DESIGN AND ANALYSIS OF PHOTONIC CRYSTAL FIBER-BASED BIOSENSOR IN THE TERAHERTZ REGIME

A DISSERTATION

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE
OF

MASTER OF SCIENCE
IN
PHYSICS

Submitted by:

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CANDIDATE'S DECLARATION

I, **Jaydeep Singh |** 2K22/MSCPHY/17, hereby certify that the work which is being presented in the thesis entitled **"Design and Analysis of Photonic Crystal Fiber-based Biosensor in the Terahertz Regime"** in partial fulfillment of the requirements for the award of the **Degree of Master of Science in Physics**, submitted to the Department of Applied Physics, Delhi Technological University is an authentic record of my own work carried out during the period from August 2023 to June 2024 under the supervision of Dr. Ajeet Kumar.

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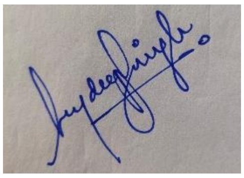

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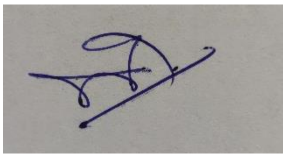

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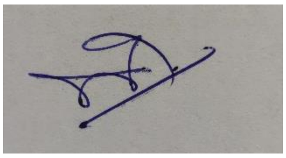
Certified that **Jaydeep Singh** | 2K22/MSCPHY/17 has carried out their research work presented in this thesis entitled **"Design and Analysis of Photonic Crystal Fiber-based Biosensor in the Terahertz Regime"** for the award of **Master of Science** from Department of Applied Physics, Delhi Technological University, Delhi, under my supervision. The thesis embodies results of original work, and the studies carried out by the student himself and the contents of the thesis do not form the basis of award of any other degree to the candidate or to anybody else from this or any other University/Institution.



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-Jaydeep Singh

ABSTRACT

This work presents the design and simulation of photonic crystal fiber (PCF) based sensor in terahertz regime for detection of cancer cells. One of the most popular applications of photonic crystal fibers is biosensing and the proposed sensor works on the principle of refractive index (RI) sensing. COMSOL Multiphysics, which is based on the Finite Element Method (FEM), is used to analyze different optical characteristics in order to assess the effectiveness of the proposed model. In this study, two analytes Basal (1.380) and Jurkat (1.390) which are responsible for skin cancer and blood cancer respectively, have been taken into consideration for sensing. Analytes are introduced into the core of the fiber one at a time. To assess optical qualities, the model is simulated in the THz regime (0.5 THz-1.5 THz). At an operating frequency 1.6 THz, the suggested structural design demonstrated a high relative sensitivity of 99.076% and 98.519% for Basal and Jurkat, respectively. With 1.7553×10^{-12} dB/m for Basal and 4.3484×10^{-12} dB/m, the confinement loss for the suggested model is likewise extremely low. Furthermore, for both the analytes, the effective material loss for the proposed PCF is likewise found to be extremely low. In addition, the PCF exhibits effective mode area within the specified range. The suggested PCF structure can be implemented practically with the help of current fabrication methods. Thus, the suggested PCF design ought to be beneficial in the field of biological sensing and can certainly be helpful in early detection of cancer cells.

CONTENTS

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List of Abbreviations/Symbols

PCF	Photonic crystal fiber
TIR	Total internal reflection
n	Refractive index
HC-PCF	Hollow core photonic crystal fiber
PBG	Photonic bandgap
mTIR	Modified total internal reflection
LC	Liquid crystal
MOF	Microstructured optical fiber
ϵ	Dielectric permittivity of the medium
μ	Magnetic permeability of the medium
ϵ_o	Dielectric permittivity of air/vacuum
μ_o	Magnetic permeability of air/vacuum
THz	Terahertz
Lconf	Confinement loss
n_{eff}	Effective mode index
A_{eff}	Effective mode area
L_{mat}	Effective material loss
γ	Nonlinearity coefficient
NA	Numerical aperture
Pf	Power fraction
FEM	Finite element method
PML	Perfectly matched layer
PDE	Partial differential equation
FDTD	Finite difference time domain
BPM	Beam propagation method
PWE	Plane wave expansion
FDFD	Finite difference frequency domain

Chapter 1

Introduction

The purpose of this chapter is to provide an overview of the crucial background information required to comprehend the work that is presented in the upcoming chapters 2, 3, and 4. It is meant to serve as a helpful point of reference for the reader rather than being exhaustive. Important characteristics of photonic crystals and photonic crystal fibers are covered, along with a brief history and introduction. Latest developments and related applications of conventional optical fibers and photonic crystal fibers are discussed in later part to get a good grasp of the subject. The last two sections of the chapter discuss motivation, objectives and layout of the thesis.

1.1. BRIEF HISTORY AND INTRODUCTION

Since the natural world is full of examples of periodic structures' visual characteristics, such as the patterns on butterflies' wings and the way a gemstone changes color when exposed to light. Photonic crystals have been used by nature for millions of years [1], but only recently have people started recognizing their full potential.

1.1.1. Introduction to Photonic Crystals

Periodic dielectric structures called photonic crystals are made to shape the energy band structure of photons, allowing or prohibiting the propagation of electromagnetic waves within specific frequency ranges. This property makes photonic crystals perfect for applications related to light harvesting. Since 1887, photonic crystals have been investigated in various forms. However, the word phonic crystal was not used until nearly a century later, when Yablonovitch and Sajeev John published two seminal studies on the topic in 1987.

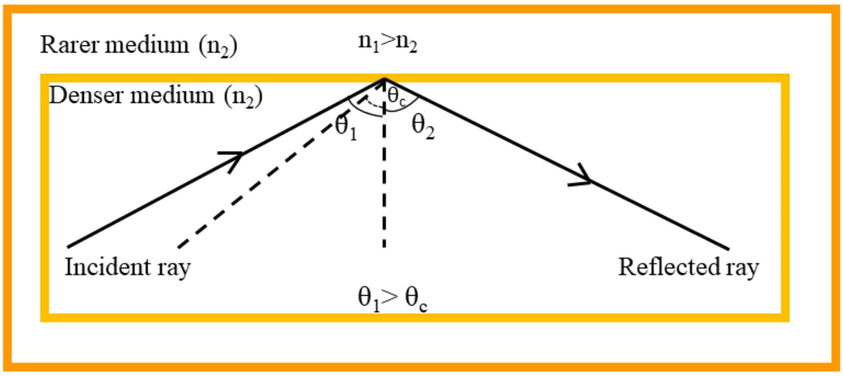
Although three-dimensional photonic crystals were initially proposed by Yablonovitch [2] and John [3] in 1987, one-dimensional periodic structures in the form of thin film stacks have been explored for many years [4]. Yablonovitch pointed out that an electromagnetic bandgap more precisely photonic bandgap, or a range of frequencies at which light cannot pass through a structure in any direction, could be present in three-dimensional periodic dielectric structures.

This observation, led to the quick development of the idea of regulating light with periodic structures, which is now a subject of intense global research. Since electronic bandgaps in semiconductors have transformed electronics, solid-state physics has provided us with a thorough understanding of bandgaps in periodic materials. Perhaps this is why photonic crystal research has advanced so quickly in less than 20 years: many solid-state research concepts, including terminology and notation, have been transferred to photonic crystals.

Since 1987, photonic crystals have been used in a wide range of applications, including photonic crystal fiber (PCF), low-loss optical waveguides, and Bragg reflectors, etc.

1.1.2. Introduction to Optical Fibers

The field of guiding light via optical fibers has expanded since its initial investigation in the mid-1900s, primarily because rapid communications networks are required. This has prompted study into fiber lasers and amplifiers in addition to the creation of low-loss long-distance telecom fibers. The dependable, comparatively low-maintenance components that are a part of the extensive global communications network of today are one outcome of this. However, optical fibers and fiber lasers have many other applications outside of communications, especially in the fields of medical and basic science studying the nature of light. This chapter introduces the specific qualities of photonic crystal fibers, the focus of this work, and provides an overview of optical fiber properties that are crucial to understanding the remainder of this thesis. Unlike ordinary fibers, photonic crystal fibers operate on photonic



n= refractive index , θ_c= critical angle, θ_1=angle of incidence, θ_2=angle of reflection

Fig. 1.1 Total internal reflection taking place at the interface of two media.

band gaps and occasionally apply internal reflections [5]. Let's start with step index fibers in order to comprehend photonic crystal fibers.

Light is guided by total internal reflection (TIR) in conventional optical fibers [6]. Light is either refracted or reflected when it strikes a border between two materials with differing refractive indices. Refracted light moves along the boundaries when it passes over the critical angle, which occurs as light in a high-index material approaches the boundary with a material with a lower refractive index nearing parallel. All light is reflected back into the material at angles larger than this with respect to the normal to the boundary. In their most basic configuration, optical fibers use TIR guidance to achieve guiding. They are made up of two regions: a high-index core and a cladding region with a slightly lower refractive index (Fig 1.1), which allows TIR to occur all the way along the fiber. In order to significantly alter the refractive index, various dopants are often added to fused silica, which is utilized for both the core and cladding [7]. Long-distance communication fibers generally have a cladding made entirely of silica and a core doped with germanium. A somewhat higher refractive index is obtained from the germanium doping compared to pure silica. Fluorine and boron lower the refractive index of silica, while aluminum, phosphorus, and nitrogen are other dopants that boost it. Low index claddings made of pure silica cores can be created around them using the index-lowering dopants.

1.1.3. Introduction to Photonic Crystal Fibers

A novel type of optical fiber was described in 1996; instead of having a cladding section made of a single piece of glass, it had a cladding region made up of a series of tiny air holes spaced throughout the fiber's length [8,9]. This was later dubbed photonic crystal fiber (PCF), and fig. 1.2 shows a schematic representation of it. Compared to traditional TIR guiding fibers, PCFs have considerably different guidance characteristics due to the cladding's array of air holes. This is due to the fact that the cladding's effective refractive index may be changed by adjusting the size of its air pores, which in turn modifies the index contrast between the cladding and the core, which is usually pure silica. It is possible to significantly tailor fiber qualities like dispersion and nonlinearity by controlling the effective refractive index. Additionally, PCFs can exhibit qualities not found in traditional fibers. For instance, regardless

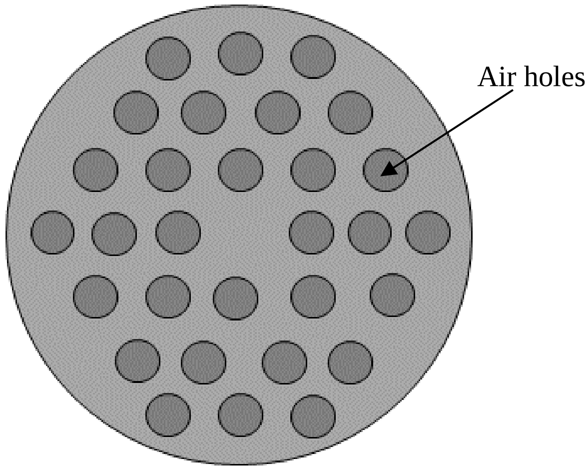


Fig. 1.2 Cross-sectional view of a photonic crystal fiber.

of wavelength, they can only ever sustain the fundamental guided mode at specific hole size to hole separation ratios [10,11].

These days, optical fibers are used for data transmission in the telecommunications sector. Since a vast amount of information is dispersed over the network of fibers, it serves as the foundation of the information society. Every day in our lives, we use optical fiber to read our emails, make phone calls, and connect to the internet. Compared to traditional fibers, the photonic crystal fiber offers a variety of new and enhanced features [12]. Unlike conventional technologies, a single type of glass can be used to create PCFs. To provide light guidance in PCFs, an air hole arrangement around the core is introduced, and these air holes run the entire length of the fiber. Optical fibers have been widely used in fields like spectroscopy, astronomy, diagnostics, biomedical imaging, and structural sensing and telecommunication in recent years. Temperature, magnetic field, and electric field sensors are examples of physical sensors that continue to be used extensively [13].

1.2. MOTIVATION AND OBJECTIVES OF THESIS

The motivation we address in the present thesis is to design and analyze highly effective and sensitive PCF-based biosensor for the detection of cancer cells in terahertz regime. The proposed sensor should be based on the principle of refractive index sensing and should be highly sensitive. In order to attain these objectives, the whole research work was done in various steps. The first step was to design a novel PCF with design parameters such that it can operate in terahertz regime. Once all the necessary steps involved in the design process like geometry building, materials assignment to various domains and sub-domains, mesh setup, etc., are done, study of modal analysis is done to the designed optical fiber in which all the required mathematical study of the input optical signal is obtained. The last and the foremost objective of the work is to analyze the designed optical fiber-based sensor for various optical parameters with different analytes. The results obtained for optical parameters are then analyzed and compiled through graphical and other mathematical models to meet the prime objective which is to obtain highly effective and sensitive PCF-based biosensors for detection of cancer cells in terahertz regime.

1.3. ORGANIZATION OF THE THESIS

The thesis presents various advancement in the field of photonic crystal fibers and its applications over the last few decades. Of all the applications of photonic crystal fibers discussed so far, sensing in terahertz regime is of utmost importance in the present work. In order to meet the objectives and motivation, the present piece of work is dissected into various chapters with their sections and sub-sections to fundamentally and thoroughly understand the whole subject.

Chapters 1 and 2 provide the background knowledge require to grasp the content of following chapters which represent the specifications of the work. In the present chapter, we have gone through the early history and brief information about the photonic crystals and photonic crystal fibers while in the upcoming chapter i.e. chapter 2, we will understand the various types of photonic crystal fibers and their modes of operation. This chapter also explores the wave propagation mechanism in optical fibers and how to obtain modes using Maxwell's equations. Later, the chapter introduces the terahertz wave transmission in PCFs and their application in terahertz regime.

In Chapter 3, the introduction of various optical parameters required to evaluate the performance of a PCF based sensor are discussed. PCF-based sensing and its advantages are explored with introducing the fact that how modifying the cladding structure of photonic crystal fibers might influence their properties. These optical parameters are the key performance metrics of any PCF based sensor. These optical parameters are directly linked to the light guiding properties of any proposed fiber model and are important in analyzing the overall effectiveness and applicability of any proposed fiber-based sensor model.

In Chapter 4, a detailed information of simulation and modelling of photonic crystal fibers and

PCF-based sensors is given. Various numerical methods and software are discussed for PCF simulation. The finite element method (FEM) based COMSOL Multiphysics software is elaborated along with FEM, perfectly matched layer and boundary conditions.

In Chapter 5, The proposed sensor model and its modelling parameters are discussed along with materials assignment to various sub-domains. The chapter contains design and numerical analysis of a novel PCF-based sensor detecting skin cancer and blood cancer in terahertz regime. In the later part of the chapter, results and discussion along with conclusion are added. Finally, The last chapter of the thesis lights us on the conclusion and future scope of the work.

Chapter 2

Optical Fibers

These days, optical fibers are used for data transmission in the telecommunications sector. Since a vast amount of information is dispersed over the network of fibers, it serves as the foundation of the information society. As discussed in the previous chapter, compared to traditional fibers, the photonic crystal fiber offers a variety of new and enhanced features. Unlike conventional technologies, a single type of glass can be used to create PCFs. By adding an array of air holes around the core of PCFs, light guidance can be accomplished. These air holes run the entire length of the fiber. Optical fibers have been widely used in fields like spectroscopy [14], medical [15], sensor technology [16], and telecommunication [17] in recent years. In order to understand the above-mentioned facts, let us understand the basic concepts related to optical fibers and deep dive into various kinds of photonic crystal fibers.

2.1. BASIC CONCEPTS

2.1.1. CONVENTIONAL OPTICAL FIBER OR STEP-INDEX FIBER

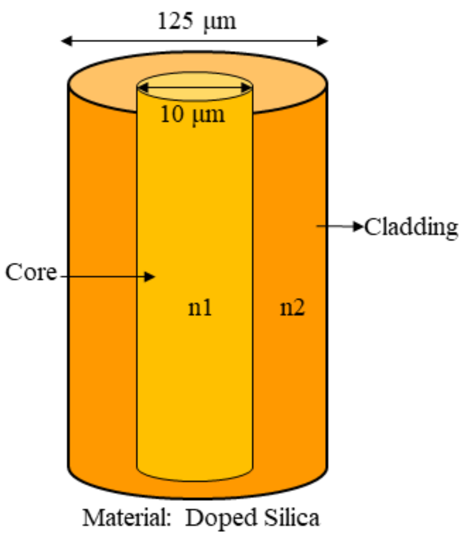


Fig. 2.1 Schematic representation of a step-index fiber

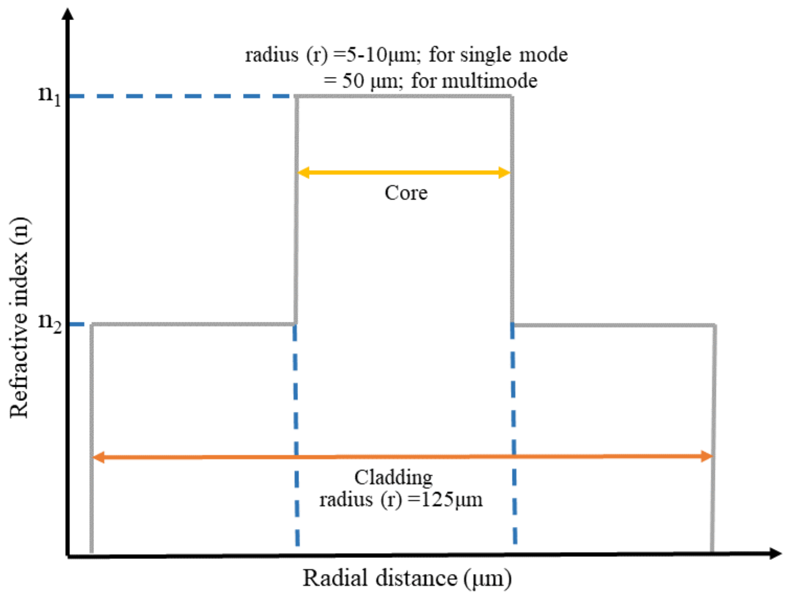


Fig. 2.2 Refractive index profile of a step-index fiber.

A step-index or conventional fiber is composed of core-cladding structures that rely on TIR. The fiber comprises of a core and cladding layer formed of dielectric materials. The core must have a higher refractive index than the cladding to contain the optical signal. Conventional optical fibers are made from two types of silica. The core of an optical fiber has a greater refractive index, whereas the glad surrounds it with a lower refractive index ($n_1>n_2$) as shown in the figure 2.2.

When light passes between surfaces with different refractive indices, some of it is reflected. Fused silica mixed with various dopants is the fundamental material utilized for the core and

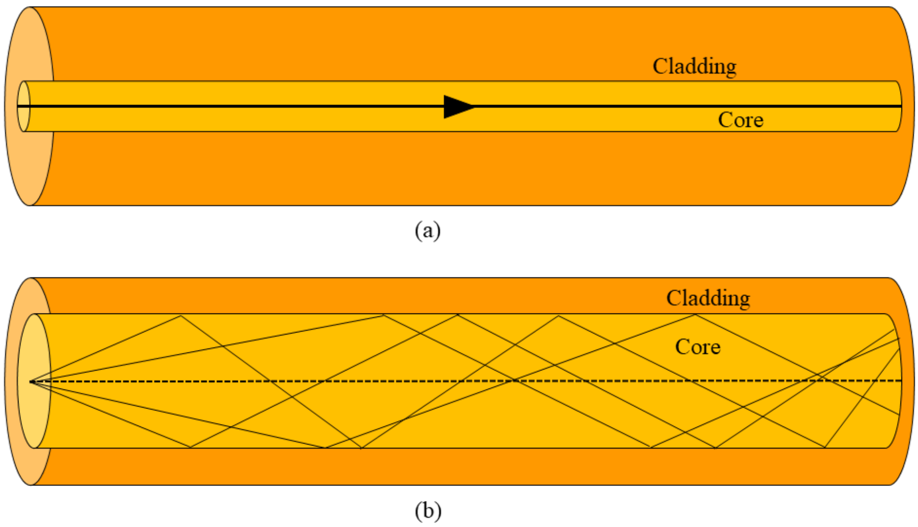


Fig. 2.3 (a) Step-index fiber in mono-mode; (b) step-index fiber in multi-mode [18].

cladding. Long-distance communication fibers are made of a cladding of pure silica and a core doped with germanium. The refractive index of the germanium-doped silica is marginally greater than that of the pure material. The refractive indices of silica are also raised by nitrogen, phosphorus, and aluminum, while they are lowered by boron and fluorine. Low index claddings can be created around a pure silica core by utilizing the index-lowering dopants.

2.1.2. PHOTONIC CRYSTAL FIBER

Photonic Crystal Fibers (PCFs) are innovative optical fibers featuring a micro structured pattern of air holes along their length, creating a photonic bandgap that guides light in unique ways. This design allows precise control over properties like dispersion and birefringence, enabling applications in supercontinuum generation, sensing, and nonlinear optics. PCFs offer advantages such as endlessly single-mode guidance and tailored dispersion profiles. Fabricated through techniques like stack-and-draw, they find use in diverse fields where their distinctive optical characteristics, including strong birefringence and customizable guiding

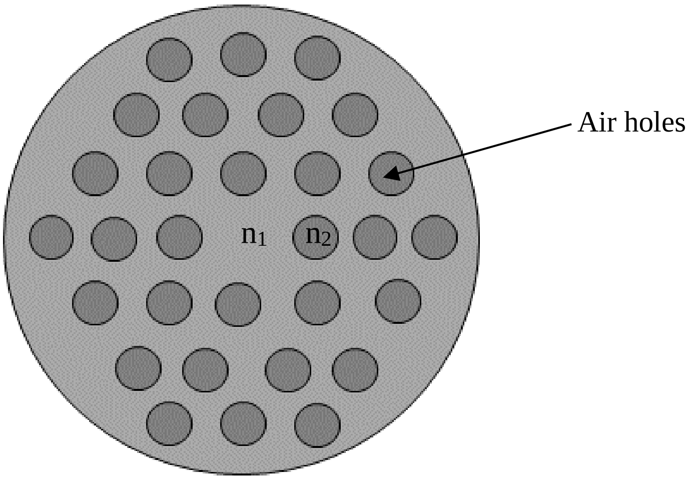


Fig. 2.4 Diagrammatic representation of a photonic crystal fiber.

mechanisms [19], contribute to advancements in telecommunications, spectroscopy, and sensing technologies. Ongoing research explores further optimizations and specialized designs for enhanced performance [20].

2.1.3. TYPES OF PHOTONIC CRYSTAL FIBER

Photonic Crystal Fibers (PCFs) come in various types, each designed to cater to specific applications and requirements. There are three types of PCFs:

1. Solid-core PCF,
2. Hollow-core PCF, and
3. Porous-core PCF.

2.1.3.1. Solid-core PCF:

Solid Core Photonic Crystal Fibers (PCFs) exhibit a microstructured design with a solid glass core surrounded by a periodic arrangement of air holes. Unlike traditional fibers, they exploit a photonic bandgap for light guidance [21]. Offering precise control over optical properties like dispersion, Solid Core PCFs find application in supercontinuum generation and sensing. Fabricated through techniques like stack-and-draw, these fibers enable tailored designs for diverse applications. Ongoing research focuses on optimizing properties such as bandwidth and dispersion while balancing potential trade-offs, showcasing their versatility in telecommunications, spectroscopy, and other advanced optical technologies.

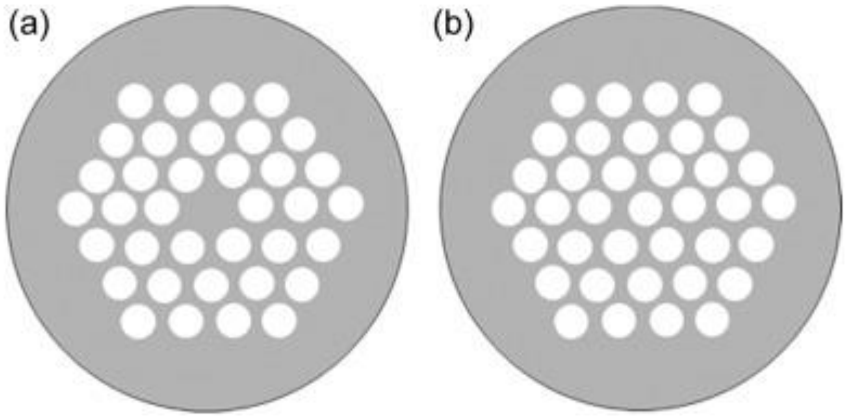


Fig. 2.5 Diagrammatic representation of **(**a) Solid-core PCF and (b) Hollow-core PCF [21].

2.1.3.2. Hollow-core PCF:

Hollow Core Photonic Crystal Fibers (HC-PCFs) feature a core devoid of solid material, either containing air or a gas. Employing a photonic bandgap mechanism, these fibers mitigate nonlinear effects, making them ideal for high-power laser transmission. Notable for gas sensing applications, the hollow core allows direct interaction with gases. Fabricated through techniques like stack-and-draw, HC-PCFs are continuously refined for reduced losses and enhanced performance [22]. Challenges include maintaining structural integrity and achieving low loss, driving ongoing research to optimize designs and broaden their applications in areas such as telecommunications and precision sensing.

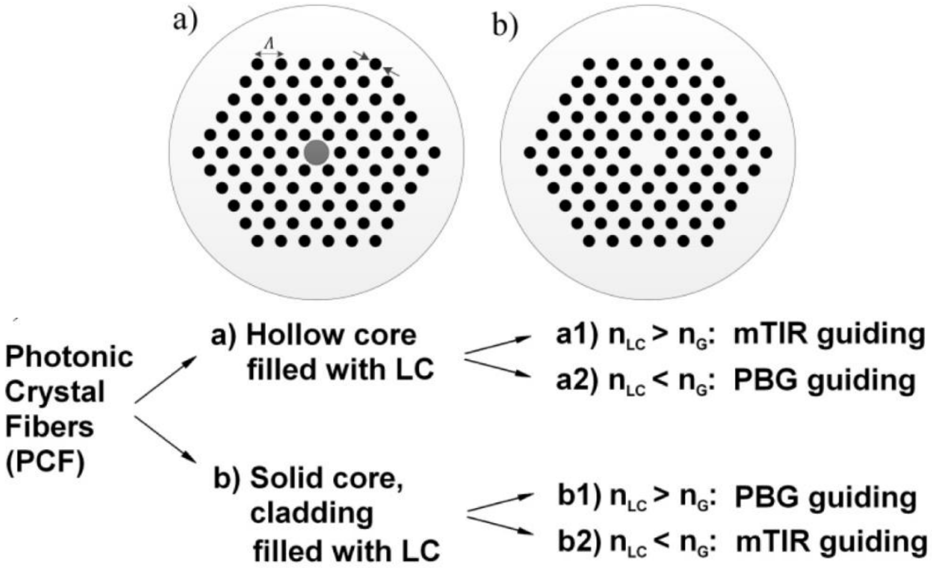


Fig. 2.6 Schematic representation of a (a) hollow-core PCF and (b) solid-core PCF with modes of operation [23].

2.1.3.3. Porous-core PCF:

Porous Core Photonic Crystal Fibers (PCFs) feature a core with a lattice of air holes or pores, enabling unique optical properties. The porous structure enhances the interaction between light and external substances, making them ideal for sensing applications. These fibers offer tailored modal properties, including control over dispersion and confinement, crucial for

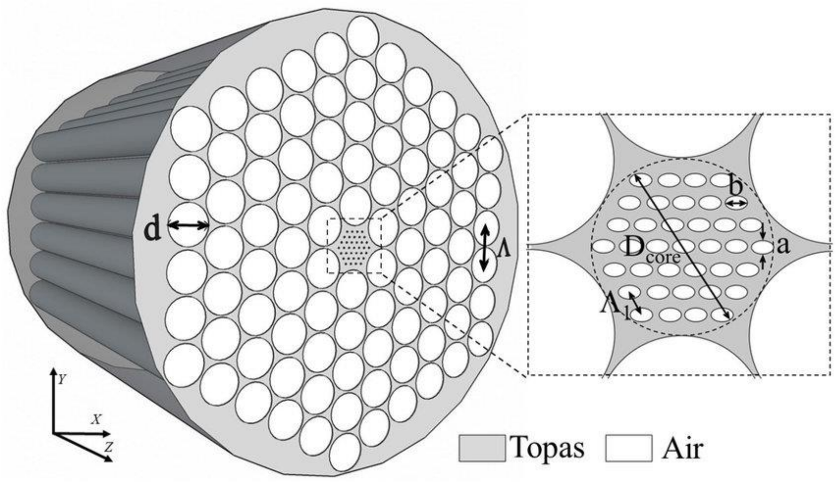


Fig. 2.7 Schematic diagram of a porous-core PCF [24].

applications like gas sensing and nonlinear optics [25]. Fabricated using techniques such as the stack-and-draw method, Porous Core PCFs provide versatility in designing specialized sensors. Ongoing research aims to optimize their performance, expand their sensing capabilities, and explore new applications in fields such as environmental monitoring and chemical analysis.

2.1.4. TYPES OF PCFs BASED ON MODE OF OPERATION

Photonic crystal fibers can be broadly classified into two types based on the way they operate: Index guiding PCFs and Photonic bandgap PCFs. Due to the distinct wave guiding characteristics of these two photonic crystal fibers and the needs of the applications, they are utilized in the actual world [26]. A brief introduction of these two categories based on modes of operation is given below:

2.1.4.1 Index guiding PCFs

Index guiding PCFs use complete internal reflection to transmit light through a solid core, much like conventional fibers do. By reducing the cladding's index, the microstructured air-

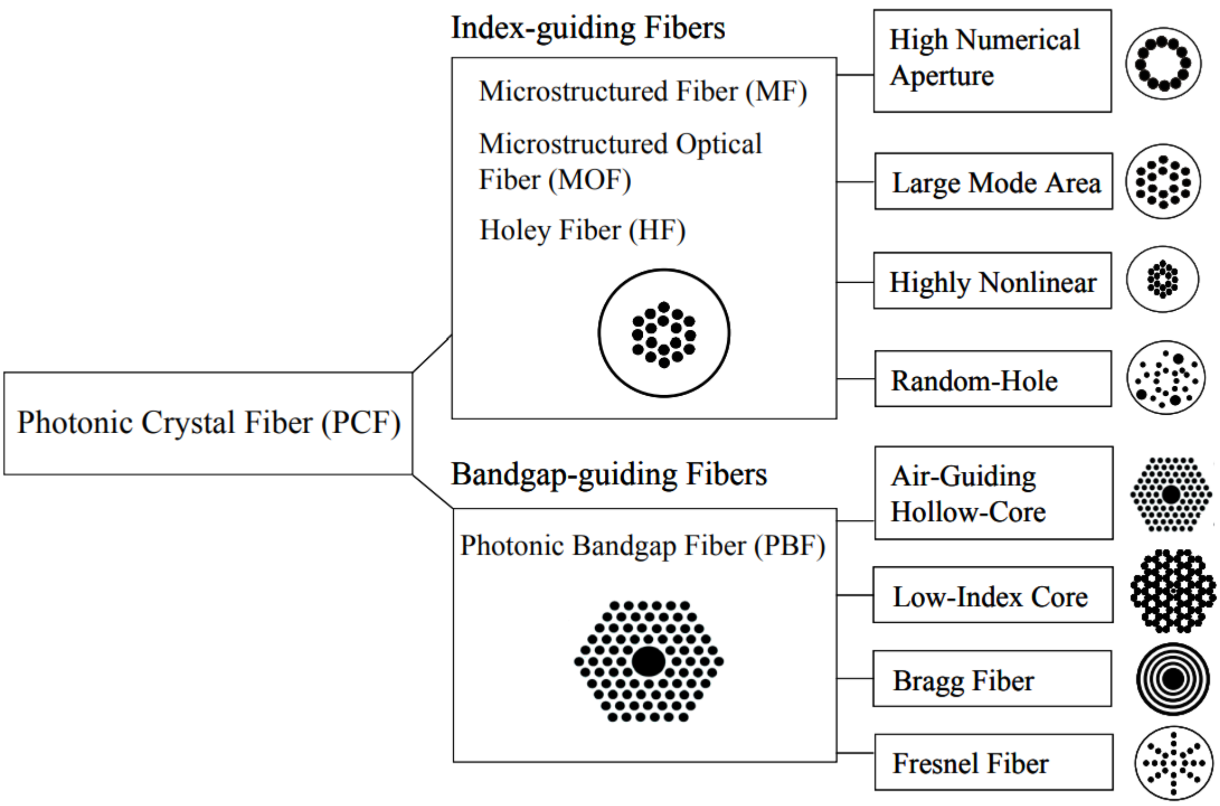


Fig. 2.8 Fig: Classification of photonic crystal fibers based on the mode of operation [27].

filled area in PCFs essentially produces a step-index optical fiber. The fiber has some benefits over normal step-index fibers, but it acts in many of the same ways. Undoped silica, used to make index guiding PCFs, has very low losses, can handle high voltages and temperatures, and may be resistant to nuclear radiation. It is possible to use the air in the cladding to produce fibers with very low or very high index steps, depending on PCF design.

2.1.4.2 Photonic bandgap PCFs

Using the Photonic Bandgap (PBG) effect, the PCF technological advances offers the intriguing possibility of producing fibers that guide light in a hollow (air) core. A photonic bandgap is produced by the highly periodic nature of the air holes in the fiber's cladding. This indicates that light with frequencies inside the PBG may become caught in the fiber's core instead of being able to travel through the cladding. Unlike index-guiding fibers, the refractive index of the core area does not have to be greater than the index of the cladding.

2.1.5. THE WAVE PROPAGATION MECHANISM IN OPTICAL FIBERS

The propagation characteristics of optical signal in optical fibers are obtained from the Maxwell's equations [18]. The Maxwell's equations for an isotropic, linear, nonconducting and nonmagnetic medium are given as:

$$\nabla \times \mathbf{E} = -\frac{\partial \boldsymbol{B}}{\partial t} = -\mu_o \frac{\partial \boldsymbol{H}}{\partial t} \tag{2.1}$$

$$\nabla \times \mathbf{H} = \frac{\partial \boldsymbol{D}}{\partial t} = \epsilon_o n^2 \frac{\partial \boldsymbol{E}}{\partial t} \tag{2.2}$$

$$\nabla . \mathbf{D} = 0 \tag{2.3}$$

$$\nabla . \mathbf{B} = 0 \tag{2.4}$$

where ∇ is the del operator and **E, D, B,** and **H** represents the electric field, electric displacement, magnetic induction, and magnetic intensity, respectively. The $\boldsymbol{D} = \epsilon \boldsymbol{E} = \epsilon_o n^2 \mathbf{E}$, and $\boldsymbol{B} = \mu_o \boldsymbol{H}$. The symbols $\boldsymbol{\epsilon}$ represents the dielectric permittivity of the medium, $\boldsymbol{\mu}$ represents the magnetic permeability of the medium and n represents the refractive index of the medium.

On taking the curl of the equations (1.1) and (1.2) and substituting **D** and **B** in the equations, we get:

$$\nabla \times (\nabla \times \mathbf{E}) = -\mu\epsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} \qquad (2.5)$$

$$\nabla \times (\nabla \times \mathbf{H}) = -\mu\epsilon \frac{\partial^2 H}{\partial t^2} \qquad (2.6)$$

Now, applying the vector algebra identities in the equations (1.5) and (1.6), i.e. $\nabla \times (\nabla \times \boldsymbol{A}) = \nabla (\nabla . \boldsymbol{A}) - \nabla^2 \boldsymbol{A}$, we will obtain the equations as given below:

$$\nabla^2 \boldsymbol{E} = \mu\epsilon \frac{\partial^2 \boldsymbol{E}}{\partial t^2} \qquad (2.7)$$

$$\nabla^2 \boldsymbol{H} = \mu\epsilon \frac{\partial^2 H}{\partial t^2} \qquad (2.8)$$

Where ∇^2 represents the Laplacian operator. The above equations are applied to the medium of optical fibers with corresponding coordinate system like cylindrical polar coordinates. On applying the boundary conditions to the interface of two media, we get particular solutions and wave guiding characteristics in optical fibers. The general solution of the above-mentioned wave equations comes out to be as sinusoidal wave function represented below:

$$\psi = \psi_0 \exp\{ j (\omega t - \boldsymbol{k} . \boldsymbol{r})\}) \qquad (2.9)$$

where **k** denotes the wave propagation vector, $k = \frac{2\pi}{\lambda}$ and **r** represents the position vector.

In optical fibers, light can only propagate in certain modes which are distributions of electromagnetic fields, which are theoretically represented by Maxwell's equations [28]. The physical parameters of an optical fiber decide the allowed number of modes and the intensity distribution [29].

2.1.6. TERAHERTZ WAVE TRANSMISSION IN PHOTONIC CRYSTAL FIBERS

The term "terahertz" (THz) refers to far-infrared radiation in the electromagnetic spectrum that falls between microwaves and infrared regions and has a frequency range of 0.1 to 10 THz [25]. Photonic crystal fibers have rapidly acquired popularity in the THz regime in recent years for wave guidance and sensing applications. By optimizing the geometrical parameters, one may regulate the optical properties of PCF. PCF geometry has been created for THz wave propagation since terahertz frequency has so many uses in non-invasive medical imaging [30,31], biomedical sensing [32], security [33], spectroscopy [34], the field of biotechnology

[35], cancer diagnosis [36], telecommunication [37,38], ecological concerns [39], oral healthcare [40], military [33], pharmaceutical drug testing [41], astronomy [42], etc. Scientists all over the world are currently very interested in it. Terahertz PCF based sensors have been extensively researched and used because of their special benefits and high sensitivity. Conventional and hybrid porous core PCF-based sensors were first proposed, however they had a low level of sensitivity. Hybrid structured hollow-core PCFs have been described, and they offer better sensing properties than the earlier varieties because of the advancements in PCF fabrication techniques.

Chapter 3

PCF-based Sensing and Optical Parameters

In the present chapter, we will introduce ourselves to the world of sensing based on photonic crystal fibers. The various types of PCF-based sensors along with their advantages and applications are discussed. A brief introduction of various PCF-based sensors along with the effectivity of PCFs in sensing applications is elaborated. Later, various important optical parameters required to analyze the fiber-based sensors are introduced with their respective mathematical information. Let us understand the same in the sections given below:

3.1. PCF-BASED SENSING

In the last few decades, PCF-based sensing has attracted a great amount of interest of the researchers in optics field. The optical fiber sensor technology is a direct outgrowth of the revolutions taken place in optoelectronics and fiber optics communication industries. It is expected that that as the time progresses the optical fiber sensors will replace the conventional devices for the measurements of the various physical, chemical and biological parameters such as electric and magnetic fields, temperature, pressure, strain, pH, glucose, chemicals like Benzene, alcohols, water, etc., cancer cells, pollutants etc. [43]. Optical fiber sensor technology is an extremely promising and fast-growing technology as the reports of market expedition in this field shows.

3.2. MECHANISM AND ADVANTAGES OF PCF-BASED SENSING

An optical input signal corresponding to the parameter of interest to be measured is produced when light interacts with any kind of measurable parameter—physical, chemical, or biological quantities—in an optical fiber within a specific interaction region. This process is known as an optical fiber sensing method. PCF-based sensors have shown huge potential in recent times and have been researched a lot due to their high efficiency and efficacy [44]. The models proposed so far for the PCF-based sensing have shown great potential to be realized in industry. A high degree of design flexibility is provided by photonic crystal fiber, which makes it easier to develop new sensing applications. Variations in the size and location of cladding holes and/or the fiber transmission spectrum's core, as well as in dispersion, mode shape, air filling fraction, nonlinearity, and birefringence, can be made to reach values that are not possible with traditional optical fibers. Additionally, the presence of air holes permits light to travel through the atmosphere and allows liquids or gasses to seep into the holes. This makes it possible for light and sample to interact in a controlled way, opening up new sensing applications. Various advantages of fiber-based sensors are listed below [45]:

- Small size, light weight and flexible,
- High sensitivity,
- Potential of distributed sensing,
- Compactness,
- Remote sensing,
- Environmental ruggedness and resistant, etc.

3.3. OPTICAL PARAMETERS: FORMULATION

From the above section, we can conclude that PCF-based sensing requires a significant amount of research and development due to the high applicability and efficacy of the optical fiber sensing. In order to meet this objective, the analysis of photonic crystal fiber-based sensors is required which is done by optimizing the various optical parameters. The optical parameters which are observed in PCF-based sensors are relative sensitivity, effective material loss, confinement loss, effective mode area, etc. In order to obtain PCF-based sensors industry ready, losses are minimized, and sensitivity of the sensors is enhanced. Hence, these optical properties play a crucial role in PCF-based sensing. Let us understand these various optical parameters in detail:

3.3.1. BIREFRINGENCE

Birefringent PCFs are used to control the polarization of the optical signal propagating in them. By exploiting this property, we can manipulate the polarization state, which is crucial in optic gyroscope for rotation sensing, temperature, strain, etc. The characteristic that helps in preserving a fiber's polarization state is called birefringence. The difference in the fundamental mode of the fiber's effective refractive indices in the x and y polarizations is known as birefringence. Mathematically, it is represented as [46]:

$$B = |n_x - n_y| \tag{3.1}$$

Where n_x and n_y represent the effective mode indices of x-polarization and y-polarization, respectively.

3.3.2. CONFINEMENT LOSS

Confinement loss (L_{conf}) is the wave propagation loss resulting from leakage that indicates a PCF's capacity to confine light. The smaller the confinement loss, the greater the confining ability, which is essential for any PCF-based sensor type. It is a crucial aspect of PCF-based sensor's performance. The main reasons responsible for L_{conf} within an optical fiber are material absorption, scattering, radiation loss, bending, etc. L_{conf} depends upon the imaginary part of the effective mode index and is represented by the equation given below [47]:

$$L_{conf} = 8.868 \times k_o I_m\left(n_{eff}\right) dBm^{-1} \tag{3.2}$$

Here, $k_o = \frac{2\pi}{\lambda}$, where λ is the wavelength of the operating signal and $I_m\left(n_{eff}\right)$ denotes the imaginary part of the effective refractive index experienced by the input signal.

3.3.3. EFFECTIVE MODE INDEX

The overall refractive index that the light's mode experiences while passing through the fiber's core is known as the effective mode index, or n_{eff}. It is essential for figuring out a sensor's sensitivity. The effective refractive index of PCFs can be used to design sensors that are highly sensitive to changes in the surrounding medium. The n_{eff} considers the refractive indices of core and clad of the fiber. It is highly dependent on the shape, size and structure of the air holes in the PCF. It is represented by the relation as given below [48]:

$$n_{eff} = \frac{\beta}{k_o} \tag{3.3}$$

where β represents the propagation constant and k_o is the free space wave vector as discussed earlier.

3.3.4. EFFECTIVE MODE AREA

In any PCF, the effective mode area (A_{eff}) is a crucial optical property. PCFs with a large effective mode area have potential applications in optical and electronic devices, whereas low effective mode area PCFs can be helpful in non-linear optics. It provides an estimate of the quantity of light that is propagating through the fiber's cladding and core, in which the analyte is supposed to be filled. The high A_{eff} in a PCF-based sensor model denotes low confinement loss and high relative sensitivity. It is simply expressed in terms of transverse electric field intensity and can be assessed as follows [49,47]:

$$A_{eff} = \frac{\left[\int I(r)dr\right]^2}{\left[\int I^2(r)dr\right]} \tag{3.4}$$

Here, the $I(r)$ represents the electric field intensity of the optical signal propagating within the core of the fiber.

3.3.5. EFFECTIVE MATERIAL LOSS

The substantial amount of loss introduced by the fiber's background material is known as the effective material loss (L_{mat}). The L_{mat} in an optical fiber is due to the sum of various loss mechanism like material absorption, Rayleigh scattering, residual dopant absorption, surface roughness loss, etc. The following equation provides the mathematical representation of the fiber's L_{mat} [47]:

$$L_{mat} = \sqrt{\frac{\varepsilon_o}{\mu_o}}\left(\frac{\int_{zeonex} n_{zeonex}\alpha_{zeonex}|E|^2 dxdy}{\left|\int_{all} P_z dA\right|}\right) \tag{3.5}$$

where n_{zeonex} denotes the refractive index of the fiber's background material which is taken zeonex here and α_{zeonex} denotes the bulk absorption parameter of the material i.e. zeonex. The permeability and permittivity of free space are shown by the symbols μ_o and ε_o respectively.

3.3.6. NON-LINEAR COEFFICIENT

The nonlinear coefficient (γ) in PCFs is an optical parameter which quantifies the strength of non-linear effects occurring within the optical fiber. These effects arise due to the interaction of high intensity light with the material of fiber. Various nonlinear phenomena are self-phase modulation, four-wave mixing, stimulated Raman scattering, etc. The standard unit of γ is $W^{-1}m^{-1}$ and is formulated as given below [48]:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} = \frac{2\pi f n_2}{c A_{eff}} \tag{3.6}$$

Here, n_2 is the nonlinear refractive index of the fiber material, λ is the wavelength of the input optical signal, A_{eff} is the effective mode area and f is the frequency of the light signal which is in terahertz.

3.3.7. NUMERICAL APERATURE

Another important parameter that is crucial for evaluating the effectiveness of any PCF-based sensor model is numerical aperture (NA). Larger numerical apertures are often chosen for better sensing findings because they increase the fiber's light-gathering capacity and angular acceptance, which enhances the field interaction with the analyte even more. NA is generally determined by the refractive index contrast between the core and the surrounding medium. NA also depends on the structure of the cladding and guiding mechanism. The relation is as follows [47]:

$$NA = \left(1 + \frac{\pi A_{eff} f^2}{c^2}\right)^{-\frac{1}{2}} \tag{3.7}$$

Where all the symbols have their respective meanings as discussed earlier.

3.3.8. RELATIVE SENSITIVITY

Relative Sensitivity is the primary metric used to analyze a sensor's performance. The power conveyed by the optical signal in the fiber's core area directly affects relative sensitivity. Relative sensitivity shows how the changes in the refractive index of the surrounding medium affects the changes in the sensor's output signal. It quantifies the ability to detect small changes in refractive index relative to standard condition. It is essentially the ratio of the analyte's refractive index (n_a) to the effective refractive index of the mode of the input light wave (n_{eff}). Mathematically, It can be calculated as [47,48,50]:

$$Relative\ Sensitivity = \frac{n_a}{n_{eff}} \times Pf \tag{3.8}$$

where Pf represents the power fraction, n_a denotes the refractive indices of the analytes and n_{eff} have its usual meaning.

3.3.9. POWER FRACTION

In PCF-based sensors, power fraction (Pf) indicates the total amount of propagating light that interacts with the analyte in the core region. It is a crucial parameter as it directly affects the sensor's relative sensitivity. Pf is defined as the ratio of the power of light contained in the core to the total power pumped across the entire surface area of the fiber. Therefore, the power fraction is a unit less quantity. Mathematically, It can be estimated as follow [47,50]:

$$Pf = \frac{\int_{analyte} R_e(E_x H_y - E_y H_x) dxdy}{\int_{total} R_e(E_x H_y - E_y H_x) dxdy} \times 100 \qquad (3.9)$$

where the equation mentioned above uses integration to determine the amount of light propagated through a certain analyte with respect to the fiber's cross section. In this case, the components of the magnetic field are represented by H_x and H_y, and the components of the electric field by E_x and E_y.

The preceding analysis indicates that photonic crystal fiber (PCF) sensor technology represents a highly promising field within contemporary optics, with extensive potential applications. For PCF sensors to effectively compete with currently available commercial solutions, advancements are required in real-time and industrial applications as well as in fabrication technologies. Presently, numerous PCF sensors exhibit high sensitivity and demonstrate significant potential across various sensing applications, attributed to their compact size, robustness, flexibility, and resistance to harsh environments, among other attributes. Consequently, it is anticipated that PCF-based sensors will soon overcome existing challenges and prove suitable for both everyday use and large-scale industrial applications.

Chapter 4

Simulation and Modelling

Numerical simulation for optical devices is becoming more cost-effective, facilitating production and characterization throughout optimization phases. After the initial experimental demonstration of PCF in 1966, many modeling methods have been developed to better understand it [9]. Practically, it is difficult to manufacture an actual design or structure in order to determine its reliability but with the advancement in the emerging world of computing and simulation, it has become easier to modeling the real-world designs. Various software such as RP Fiber, Ansys Multiphysics, and COMSOL Multiphysics Simulation, can now construct basic to complex concepts for fiber or other physical designs, including their numerical computations. It is possible to perform these computations without using laboratory fabrication.

Most commonly used numerical methods for PCF simulation are:

- Finite Difference Time Domain Method (FDTD),
- Finite element Method (FEM),
- Beam Propagation Method (BPM),
- Plane Wave Expansion Method (PWE),
- Multipole Method,
- Localized Function,
- Finite Difference Frequency Domain Method (FDFD), etc.

These numerical methods are highly efficient and can easily model the real world designs and structures in a simulation software. For the presented work in the thesis, we used FEM based COMSOL Multiphysics software because of its capability to easily describe and define arbitrary structures and analyze the optical properties with a wide range of frequencies.

4.1. COMSOL MULTIPHYSICS SOFTWARE

A robust interactive simulation platform called COMSOL Multiphysics is used to model and resolve a wide range of research and engineering challenges. With its robust integrated desktop environment and Model Builder, the program offers you access to all features and a comprehensive overview of the model. It is simple to convert traditional models for one kind of physics into Multiphysics models that address related physics phenomena simultaneously using COMSOL Multiphysics. It is not necessary to have extensive mathematical or numerical analysis knowledge in order to access this power [51].

Fig. 4.1 COMSOL Multiphysics software logo [51].

You can create models by specifying the pertinent physical characteristics, such as material properties, loads, restrictions, sources, and fluxes, rather than by specifying the underlying equations, thanks to the integrated physics interfaces and the enhanced support for material properties. Regardless of the computational mesh, you can always apply these variables, expressions, or numbers directly to borders, points, edges, and solid and fluid domains. After that, the COMSOL Multiphysics program internally creates a set of equations that describe the complete model.

4.2. FINITE ELEMENT METHOD

For engineering-based applications, FEM is a versatile and tested technique that is mostly used for structural analysis in fiber optic technology. When it comes to solving partial differential equations (PDE), it is a suitable instrument. The numerical method called the FEM is used to estimate the solution of PDE integral equations [52]. The best results were obtained when the full-vector finite element method was applied to PCF modeling [53]. However, the complex electromagnetic analysis is caused by MOF's index contrast between the cladding and core. For more complex simulations and modeling, advanced FEM software packages added for better capabilities and detailed documentation.

The general steps involved in the modelling of PCF-based sensor in FEM based COMSOL Multiphysics software are given below:

- Defining the PCF geometry
- Materials assignment to various domains and sub-domains
- Mesh generation
- Setting up boundary conditions
- Solving the Maxwell’s PDEs
- Post-processing and Analysis

FEM used in COMSOL Multiphysics software enables us to calculate a numerous amount of optical properties such as the ones discussed in chapter 3. By using perfectly matched layer (PML) with FEM in designed models for PCF-based sensor, modal analysis on PCF have been achieved and solutions of PDEs were obtained. Mesh resolution helps to implement this method by breaking up the various domains in various elements of simple shapes. In simple words, FEM subdivides a large model or problem into smaller and simpler parts which are known as ‘elements’. These elements are finite in number and the solution to each element is obtained using set of functions, and these local elementary solutions are assembled to form a one complete global solution [54].

4.3. BOUNDARY CONDITIONS

For the simulation analysis, we terminate the computational region with boundary conditions. They are suitable boundary conditions for a system whose differential equations are those mentioned above. Outside, there is a dynamic electromagnetic field that they must absorb. For this aim, FEM, ABC (Absorbing Boundary Condition), PML (Perfectly Matched Layer), and PBC (Periodic Boundary Condition) are often utilized techniques. In order to specify how the model interacts with its environment and to guarantee that the physical problem is well-posed, boundary conditions are crucial in COMSOL Multiphysics.

4.4. PERFECTLY MATCHED LAYER

The perfectly matched layer, or PML mathematical model, which lacks a physical medium, was first presented by J.P. Berenger in 1994. The material covering the computing domain absorbs undesired reflections, causing the field inside the PML region to decrease exponentially. A wave's impedance needs to be balanced by the split field between the computing domain and the absorbing layer. In simpler words, a boundary condition that is utilized to remove any numerical mistakes from the structure is called PML. For instance, when using volume discretization to solve partial differential equations numerically, it is crucial to truncate the computational mistakes. The application of the artifact ensures that the geometry is not disturbed.

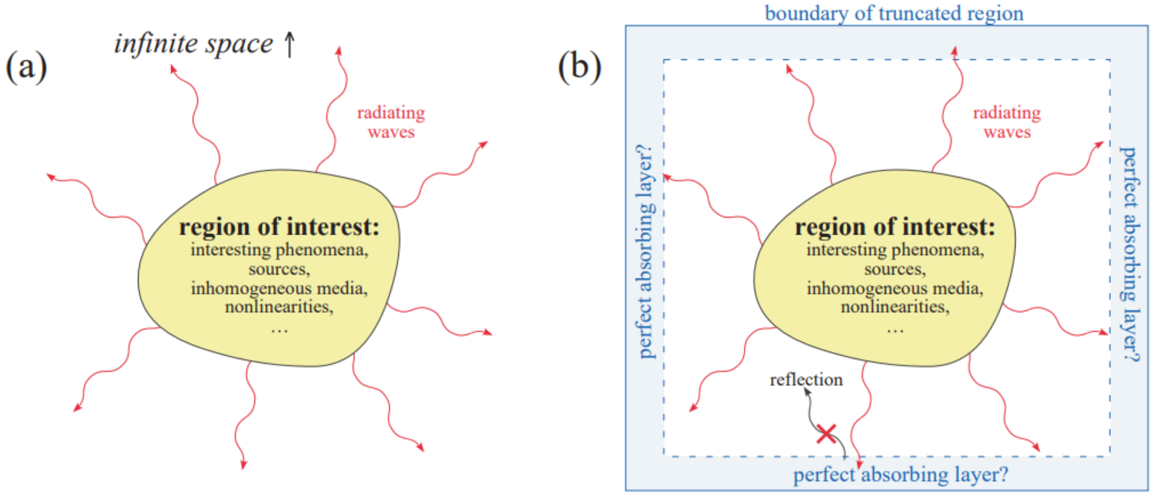


Fig. 4.2 (a) A typical wave-equation problem involves in which radiations may escape to infinity. (b) The identical problem, except the space has been truncated to some computational region. To absorb outgoing waves, an absorbing layer is placed near the computing region's edges [55].

While PML in computational studies for solving PDEs or wave equations is of huge advantage, but it also offers a certain number of limitations. These limitations are listed below [55]:

- Discretization and numerical reflections,
- Angle-dependent absorption,
- Inhomogeneous media where PML fails.

Chapter 5

Design and Numerical Analysis of a Novel PCF-based Sensor detecting Skin Cancer and Blood Cancer in Terahertz Regime[1]

5.1. INTRODUCTION

Cancer has always been a lethal and complicated public health issue across the whole world. It is characterized by the development of infected cells that have the ability to divide incessantly and destroy the functioning of normal blood tissues which consequently leads to death. It is caused by the consequences of several factors like carcinogens, hormones, radiation, alcohol, tobacco, diet and radon. In the present times, it has become the second leading cause of death globally. In the medical science, no cure has been reported so far that can help eradicate cancer completely. We cannot treat out way out of this fatal issue. The only solution is proper and early diagnoses, which can help in taking the required precautions at an early stage. Researchers have been working on developing an efficient and effective techniques for early detection of cancer cells. The optical behavior of the infected cells can lead to great results in the detection of cancer.

Recently, the researchers have found the application of Photonic Crystal Fibers (PCFs) in the field of sensing and disease detection. PCF based sensors do not require a lot of mechanical elements for the detection and sensing purposes and hence are more feasible. In a PCF, we can alter different parameters like the size and shape of air holes in the core and cladding region, pitch and the geometric pattern of air holes in the cladding region which can help in reducing the confinement losses and enhancing the relative sensitivity. PCFs holds various applications in the optical fields like telecommunication, chemical sensing, gas sensing and biomedical sensing. Distortion free light propagation with large mode area can be obtained using segmented cladding based PCFs. In the sensing field, various sensors have been developed like temperature sensors, salinity sensors, blood component sensors and diagnosing

[1] A part of this chapter has been accepted for publication in ICAMNOP Conference 2023, Springer Proceedings.

diseases. Biosensors have played a crucial role in the early detection of presence of cancerous cells in human blood.

Due to the large number of applications in genetic, organic area, spectroscopy, bio sensing, chemical sensing, astronomy, temperature sensing and communication fields, Terahertz regime (THz) of waves has been center of focus in recent years. For sensing purposes, PCF based sensors have been found to work exceptionally well in the THz regime.

In our proposed research work, the prime objective is to model and investigate a highly effective PCF based biosensor for sensing skin and blood cancer cells in terahertz regime. To complete this objective, various optical parameters of the fiber like relative sensitivity, effective mode area. effective mode index, confinement loss etc. are analyzed. The further section shows the designing and fabrication feasibility of the proposed sensor. Later, the results were analyzed, and performance of this sensor is reported. Finally, results along with conclusive part are provided.

5.2. SENSOR MODEL DESIGN PARAMETERS AND FABRICATION

In this study, we have proposed a PCF-based biosensor having a square shaped core with rectangular air holes constituting the cladding region. Finite element method based COMSOL Multiphysics software has been used for modelling and analysis purposes. Initially, the global parameters and probable geometry were defined for the sensor model. Materials were assigned to various sub-domains of the photonic crystal fiber and a meshing setup was built for boundaries conditions. Finally, Partial differential equations solutions were performed to get various optical parameters. These parameters were analyzed, and the same steps were repeated until significant results were obtained. A cross-sectional representation with various parameters of the proposed biosensor is shown in the Fig. 5.1. The specifications of the

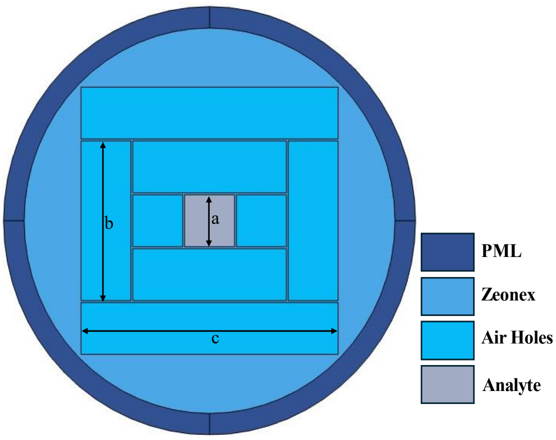


Fig. 5.1 Cross-sectional representation of the proposed biosensor with various sub-domains.

geometry of the proposed sensor model are shown in the table 1. The overall diameter of the fiber is taken as 3300 μm. The dimensions of the larger and smaller rectangular air holes in cladding region and square shaped core are mentioned in the same table. The analyte is infiltrated in this core for the sensing application. The background material of the optical fiber-based sensor is taken zeonex of its low loss properties. In the terahertz regime, zeonex shows a low bulk absorption loss of $0.2cm^{-1}$ and in 0.1-10 THz range, the refractive index remains almost constant i.e. 1.53.

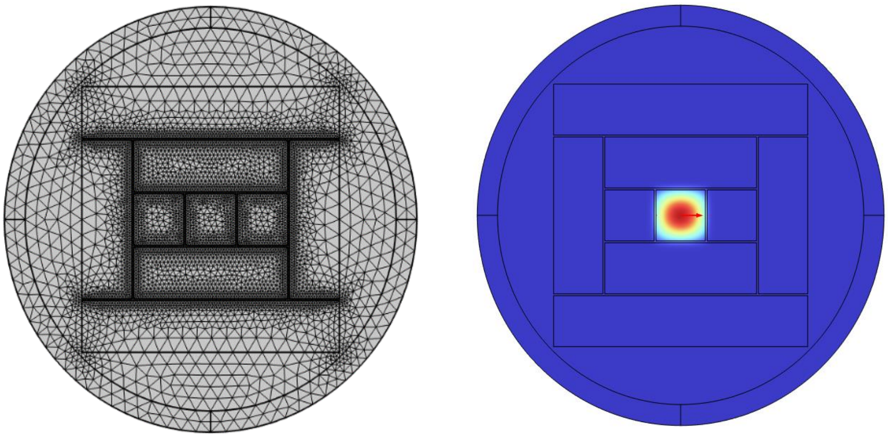


Fig. 5.2 (a) A finer mesh resolution of the proposed sensor model and (b) mode field distribution at 1.6 THz frequency optical signal.

Fig. 5.2 (a) and (b) shows the finer mesh setup of the proposed fiber which consists of 11514 domain elements and 1250 boundary elements and Mode field distribution of the designed PCF-based sensor for x polarization in the tested frequency range with skin cancer cells as an analyte respectively. Numerous fabrication methods, including capillary stacking, sol-gel, extrusion, 3D printing, etc., have been documented up to this time. These include the widely utilized capillary stacking and sol-gel techniques for creating circular air holes, as well as the extrusion and 3D printing techniques for creating asymmetric (rectangular and elliptical) hole architectures. For the construction of the proposed PC-based sensor structure, extrusion and 3D printing are therefore recommended.

Table 5.1 Design parameters of PCF-based sensor model.

Sr. No.	Parameters for design	Integral value
1.	Diameter of the fiber sensor	3300 μm
2.	Dimension of square shaped core *(a)*	400 μm
3.	Length of smaller rectangles *(b)*	1230 μm
4.	Width of larger rectangles *(c)*	2060 μm
5.	Pitch *(boundary to boundary Distance)*	15 μm

5.3. RESULTS AND DISCUSSION

The investigation of various performance metrics of the proposed PCF based sensor was performed using Finite element method (FEM) based COMSOL Multiphysics software. After that an analysis of the obtained result was done in order to obtain a highly effective PCF-based biosensor. For analysis, the analyte liquid is infiltrated in the core of the optical fiber. When optical signal is applied in the core of the fiber, the speed of light varies with the refractive index of the material. In the present study, optical parameters like effective mode index (EMI), effective mode area (EMA), confinement loss (L_c), effective material loss (L_{mat}) and relativity sensitivity were calculated in the 1-2 THz range of the applied optical signal. The proposed optical sensor detects the variation in the refractive index of cancer infected cells i.e. skin cancer and blood cancer. The refractive index of these cancer cells is summarized in the table 5.2 given below

Table 5.2 Refractive indices of cancer cells responsible for skin cancer and blood cancer.

Sr. No.	Type of Cancer	Cell Name	Refractive Index (cancer infected cell)
1.	Skin Cancer	Basal	1.380
2.	Blood Cancer	Jurkat	1.390

The most important parameter of an optical fiber-based sensor is its analyte's relative sensitivity profile. The effective of an optical sensor is reflected by its relative sensitivity which given in the equation shown below:

$$Relative\ Senstivity = \frac{n_{analyte}}{n_{eff}} \times Pf \qquad (5.1)$$

where $n_{analyte}$ denotes the refractive index of the analyte infiltrated in the core, n_{eff} is the effective refractive index experienced by the fundamental mode, and Pf represents the power fraction which is represented in electric (E) and magnetic (H) field components as shown in the equation given below:

$$Pf = \frac{analyte \int Re(E_x H_y - E_y H_x) dxdy}{total \int Re(E_x H_y - E_y H_x) dxdy} \qquad (5.2)$$

where the numerator and denominator represent the amount of light propagating within the analyte region i.e. core of the fiber and the total optical fiber-based sensor respectively. In fig. 5.3, the variation of relative sensitivity (%) with applied optical signal's frequency is shown in the range 1-2 THz. The proposed PCF based sensor gave the highest sensitivity of 99.076% for Basal (skin cancer) and 98.519% for Jurkat (blood cancer) at 1.6 THz frequency optical signal.

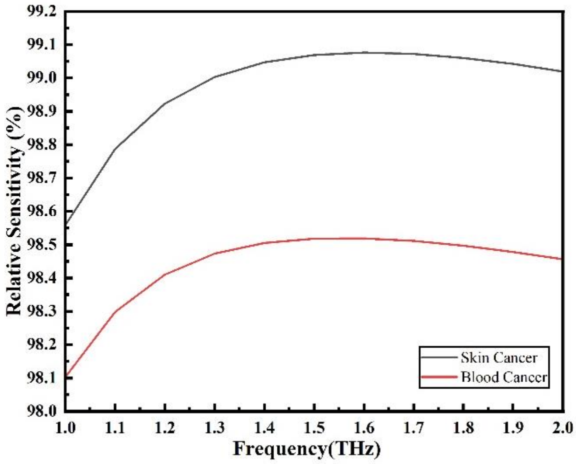


Fig. 5.3 Relative sensitivity vs. applied optical signal frequency (THz) for skin cancer and blood cancer.

Confinement loss (L_C) is defined as the amount of loss occurred due to the less optical confinement of input optical signal in the core of the optical fiber. This loss denotes the amount of light captured by the cladding region. While analyzing a PCF-based sensor for high sensitivity, care must be taken so that it offers very minimal loss. Mathematically, it is represented by the equation:

$$L_c = 8.868 \times K_o l_m(n_{eff}) \text{ dB/m} \tag{5.3}$$

Here, $I_m(n_{eff})$ denotes the imaginary part of the effective mode index, and $K_o = \frac{2\pi}{\lambda}$, where λ is the wavelength of the applied optical signal.

The effective material loss is defined as the significant amount of loss introduced due to the background material of the fiber. The effective material loss of the fiber is represented mathematically by the equation:

$$Lmat = \sqrt{\frac{\varepsilon_o}{\mu_o}}\left(\frac{\int_{mat} n_{zeonex}\, \alpha_{zeonex}\, |E|^2 dxdy}{|\int_{all} P_z dA|}\right) \tag{5.4}$$

where n_{zeonex} represents the refractive index of zeonex and α_{zeonex} represents the bulk absorption parameter of zeonex. The permeability and permittivity of free space is represented by the symbols μ_o and $\boldsymbol{\varepsilon_o}$ respectively.

The amount of area available for the propagation of input optical signal's fundamental mode is known as effective mode area (EMA). This area quantifies the area available for the analyte and mode interaction. The higher the EMA, the higher the interaction of input optical signal with analyte in the core region. It is represented by the equation:

$$EMA = \frac{\left(\iint |E|^2 dxdy\right)^2}{\iint |E|^4 dxdy} \tag{5.5}$$

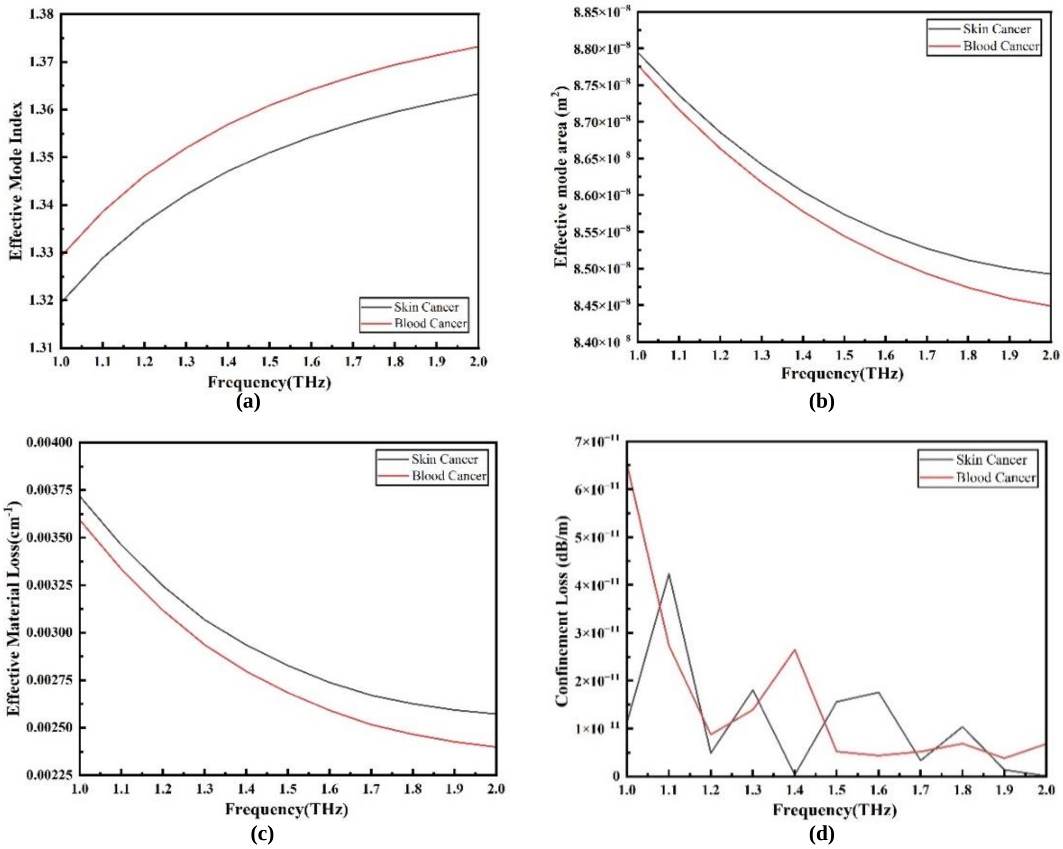


Fig.5.4 The variation of **(a)** effective refractive index, **(b)** effective mode area, **(c)** effective material loss and **(d)** confinement loss vs. applied optical frequency (THz) for skin cancer and blood cancer.

The effective refractive index experienced by the input optical signal in the optical fiber due to the core and cladding structure of the photonic crystal fiber is known as the effective mode index (EMI). We can create sensors that are highly sensitive to the small change in the background medium of the fiber by controlling its properties. EMI of any optical fiber is given by the equation as shown below:

$$EMI \ or \ n_{eff} = \frac{\beta}{k_o} \tag{5.6}$$

where $k_o = \frac{2\pi}{\lambda}$, where λ is the wavelength of the applied optical signal.

In figure 5.4 (a), The variation of effective mode index for the applied optical signal of frequency range 1-2 THz is shown. The trend shows that the EMI experienced by the fundamental mode in the core of the optical fiber increases as we increase the applied optical signal's frequency in terahertz regime. The skin cancer cells, and blood cancer cells resulted in an effective mode index of 1.3543 and 1.3642 at 1.6 THZ frequency optical signal respectively. Fig. 5.4 (b) shows the effective mode area of the skin and blood cancer with optical signal's frequency. The effective mode area decreases with frequency and attains the highest value of $8.7943\times10^{-8}m^2$ and $8.7771\times10^{-8}m^2$ for skin cancer and blood cancer respectively at 1 THz frequency optical signal.

Fig. 5.4 (c) shows the effective material loss of Basal (skin cancer) and Jurkat (blood cancer) with frequency. The trend shows that as we increase the frequency of the applied input signal, the effective material loss decreases significantly. At 1.6 THz frequency optical signal, the reported value of effective material loss for skin cancer cells i.e. Basal was 0.002738cm^{-1} and 0.002592cm^{-1} for blood cancer cells i.e. Jurkat. The graphical representation of confinement loss with input signal frequency in THz regime is shown in the fig. 5.4 (d). The confinement loss observed for the proposed PCF-based sensor at 1.6 THz for cancer cells is very low of order 10^{-12} dB/m.

Table 5.3 The obtained optical parameters for proposed biosensor at 1.6 THz frequency.

Analyte	Relative Sensitivity (%)	L_c (10^{-12}dB/m)	L_{mat} (cm^{-1})	EMA (10^{-8}m^2)	EMI
Basal	99.076%	1.7553	0.00274	8.5479	1.3543
Jurkat	98.519%	4.3484	0.00259	8.5160	1.3642

5.4 CONCLUSION

One of the most opposed and feared diseases at present is cancer. According to the World Health Organization, it ranks as the second most common cause of death. The only way to treat cancer is its early diagnosis and successful treatment. The prime objective of this study was to design a highly effective PCF-based biosensor for detecting skin and blood cancer and it resulted in a high sensing performance with standard results of other optical parameters. For the proposed sensor model, the applied frequency range is taken as 1-2 THz, and the relative sensitivity was reported as 99.076% for skin cancer and 98.519% for blood cancer. The optical parameters obtained i.e. EMA of order 10^{-8} m^2, L_c of order 10^{-12} dB/m and L_{mat} of order 0.00259 cm^{-1}, etc. were very significant. Besides, the suggested PCF based sensor for skin and blood cancer detection can be fabricated with existing fabrication mechanisms and can be used for early diagnosis of cancer in biosensing applications.

Chapter 6

Conclusion and Scope for Future Work

6.1. CONCLUSION

In summary, a rectangular-core PCF-based biosensor model is presented for its terahertz region sensing application. Various optical properties of the proposed sensor model have been investigated in the 1-2 THz range using zeonex as the background material. With FEM-based COMSOL Multiphysics software, PML boundary condition is used for all numerical computations. At 1.6 THz operating frequency of the optical signal, the suggested model of the proposed biosensor shows low values of confinement loss as 1.7553×10^{-12} dB/m for Basal (1.380) and 4.3484×10^{-12} dB/m for Jurkat (1.390), respectively, and high relative sensitivities of 99.076% and 98.519%. Additionally, the model's effective material loss turns out to be quite minimal, which elevates our suggested sensor model to the level of adept sensing. Due to its high sensitivity and design that can be manufactured using current fabrication processes, this suggested model has the potential to be extremely important for the early identification of cancer cells in the medical field. Furthermore, it is possible to fabricate the suggested PCF thanks to advancements with modern manufacturing processes.

6.2. SCOPE FOR FUTURE WORK

One of the most rapid and widely used innovations in sensor implementation nowadays is the use of photonic crystal fibers (PCF). Because of their special features and capacities resulting from their geometric design, PCFs are a perfect fit for sensing applications. An analytical tool known as a biosensor uses biological or chemical components to analyze a biological system. The solutions filled into PCF provide good results in the diagnosis of illnesses, cancers, antibodies, and hemoglobin levels. PCF type biosensors are extensively employed in clinical trials, drug development, biological research, and other fields. From the above discussion we can conclude that various PCF forms in biological sensors has been extensively studied and this can have huge potential at industrial level.

Photonic Crystal Fiber (PCF)-based sensors show great potential for the future of biosensing applications due to their excellent sensitivity, tunability, and adaptability. These sensors take advantage of PCFs' unique structural capabilities, such as their ability to confine light within narrow channels, resulting in highly sensitive detection of biological molecules and chemical compounds. As nanotechnology and material science improve, PCF-based sensors are predicted to achieve even higher levels of precision and usefulness. Innovative approaches such as functionalizing PCF surfaces with specialized bio recognition features or incorporating modern signal processing techniques should improve their ability to detect low-concentration analytes in complicated biological settings.

Additionally, PCF-based sensors have the ability to be miniaturized and integrated into portable diagnostic devices, which makes them essential parts of the development of personalized healthcare solutions, environmental monitoring, and next-generation medical diagnostics. PCF-based biosensing has a promising future since continued research is anticipated to find new uses and enhance current technologies, greatly expanding the field of biosensing.

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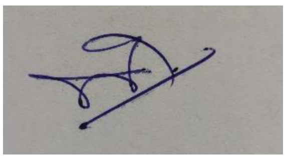
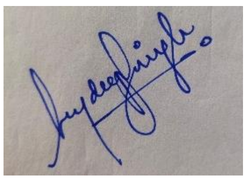

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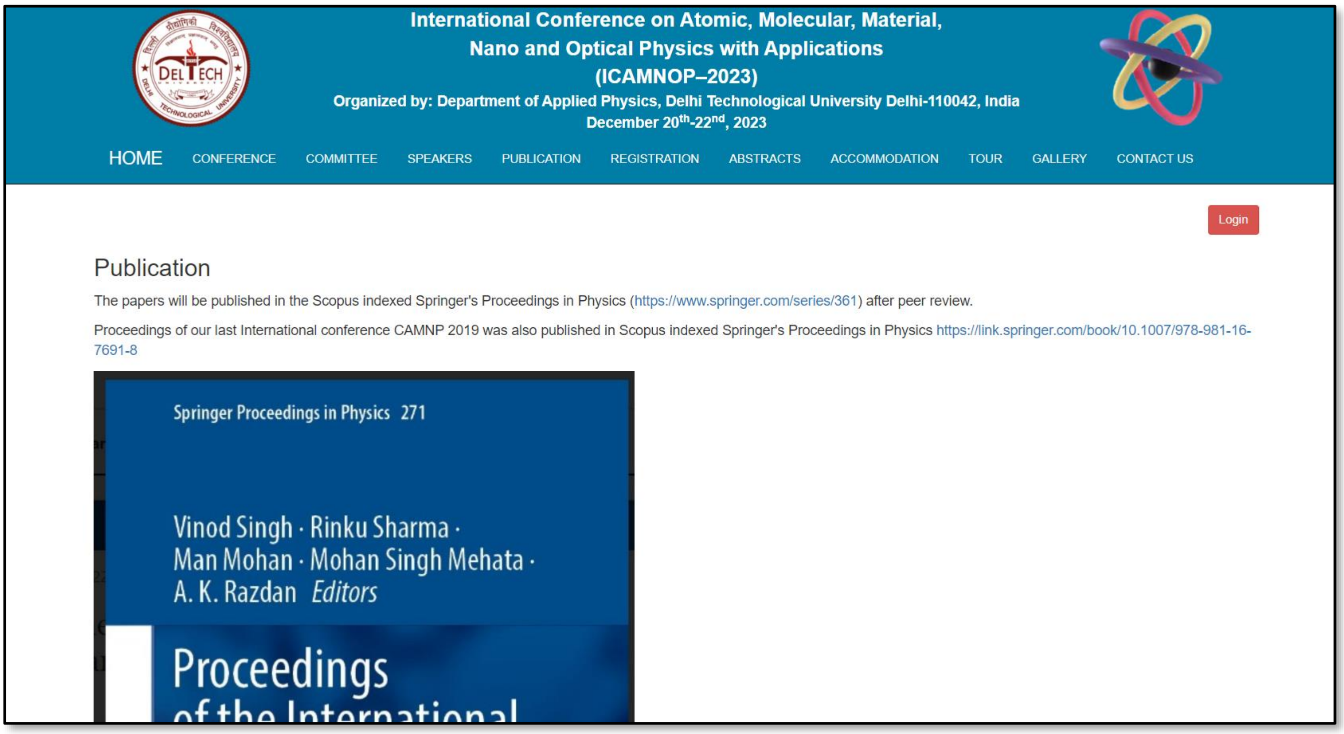

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