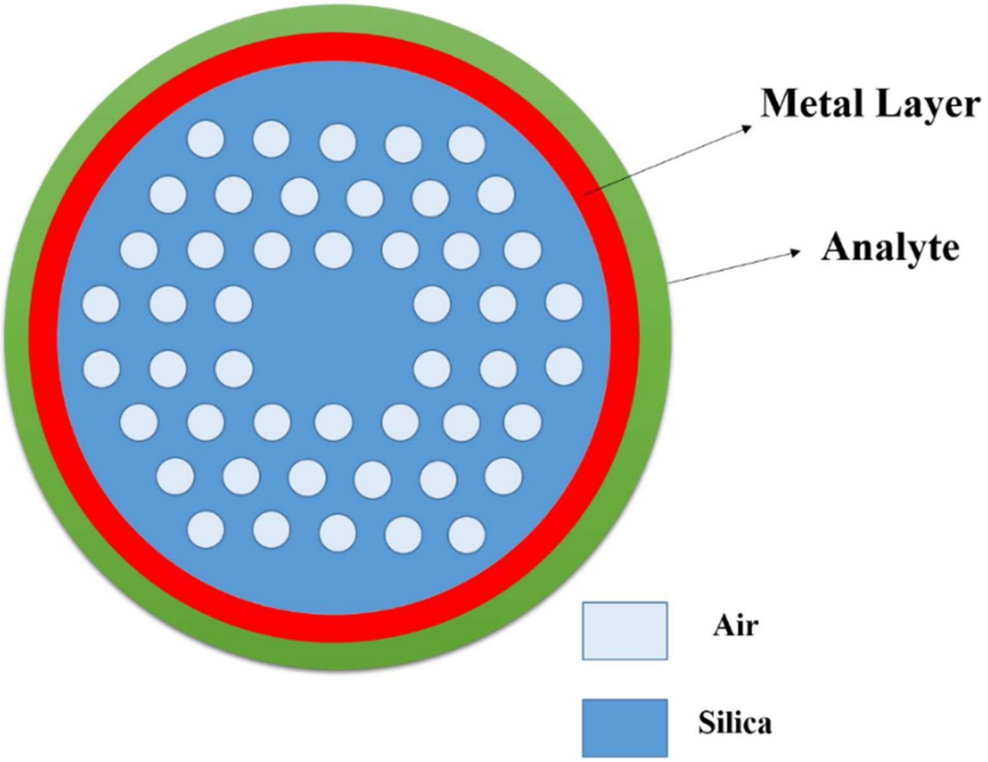


Figure 1. 12 Cross – Section view of external sensing-based PCF sensor

1.6.2 Application based PCF sensors

Photonic crystal fiber sensor has achieved a new height in the sensing field due to the versatile nature of structure modifications depending on core–cladding air holes pattern. On the basis of application, the PCF has been categorized into three categories, as mentioned in section 1.6. A brief view of these three categories will be discussed in this section.

1.6.2.1 Physical sensors

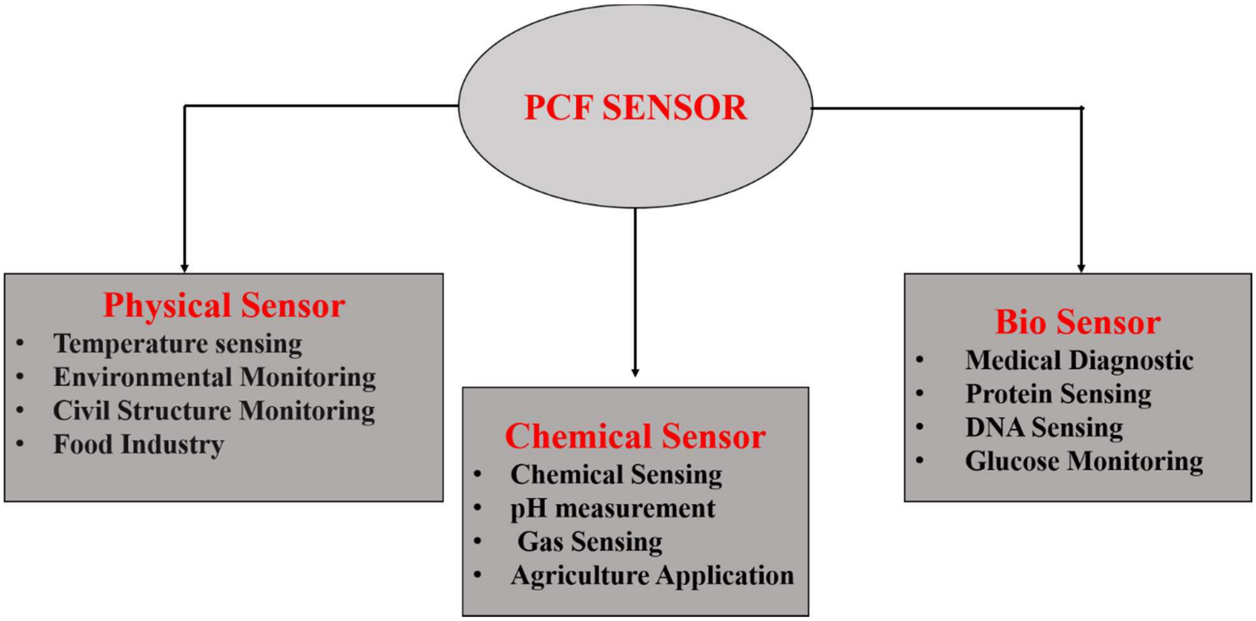
Physical sensors represent the sensing of physical parameters like pressure, temperature, viscosity, displacement, strain, vibrations, electric field, torsion, refractive index, etc. In order to measure the refractive index (RI) of various chemicals, multiple biomolecules, foods, and beverages for quality check, PCF based refractive index sensors are the best technique. PCF-based temperature sensors are also powerful tools to measure temperature in hazardous conditions such as developing welding equipment, generating high power operations, etc. [43]. Additionally, in civil engineering, physical sensors such as bending, strain, displacement, curvature, and torsion sensors are implemented to look after the health of civil structures like bridges, pipelines, buildings, tunnels, dams, etc. Electric field and magnetic field sensors are vastly used for sensing at high voltage and are highly insulted compared to the standard electric sensors [27].

1.6.2.2 Chemical sensors

Different types of chemicals in liquid form or gas form can easily be detected with the help of a PCF sensor. Sensing of chemicals based on their pH values, different types of gases, and impure water containing harmful chemicals is performed with the help of PCF sensors. Hollow core PCF (HC – PCF) is primarily used for sensing hazardous gases emerging from power plants, chemical industries, vehicles, and many others that harm the environment [44]. PCF sensor plays a vital role in the medical field, food and beverage industry [45], and biotechnology, where chemical sensing is performed based on pH values of chemicals [46].

1.6.2.3 Bio sensors

Bio sensors detect biological analytes such as DNA, glucose monitoring, different type of proteins, molecules, and cells. In biological detection with some available sensors, tags or labels are required along with an analyte to have an optical response. PCF based on the SPR technique is the most promising tool for biological analyte detection because it is free from tags and labels and provides real-time sensing. Testing can easily be performed with the help of PCF sensors to detect different diseases, pregnancy, and medical diagnoses [47].



1.7 Different numerical methods for PCF structure modeling

To fabricate a desired PCF structure, first of all, it is necessary to simulate its structure. A numerical simulation is an essential tool for choosing optical parameters such as the size of air holes and distance between air holes called pitch, characterization of PCF, and fabrication perspective. Various modeling and simulation techniques have been developed for PCF simulation after the first experimental affirmation of PCF in the year 1996 [48].

There are several methods for modeling and simulation purposes plane wave expansion method[49], localized function method[50], Finite difference frequency domain method (FDFD)[51], Finite difference time domain method (FDTD)[52], and Finite element method (FEM)[53]. Each method has its own merits and demerits with its limitations [54].

1.7.1 Finite difference time domain method (FDTD)

Three methods, FDFD, FDTD, and FEM, are used to design and numerically analyze the PCF structure and its optical property. The finite difference time domain (FDTD) technique can explore the optical properties of PCF for a broader range of wavelengths in a single simulation process. This technique analyzes the EM wave in the computational domain to provide a detailed graphical view of the EM wave propagating through the fiber. This method is potent with a simple methodology, but the main demerit of this method is that computation time is relatively high along with a complex algorithm [52].

1.7.2 Finite Element Method (FEM)

The complete modeling process is performed using a radio frequency (RF) module in electromagnetic wave frequency domain-based mode analysis in COMSOL Multiphysics software, and the FEM technique performs the computational work. FEM is a fundamental and verified method for free engineering in optical fiber technology. This method was proposed in 1940 for the first time, and it has versatile nature to be used in every field of science and engineering. The FEM is a numerical technique to find the rough solution of the partial differential equation (PDE). The superiority of this method is that it takes less computational time than other methods for any complex structure [53].

The term ‘finite’ in the finite element method (FEM) describes the limitation or the limited degrees of freedom characterized by the behavior of every particular element in the specific system. Every particular element are joined together known at a point known as a node point. The assembly of these small elements combined together to form a mesh. Discretization is an essential step of the FEM method in collecting these finite elements.

Compared with other numerical simulation methods, FEM dispenses more precise results with less computation time for different types of complex structures like PCF. Execution of the FEM method for a complex structure, there are a few steps:

- The given solution region is discretized into finite sub – regions.
- Derive the equations for every sub–regions.
- Collection of all finite elements in the solution region.
- Finally, solve the system of equations.

1.8 Finite element method for PCF utilizing COMSOL Multiphysics software

PCF simulation and modeling in this thesis have been performed by the FEM method by using COMSOL Multiphysics software. This modeling process has a few steps. First, the complete cross-section of PCF is divided into a mesh of various geometrical shapes, such as triangular, cubic, and linear. These are termed as "elements." For accuracy, we have chosen triangular mesh elements mentioned in figure 1.13. To improve the accuracy of the findings and numerical simulation, we apply structural symmetry [53]. In the next step, we apply the perfect match layers (PML) to reduce scattering losses. Moving forward, Maxwell's equation for each single mesh element leads to a complete set of elementary matrices, and then these matrices are combined together to form a global matrix system to study the structure. In the last step, the real and imaginary parts of the effective index (n_{eff}) are computed numerically and with the help of this (n_{eff}) the desired parameter of PCF are calculated with high accuracy.

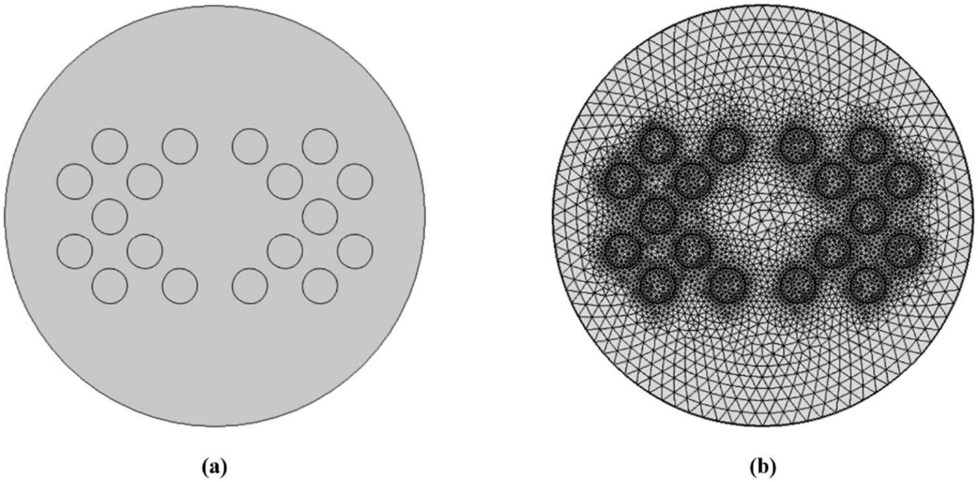


Figure 1. 13 (a) PCF model designing through COMSOL Multiphysics **(b)** PCF with triangular mesh elements

COMSOL software has the privilege of choosing a variety of predefined materials from the material section along with their optical properties, such as conductivity, dielectric constant, permittivity, permeability, and refractive index. A complete sequence and computational approach of modeling and simulation is displayed in figure 1.14.

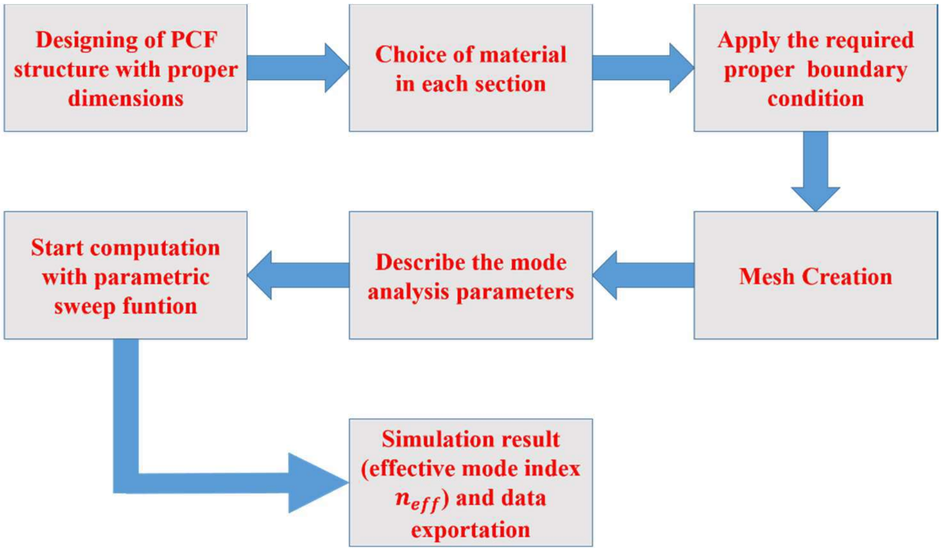


Figure 1. 14 Flow chart of the complete simulation process

1.9 Principles and properties of different theoretical methods for PCF structure analysis

To achieve a better sensing performance through PCF structure, theoretical analysis of PCF is as essential as numerical simulation. Hence, this section will have a detailed study of the different principles and properties of theoretical methods used in this thesis.

1.9.1 Sellmeier's equation for material dispersion

When light propagates through any medium, its propagation depends on the refractive index of the media as well as the frequency of light propagating. For both transparent or non – transparent mediums, its refractive index relies on the wavelength of light propagating, and Sellmeier reported this in 1871 [55]. Variation of the refractive index of media with a wavelength of incident light is termed material dispersion. Throughout this thesis, we use the sellmeier equation to evaluate the refractive index of background material. The sellmeier's equation is given by

$$\boldsymbol{n^2(\lambda) = 1 + \frac{A_1\lambda^2}{\lambda^2 - B_1} + \frac{A_2\lambda^2}{\lambda^2 - B_2} + \frac{A_3\lambda^2}{\lambda^2 - B_3}} \tag{1.5}$$

Term $n(\lambda)$ is wavelength dependent refractive index (RI), while (λ) is the operating wavelength and $A_{1,2,3}$ and $B_{1,2,3}$ are the sellmeier's constant having different values for different materials. Generally, our thesis's background material for the PCF structure is fused silica. Different materials like GeO_2 silica and BK7 glass have different sellmeier constant values [56].

1.9.2 Effective mode index of PCF

The effective refractive index of the cladding region is employed to specify the modal distribution in PCF. The effective mode index (n_{eff}) of a mode in PCF is specified by the following equation

$$\boldsymbol{n_{eff} = \frac{\beta}{k_o}} \tag{1.6}$$

where, the term k_o is the wave vector in free space, and β represents the propagation constant. The term effective modes for each mode in PCF has the same meaning as the refractive index in the free space [57]. In PCF, there is a solid core, and finite micro-structured air holes are available around this core. Hence the effective mode index of the cladding region is lower than the effective mode index of the core region, and the value of n_{eff} varies with the wavelength of propagating light through PCF [57].

1.9.3 Confinement loss

A PCF has a solid or hollow core region and a number of finite air holes in the cladding part. Since the light confining area in PCF is of finite dimension, all the light guiding modes in the PCF are not strictly confined. This results in light leakage, considered leaky or lossy mode [58].

With each leaky mode, a complex effective mode index is linked, and the imaginary part of this effective mode index is to calculate confinement loss, and it is given by following equation [59]

$$\boldsymbol{\alpha\left(\frac{dB}{cm}\right) = 8.868 \times \frac{2\pi}{\lambda_0} \times Im\left(n_{eff}\right) \times 10^4} \tag{1.7}$$

Here, λ_0 is termed as the wavelength of light in free space and $Im\left(n_{eff}\right)$ is the imaginary part of the effective mode index. Along with these parameters, confinement loss depends on other factors, such as the diameter of air holes (d), the distance between two air holes called pitch (Λ), and the ratio of ${}^{(d)}\!/_{(\Lambda)}$.

1.10 Surface plasmon resonance theory accompanied with PCF structure

The surface plasmon resonance technique is the most promising tool in the field of sensing. Several methods include quartz crystal microbalance (QCM) [60], ellipsometry [61], surface plasmon resonance (SPR) [62], etc. Among these, SPR is a label-free sensing technique for accurate time detection. In this thesis, all the proposed PCF sensors are based on the SPR technique. We will discuss a detailed explanation of the coupling between PCF and SPR in this section. Confinement of the collective oscillation of free electrons at the metal – dielectric interface is known as surface plasmon (SP). These surface plasmons (SP) wake up due to interactivity between incident EM waves and free electrons present at the metal surface [62]. The basic concept behind explaining surface plasmon excitation is an attenuated total internal reflection (ATR) [63]. Based on this ATR concept, two different configurations were evolved. The first configuration was Otto's configuration, and the second was Kretschmann's configuration [64]. The Otto configuration has an air gap between the prism and plasmonic metal to obtain SPR condition. Hence, this method is a bit difficult for practical realization [65].

The following method is Kretschmann's configuration based on the ATR concept in which a metal layer is sandwiched between the prism and dielectric material to remove the difficulty in Otto configuration. A detailed view of this configuration is displayed in figure 1.15.

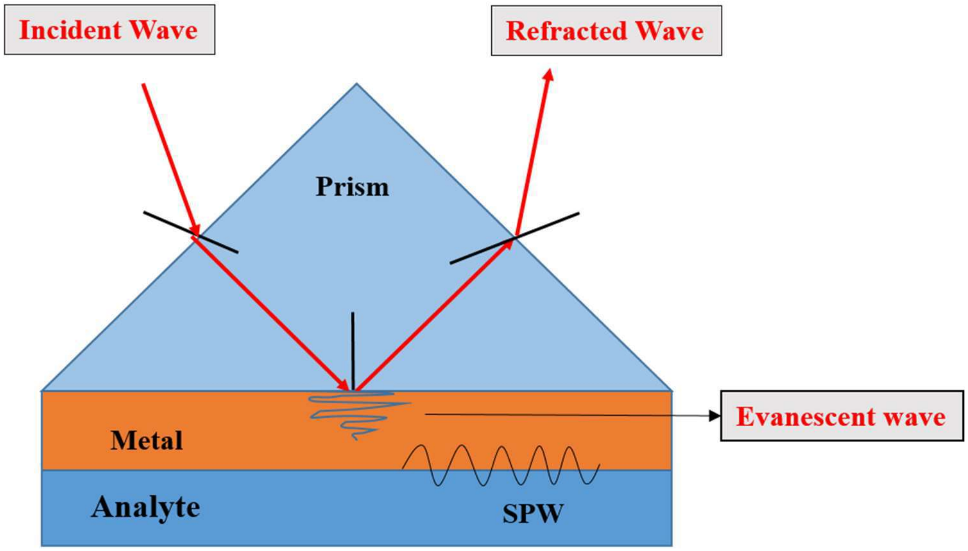


Figure 1. 15 Kretschmann's configuration for SPR phenomenon

A light ray starting from a light source incident at the interface of prism and metal interface, a part of this light is reflected to prism and then finally refracted from the prism and the rest part of this incident light decays exponentially perpendicular to the interface the surface and this inhomogeneous wave is known as an evanescent wave. This wave penetrates through the metal surface (thickness around 100 nm) and reaches near to surface plasmon wave (SPW) at metal–dielectric interface coupled with them. When the evanescent wave couples with SPW at a particular angle of incidence, the propagation constant value of both waves matches numerically. This angle is known as the coupling angle or resonance angle [64].

Mathematically we have,

$$\boldsymbol{\beta_{EW}} = \frac{\omega}{c}\mu_p \sin\theta_{res} = \boldsymbol{\beta_{SP}} = \frac{\omega}{c}\left(\frac{\varepsilon_m\varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{\frac{1}{2}} \tag{1.8}$$

Here μ_p be the refractive index of the prism, θ_{res} is the coupling or resonance angle, and ω be the frequency of the incident wave. Term ε_m and ε_d denotes the permittivity of metal and dielectric samples, respectively.

Similarly, we can use this SPR technique with a PCF structure where we have to replace this prism with PCF, and the procedure is the same as Kretschmann's configuration. Figure 1.16 reveal the general configuration of PCF with the SPR technique. The plasmonic (metal) layer is sandwiched between PCF and dielectric material in this configuration. A light ray starting to enter from the core suffers the M – TIR that generates an evanescent wave. This evanescent wave propagates perpendicular to the metal and PCF interface and decay exponentially. At metal – dielectric interface, it couples with SPW.

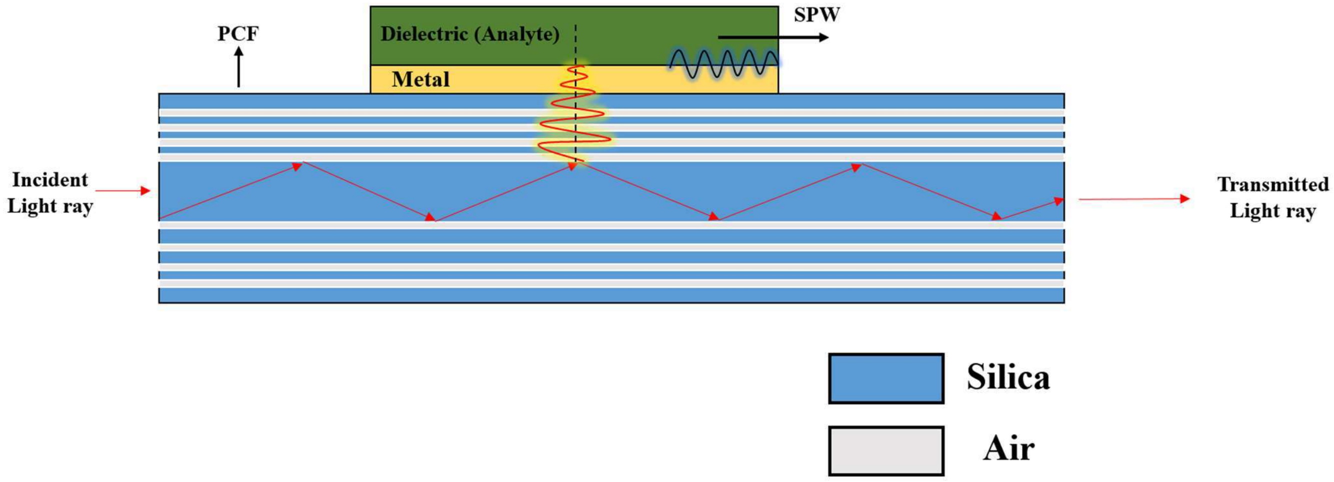


Figure 1. 16 Configuration of PCF with SPR technique

The coupling phenomenon occurs for each incident wavelength, and energy and momentum are transferred from core mode to SP mode. But at a particular wavelength of the incident light, coupling (resonance) occurs between evanescent wave and SPW, and maximum energy and momentum are transferred from core to SP mode. This particular wavelength is called resonance wavelength [62].

1.11 Fabrication of PCF

There are numerous methods of photonic crystal fiber fabrication. Some of them are as follows:

(i) Stack and Draw method [66]

(ii) Extrusion process [67]

(iii) Laser drilling process [68]

(iv) Injection Molding [66]

(v) Sol-gel method [69]

Among these methods listed above, the stack and draw method is the most convenient and easy process for fabricating the desired shape of photonic crystal fiber. There are a few steps in the stack and draw process to fabricate the desired structure of PCF. In the first step, capillaries are manufactured. This step is the building block of the stack and draw process, so capillaries with the required shape and size, with correct inner and outer diameter wall diameter, depending on the size of pitch needed (Λ), diameter to pitch ratio (d/Λ) is manufactured. Basically, undoped silica material is used for capillary material.

Stacking of capillaries is the next process after capillaries fabrication. Before stacking cleaning capillaries with iso–propyl alcohol or other cleaning agents is mandatory because contamination present in it will enhance the different types of losses in PCF. Now these capillaries are stacked in the desired shape, such as hexagonal cams, and are used to draw a triangular structure, and then this preform is inserted into a suitable cane. Drawing the PCF is the last step in which the stacked preform passes through the furnace maintained at a temperature range of 1900˚C – 2000˚C and then finally passes from the different processes such as canning and fiber pulling. The desired PCF is drawn [66]. A complete procedure of this process is displayed in figure 1.17.

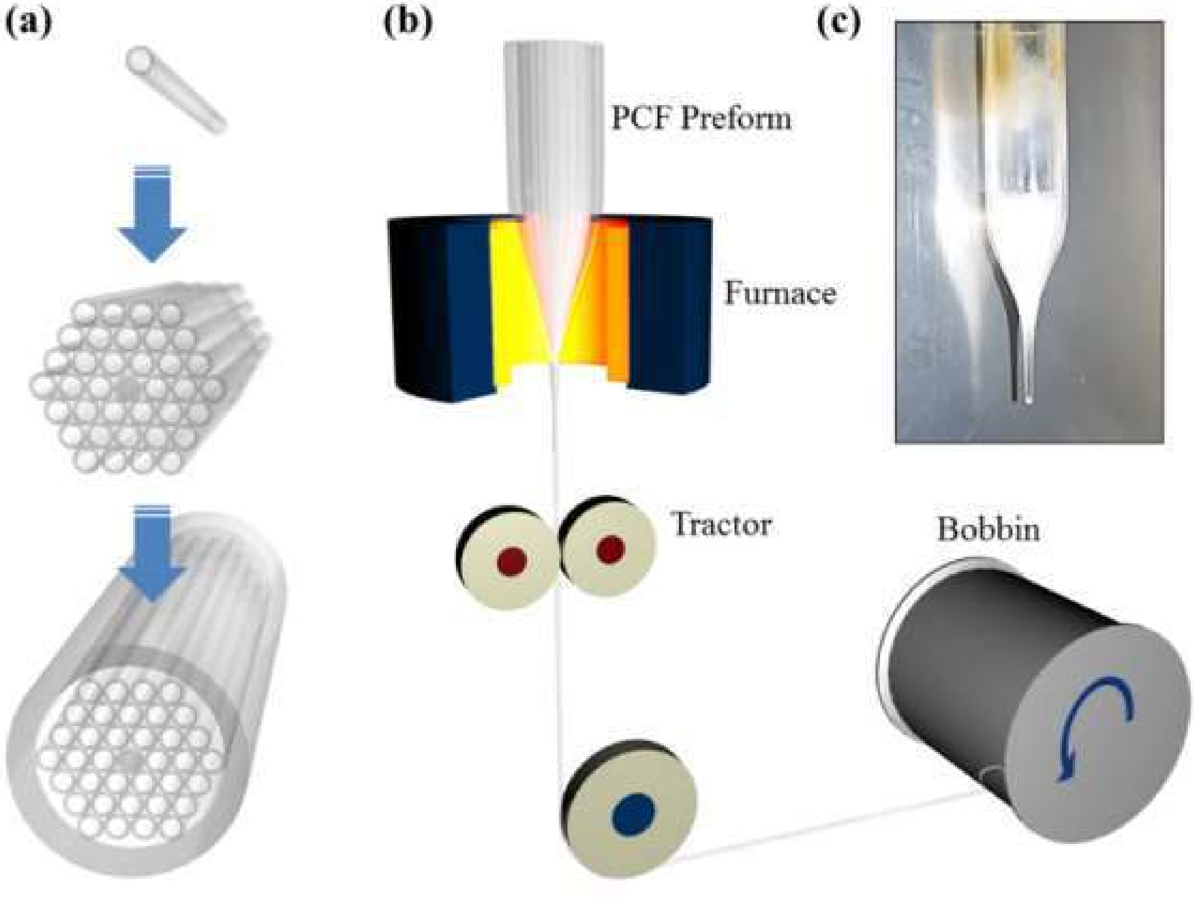


Figure 1. 17 A complete process of the stack and draw process [66].

1.12 Advantage of photonic crystal fiber sensors

We live in the age of technology where sensors are one of the most prominent techniques in our life. Sensors are used in different fields of science to make our job easy. So many sensors are available before PCF sensors, but this PCF sensing technique is superior to them in many prospects [70]. Some advantages are mentioned below

I. PCF has micro-structured air holes in the cladding region, due to which a number of geometries with different core–cladding structures are modeled and fabricated for other sensing purposes.

II. Single background material such as pure silica or fused silica is used for PCF fabrication, and these materials do not interfere with electromagnetic waves. Hence, no disturbance is produced in optical signals, even in a strong electric field or magnetic field environment.

III. In PCF, parameters like air filling fraction, dispersion, birefringence, mode shape, non-linearity, and others in PCF can be tuned easily compared to optical fibers.

IV. The signal propagating through PCF is an optical signal, not an electric signal. Hence, propagation through PCF is risk free from fire or spark, and these sensors can work in any harsh environment, such as mining areas, radioactive zones, oil refineries, etc.

V. Both PCF and optical fiber have unique properties of lightweight and compact size, making the sensing system portable and easily transportable.

1.13 Literature review

Presently, the sensor is one of the leading technology in every field or every industry, such as the environmental field, biomedical field, laboratories, pathologies, food and beverage industry, chemical industry, etc. PCF sensing technology is far better than previously reported different electrical sensing techniques as explained in section 1.6.1. Since PCF has a unique property to tune parameters such as air hole diameter in the cladding portion, the distance between air holes called pitch, and core segments such as single-core, dual-core, and multi-core. These properties of PCF can be implemented for different applications. Many scientists and researchers are working globally continuously to bring PCF sensing to a new height in the sensing field.

Several techniques exist, such as surface plasmon resonance, quartz crystal microbalance, and ellipsometry for different biosensing applications. Among these techniques, surface plasmon resonance (SPR) based sensing technique is trending and most effective for real time and label-free sensing. Moreover, a combination of the SPR technique with PCF becomes an excellent tool in the field of sensing due to compressed size, high EM immunity, and higher sensing performance over the conventional prism based sensing approach.

In 2007, J. Sun and C.C Chan reported a photonic bandgap-based RI sensor to detect the analyte refractive index range 1.333 – 1.39 with a wavelength shift of 280 nm [71]. Xia Yu et al. published a research paper on a PCF-based refractive index sensor with selectively gold (Au) coating to obtain maximum wavelength sensitivity of 5500 nm/RIU [72]. Internal sensing based PCF sensors have also been proposed for highly sensing approach and range of analyte RI detection. Ahmmed et al. proposed a graphene – silver based PCF sensor with an internal sensing approach to obtain maximum wavelength sensitivity 3000 nm/RIU and sensor resolution 2.4 × 10^{-5} RIU for analyte RI of 1.46 – 1.49 [73]. J. Narayan et al. proposed a conducting metal oxide (ITO) based PCF and reported maximum wavelength sensitivity of 2000 nm/RIU and a wavelength resolution of 5 × 10^{-5} RIU [74]. This microchannel infiltrated process based PCF can achieve an enhanced sensitive response. Though this process provides a better sensitivity response, it comes with limitations. Every time we need to change the analyte sample and then clean the microchannel of PCF. This becomes an uphill task. Hence an alternative to this method must be needed, which can overcome this complex process. External sensing mechanism-based PCF sensors have also achieved a milestone in refractive index sensing fields such as biochemical, bio-medical, food quality management, etc. This method overcomes the difficulty of the internal sensing mechanism method. In this process, the analyte sample is placed externally in contact with PCF, and using the SPR method sensing process is completed. Md. R. Hasan et al. proposed spiral PCF using an external sensing concept and obtained maximum wavelength sensitivity of 4600 nm/RIU for analyte sample RI range 1.33 – 1.38 [75]. Single layer coating PCF suggested by M. Liu et al. has a sensitivity value of 15180 nm/RIU for sample RI 1.40 – 1.43 [76]. A. K. Paul et al. submitted an air – core PCF has maximum wavelength sensitivity of 11500 nm/RIU for analyte sample RI 1.33 – 1.41 with wavelength resolution 8.55 × 10^{-6} RIU [77]. The asymmetric nature of PCF also helps to improve the sensing performance [78]. A birefringent fiber is asymmetric due to the uneven nature of cladding air holes around the core. Using a highly birefringent photonic crystal fiber, H. M. Kim et al. proposed a torsion sensor of birefringence of order of 10^{-3} [79]. S. Das, V. K. Singh presented a selectively infiltrated PCF with a birefringence of order 10^{-4} for the RI range of 1.36 – 1.41 [80]. So, from the literature survey, it is clear that the asymmetric nature of PCF can also play a vital role in sensing improvement.

Surface plasmon resonance is a crucial ingredient for the sensing method, and using this method with photonic crystal fiber is a revolutionary step in the field of sensing technology. The first SPR-based sensing technique was investigated in 1970 during the thin film monitoring process [81]. R. C. Jorgenson with S. S. Yee proposed an experimental setup for SPR based optical fiber sensor [82]. The experimental design of gold coated PCF sensor was well demonstrated by T. Wu et al. for analyte sample RI 1.30 – 1.41 [83]. Since conventional optical fiber has advantages like cost–efficiency and ease of use, the major limitation arises that the conventional optical is skilled to sense the analyte with RI lower than fiber core RI. In the case of PCF, sensing cladding is made up of micro-structured air holes, which enable us for different sensing structures, which helps to operate a broad range of sensing with better and enhanced sensitivity [84].

1.14 Motivation

In recent photonics, several research papers have been reported based on the PCF sensing technique. PCF is a particular class of optical fiber with micro-structured air holes in the cladding portion, which provides many geometrical alterations, structure flexibility, high birefringence, etc. These extraordinary features of the PCF structure motivate us to further research in this field. Since the sensor is a crucial tool in the modern era as the sensor is used in different areas such as the biomedical field, biochemical field, environmental field, food quality controlling department, etc. So sensing in these areas needed PCF based sensors which should be cost-effective, highly responsive, and have real-time detection. It motivates us to simulate such sensors in the PCF sensing field. So our primary motivation is to simulate a PCF sensor with a highly sensitive response, flexible design, compact size, and wider range of analyte (RIs) detection. In a further chapter of this thesis, we have focused on these parameters and worked to improve them.

1.15 Objective of this Thesis

The primary objective of this thesis is to "Design and analysis of some surface plasmon resonance based photonic crystal fiber refractive index sensors." This primary objective has been divided into four sub-objectives mentioned below

1st Objective: To design and analyze metal wires assisted photonic crystal fiber refractive index sensor.

2nd Objective: To design and analyze SPR based both side polished PCF based refractive index sensor.

3rd Objective: To design and analyze a rectangular shape cladding based PCF based refractive index sensor.

4th Objective: To design and analyze dual core PCF based plasmonic sensor for a wide range of refractive index sensing.