BACHELOR OF SCIENCE IN ELECTRONIC AND TELECOMMUNICATION ENGINEERING

Development of A Small-Scale Photonic Crystal Fiber (PCF) Sensor for Detecting Alcohol Substances

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Dedication

This thesis is dedicated to all of my respectable and honorable Teachers and Faculty's, supervisor who always directs towards a right track, my respected parents who always supported me in every situation, my beloved seniors who helped me whenever I needed them and all well-wishers and mentors who helped me to fulfill my ambitions.

Candidate Declaration

I, hereby firmly declaring that any part of the work submitted in this thesis is uttered not to have been done and presented elsewhere for the award of any degree and does not consist of any unethical and illegal declaration, instead the whole work is original and performed by myself as listed below.

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Approval

The thesis titled **"Development of A Small-Scale Photonic Crystal Fiber (PCF) Sensor for Detecting Alcohol Substances"**, submitted by **Mohammad Shahriar Rabbani Abir (T191005)** in the Spring 2023 session, to the Department of Electronics and Telecommunication Engineering, International Islamic University Chittagong, has been accepted as satisfactory in partial fulfillment of the requirements for the degree of Bachelor of Science in Electronic and Telecommunication Engineering and approved as to its style and contents on March, 2024.

Engr. Mohammed Jashim Uddin

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Acknowledgement

In the name of Allah (swt), the almighty and most superior, the most gracious and merciful. All praises go to Allah (swt) for His eternal blessings, graces, and guidance throughout our lives. May peace and blessings of Allah (swt) be on our beloved Prophet Muhammad (pbuh), who is our ever inspiration. Firstly, I would like to thank Allah (SWT) for granting us the ability and opportunity to complete our research. Secondly, I would like to show my sincere gratitude to the supervisor of my thesis, **Engr. Mohammed Jashim Uddin** for his excellency, invaluable guidance, and motivations towards the completion of our research. Moreover, I also express my indebtedness to **Md. Ibrahim Rupom**, Chairman of the Department of Electronic and Telecommunications Engineering, IIUC for providing us with the finest requirements of the department and giving us the best facilities and timely advice in the department. Also, I would like to thank **Engr. Mohammed Jashim Uddin**, Convener of our thesis for his diligence and sacrifices. Moreover, I am obliged to all our teachers for bestowing us with their wholehearted efforts in our whole academic life. I behold to our mates who assisted me in completing my research work. Most significantly, I couldn't have done all of this without my parent’s unconditional support and patience. My sincere thanks to my families, loved ones, and all the well-wishers who prayed for me.

Abstract

A variation of optical fiber, referred to as PCF, capitalizes on the advantageous attributes of photonic crystals. PCFs, distinguished by their distinctive optical features such as high sensitivity, minimal loss, and adaptability, have emerged as promising candidates for the development of highly efficient sensors for alcohol detection. Alcohol consumption is prevalent in our society, though not always openly acknowledged. Therefore, it is imperative to have precise and dependable methods for detecting alcohol, especially in the context of preventing drunk driving on highways. Presented here is a proposal for an optical sensor designed to detect alcohols for drunk driving on highways. This sensor is crafted with a cladding featuring circular air holes (CAH), forming a hexagonal in shape and a compact hexagonal core. The simulation and analysis of this PCF-based sensor's sensing capabilities are conducted using COMSOL Multiphysics software, employing specific elements for a technical solution. In the THz frequency band, the described PCF structure exhibits a notable relative sensitivity of 83.05%, 82.96%, 82.75%, and 82.64%. Concomitantly, the confinement losses (CLs) are measured at low values: 6.17×10^{-08} dB/m, 5.89×10^{-08} dB/m, 5.82×10^{-08} dB/m, and 6.38×10^{-08} dB/m for four types of alcohols - Methanol (n=1.326), Ethanol (n=1.354), Propanol (n=1.387), and Butanol (n=1.399) respectively observed at 1 THz. This content and analysis in the THz frequency range is based on Photonic crystal fiber (PCF). Also, the effective mode index is also determined in the frequency range of (0.5-3) THz. As it has good wave guiding characteristics, this suggested sensor has the potential to be employed in alcohol detection.

List of Symbols used in this research

Hertz	Hz
Hertz	Hz
Terahertz	THz
Gigahertz	GHz
Frequency	f
Angular frequency	ω
Wavelength	λ
Pi	π
Byte	B
Megabyte	MB
Gigabyte	GB
Second	s
Per second	ps or s-1
Megabyte per second	MBps
Gigabyte per second	GBps
Meter	m
Millimeter	mm
Centimeter	cm
Kilometer	km
Micrometer	µm
Nanometer	nm
Per meter	m-1
Meter per second	ms-1
Per centimeter	cm-1
Gram per centimeter cube	g/cm3
Decibel per meter	dB/m
Decibel per centimeter	dB/cm
Decibel per kilometer	dB/km
Watt	W
Kilo joule per meter	kJ/M
Per second per terahertz per centimeter Percentage	ps/THz/cm
Percentage	%
Major diameter of ellipse Minor diameter of ellipse	a
Minor diameter of ellipse	b
Elasticity	η
Pitch	Λ

▪ Speed of light	c
▪ Refractive index	n
▪ Effective refractive index	$neff$
▪ Bulk material absorption loss	αmat
▪ Effective material loss	αeff
▪ Poynting Vector	S
▪ Birefringence	B
▪ Imaginary	Im
▪ Real	Re
▪ Relative permittivity	ε
▪ Relative permeability	μ
▪ Electric field	E
▪ Magnetic field	H
▪ Confinement loss	LC
▪ Dispersion	$\beta 2$
▪ Normalized frequency	V
▪ Effective mode area	$Aeff$
▪ Nonlinearity	γ
▪ Kerr coefficient	$n2$
▪ Core power fraction	η'

List of Abbreviations used in this research

WDM	Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
LED	Light Emitting Diode
TIR	Total Internal Reflection
SMF	Single Mode Fiber
NHMFL	National High Magnetic Field Laboratory
TE	Transverse Electric
TM	Transverse Magnetic
MOF	Micro-structured Optical Fiber
PM	Polarization Maintaining
0D	Zero-Dimensional
1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
PCF	Photonic Crystal Fiber
MSF	Micro Steel Fiber
MCF	Multi-core Fiber
PGB	Photonic Bandgap
M-TIR	Modified Total Internal Reflection
COC	Cyclic Olefin Copolymers
TFE	Tetra-fluoro-Ethylene
PTFE	Polytetrafluoroethylene
MMA	Methyl Methacrylate
UV	Ultraviolet
EML	Effective Material Loss
CL	Confinement Loss
TL	Total Loss
PF	Power Fraction
FEM	Finite Element Method
PML	Perfectly Matched Layer
X-pol	X-polarization
Y-pol	Y-polarization
PS	Partially Slotted
FS	Fully Slotted
LFM	Localized-function Method
BPM	Beam Propagation Method

FDM	Frequency Division Multiplexing
FDTD	Finite-difference Time-domain
BEM	Boundary Element Method
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Conductor
PDE	Partial Differential Equation
ewfd	Electromagnetic Wave, Frequency Domain
AFF	Air Filling Fraction
ENZ	Epsilon-Near-Zero

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Chapter 01

Introduction

In recent years, the development of compact and highly sensitive sensors for chemical detection has garnered significant attention in both academic and industrial realms[1]. Among the plethora of sensing techniques, Photonic Crystal Fiber (PCF) sensors have emerged as a promising avenue, owing to their unique structural properties and capacity for precise control of light-matter interactions[2]. This research endeavors to contribute to this burgeoning field by focusing on the design and characterization of a compact-sized PCF sensor tailored for the detection of a range of alcohol substances, including Ethanol, Methanol, Propanol, and Butanol[3]. Alcohol detection holds paramount importance across various domains, encompassing breath analysis for forensic applications, industrial safety measures, and healthcare diagnostics[4]. The accurate and swift identification of alcohol concentrations in diverse environments necessitates sensors that can provide reliable measurements, often in confined spaces or under real-time conditions[5]. The utilization of PCF as the sensing platform offers distinctive advantages, including its high surface area-to-volume ratio, low propagation loss, and the capability to exploit various modalities for transduction[6]. In this investigation, we delve into the intricacies of PCF sensor design, emphasizing the crucial role played by the refractive indices of target alcohol substances. Ethanol, Methanol, Propanol, and Butanol exhibit distinct optical signatures due to disparities in their refractive indices[7]. This thesis is structured as follows:

Chapter 1 provides the introduction to Photonic Crystal Fiber (PCF) briefly and the background of this technology in the field of detection or sensing.

Chapter 2 provides an extensive review of the pertinent literature, encompassing PCF sensor technology, principles of alcohol detection, and the optical properties of the aforementioned alcohols.

Chapter 3 delineates the methodology employed in the design, fabrication, and characterization of the compact-sized PCF sensor.

Chapter 4 presents the experimental results and discusses the implications of the findings.

Chapter 5 summarizes the contributions of this research and outlines avenues for future exploration in this domain. Through the amalgamation of advanced photonics, material science, and sensor technology, this work endeavors to pave the way for a new paradigm in compact-sized with a highly sensitive alcohol sensors with potential applications.

1.1 Background of the research

1.1.1 Optical Fiber

Optical fiber is a technology that enables the transmission of information in the form of light pulses through thin, flexible strands of glass or plastic fibers[8]. These fibers act as a waveguide to guide light along a specific path, allowing for high-speed data transmission over long distances with minimal signal loss[9].

1.1.2 Structure of Optical Fiber

Core: The core is the central part of the optical fiber where light travels. It is made of high-quality glass or plastic with a high refractive index to facilitate internal reflection.

Cladding: Surrounding the core is the cladding, which is a layer of material with a lower refractive index than the core. The cladding helps to confine the light within the core through total internal reflection.

Buffer Coating: A protective layer, called the buffer coating, surrounds the cladding. It provides mechanical protection and insulation for the fiber.

1.1.3 Working Principle of Optical Fiber

Total Internal Reflection: When light enters the core of the optical fiber, it undergoes total internal reflection at the core-cladding interface. This phenomenon allows the light to bounce within the core, preventing significant loss of signal strength.

Principle of Least Time: Light follows the path of least time between two points. In the case of optical fibers, this principle ensures that light takes the most direct route through the core, even if the fiber is bent.

1.1.4 Types of Optical Fiber

Single-Mode Fiber (SMF): Designed for the transmission of a single mode (a single beam of light). It is suitable for long-distance communication and high-bandwidth applications.

Multi-Mode Fiber (MMF): Designed to transmit multiple modes (multiple beams of light) simultaneously. MMF is commonly used for shorter-distance communication.

1.1.5 Optical Fibers based on Refractive Index

Optical fibers are communication channels that use light to transmit data. They are composed of a core material surrounded by a cladding material. The refractive index plays a crucial role in the operation of optical fibers. Here's how it works[10].

Core Material: The core of an optical fiber is typically made of glass or plastic. Also, the core has a higher refractive index compared to the cladding, which allows for the phenomenon of total internal reflection to occur.

Cladding Material: The cladding surrounds the core and has a lower refractive index than the core. This refractive index contrast is essential for guiding light within the core through the total internal reflection process.

Light Propagation: Due to total internal reflection, light can travel long distances within the core of the optical fiber without significant loss. This property is crucial for efficient data transmission over large distances.

Modes of Propagation: Depending on the design of the optical fiber, it can support one or more modes of light propagation. Multimode fibers allow multiple paths for light to travel, while single-mode fibers support only one mode of propagation.

Dispersion: The refractive index profile of an optical fiber affects the dispersion characteristics. Dispersion is the spreading of light pulses as they travel through the fiber. Proper design of the refractive index profile helps minimize dispersion and ensures accurate transmission of data[11].

1.1.6 Advantages of Optical Fiber

Optical fibers offer several advantages compared to traditional communication mediums like copper cables. Here are some key advantages of optical fibers:

High Bandwidth: Optical fibers have a much higher bandwidth compared to traditional copper cables. This allows them to transmit large amounts of data over longer distances without signal degradation.

Low Signal Attenuation: Optical fibers experience much lower signal loss (attenuation) over long distances compared to copper cables. This enables the transmission of signals over much greater distances without the need for signal repeaters.

Lightweight and Thin: Optical fibers are thin and lightweight, making them easier to install and handle. They are also more flexible, allowing for easier installation in various environments.

Low Latency: Optical fibers transmit signals at speeds that approach the speed of light, resulting in low latency. This is crucial for applications that require real-time data transmission, such as video conferencing and online gaming.

Long Transmission Distances: Optical fibers can transmit signals over much longer distances without the need for signal repeaters, which is especially important for long-haul communication networks[12].

1.1.7 Light propagation in optical fibers

Light propagation in optical fibers is based on the principles of optics, particularly the phenomenon of total internal reflection. Optical fibers use the interaction between materials with different refractive indices to guide and transmit light signals efficiently[13]. Explanation of light propagation in an optical fiber is given below:

Incident Light: Light signals, typically in the form of laser light or light-emitting diodes (LEDs), are launched into one end of the optical fiber. These light signals consist of photons that travel through the core of the fiber[14].

Core and Cladding: The optical fiber consists of two main parts: the core and the cladding. The core is the central region through which light propagates, and the cladding surrounds the core. The refractive index of the core is higher than that of the cladding.

Modes of Propagation: Depending on the design of the optical fiber, it may support one or more modes of propagation. Multimode fibers allow multiple light paths, while single-mode fibers support only one mode. Single-mode fibers, with a smaller core, are often used for long-distance communication as they minimize dispersion.

1.1.8 Wave propagation in optical fibers

Wave propagation in optical fibers involves the transmission of light waves through the core of the fiber. The behavior of these waves is influenced by the principles of wave optics[15]. Here is a more detailed explanation:

Light as an Electromagnetic Wave: Light is an electromagnetic wave, and when it travels through an optical fiber, it exhibits wave-like characteristics. These waves are characterized by their wavelength (λ) and frequency (f).

Index of Refraction: The core of an optical fiber has a higher refractive index compared to the cladding. The refractive index (n) is a measure of how much the speed of light is reduced in a medium compared to its speed in a vacuum. The relationship between the refractive indices of the core (n_core) and cladding (n_clad) is crucial for guiding light within the fiber.

Propagation Modes: Depending on the design of the optical fiber, it may support different modes of wave propagation. Multimode fibers allow multiple modes, which are different paths that light can take through the core[16].

Waveguide Dispersion: In the context of optical fibers, the term "dispersion" refers to the spreading of different wavelengths or modes of light as they propagate through the fiber. Waveguide dispersion occurs due to the different speeds at which various wavelengths travel through the core.

1.1.9 Losses in optical fibers

Losses in optical fibers refer to the reduction in the strength or power of an optical signal as it travels through the fiber[17]. Several factors contribute to these losses, and minimizing them is crucial for efficient and reliable fiber optic communication. Here are the main types of losses in optical fibers:

Absorption Loss: Absorption loss is a significant type of loss in optical fiber that occurs when light is absorbed by the material of the fiber, which can be caused by impurities in the fiber or by the natural absorption of the material itself.

Scattering Loss: The nonlinear scattering effects in optical fibers are due to the inelastic scattering of a photon to a lower energy photon. The energy difference is absorbed by the molecular vibrations or phonons in the medium.

Bend Loss (Macro bending and Microlending): Bend losses are a frequently encountered problem in the context of waveguides, and in particular in fiber optics, since fibers can be easily bent. Bend losses mean that optical fibers exhibit additional propagation losses by coupling light from core modes (guided modes) to cladding modes when they are bent.

1.2 Photonic Crystal Fiber (PCF)

Photonic crystal fiber (PCF) is a specialized type of optical fiber that incorporates a periodic arrangement of microscopic and usually air holes running along the length of the fiber. This unique structure gives PCF distinct optical properties compared to conventional optical fibers. Here's a brief overview of the background and relation of photonic crystal fiber to optical fiber[18]. It is a type of optical fiber that uses a periodic arrangement of microscopic, high-index glass or dielectric materials to manipulate light in a unique way. Unlike conventional optical fibers, which typically have a homogeneous core and cladding, PCFs have a structured pattern of air holes or channels running along the length of the fiber[19].

1.2.1 Background of PCF

Origin: Photonic crystal fibers were first proposed in the late 1990s. The concept draws inspiration from the photonic bandgap materials used in the field of optics. The idea was to create a fiber with a periodic microstructure that could control the propagation of light in novel ways.

Microstructure: The key feature of PCF is its periodic microstructure, typically formed by introducing air holes into the core and/or cladding region of the fiber. The arrangement of these holes creates a photonic bandgap, allowing for control over the guiding properties of the fiber.

Design Flexibility: One of the significant advantages of PCF is the flexibility in designing its properties by adjusting the size, shape, and arrangement of the air holes. This design flexibility enables tailoring of various optical characteristics, such as dispersion, nonlinearity, and birefringence, to meet specific application requirements.

1.2.2 How PCF is related to Optical Fiber

Guiding Mechanism: Like conventional optical fibers, PCF guides light through total internal reflection. However, the guiding mechanism in PCF is not solely reliant on the refractive index contrast between the core and cladding. The periodic microstructure introduces additional mechanisms for light guidance, allowing for unique and customizable optical properties[20].

Enhanced Performance: PCF can provide enhanced performance in terms of bandwidth, dispersion control, and nonlinear effects. For example, it can enable the generation of broad spectra in supercontinuum sources, which find applications in areas such as spectroscopy and telecommunications[21].

1.2.3 Types of Photonic Crystal Fibers (PCF)

Photonic Crystal Fiber (PCF) is a specialized type of optical fiber with a unique structure that allows for control over its optical properties. Here's a brief overview of some common types:

Solid-Core PCF: This type of PCF has a solid glass core surrounded by air-filled holes that form a periodic pattern. It allows for low-loss transmission and is commonly used in applications requiring single-mode propagation.

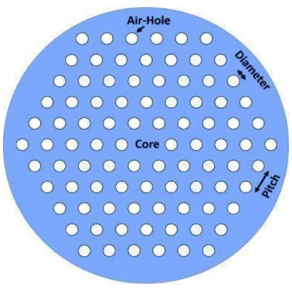


fig. (1.1): Structure of a Solid-core pcf sensor[22].

Photonic Bandgap PCF: Photonic bandgap fibers are designed to have a bandgap structure, creating a range of wavelengths where light cannot propagate. They are useful for applications such as supercontinuum generation and dispersion management. Figures of Various types of hollow-core photonic bandgap fibers are given below. in fig. (1.2). Which are: (a) Photonic crystal fiber featuring a small hollow core surrounded by a periodic array of large air holes. (b) Micro structured fiber featuring medium-sized hollow cores surrounded by several rings of small air holes separated by nano-size bridges. (c) Bragg fiber featuring large hollow core surrounded by a periodic sequence of high and low refractive index layers

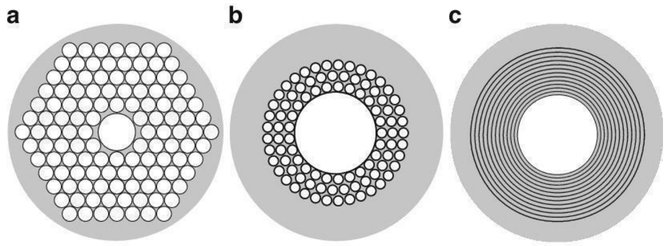


fig. (1.2): Various types of hollow-core photonic bandgap fibers[23].

Micro structured Optical Fibers (MOFs):

MOFs encompass a broad category of PCFs with various designs, including solid-core, holey-core, and multicore structures. They are known for their flexibility in tailoring optical properties and are used in diverse applications, including sensing and telecommunications[24].

Holey Fiber: Holey fibers have a periodic pattern of air holes running along the length of the fiber. This design allows for control over dispersion and nonlinear effects. Holey fibers find applications in high-power laser delivery and sensing.

Liquid-Core PCF: Liquid-core PCFs use a core filled with liquid or gas instead of a solid material. They are suitable for applications where interactions with the material inside the core are important, such as in chemical and biological sensing.

Dual-Core PCF: Dual-core PCFs consist of two separate cores within the same fiber, allowing for unique interactions between the cores. These fibers are used in applications like interferometric sensing and quantum optics. An example of a dual core pcf in fig. (1.3) is given below:

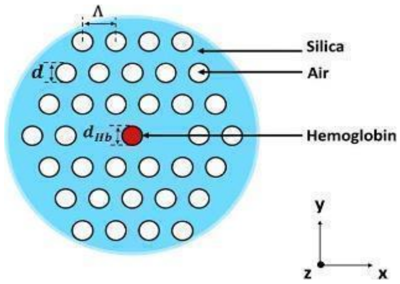


fig. (1.3): Structure of a dual-core pcf sensor[24]

Air-Core PCF: Air-core PCFs have a core region composed of air, surrounded by a periodic arrangement of glass or other materials. They are known for low-loss transmission and are employed in various applications, including sensing and telecommunications. The versatility of PCFs lies in their ability to be tailored for specific applications by adjusting parameters such as core size, hole size, and periodicity[25].

1.2.4 Advantages of photonic crystal fibers (PCF)

Photonic Crystal Fiber (PCF) based sensors offer several advantages compared to traditional sensors. Which makes photonic crystal fiber (PCF) more useful to implement in real field of sensors and detection. Here are some key advantages:

High Sensitivity: PCFs can be designed to have high sensitivity to changes in the surrounding environment, such as variations in refractive index. This makes them effective for sensing applications.

Compact Size: PCFs can be designed with small dimensions, making them compact and suitable for applications where space is limited.

Low Losses: PCFs can exhibit lower propagation losses compared to traditional optical fibers, allowing for the efficient transmission of light and improving overall sensor performance.

Temperature Sensitivity Control: The sensitivity of PCFs to temperature changes can be controlled, and the temperature dependence can be utilized or minimized depending on the application.

High Birefringence: Some PCFs can exhibit high birefringence, allowing for polarization-dependent sensing mechanisms and additional degrees of freedom in sensor design.

Multiparameter Sensing: PCFs can be designed to enable multiparameter sensing by simultaneously detecting different physical or chemical parameters, enhancing the information obtained from a single sensor.

Wavelength Flexibility: PCFs can operate over a broad range of wavelengths, providing flexibility in the choice of the detection wavelength for specific applications.

1.2.5 Disadvantages of photonic crystal fibers (PCF)

PCFs with extremely small core sizes may have limitations in term of the amount of light they can guide, impacting their sensitivity and overall performance.

Temperature Sensitivity: The properties of PCFs can be sensitive to temperature variations, which may require additional measures for temperature compensation in sensing applications.

Specialized Expertise: Designing and optimizing PCF-based sensors often require specialized knowledge in photonics and optical design, limiting the accessibility of these sensors to a broader user base. It's essential to carefully consider these disadvantages in the context of specific application requirements when choosing between PCF-based sensors and other sensing technologies.

1.2.6 Performance parameters of PCF

Effective Refractive index: A number that compares the phase delay in a waveguide per unit length to the phase delayed in vacuum.

Birefringence: Birefringence is defined as the difference between workable refractive indices of the two polarization modes x and y in fiber. The term of birefringence is given below:

$$B = |R\ (neff\ x) - Re\ (neff\ y)\ | \tag{01}$$

where, B is called birefringence, Re (n x eff) and Re (n y eff) are the genuine parts of the effective refractive index of the primary modes of x and y polarization.

Effective Material Loss: The dielectric characteristics of the material produce effective material loss (EML), which is a major factor affecting the useful application of THz waveguides. Which is defined by the given formula:

$$\text{Area} = \frac{[\int I(e)ede]2}{[\int I2(e)de]2} \tag{02}$$

Confinement Loss (CL): Another loss source in THz waveguides is confinement loss, which describes the PCF's capacity to confine light to the core. The confinement loss of the proposed PCF which is defined by the given formula:

$$Lc = \frac{4\pi f}{\lambda c \times Im[\eta eff]}\ dB/m \tag{03}$$

Where, Lc is Confinement Loss. Im$[\eta eff]$ is imaginary part of effective refractive index[26].

Relative Sensitivity (RS): Relative Sensitivity (RS) of a photonic crystal sensor is crucial to check the sensitivity of the sensor. The RS of PCF is determined by the given formula:

$$R = \left(\frac{nr}{n\,eff}\right) E \tag{04}$$

1.2.7 Various applications of PCF

Temperature Sensing: PCF sensors can be designed to be sensitive to temperature changes. The interactions between light and the PCF structure can be influenced by temperature, making them suitable for temperature sensing applications[27].

Gas Sensing: PCF sensors can be configured to detect specific gasses by filling the air holes with gas-sensitive materials. The interaction between light and the gas within the PCF can be measured, providing a basis for gas sensing applications[28].

Biomedical Sensing: PCF sensors can be utilized in biomedical applications, such as detecting changes in refractive index for label-free biosensing. The high surface area of PCF can enhance interactions with biological substances[29].

Pressure Sensing: The structure of PCF can be designed to respond to pressure changes. PCF sensors can thus be employed for pressure sensing in various environments[30].

Fiber Optic Gyroscopes: PCF sensors can be integrated into fiber optic gyroscopes for precise measurement of rotation. The PCF structure can influence the propagation of light in a way that is sensitive to rotation[31].

Communication Systems: PCF can be used in telecommunications for signal propagation and manipulation due to its unique optical properties. This includes applications in data transmission and signal processing[32].

Light Sources: PCF can be used to generate supercontinuum light sources that span a broad range of wavelengths. These sources find applications in fields such as spectroscopy and imaging. It's important to note that the field of photonic crystal fibers and their applications is dynamic, and ongoing research and development may lead to new applications and implementations[33].

1.3 Objectives of this study

— To design a compact sized PCF sensor to detect various alcohols like (Methanol, Ethanol, Propanol and Butanol).

— To verify the sensor performance and draw conclusions from the analysis of data.

1.4 Motivation of the research

The main purpose of the alcohol detection with PCF sensor is to detect drunk driving and prevent accidents on highways[34]. Unfortunately, so many accidents are occurring due to alcohol consumption nowadays. Only because of the driver or the person who is driving the vehicle after consuming alcohol. These PCF sensors are basically designed to detect alcohol substances in terahertz regime. The basic four substances of alcohol that we've considered for our sensor investigation are Methanol, Ethanol, Propanol and Butanol.

As we have studied the existing works, sensor size hasn’t been much compact in previous designs. We tried to make the pitch and hole diameter smaller. Also, the detection method could be more accurate with less confinement loss to detect the alcohols like ethanol, methanol, propanol and butanol. So, we tried to design a compact sized sensor with lower pitch and hole size, which will be able to detect the presence of alcohols with lower confinement loss and more relative sensitivity.

Chapter 02

Literature review

2.1 Paper Review

Paper no: 01

Title: ***ZEONEX based hollow core rectangular core photonic crystal fiber (pcf) sensor design and numerical investigation for alcohol detection of variant classes.***

Journal: Optical and Quantum Electronics

Published: 5 September, 2023

Author: Rayhan Habib Jibon, Amin Khodeai, P. Poorna Priya, Ahmed Nabih Zaki Rashed, Md Amzad Hossain.

Results and summary: In this paper, they designed a ZEONEX based rectangular core pcf sensor. The finite element method based commercial software is utilized for numerical analysis. Four variant classes of alcohols namely Methanol, Ethanol, Propanol, Butanol are considered in this investigation. These analytes are injected into the rectangular core and the investigation is accomplished in the 1-2 THz regimes. The investigated results exhibit comparatively higher sensitivities of 83.21% for Ethanol than the other alcohol variants. Besides, almost low confinement losses are found for all analytes just after 1.3THz frequency. Generally, within any chemical solution, water and alcohol are considered as vital agile stuff. Various chemical or biological solutions contain an enormous amount of soluble alcohol as an effective ingredient. The uses of alcohol are extended to various application fields like cosmetics, cleaning products, pharmaceuticals, fuels, beverages, etc. Besides, various biomedical solutions are contaminated with alcohol. Again, variant classes of alcohol are mixed with drinkable liquids. Drinking too much alcohol is deleterious to our health. For alcoholic beverages, the existing amount and categories of variant alcohols that are present with mixed water, need to be detected in a decisive and impeccable manner[35].

Paper no: 02

Title: ***Terahertz detection of alcohol using a photonic crystal fiber sensor.***

Journal: Applied optics

Published: March 23,2018

Author: Jakeya Sultana,Md Saiful Islam,Kawser Ahmed, Alex Dinovitser,Brian W.-H. Ng,Derek Abbott

Results and summary: In this paper, they detect a novel zeonex based pcf has been modeled and analyzed alcohol detection in terahertz regime. A finite element method-based simulation of the pcf sensor shows a high relative sensitivity of 68.87% with negligible CL of 7.79×$^{10\wedge-12}$ cm^-1 at 1THz frequency and x polarization mode. With wave guiding properties the proposed sensor can potentially be used in Ethanol detection as well as polarization preserving applications of terahertz waves. Photonic crystal fiber (PCF)-based sensors are significant because of their high relative sensitivity, small size, flexibility, and robustness. In a PCF, characteristics such as relative sensitivity, core power fraction, effective material loss (EML), birefringence, dispersion, etc. can be engineered by optimizing the shape and position of air holes, core diameter, diameter of the air holes used in both the core and cladding, and the pitch (distance between two consecutive air holes), which is difficult to achieve using conventional optical fiber. Moreover, PCF is robust to environmental conditions such as strong electromagnetic fields, noise, high voltages, chemically corrosive environments, and high temperatures. The existence of air holes in both the core and cladding of a PCF allows guided transmission of light through them and provides the ability to insert analytes (gasses, chemicals, etc.) into the air holes, facilitating confined interaction of light with the sample, leading to new sensing applications. They focus this study on ethanol, being a common form of alcohol used in both industrial processes and in the beverage industry. There are several methods to quantify the amount of alcohol in beverages that include physical (densitometry, pycnometry, and hydrometry), chemical (dichromate oxidation), spectrometric, and chromatographic analyseIn[36].

Paper no: 03

Title: ***Performance analysis of alcohol sensing with optical sensor procedure using circular photonic crystal fiber in terahertz regime.***

Journal: Sensing and biosensing research

Published: 2022

Author: Md Selim Hossain,Nazmul Hussain,Zakir Hossain, Md Sakib Jaman, Md Navid Hasan Rangon, Md Abdullah Al Shafi, Shuvo Sen, Mir Mohammad Azad.

Result and summary: A TOPAS-based optical sensor for detecting alcohols in drinks and liquids, made of circular air holes (CAH) in the cladding and a hexahedron core is suggested here. In addition, COMSOL Multiphysics program for development and analysis of the sensing qualities of a PCF-based sensor using finite element technique as a solution. In the THz frequency band, the described C-PCF structure has an exceptionally high relative sensitivity of 86.60%, 88.70%, and 84.71% for three alcohols such as Ethanol (n = 1.354), Butanol (n = 1.399), and Propanol (n = 1.387), respectively at a monitoring region of 1 THz. Humans are extremely vulnerable to the effects of alcoholic agents. Given the amount of danger, an effective and adaptable alcohol detection technology is critical. In this context, a hollow core photonic crystal fiber (HC-PCF)-based optical sensor with circular air holes in the cladding section and a hexahedron core is proposed for detecting alcohol in drinks as well as other liquid samples. COMSOL Multiphysics software with a finite element technique as a solver is used to develop and analyze the sensing properties of a PCF-based sensor. In the THz frequency band, the described PCF structure has exceptionally high sensitivity and low confinement losses for Ethanol, Butanol and Propanol, respectively at a monitoring region of 1 THz. So, we know that alcohol is widely utilized in both chemical industrial processes and the food and beverage industries. As a result, we can say clearly that the alcohols detection system-based C-PCF in the terahertz frequency range will be perfect for alcohols detection successfully[37].

Paper no: 04

Title: ***Dual polarized PCF-SPR for alcohol detection at low temperature.***

Journal: Journal Penelitian Pendidikan IPA (JPPIPA) Indonesia.

Published: March 5, 2022

Author: Azhar Azhar,Khaikal Ramadhan,Dedi Irawan

Results and summary: They've used a simple geometrical structure of the sensor by using fused silica and gold as the sensor’s core and plasmonic material. Observations were made in the alcohol concentration range of 15%,40%,60%, & 70%. In the literature, we find the refractive index of each alcohol concentration and input its value into the proposed sensor. The proposed sensor shows that the sensor has a sensitivity in detecting alcohol concentrations at low temp. of 91 nm/%. In detecting alcohol concentration, they have proposed a PCF-SPR sensor with a simple geometric structure to be used as a sensing component. In this work, they have investigated the performance of a dual-polarized PCF-SPR sensor in detecting alcohol concentration in numerical simulation using the finite element method. They found that the proposed sensor can detect changes in concentration in a mixture of water and alcohol with a sensitivity. They observed two techniques, namely the wavelength technique (WS) and the amplitude sensitivity technique(AS)[38].

Paper no: 05

Title: ***Efficient way for detection of alcohols using hollow core photonic crystal fiber sensor.***

Journal: The Optical Society of Japan

Published: 2022

Author: Md Ahasan Habib, Md Shamim Anower, Ahmed Alhamdi, Osama S Faragallah, Mahmoud M A Eid, Ahmed Nabih Zaki Rashed.

Results and summary: A simple hollow core hexagonal structured photonic crystal fiber is offered and they analyze different types of alcohol in daily life. The proposed sensor guiding properties are numerically investigated using a full vectorial finite element software-based scheme. Also ensures high accuracy, the properties of alcohols at different wavelengths are used to calculate the behavior of the sensor. Simulation results ensure that extremely high relative sensitivity around 89% can be achieved from the sensor at optimum structural condition. Day by day, the use of alcohol is increasing extensively in our daily life. To ensure better consumption and protection, the identification between different alcohols are important. This paper proposes a simple hollow core photonic crystal fiber that can detect and differentiate various alcohols. The exact wavelength-dependent refractive index and temperature-dependent relative permeability and permittivity are used to create a realistic alcoholic environment to increase the simulation accuracy. As a result, the sensor offers an extremely higher relative sensitivity of 87% and negligible CL of 10 –10 dB/m at a fixed geometric structure. In addition, other important properties of any PCF based sensor are investigated and analyzed in detail in this manuscript. Furthermore, the geometry of the reported sensor is very easy to understand, so that it might be produced without any complexity using ongoing fabrication technology. So, this sensor may create a huge impact in the field of alcohol detection[39].

Paper no: 06

Title: ***Design of Quasi-Shaped spectroscopy based optical sensor for the detection of alcohol***.

Journal: Sensing and Bio-Sensing Research, Volume 41,

Published: August 2023, 100572.

Author: Md Selim Hossain, Rakib Hosen,Md Abdul Ala Walid, Syada Tasmia Alvi, Md Al Amin, Shuvo sen, Mir Mohammad Azad.

Results and summary : In this research, an entirely novel optical sensor for alcohol detection based on quasi-shaped spectroscopy is offered. A quasi shape with a tightly bonded structure in the cladding region and a hexahedron core region makes up the recommended design, which has a remarkable sensitivity of about 91.35%, 92.55%, and 90.40%and low confinement losses (CLs) of 5.44×10^{-08} dB/m, 6.75×10^{-08} dB/m, and 5.85×10^{-08} dB/m for detecting alcohol like ethanol (n = 1.354), butanol (n = 1.3993), and propanol (n = 1.384), at 1 THz. The numerical aperture, the effective area, and the V-parameter have all been identified and assessed. The 0.8THz to 3 THz operational wavelength range is stated. In the COMSOL Multiphysics (Version 5.6) environment, the properties of these suggested alcohol sensors are numerically examined utilizing the FEM (finite element method) with full vectors. In contrast to other efforts, the proposed sensor, which consists of a quasi-lattice PCF with a perfectly matched layer (PML) of a circular air hole shape and TOPAS as the background material, aims to improve sensitivity response. The proposed sensor might be crucial in the alcohol detection process due to its superior sensitivity response, a single mode of operation across the entire operational terahertz range, and shallow confinement loss. So, this PCF can proficiently be pragmatic in many biological sensing and other THz technology domains. Their idea involves employing fibers with hexahedron cores and

Quasi shape cladding for alcohol and sensory monitoring. Here, they designed this fiber using the perfectly matched layer (PML) as well as COMSOL software that is based on the finite element approach to get all the numerical sensitivity and low confinement losses (CLs) for detecting alcohols like ethanol, butanol, and propanol at 1 THz. The suggested sensor is believed to have an enhanced geometrical structure that is production friendly, enabling it to be used in practical settings like industry and biological medicine[40].

Paper no: 07

Title: ***Alcohol sensing and classification using PCF-based sensors.***

Journal: Sensing and Bio-Sensing Research, Volume 30.

Published: December 2020, 100384.

Author: Faysal Iqbal, Sandipa Biswas, Abdullah Al Mamun Bulbul, Hasibur Rahaman, Md Belal Hossain, Md Ekhlasur Rahaman, Md Abdul Awal.

Results and summary : This paper focuses on designing a Photonic Crystal Fiber (PCF) based sensor model. The anticipated sensor is modeled and simulated using COMSOL Multiphysics to carry-out experiments on multiple optical parameters that evaluate the efficiency of this model. This model aims to detect alcohol and classify it. Three variants of alcohol, namely methanol, ethanol, and propanol, have been considered in this study. These analytes are then injected into the core-region separately. The model is then simulated between 1.0 THz and 2.5 THz frequency band to evaluate the optical properties. Simulation results demonstrate higher relative sensitivity of approximately 88%, 91%, and 92% at 2.0 THz for methanol, ethanol, and propanol, respectively. Besides, the confinement loss for this model approaches nearly zero immediately after 1.2 THz. Furthermore, a shallow effective material loss (EML) is found for this sensor model to sense these three types of alcohol. For instance, the EML value is only 0.0056 cm^{-1} in the case of methanol sensing. Finally, different optical parameters presented in this study demonstrate the effectiveness of the proposed model in sensing various alcohols. The proposed hexagonal photonic crystal fiber sensor model for sensing and classifying alcohol using the optical properties provides enough flexibility in the optical parameters and shows a high sensing performance. The values of the optical parameters for the proposed sensor are shown. They proposed this hexagonal PCF sensor model for sensing and classifying alcohol because of providing a greater sensing performance for liquid and chemical sensing. The proposed model with this effective optical parameter is better than any other existing model, and this can prove itself. In this PCF sensor model, the operating frequency is 2 THz, and the corresponding optical parameters for alcohol sensing and classifying are 89.29% and 89.51% for methanol, 91.30% and 91.50% for ethanol, 92.32% and 92.52% for propanol, 90.03% and 90.30% for water in x and y-axis respectively. CLs are 0 for methanol, 1.515×10^{-14} for ethanol, 5.935×10^{-15} for propanol, and 1.07×10^{-14} cm^{-1} for water. EMLs are 0.005639 for methanol, 0.006486 for ethanol, 0.006977 for propanol and 0.005936 cm^{-1} for water. The EAs are 209,930 for methanol, 224,630 for ethanol 230,660 for propanol, and 215630μm^2 for water. The values of birefringence are 0.001 for methanol, 0.0009 for ethanol, 0.0008 for propanol, and 0.0019 for water[41].

Paper no: 08

Title: ***Design of a Terahertz Alcohol Sensor Using a Steering-Wheel Micro structured Photonic Crystal Fiber.***

Journal: IETE Journal of Research

Published:25 Aug 2020.

Author: S. Nivedha, k. Senthilnathan.

Volume 69,2023-Issue-1.

Results and summary: In this paper they designed a novel photonic crystal fiber (PCF) chemical sensor wherein the cladding structure is made of a steering-wheel (SW)-shaped large non-circular air-hole. In this PCF, they introduce the rectangular air holes in the core and they are filled with any one of the analytes, namely, water, ethanol and benzene. They use the full-vectorial finite element method (FEM) to optimize the structural parameters. Based on the numerical results, the proposed sensor exhibits a high relative sensitivity of 92.8%, 93.2% and 93.4% for water, ethanol and benzene, respectively, at THz. Furthermore, they study the various optical characteristics of the proposed PCF, namely, birefringence, effective area and numerical aperture (NA). They have introduced four large non-circular air holes in the cladding region and rectangular air holes in the core region to design a novel steering wheel microstructure fiber chemical sensor at THz frequency. Based on the numerical results, it has been found that the proposed sensor exhibits a maximum relative sensitivity of water, ethanol and benzene respectively at 2.1 THz in the y-polarization direction. By considering the practical realization of the proposed sensor, we have carried out the perturbation analysis of the geometrical parameters and it has been found that the proposed sensor is a robust one against geometrical variations. Thus, the proposed sensor would be highly suitable for the detection of alcohol content in medical and food industries. Also, the proposed fiber exhibits a negligible confinement loss, high birefringence, a high effective mode area and a large numerical aperture. At this juncture, it should be emphasized that one could design various photonic devices by exploiting the above-mentioned optical properties of the proposed fiber. The proposed fiber may also be useful for polarization preserving applications as the birefringence turns maximum. To the best of our knowledge, they believe that the proposed fiber may easily be fabricated with the existing fabrication techniques of drilling and 3D printing[42].

Paper no: 09

Title: ***Performance analysis of octagonal photonic crystal fiber (O-PCF) for various communication applications.***

Journal: Physica Scripta,Volume 96.

Published: 25 February, 2021.

Author: Md. Selim Hossain, Shuvo Sen and Md. Mahabub Hossain

Results and summary： In this research work, a novel design of octagonal cladding with two elliptical cores in photonic crystal fiber (O-PCF) is studied for application in the terahertz (THz) frequency regime. There exists five layers of octagonal shape in circular air holes (CAH) of cladding region with two elliptical shapes of core area are proposed in this research work. The O-PCF features of the fiber have been explored using a full vector finite element method (FEM) with perfectly matched layer (PML) boundary conditions that have been used to confine the light inside the core region properly. Some supplementary significant fiber features for THz signal spread with low confinement loss, high core power fraction, scattering loss and single-mode PCF circumstances of the fiber have also been considered. Simulated results exhibition compares to the low effective material loss (EML) of 0.0153 cm^{-1}, larger effective area of 5.95×10^{-8} m^2, core power fraction of 79%, a low confinement loss and scattering loss such as 3.36×10^{-14} dB m−1 and 1.25×10^{-10} dB km−1 respectively at 1 THz frequency regime. To shorten design and smooth fabrication, only circular shaped air holes have been employed. Due to its promising characteristics, the proposed SM-OPCF waveguide provides efficient transmission of broadband terahertz signals. The suggested excellent design of O-PCF can be used mostly in nano-optics, biomedical signal processing, optical amplification, SONET and other communication areas[43].

Paper no: 10

Title: ***Terahertz Sensing in a Hollow Core Photonic Crystal Fiber.***

Journal: IEEE Sensors Journal

Published: Volume: 18, Issue: 10, 15 May 2018.

Author: Md. Saiful Islam; Jakeya Sultana; Ahmmed A. Rifat; Alex Dinovitser; Brian Wai-Him Ng; Derek Abbott.

Results and summary: A terahertz sensor based on a hollow core photonic crystal fiber has been proposed in this paper for chemical analyte detection in the terahertz frequency range. The Zeonex-based asymmetrical hollow core is filled with an analyte and surrounded by a number of asymmetrical rectangular air holes bounded by a perfectly matched layer with absorbing boundary conditions. The performance of the proposed sensor is numerically investigated by using finite element method-based COMSOL software. It is found that a hollow core provides a high relative sensitivity as well as low transmission loss. Moreover, simplicity in design facilitates manufacturability, making it practical for a number of different biological and industrial applications. A hollow core photonic crystal fiber is designed and analyzed for chemical analyte detection in the terahertz frequency range. Using Zeonex as the substrate and at optimal design conditions, simulation results show a high relative sensitivity of 96.69%, 96.97%, and 97.2% for water, ethanol and benzene respectively. In addition, the sensor shows low EML and negligible confinement loss that is useful for efficient sensing. Moreover, the obtained high birefringence property is suitable to increase the sensing performance. Using the existing fabrication methods, the proposed PCF is feasible to fabricate. Therefore, with such remarkable sensing properties and design flexibility the proposed sensor will open a new window for next generation terahertz research and can potentially be applicable in different food and biomedical industries[44].

Paper no: 11

Title: ***Alcohol Sensing through Photonic Crystal Fiber at Different Temperature.***

Journal: Optics and Photonics Journal

Published: Vol.08 No.10(2018), Article ID:87892,8 pages.

Author: Etu Podder, Rayhan Habib Jibon, Md. Bellal Hossain, Abdullah Al-Mamun Bulbul, Sagor Biswas, Md. Anamul Kabir.

Results and summary: This paper presents the investigation of the relative sensitivity profile of Alcohol through Photonic Crystal fiber at different temperatures. Here, 15%, 40%, 60%, 75% of Ethyl Alcohol-water mixture is inserted through the core of Photonic crystal fiber at temperatures like 20˚C, 25˚C and 30˚C. COMSOL Multiphysics is used as simulation software and the simulation process is done at wavelength range 600 nm to 1600 nm. From this work, the relative sensitivity is obtained approximately 44, 44.59, 44.85, 45 in percentage at temperature 20˚C, 42, 44.2, 44.8, 44.9 in percentage at temperature 25˚C, and 42, 43.8, 44.5, 44.85 in percentage at temperature 30˚C for 15%, 40%, 60%, 75% of Ethyl Alcohol-water mixture at wavelength 1500 nm respectively. Again, higher sensitivity is achieved when this sensor is operated at lower temperature. Optical fiber technology was developed for telecommunication applications. After that this technology got huge positive feedback among the researchers. Very soon optical fibers were seen to expand its application area like the sensing field. The growths of photonic crystal fibers (PCFs) with their significant optical properties have confirmed the prospective benefits of optical fibers in chemical and biological sensing[45].

Paper no: 12

Title: ***A single mode porous-core square lattice photonic crystal fiber for THz wave propagation.***

Journal: Journal of the European Optical Society-Rapid Publications

Published: volume 12, Article number: 15 (2016).

Author: Md. Rabiul Hasan, Md. Ariful Islam & Ahmmed A. Rifat.

Results and summary: Interests on low-loss terahertz (THz) waveguides are increasing due to their remarkable applications in various fields. Since most the materials are highly absorbent to THz waves therefore it is an ongoing challenge to obtain a low-loss waveguide. This paper presents a novel porous-core square lattice photonic crystal fiber (PCF) for efficient transmission of THz waves. The guiding properties of the proposed fiber are characterized by using finite element method (FEM) with circular perfectly matched layer (PML) boundary conditions. It is demonstrated that the designed PCF shows very low effective material loss (EML) of 0.076 cm^{-1} at 1.0 THz that indicates about 62 % reduction of bulk absorption loss of the background material. In addition to this, the proposed fiber exhibits low confinement loss of 8.96×10^{-3} dB/cm and low flattened dispersion of 0.96 ± 0.086 ps/THz/cm for the optimal design parameters. Other important propagation characteristics such as single mode propagation, power fraction, and bending loss are also investigated thoroughly. In this paper, they introduce a new design that consists of square lattice in both outer cladding and inner porous-core. It has been demonstrated that by properly tailoring the fiber's design parameters EML can be lowered significantly, while other guiding parameters such as confinement loss and power fraction can be kept above acceptable limits. In addition to these, single mode guidance and bending loss characteristics of the proposed structure has been analyzed rigorously. The whole PCF is based on cyclic-olefin copolymer (COC), which is commercially known as TOPAS. Compared to other polymer materials (such as PMMA, HDPE, PP etc.). TOPAS provides few definite advantages. It shows a nearly constant refractive index over 0.1–2 THz frequencies. Moreover, it shows low dispersion, low confinement loss and good protection against water vapor absorption[46] .

Paper no: 13

Title: ***Novel optical fiber refractive sensor fabricated with an alcohol-filled photonic crystal fiber based on a Mach–Zehnder interferometer***

Journal: Optical Fiber Technology, Volume 48

Published: March 2019, Pages 278-282

Author: Yan Luo, Ronghua Fan, Yupei Zhang, Qiong Wu, Zhijun Ren, Baojin Peng.

Results and summary: A novel alcohol-filled optical fiber sensor that consists of a single-mode fiber–photonic crystal fiber–single-mode fiber (SMF–PCF–SMF) structure is proposed and experimentally validated. The proposed sensor is based on a Mach–Zehnder interferometer, which is fabricated by splicing a section of uncoated photonic crystal fiber (PCF) between two short sections of single-mode fibers with a fiber fusion splicer. The air holes of the PCF are filled with alcohol to fabricate a refractive sensing probe that can detect changes in the external refractive index (RI). Experimental results show that changes in the external RI cause shifts in the positions of wavelength peaks. The sensitivity of the proposed structure reaches 386.66 nm/RIU under the external RI of 1.335–1.350. The linearity of the shift of the wavelength valley with RI is 97.9%. Construction methods for a measurement system based on the SMF–PCF–SMF structure are also proposed. Notably, voltage change indirectly reflects the change in the external RI. Given this characteristic, the SMF–PCF–SMF structure has potential applications in fiber-based RI sensing. They proposed a MZ interferometer RI sensor based on an alcohol-filled, solid-core, single-mode PCF. The sensor is fabricated by splicing a 4 cm-long alcohol-filled PCF between two sections of SMFs. Filling the PCF with alcohol reduces the difference between the RIs of the core and the cladding. This effect, in turn, increases the sensitivity of the sensor to the external RI and ensures the high-sensitivity measurement of the RI[47].

Paper No: 14

Title: ***Oligoporus-core Quasi cladding photonic crystal fiber based micro-sensor for alcohol detection.***

Journal: Physica B: Condensed Matter, Volume 584

Published: 1 May 2020, 412104

Author: Bikash Kumar Paul, Kawsar Ahmed, Vigneswaran Dhasarathan, Truong Khang Nguyen.

Results and summary : A novel quasi-fiber sensor is introduced for alcohol sensing applications with efficient optical guiding properties. The Finite Element Method (FEM) has been employed to explore the guiding properties over a wide range of 0.80 μm–2.8 μm wavelength. The integral purported sensor structure is implemented with a scattering boundary condition (SBC) on its outer boundary. The numerical investigation of the optimum structure reveals its relative sensitivity as 60%-98% corresponding to the power fractional distribution of 75% and 72% respectively. Furthermore, a high Numerical Aperture (NA) of 0.68 is obtained from the introduced sensor at the operating wavelength of 2.6 μm. The overall results promise for better performances of proposing sensors, particularly in medical imaging applications. A novel quasi oligo-porous core PCF based alcohol sensor has been proposed and explored different optical guiding properties. Investigated results have exhibited the maximum sensitivity, core power fraction and NA of 75%, 72% and 0.58 respectively. These characteristics are very attractive in sensing and biomedical imaging applications. Moreover, low scattering loss, confinement loss of 1.53×10^{-8} dB/cm, 1.15×10^{-7} dB/cm respectively have also been gained for the optimum structure at 1.5 μm[48].

Paper No: 15

Title: ***Advances in photonic crystal fiber: sensing and supercontinuum generation applications.***

Journal: Optical Fiber Technology, Volume 72.

Published: September 2022, 102982

Author: Baljinder Kaur, Santosh Kumar, Brajesh Kumar Kaushik.

Results and summary: Photonic crystal fiber (PCF) guides the light through microscopic air channels having the potential to overcome the limitations associated with conventional fibers. PCF can operate in both conditions, if the refractive index (RI) of core is higher or lower than clad RI, in the former condition light is guided through total internal reflection while in latter it is achieved with photonic band gap effect that cannot be obtained with conventional fibers. It offers endless single mode operation, high birefringence, ability to carry more power, ultrahigh non-linearities, low bending and dispersion losses. PCF has an advantage of high surface to volume ratio in air hole arrays that enhances interaction between analyte-sensing mediums, elevating the performance of the sensor. PCF sensors require less volume of the sample (few µL-nL) due to tight confinement of electromagnetic energy, narrow channels and long path length in the range of a few meters make them excellent candidates for potential applications. This review presents an overview and analysis of the recent developments in PCF sensor design for sensing and supercontinuum generation applications. The sensor design involves the principle of surface enhanced Raman scattering (SERS), surface plasmon resonance (SPR), evanescent waves (EWs) and interferometry. Advancements in various optical sensing techniques with their pros, cons and future outlook towards point of care applications are discussed in detail. In this article, PCF sensors based on different physical sensing mechanisms such as SERS, SPR interferometry and super continuum generation are reviewed. Most of the PCF based sensors demonstrated theoretically using FEM are limited by fabrication difficulties of these structures. Performance comparison of different sensing techniques in terms of sensitivity and resolution for various bio-targets, chemicals, and gasses are summarized[49].

Paper no: 16

Title: ***Hexahedron core with sensor based photonic crystal fiber: An approach of design and performance analysis.***

Journal: Sensing and Bio-Sensing Research,Volume 32.

Published: June 2021, 100426

Author: Md. Selim Hossain, M.M. Kamruzzaman Kamruzzaman, Shuvo Sen, Mir Mohammad Azad, Mohammad Sarwar Hossain Mollah.

Results and summary: A new structure of hexahedron core with the heptagonal shape of cladding regions based on material loss (EML), V-Parameter are also analyzed through essential graphic outputs. So, the results show the strong potential of this suggested Hx-PCF fiber for bio-medical areas to detect biochemicals and also industrial areas for identifying many types of chemicals by sensing procedure in the terahertz (THz) waveguide system.In this proposed work, an excellent design of the Hx- PCF fiber with five layers of the heptagonal shape of cladding areas and two layers of hexahedron core regions based photonic crystal fiber have been examined and explained using the finite element method (FEM) and perfectly matched layers (PML) based COMSOL Multiphysics computer program instrument. Here, Zeonex is applied photonic crystal fiber (Hx-PCF) is presented in this research work. The finite element method (FEM) and perfectly matched layers (PML) based COMSOL Multiphysics has been used to design this photonic crystal fiber (Hx-PCF) with appropriate design parameters. The fiber discloses the high relative sensitivity (RS) which stand 86.32%, 88.36%, and 84.25%, and low confinement losses along with the value of 5.60×10^{-08}, 6.60×10^{-08} dB/m, and 5.55×10^{-08} dB/m for three chemicals such as Ethanol (n = 1.354), Benzene (n = 1.366) and Water (n = 1.330), respectively at operating region of 1 THz (THz). Furthermore, some other optical characteristics such as an effective mode index (EMI), effective area (EA), total power fraction (TPF), effective as background material to reduce the different types of losses such as confinement losses and effective material loss of the Hx- PCF fiber. After the numerical results, our detailed hexahedron PCF fiber uncovers the high relative sensitivity of 84.25%, 86.32%, 88.36%, and the low confinement losses of 5.55 × 10–08 dB/m, 5.60 × 10–08 and 6.60 × 10–08 dB/m for three chemicals like as Water (n = 1.330), Ethanol (n = 1.354) and Benzene (n = 1.366) and the effective material loss of 0.00699 cm − 1 correspondingly, at monitoring region of 1 THz. So, it is clearly said that the proposed hexahedron Hx- PCF fiber will be suitable and useful for detecting any kinds of chemicals in the biomedical and industrial regions[50].

Paper No: 17

Title: ***Ethanol Detection Through Photonic Crystal Fiber.***

Journal: International Joint Conference on Computational Intelligence, pp 175–182.

Published: 4 July,2019.

Author:Etu Podder, Md. Bellal Hossain, Abdullah Al Mamun Bulbul,Himadri Shekhar Mondal.

Results and summary: This article presents a photonic crystal fiber (PCF) sensor model with enlarged sensing performance for ethanol detection. Comsol Multiphysics (Version-5.2) is used to simulate the sensor model and MATLAB is used to plot expected sensing profiles. The proposed sensor model provides the sensitivity of around 54% at a wavelength of 1.6um. The sensor model also shows zero confinement loss till 1.6um and after that around 0.65×10^{-7} dB/m confinement loss is observed at a wavelength of 1.8um. Effective area is also investigated in this work and it is obtained around 19um at wavelength 1.6um . The proposed model is very simple and hopefully, possible to fabricate by using the existing fabrication model[51].

Paper No: 18

Title: ***Numerical investigation of photonic crystal fiber-based plasmonic material for alcohol concentration detection.***

Journal: Materials Today: Proceedings

Published: Volume 87, Part 2, 2023, Pages 299-302.

Author:Dedi Irawan, Khaikal Ramadhan, Saktioto, Fitmawati, Azhar, Azwir Marwin,

Results and summary: In recent years, Photonic crystal fibers (PCF) have become a great component, PCF consists of several air holes with certain arrangement and size as a core, and the silica material as the subtract or cladding. This component has an air cavity around the core and cladding. With the presence of this air cavity, a phenomenon that can be used in the world of communication and optical sensing. Many geometrical structures of PCF have been also studied, for example, the PCF was coated by two cladding layers. For sensor application, PCF was designed based on its surface plasmon resonance such PCFSPR. The material used for coating the PCFSPR was investigated by Dedi et al. In this study, PCFSPR was coated by gold material, silica, and copper. In a different study, PCF was also coated by using TOPAS. Basically, optical sensors work based on light propagation in the sample, then it will change the refractive index which will affect the wavelength or frequency of the light after passing through the sensing area. Optical sensors have wide range of applications such as refractive index sensor, strain/ stress sensor, temperature sensor, humidity sensor, etc. Due to a wide range of the operation wavelength, optical sensor promise good accuracy as a sensor, safe from human contact cause its optically work compared with electronically work, and of course, it is immune to the electromagnetic wave interference. The Parameters which were determined for ethanol concentration are commonly the confinement loss and the Amplitude Sensitivity (AS). This research focuses on the wavelength shift of the resonance wavelength due to the difference percentage of the ethanol concentration. The Parameters which were determined for ethanol concentration are commonly the confinement loss and the Amplitude Sensitivity (AS) in 1/RIU [17]. This research focuses on the wavelength shift of the resonance wavelength due to the difference percentage of the ethanol concentration. . A photonic crystal fiber for detecting the concentration of ethanol at lower temperature was successfully designed based on the surface plasmon resonance (PCFSPR). The design was utilized by Comsol Multiphsyics based on the finite element method (FEM). The proposed PCFSPR was designed by silica material, coated by gold material. The simulation results found that the peaks of the confinement loss for dual-polarized (x-polarization and y-polarization) are increased by increasing the ethanol concentration in the range of 40% to 70%. Meanwhile, the peaks of amplitude sensitivity (AS) were found for the increment of ethanol concentration. Certainly, this proposed sensor obtained a good sensor sensitivity of 91 nm/% for detecting ethanol concentration at a lower temperature of 20 °C[52].

Paper No: 19

Title: ***Performance evaluation of photonic crystal fiber sensor for controlled drugs detection: a simulation approach.***

Journal: Physica Scripta

Published: 12 October, 2023. Volume 98, Number 11.

Author: Abdul Mu'iz Maidi, Rudi Salam1, Nianyu Zou and Feroza Begum

Results and summary: This study proposes a simple and efficient Photonic Crystal Fiber sensor design for the detection of controlled drugs such as cocaine, amphetamine, and ketamine. The design uses a pentagonal core hole and circular cladding air holes in 2 layers, made of fused silica substrate. The sensing performance of the proposed PCF design is evaluated using COMSOL Multiphysics and Finite Element Method, operating in the visible and infrared range from 0.4 to 3.2 μm. Results show that the proposed PCF design achieves high relative sensitivities of 99.55%, 99.75%, and 99.99% for cocaine, amphetamine, and ketamine, respectively, at the optimum wavelength of 0.4 μm. Additionally, the design is robust, showcasing minimal variations in relative sensitivities with changes in pitch distance, air hole diameter, and core hole length. These findings make the proposed PCF design a promising candidate for practical controlled drug sensing[53].

Paper No: 20

Title: ***Sensing of Illegal Drugs by Using Photonic Crystal Fiber in Terahertz Regime.***

Journal: Journal of Optical Communication

Published: March 6, 2020.

Author: Shaymaa Riyadh Tahhan and Hadeel K. Aljobou.

Results and summary: Stimulant abuse enhances dopamine release, thereby causing increased excitation. Any extent of stimulant abuse can considerably harm the user. Thus, methods of detecting stimulants must be precise, accurate, and reliable. A novel terahertz (THz) photonic crystal fiber with a Topas substrate is designed and rigorously investigated for detecting liquid amphetamine, cocaine, and ketamine. The fiber structure has a pentagonal shape and comprises circular air holes in the core and cladding spatial extents. As shown in finite element simulation, the proposed fiber yields a high relative sensitivity of approximately 80 % when any of the liquid stimulants is infiltrated in the core air holes. At 1 THz operating frequency, the proposed fiber produces a large effective mode area, negligible confinement loss, and extremely low bending and effective material losses. Other THz waveguiding properties, such as core power fraction and total loss, are also studied. Lastly, a positive and negative 2 % fabrication tolerance is set to ensure seamless potential practical realization of the fiber[54].

Paper No: 21

Title: ***Compact Photonic Crystal Fiber for Sensing Applications in the THz Regime.***

Journal: Terahertz Devices, Circuits and Systems, pp 205–224.

Published: 27 September 2022.

Author: N. Ayyanar, Abinash Panda, S. Rajaram, D. Vigneswaran & Puspa D. Pukhrambam

Results and summary: This paper deals with terahertz (THz) sensor-based photonic crystal fiber (PCF) and its various useful applications in multiple domains such as chemical, gas, biomedical and environmental. In the visible and infrared areas of optical fiber sensors, the probing length of evanescent fields is sub wavelength, limiting its use for identification of bigger targets. Because THz signal has a higher wavelength and THz sensors could be fit for a variety of sensing applications. The THz radiation (0.1 -

10 THz) has a huge potential in a wide application domain like sensing, biomedical industry, astronomy, medical imaging, security, agricultural industry, etc. Due to their adaptive design flexibility and wide range of applications in the THz spectrum, PCFs have emerged as an appealing alternative to electronics technology in this regard. Owing to the recent revolution in the biomedical industry, nowadays the scientists are more focused in designing optical biosensors, where the PCF-based sensors are the most researched devices and almost controlling the modern photonic industry. PCFs-based sensors in the THz regime have been extensively investigated owing to their high birefringence, ultra-high sensitivity, effective mode area, ultra-high sensitivity and minimum loss. With the advancement in technology, different hollow core and porous core PCFs have been successfully fabricated with extensive analysis of propagation characteristics and tested for various sensing applications like blood, gas, salinity, DNA, alcohol, liquid, food, hormones, enzymes, cells, urine, glucose, chemicals, etc. From the numerical analysis, the suitable background materials such as Teflon, Zeonex, PMMA and TOPAS are used for operation in THz region due to their high transparency in THz spectrum and feeble loss coefficient. Recently, more effective THz sensors are envisaged through plasmonic principle by integrating novel metals and transition-metal dichalcogenide (TMDC) materials in the design of PCFs. In this chapter, different geometries of PCF and their light guiding mechanisms are thoroughly studied. Moreover, an extensive investigation is carried out vis-à-vis numerous sensing applications of PCF in the THz spectrum, and their sensing performances are compared[55].

Paper No: 22

Title: ***A Dual-Parameter Sensor Based on the Asymmetry of Alcohol Filling the Photonic Crystal Fiber in Sagnac Loop***.

Journal: IEEE Sensors Journal.

Published: Volume: 18, Issue: 15, 01 August 2018.

Author: Fuquan Q. Shi, Yan Y. Luo, Daru R. Chen, Jiajia J. Chen, Zhijun J. Ren, Baojin J. Peng

Results and summary: This paper proposes a novel temperature and stress sensor based on the asymmetric filling of alcohol into the photonic crystal fiber in a Sagnac loop. First, we etched the photonic crystal fiber and collapsed the air. Then, we filled alcohol into the asymmetric photonic crystal fiber. Next, we connected this structure into a Sagnac interference ring. When the ambient temperature changed, the thermal expansion effect of filled alcohol would lead to the change of birefringence of photonic crystal fiber, which made the interference spectrum of the sensor drift with the change of temperature. Furthermore, after adding transverse stress to the photonic crystal fiber, the fiber's strain changed. With its strain changed, the birefringence of photonic crystal fiber also changed, which made the interference spectrum drift. The experimental results showed that when the temperature or the lateral stress is added, a red shift would occur in the interference spectrum. The temperature sensitivity was found to be 0.1864 nm/°C, and the lateral stress sensitivity was 0.6201 nm/N. The sensor achieved the highly sensitive measurement of temperature and stress. Concurrently, the structure has the advantages of high stability, anti-electromagnetic interference, and easy construction, and it provides a new method for obtaining birefringence of ordinary photonic crystal fiber. In addition, an application system of the sensor has been built. Monochromatic light source with 1554-nm wavelength was used in the experiment. The drift of the interference spectrum is transformed into the change of light intensity. The relative error is less than 3%, which indicates a good application prospect[56].

Paper No: 23

Title: ***Nicotine Sensing by Photonic Crystal Fiber in THz Regime.***

Journal: 2nd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST).

Published: 01 February 2021.

Author: Rayhan Habib Jibon, Moaz Ahmed, Md. Ekhlasur Rahaman, Md. Khaled Hasan, Md. Murad Shaikh, Abul Tooshil.

Results and summary: A PCF based nicotine detection technique in THz regime that is found in cigarette smoke is presented here. A square shaped PCF is designed where the cladding consists of four air hole layers and a solid square core is used for filling up the analytes. Some of the optical properties sequentially sensitivity, confinement loss, EML, and effective area are calculated for measuring the sensor performance in the THz region of 1 THz to 2 THz. All the values are measured in three conditions namely at optimum air hole radius and optimum air hole radius ± 2%. From the simulation results a high sensitivity of 83% is achieved at 1.5 THz, besides the confinement loss becomes zero after 1.3 THz and also a low value of EML is found. A slightly higher sensitivity (83.8%) is attained at optimum air hole radius+2% but in this case the core-cladding spacing is reduced, which will create a barrier in fabrication. Hence the optimum condition of our proposed model is chosen for fabrication flexibility. A square shaped PCF is proposed in this paper for sensing nicotine of cigarette smoke in THz operating region ranging from 1 THz to 2 THz and the optimum level is pointed at 1.5 THz. The optical properties are analyzed after varying the air hole radius three times, namely optimum air hole radius and optimum air hole radius ± 2%. At optimum condition the sensitivity of 83% is obtained along with a zero-confinement loss and negligible EML value of $8.2x10^{-3}$ cm-1. A better effective area of 10.35×10^{4} pm^{2} is also ensured from this simulation. At the conditions for optimum air hole radius + 2%, represents a slightly higher profile but this may reduce the pitch distance that will cause the fabrication complexities. So, we finalized the simulation for the optimum conditions. This proposed PCF has the fabrication flexibility using the presently available fabrications technologies, since the parameters used for designing this PCF sensor maintain the standard values. By using these standard values this sensor performs well in terms of relative sensitivity, confinement loss, EML and effective area. Again, a comparison with other chemical and gas sensors ensures the usability of this PCF sensor in THz region. Besides the combustible gasses can also be detected by this proposed sensor that will ensure the safety level[57].

Paper No: 24

Title: ***High-Sensitivity Temperature Sensor Based on Photonic Crystal Fiber Filled with Ethanol and Toluene.***

Journal: Journal of Solid-State Science and Technology.

Published: 20 December, 2023.

Author: HaiPing Li, Juan Ruan, Xin Li, ZiQin Yang, ZhangLiang Xu, GuangYong Wei, Tao He and Yang Luo

Results and summary: A surface plasmon resonance photonic crystal fiber-based highly sensitive temperature sensor is proposed. The surface plasmon resonance is induced by injecting toluene into the central hole and ethanol into the side holes coated with gold film. Optimal sensor sensitivity by optimizing the size and position of the air holes. The coupling mechanism and sensing performance of the proposed sensor are analyzed. The results indicate that in the sensing range of 0 °C−70 °C, the highest figure of merit (FOM) is 0.1169/°C and the average temperature sensitivity can reach 7.13 nm/°C. Such temperature sensor exhibits tremendous potential in the domain of temperature detection[58].

Paper No: 25

Title: ***A Highly Sensitive Terahertz Waveguide Plasmonic Sensor for Ethanol Sensing.***

Journal: Journal of Plasmonics.

Published: 12 May 2023, Volume 18, pages 1511–1519.

Author: A. H. M. Iftekharul Ferdous, Benjir Newaz Sathi, Md. Shahareaj Islam, Diponkar Kundu, Twana Mohammed Kak Anwer, Shaik Hasane Ahammad, Md. Amzad Hossain, Mahmoud M. A. Eid & Ahmed Nabih Zaki Rashed

Results and summary: This paper proposes and numerically investigates a spider-web-like cladding photonic crystal fiber with a hexagonal hollow core–based ethanol sensor utilizing terahertz (THz) signal. The finite element method (FEM) technique is applied to examine sensing and guiding characteristics of this sensor by using the COMSOL Multiphysics software. The sensor outperformed other ongoing studies by achieving a high relative sensitivity of 97.09% and an incredibly low confinement loss of 3.68×10^{-12} dB/m at the optimal frequency. In addition, the sensor has a large effective area of 6.458×10^{-08} m^2 and spot size with a tiny effective material loss of 0.0051 cm^{-1}. This study represents the huge hexagonal core and a set of rectangular air holes in spider-shaped cladding to simplify manufacture. Future applications for identifying ethanol may greatly benefit from its exceptional sensitivity and guiding qualities[59].

Chapter 03

Research Methodology

3.1 Key Features of Photonic Crystal Fiber (PCF)

Photonic Crystal Fiber (PCF) is a specialized type of optical fiber that exhibits unique properties not found in traditional optical fibers. It is characterized by an array of air holes or voids that run along the length of the fiber, forming a periodic structure. These air holes are typically arranged in a hexagonal pattern, although other configurations are possible[47].

The key features of PCF that differentiate it from conventional fibers include:

Guiding Mechanism: In traditional optical fibers, light is guided through a core region with a higher refractive index than the surrounding cladding. In PCF, the periodic arrangement of air holes creates a photonic bandgap, which prevents certain wavelengths of light from propagating in the core. Instead, the light is guided in the low-index regions, often referred to as the "holes."

Endless Variety of Designs: The geometrical arrangement and size of the air holes in PCF can be precisely engineered to control various optical properties, such as dispersion, birefringence, and confinement of light in specific regions. This allows for tailoring PCF to meet specific application requirements.

Modal Flexibility: PCF can support a wide range of guided modes, including multiple higher-order modes. This versatility enables the design of PCF for a variety of applications, including single-mode operation or multi-mode operation depending on the desired outcome.

High Nonlinearity: Some PCFs are designed to have a high nonlinearity, which means they can generate new frequencies of light through nonlinear optical processes. This is essential for applications such as supercontinuum generation and frequency conversion.

Specialty Fibers for Specific Applications: PCF can be engineered for specialized applications, such as sensing, high-power lasers, and supercontinuum sources. For example, in your thesis topic, PCF is being used as a sensing platform to detect alcohol substances.

3.2 How PCF Works

Guiding of Light: When light is launched into the core of the PCF, it interacts with the periodic arrangement of air holes. The photonic bandgap effect causes certain wavelengths to be excluded from the core, forcing the light to be guided along the low-index regions (holes) of the fiber[48].

Evanescent Field Interaction: The light propagating in the core generates an evanescent field that extends into the surrounding air holes. This field interacts with substances outside the fiber, allowing for sensitive measurements of parameters like refractive index, temperature, pressure, or chemical composition.

Sensing Mechanism: In your thesis topic, the refractive indices of alcohol substances like Ethanol, Methanol, Propanol, and Butanol play a crucial role. These substances have different refractive indices, which cause distinct changes in the properties of the guided light as it interacts with them. By monitoring these changes, the presence and concentration of the alcohol substances can be detected.

Overall, the unique properties of PCF make it a versatile platform for a wide range of applications, including sensing, telecommunications, and laser technology, among others. Its ability to control and manipulate light in novel ways has opened up new avenues for innovation in the field of photonics.

3.3 Research Design

The structure created to discover answers to research inquiries is referred to as research design. The research design task defines its assets like research query, dependent- and independent in constant, investigational pattern, where utilizable, facts accumulation techniques and analytical plan[49].

The research design for proceeding and completing the whole research work is described as

• To review the development and history of optical fiber communications.

• To study the exceptional optical properties of photonic crystals.

• To study literatures on the photonic crystal fibers as a solution over conventional fibers.

• To choose the THz band of 1-10 THz for optical fiber communications.

• To study the procedures of designing PCF in COMSOL Multiphysics software.

• To investigate the essential performance parameters of the PCF.

• To execute the whole procedure.

Here the flow chart of the methodology of our proposed design fig. (3.1) is given below:

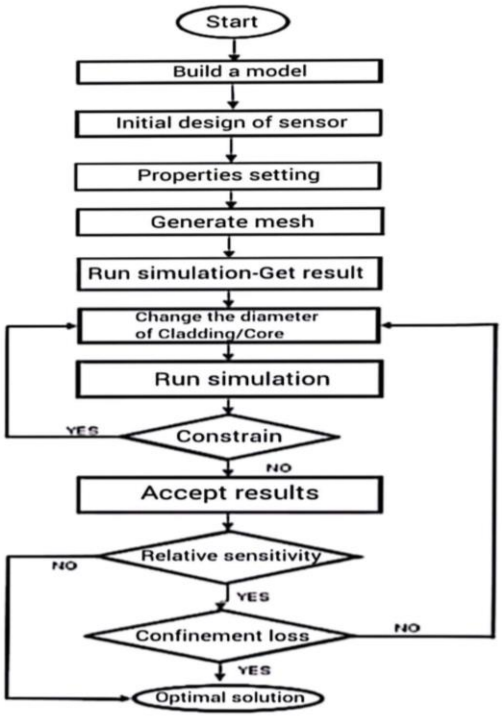


fig. (3.1): Flow chart of the methodology

3.3.1 Design procedure

There are some design procedures to complete a sensor design in Comsol Multiphysics. The steps are given below with necessary figures.

3.3.2 Analysis Method

Generally, three methods are used to analyze the structure and properties of photonic crystal fiber (PCF). They are:

i) Effective Index Approach.

ii) Basic-Function Expansion Approach.

iii) Numerical Approach.

iv) First step for research is to study some thesis books, journal papers and conference papers in a desired field which is known as Literature Review.

v) Problem Identification.

vi) Problem formulation.

vii) Designing scheme to work Collecting necessary software required for designing and analysis purpose.

viii) Improving Comsol software skill to design PCF.

ix) Designing some desired PCF on a trial-and-error basis via Comsol Multiphysics.

x) Making ready desired designs and holding out results.

xi) Keeping continuous consultation with the thesis supervisor.

3.3.3 Design platform

COMSOL Multiphysics Version 5.6

COMSOL Multiphysics is an environment to perform simulations based on Finite Elements Method (FEM) for all physics fields. The FEM decomposes the structure to be studied into a variable-size grid in which every element is analyzed by solving the corresponding set of equations –the Maxwell equations in our case– self-consistently at each node.

3.3.4 Perfectly Matched Layer (PML)

A perfectly matched layer, PML in short form, is an artificial sucking up layer for wave equations, commonly utilized to truncate computational districts in numerical strategies to simulate issues with open boundaries. The term PML, may be a layer of invented fabric which is presented on the edges of calculation windows to constrain the domain on which to apply the FEM (Finite Element Method). In the case of optical fiber, a PML is an artificial boundary condition implicating perfect absorption of incident radiation of an electric field without reflecting. This boundary condition is needed for estimating an infinite zone beyond the waveguide outer edge to a finite domain of numerical analysis[7]. This layer is created around the cladding of the optical fiber. The Effect of PML on the numerical simulation result attained, will be more noticeable when the confinement of field in the photonic crystal fiber is feeble. This layer can also be applied to find out the complex part of an effective index. The PML region can be considered as a perfect absorber with a certain magnitude of conductivity[11].

In the COMSOL, the PML is specifically assigned two types of shapes: Cartesian and Cylindrical. However, with the third option of 'user defined', this PML can be created to any shape depending on the outer shape of the designed fiber. Therefore, due to the above mentioned advantages, we used the PML as a boundary condition for our designs[22].

3.3.5 Creating a new model in COMSOL Multiphysics

A new model can be created in two ways in COMSOL. Which are:

• Models leaded by the Model wizard interface in COMSOL

• Models leaded by starting blank model interface COMSOL

Creating a Model through the Model Wizard interface in COMSOL: A created model through the 'Model Wizard' usually provides different types of comsol designed geometrical shapes. The 'Model Wizard' option is chosen when we try to create a design by using the geometrical shapes which are already designed previously in comsol. In its guided model, we can create any geometrical shapes by just giving the measurements reacquired for the respective shapes. For example, to create a circle, we just need to input a radius. The Model Wizard leads the user in fixing the space dimension, physics, and study type. Those steps are described with the proper figure below. All these steps (fig.3.2- fig.3.5) are shown below with proper figures respectively.

Step 1: At first, we have to select the new model wizard for the model component of the design. The step is shown below on the following figure (3.2):

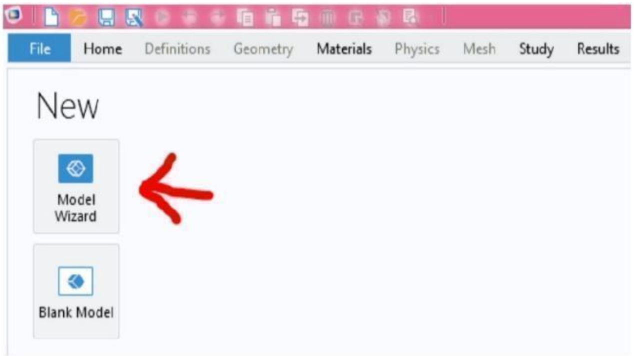


fig. (3.2): Step 1 for creating a new model

Step 2: Select the space dimension for the model component of the design. Which can be 3D, 2D Axisymmetric, 2D, 1D Axisymmetric, or 0D. (Select 2D for PCF design).

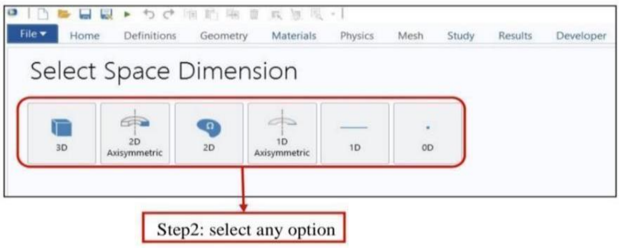


fig. (3.3): Step 2 for creating a new model

Step 3: In the Model Builder we can add physics interfaces and physics features in the Model Wizard. Depending on your license, the Model Wizard can contain different physics interfaces grouped in different physics branches. The physics interfaces shipped with COMSOL are referred to as built-in physics interfaces. With the Physics Builder you can create new physics interfaces that show up in the Model Wizard, either in an existing physics branch or in a new physics branch.

Here we have to select and prefix the types of physics. Physics interfaces are arranged in an easy manner based on branches to make it easy for the user during locating. Those boughs do not fit directly to the products. If consequences are prefixed to the user COMSOL-installation, one or multi branches will be occupied with extra physics-interfaces.

See in figure 3.4 (One can choose “optics> wave optics> ewfd” for PCF design):

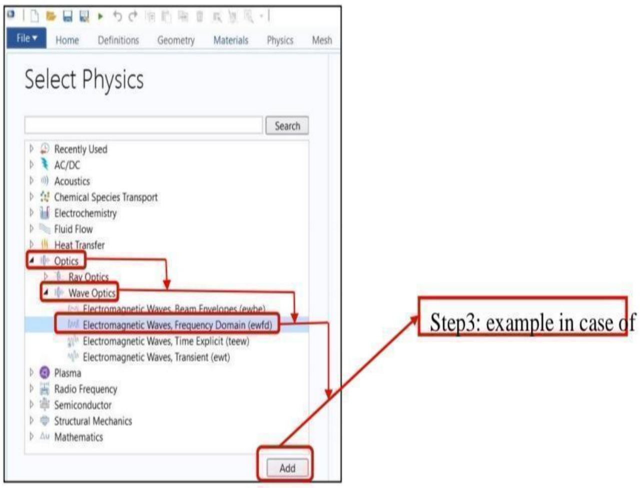


fig. (3.4): Step 3 for creating a new model

Step 4: Choose the type of study that represents the solver or set of solvers that will be used for the simulation of the design. After selecting, click 'Done' and now the laptop/desktop will show the model on the display with a tree configured according to the choices the user made in the Model Wizard. (As our aim of designing and investigating a PCF is to analyze its modes, 'Mode Analysis' is commonly chosen for pcf. See in figure 3.5:

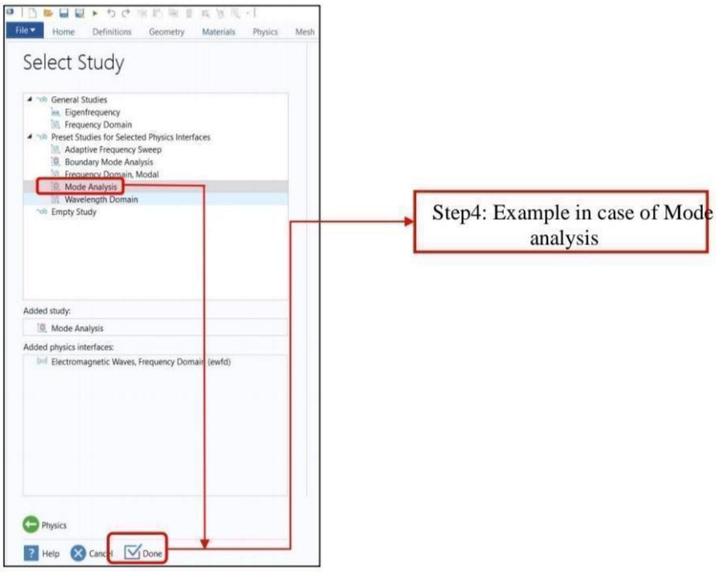


fig. (3.5): Step 4 for creating a new model.

3.3.6 Creating a model through 'Blank Model'

The option named “blank model” will open the COMSOL Desktop interface without any Component or Study. We need to click the right of model-tree for adding a Component of a given space-dimension, physics, or Study. A model guided by the blank model is given below:

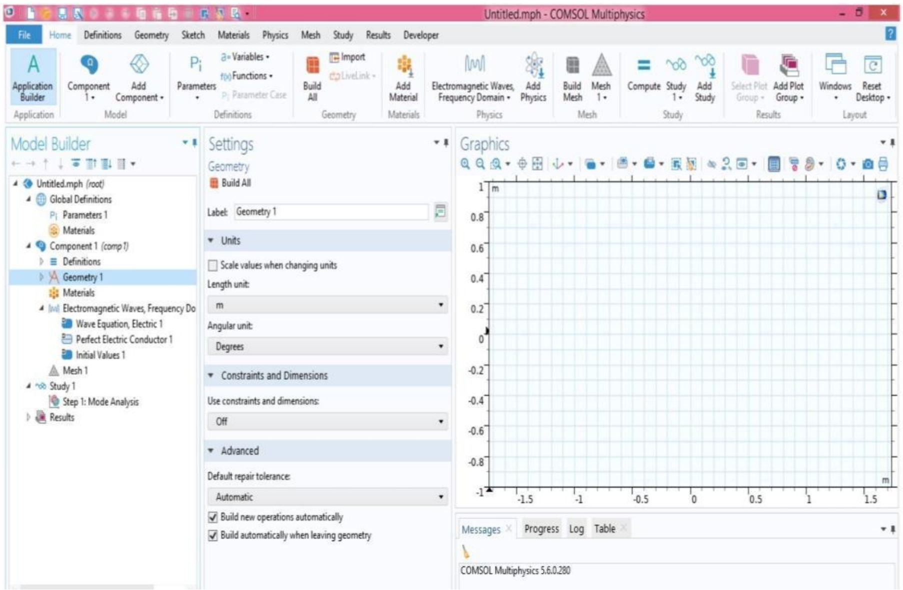


fig. (3.6): Creating a model through ‘Blank Model’

3.3.7 Geometry

It serves as the display interface for COMSOL's Model Builder, featuring a variety of pre-designed geometrical shapes. This functionality significantly contributes to the user-friendly nature of COMSOL. The diverse range of shapes available allows users to create different geometries effortlessly. This feature is closely tied to the 'parameters' option, where inputs directly impact the geometries.

By right-clicking on the geometry, users can choose from various shapes, and then specify the parameter names for the relevant measurements associated with the selected shape. For instance, to generate a circle, one can simply choose the circle shape, input the radius name defined in 'parameters,' and click 'build select,' resulting in the display of a circle[3].

Here it has been shown in fig. (3.7) in a hexagonal shape as our proposed sensor design:

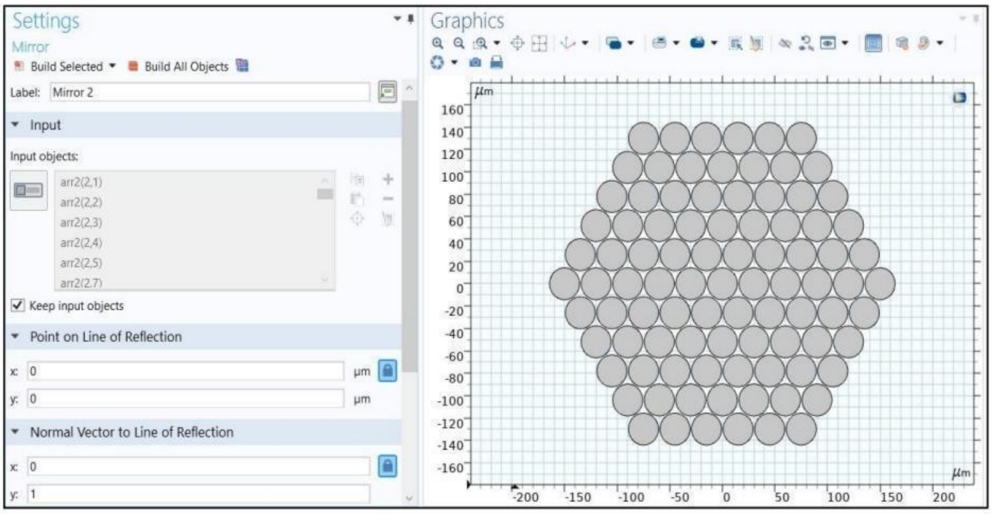


fig. (3.7): Geometry of a basic sensor design through blank model.

3.3.8 Materials

Various materials are typically employed in crafting a PCF shape. Once the design is created, the assignment of materials to individual shapes and backgrounds becomes necessary. This can be achieved by simply right-clicking on the 'material' of the respective component and choosing specific shapes for the material.

The selection of materials can occur in two ways:

i) Either by opting for 'blank material,' where users define the material name and properties, and quantities can be declared in the parameters.

ii) Or by selecting 'add from material library.' When choosing 'blank material,' users enter the material name and its properties directly or declare them in the parameters. In contrast, 'add material from library' lets users select a material from the library, and COMSOL automatically considers its properties.

This approach allows users to incorporate more materials. It is recommended to use the 'blank material' option as it minimizes computational storage by providing only the necessary properties. In contrast, COMSOL's material properties are extensive, demanding more computer RAM storage, which can lead to slower and more complex computations[4].

An example of material selection for comsol multiphysics is given below in fig. (3.8):

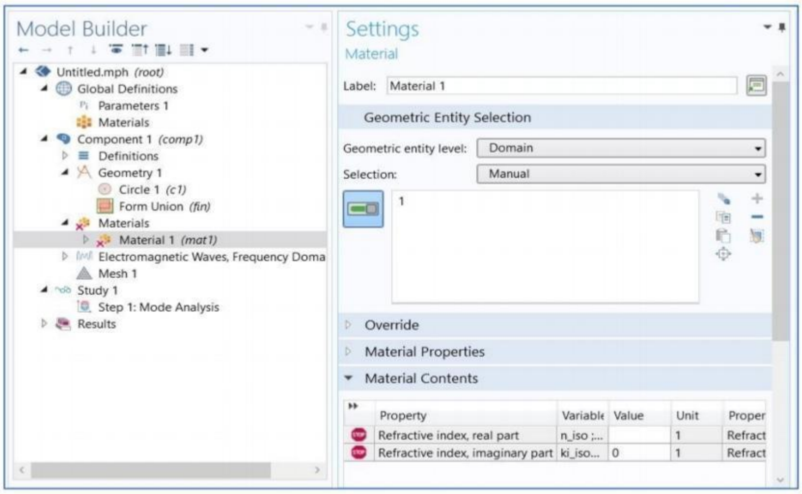


fig. (3.8): Material selection in comsol Multiphysics.

3.3.9 Boundary

After the completion of the main design geometry as a whole, the user needs to create a boundary condition in the outermost layer. Usually a perfectly matched layer (PML) is used as a boundary condition for PCF. The aim of using this layer is to absorb any incident electromagnetic wave or infinite radiated light of the PCF structure, without reflection. It can be created in different shapes, depending on the external shape of the PCF. This can be selected by just clicking the 'definition' of the respective component and then 'perfectly matched layer[15].

3.3.10 Variables

As the objective of simulation of a PCF is to investigate the characteristics or performance parameters of the modes of polarization of light in the core, these parameters have different formulas to calculate[14].

These formulas can be written in the COMSOL language and should input in the variable option before computation the model. In the same way as the declaration of parameters, variables must also be declared with Name, Expression, Unit, and Description. After completing the design and PML, just right click on the respective component's 'definition' and then click on the variable[21].

An example of variable selection for comsol multiphysics is given below in fig. (3.9):

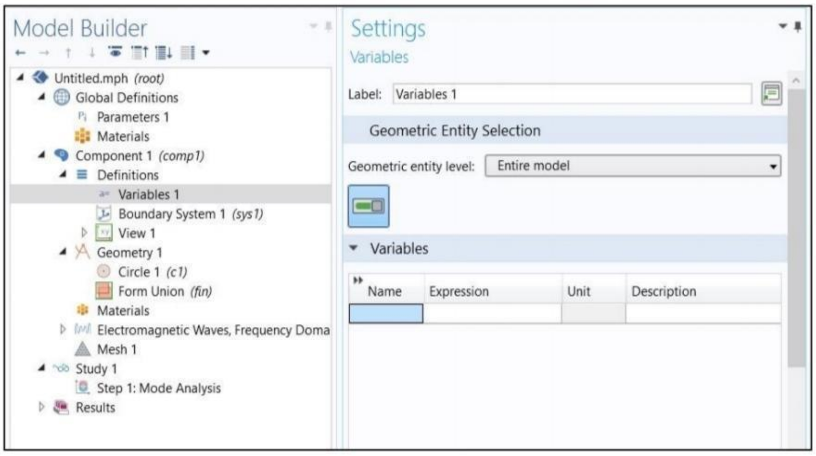


fig. (3.9): Variable selection in comsol multiphysics

3.3.11 Mesh

This is the first step towards the simulation. As the individual shapes of a PCF structure are larger, the COMSOL divides the whole structure in very small triangular shapes or others before the simulation. This process is done through mesh. The “quality of the mesh of finite-element utilized to distinct the model” is determined by the mesh parameters. The element size can be chosen as smaller than normal, normal, finer, finer, extra fine, and extremely fine. The smaller the size of the element in the mesh, the better or more accurte result will be achieved. Always ‘extremely fine’ is recommended for a better output if the user’s Laptop/ desktop is good. This can be performed after the proper adjustment of the operating frequency or wavelength in the ‘study’ option, and then by just clicking on the ‘mesh’ of the respective component[1]. An example of mesh simulation in comsol multiphysics is given below in fig. (3.10):

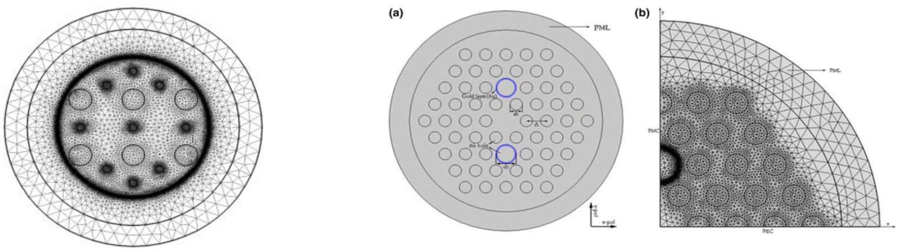


fig. (3.10): Example of mesh simulation in comsol Multiphysics[22].

3.3.12 Study

This marks the conclusive step in the design computation, following the completion of meshing. It involves the selection of parameters such as 'mode analysis frequency,' 'desired number of modes,' and 'search for modes around.' The 'mode analysis frequency' signifies the frequency at which the user wishes to simulate the operation. The 'desired number of modes' represents the user's choice for the number of modes to be tested through the fiber, which could be, for example, 10 or 20. In the case of index guiding fiber, a higher desired number of modes enhances the recognition of polarization modes in the results. After completing the computation process, users can examine all characteristics, performance parameters, and even polarization modes in this option.

To check the effective index values of the x- and y-polarized modes at 75, users can click on 'result,' then choose 'Electric Field (ewfd),' and select the surface and arrow surface of the mode field. Subsequently, from the study solution, mode field confinement can be analyzed for different effective index values.

To compute the real part of a mode's effective index value, users can click on 'global evaluation' in the 'Derived value', input the expression "real(ewfd.neff)" with the unit set to 1, and choose the desired mode value for evaluation. The same procedure can be followed for the imaginary part, using the function "imag(ewfd.neff)." Performance parameters, as defined in the 'Variable' by COMSOL language, can be calculated similarly by entering the parameter name in the expression and description of the 'Global evaluation' display. The unit will be automatically derived from the COMSOL variable. Afterward, by clicking 'evaluate' and selecting a specific table for each parameter, all the declared parameters in the variable can be assessed conveniently[9].

3.3.13 Results

Upon completion of the computation process, this option allows for the exploration of all characteristics, performance parameters, and even polarization modes. To examine the effective index values of x- and y-polarized modes, initiate the process by clicking on 'result,' followed by 'Electric Field (ewfd).' Choose the surface and arrow surface of the mode field. Subsequently, within the study solution, analyze mode field confinement for various effective index values.

For the calculation of the real part of a mode's effective index value, access the 'global evaluation' of the 'Derived value.' Input the function "real(ewfd.neff)" into the expression and description on the display, maintaining unit 1. Sequentially, select the desired mode value, click 'evaluate,' and view the result in the table[11]. Similarly, the effective index value of the imaginary part of a mode can be computed using "imag(ewfd.neff)." Performance parameters, as defined in the 'Variable' by COMSOL language, can be computed analogously to effective index value calculations. The specific parameter name from the variable should be entered into the expression and description of the 'Global evaluation' display. The respective unit will be automatically derived from the COMSOL variable. Finally, click 'evaluate' and choose a designated table for each parameter for ease of access. This streamlined approach facilitates the evaluation of all parameters declared in the variable[16].

Chapter 04

Simulation result

4.1 Why the hexagonal shape?

The choice of the shape of the Photonic Crystal Fiber (PCF) in sensors depends on the specific requirements of the application. While hexagonal-shaped PCFs are not universally better for all applications, they may offer certain advantages for detecting alcohols like methanol, ethanol, propanol, and butanol. Here are some considerations:

Higher Birefringence: Hexagonal PCFs can be designed to have higher birefringence compared to circular or other-shaped fibers. Birefringence can be useful in certain sensing applications, providing additional information about the surrounding environment.

Enhanced Mode Confinement: The hexagonal structure allows for effective control over the guiding properties of the fiber, leading to enhanced mode confinement. This can be beneficial in improving the sensitivity of the sensor to changes in the refractive index, which is crucial for detecting variations in alcohol concentrations.

Modal Characteristics: The specific modal characteristics of hexagonal PCFs, such as the distribution of guided modes, may be advantageous for certain sensing mechanisms. This can influence the interaction between light and the target analytes (alcohols), potentially enhancing the sensor's performance.

Tailorability: Hexagonal PCFs offer a high degree of tailorability in terms of design parameters, such as the size of the core and the arrangement of air holes. This flexibility allows for optimization based on the specific refractive index changes associated with alcohol detection.

Improved Light-Matter Interaction: The specific geometry of hexagonal PCFs can lead to improved light-matter interaction, potentially increasing the sensitivity of the sensor to changes in the surrounding medium's refractive index, which is influenced by alcohol presence.

Compatibility with Other Materials: The hexagonal geometry may be better suited for certain coatings or functionalization processes that enhance the sensor's selectivity to alcohols. It's important to note that the effectiveness of a hexagonal-shaped PCF for alcohol detection depends on various factors, including the concentration range, the specific refractive index changes induced by the alcohols, and the overall sensor design. Circular or other-shaped PCFs may also be suitable depending on the specific requirements of the application[13].

Ultimately, the choice of PCF shape should be part of a comprehensive sensor design process that considers the target analytes, their interaction with light, and the desired sensor performance characteristics. Experimentation, simulation, and optimization are often necessary to determine the most effective sensor design for a given application.

4.2 Basic sensor design and structure

The basic design of our sensor is hexagonal in shape. Also, the cladding and the core of the design is also hexagonal in shape. Which we have designed in COMSOL MULTIPHYSICS.

Proposed sensor design in hexagonal shaped cladding and hexagonal shaped core is given below in fig. (4.1), fig. (4.2) and fig. (4.3) respectively:

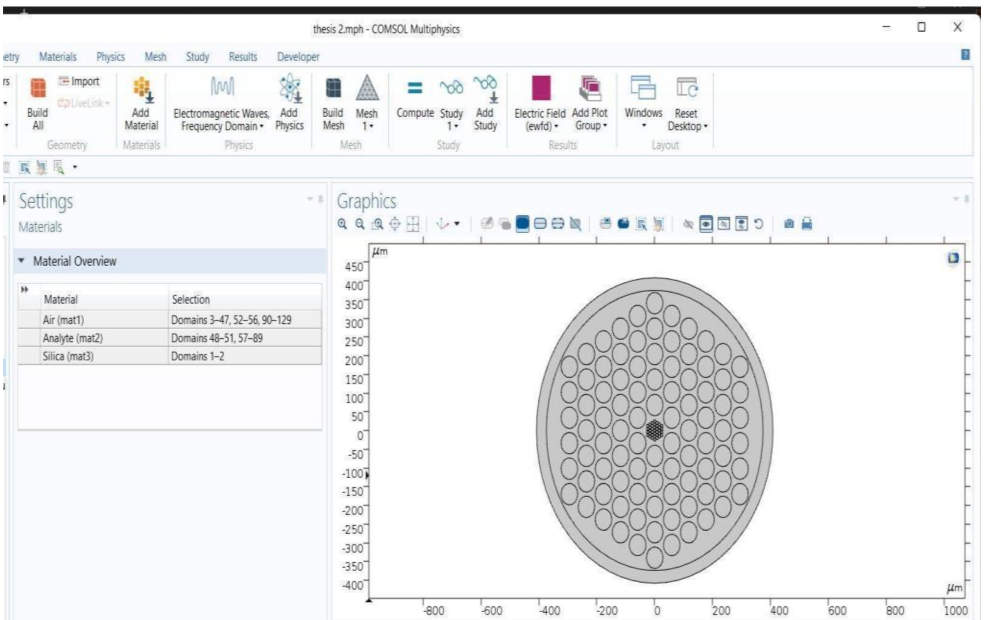
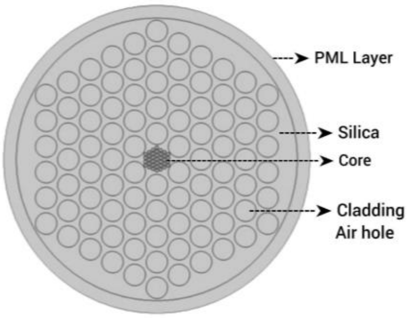


fig. (4.1): Proposed sensor design to detect alcohol.

Here are the basic design of the cladding and the core of our proposed sensor to detect alcohol. Where, the cladding is consisting of a PML layer, circular air holes and silica in a hexagonal shape.



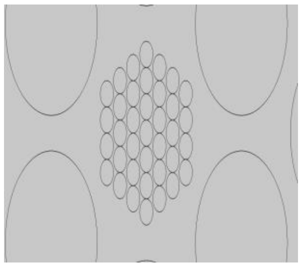


fig. (4.2): Proposed sensor design (cladding)

fig. (4.3): Proposed sensor design (core)

4.3 Design parameters

In this research, we have designed a pcf sensor with hexagonal shaped cladding and hexagonal shaped core also. Where the parameters that we have selected are given below with proper details[9]. The detailed design parameters of alcohol detecting sensor in fig. (4.4) is given below as a table:

Proposed method	Core Shape	Air hole diameter	Core air hole diameter	Pitch	PML Layer
C-PCF (Hexagonal shape)	Hexagonal	57 [um]	0.4 [um]	68 [um]	0.068 [m]

fig. (4.4): Design parameters of alcohol detecting sensor

4.4 Mesh structure

The detailed mesh structures of proposed alcohol detecting sensor in fig. (4.5) is given below:

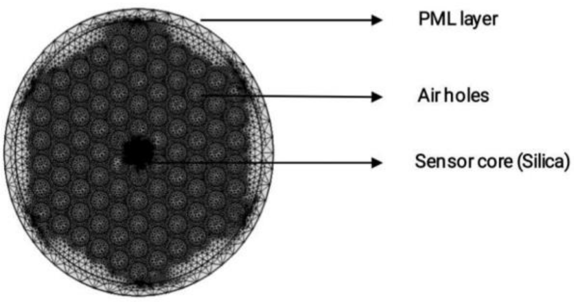


fig. (4.5): Detailed mesh structures of proposed alcohol detecting sensor

4.5 Design and simulation

In this simulation, we can see the light propagating exactly through the core of the proposed sensor that we have designed. Both the pictures of normal mode and thermal mode in fig. (4.6) and fig. (4.7) are given below:

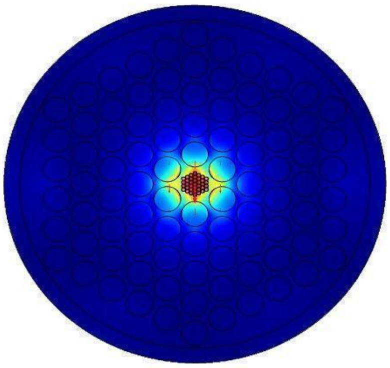


fig. (4.6): Normal mode

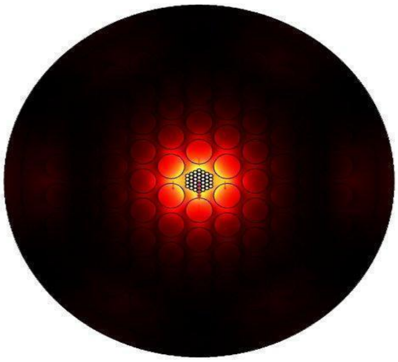


fig. (4.7): Thermal mode

4.6 Sensor parameters

All the parameters used to simulate the designed sensor are given below in fig. (4.8):

Parameters

Name	Expression	Value	Description
lamda	1.55[um]	1.55E-6 m	wavelength
p	68[um]	6.8E-5 m	pitch
t_PML	0.5*5.5*p	1.87E-4 m	
d	57[um]	5.7E-5 m	clading diameter
PML	p*1000	0.068 m	
dc	d/7	8.1429E-6 m	
p1	dc+dc	1.6286E-5 m	
A	2[um]	2E-6 m	
dcc	0.3*A	6E-7 m	
d1	0.2*A	4E-7 m	
d2	0.75*A	1.5E-6 m	
t1	5[nm]	5E-9 m	
t2	70[nm]	7E-8 m	
L	c_const/f	1.7635E-4 m	
c1	2.399964	2.4	
c2	-8.308636e-2[u...	-8.3086E10 1/...	

fig. (4.8): Sensor parameters of the proposed design

4.7 Polarization

In the Wave Optics interface, find settings related to polarization. Depending on the version of COMSOL Multiphysics, this might involve selecting polarized light sources or specifying polarization components. Choose the polarization state (linear, circular, or elliptical) of the incident light[35].

Boundary Conditions: Apply appropriate boundary conditions to simulate the interaction of light with the PCF structure. Consider whether the PCF is excited by a specific polarization state or a combination of polarizations.

Solve for Modes: Solve for the modes supported by the PCF. This can include fundamental modes and higher-order modes. The mode solutions will provide information about how different polarization states propagate through the PCF.

Visualize Results: Use post-processing tools in COMSOL to visualize the electric field components of the modes supported by the PCF. This will allow you to observe how the polarization state evolves along the length of the fiber.

Parameter Sweeps: Perform parameter sweeps if necessary. For example, you may want to study how the polarization properties change with variations in the PCF dimensions or refractive indices.

Data Analysis: Analyze the simulation results to extract relevant information about the polarization behavior. This may include calculating polarization-dependent losses, birefringence, or any other polarization-related parameters.

Optimization: If needed, use optimization tools in COMSOL to find the optimal PCF design for a specific polarization-related objective.

Evaluate Sensor Performance: Assess how the polarization characteristics impact the performance of the PCF sensor. This could involve studying the sensor's sensitivity to changes in the surrounding environment.

Remember that the specific steps and settings might vary based on the version of COMSOL Multiphysics you are using. Always refer to the software's documentation for detailed instructions and guidance on simulating polarization in PCF sensors. We can show the polarization in two poles. Which are X and Y poles. Here we have shown both polarization in normal and also in thermal mode.

4.7.1 Polarization (Normal Mode)

In the polarization section of comsol multiphysics, the polarization characteristics in normal mode impact the performance of the PCF sensor. This could involve studying the sensor's sensitivity to changes in the surrounding environment. The polarization result shows two poles of the designed sensor. Which is X-pole and Y-pole. Both the poles show how the sensor has been polarized in the result section.

All the steps before polarization are:

Geometry Setup: Define the geometry of your PCF sensor within COMSOL, including the photonic crystal fiber structure. Specify material properties, such as thermal conductivity and refractive index, for both the PCF and surrounding medium.

Physics Settings: Include the Heat Transfer Module to simulate thermal effects. Implement heat source terms to represent any heating elements or external factors affecting the sensor's temperature.

Polarization Considerations: If the sensor design involves polarization-dependent effects, set up the electromagnetic wave propagation model, considering X and Y polarizations separately.

Temperature-Dependent Refractive Index: Utilize the temperature-dependent material properties to model changes in the refractive index of the PCF and surrounding medium with temperature variations.

Boundary Conditions: Apply appropriate boundary conditions to simulate the interaction of light with the PCF structure. Consider whether the PCF is excited by a specific polarization state or a combination of polarizations.

Solver Setup: Configure appropriate solvers and boundary conditions for the thermal analysis, considering factors like conduction, convection, and radiation.

Optimization: If needed, use optimization tools in COMSOL to find the optimal PCF design for a specific polarization-related objective.

Sensitivity Analysis: Perform simulations to analyze how changes in temperature affect the guided modes of the PCF in both X and Y polarizations.

Post-Processing: Examine the simulation results to understand how the refractive index changes impact the sensor's performance.

The polarizations (both X and Y) of the designed proposed sensor are given below in the fig. (4.9) and fig. (4.10):

Polarization for X-pole:

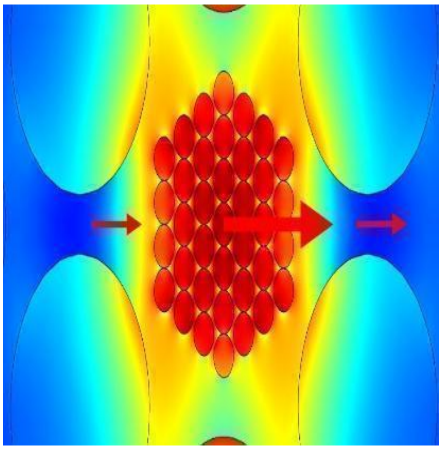


fig. (4.9): Polarization (X-pole)

Polarization for Y-pole:

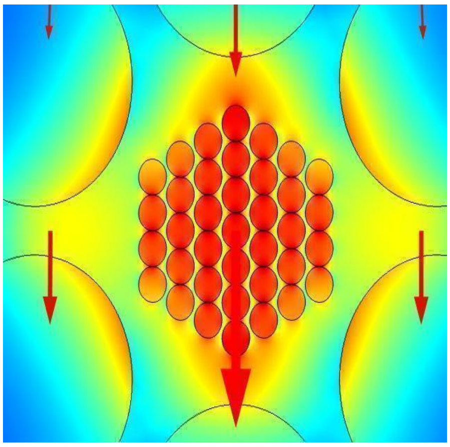


fig. (4.10): Polarization (Y-pole)

4.7.2 Polarization (Thermal mode)

In the Wave Optics interface, find settings related to polarization. Depending on the version of COMSOL Multiphysics, this might involve selecting polarized light sources or specifying polarization components. In COMSOL Multiphysics, the thermal mode in a sensor design typically involves modeling the heat transfer within the sensor structure and its interaction with the surrounding environment. Here's a simplified explanation. In a photonic crystal fiber (PCF) sensor, the thermal mode of X and Y polarization refers to the guided modes that are influenced by temperature changes. The refractive index of a substance, like alcohols, can alter with temperature variations. By detecting changes in the refractive index of the surrounding medium, the PCF sensor can indirectly sense the presence and concentration of alcohols such as Methanol, Ethanol, Propanol, and Butanol[36]. As temperature affects the refractive index differently for X and Y polarizations, monitoring the thermal modes in both polarizations allows for a more comprehensive analysis and improved sensitivity in detecting variations related to alcohol concentrations. This method leverages the interaction between the guided modes of the PCF and the refractive index changes induced by temperature fluctuations, providing a basis for alcohol detection in a sensing application. The polarizations (both X and Y) in thermal mode of the designed proposed sensor are given below in the fig. (4.11) and fig. (4.12):

Polarization for X-pole:

fig. (4.11): Thermal polarization (X-pole)

Polarization for Y-pole:

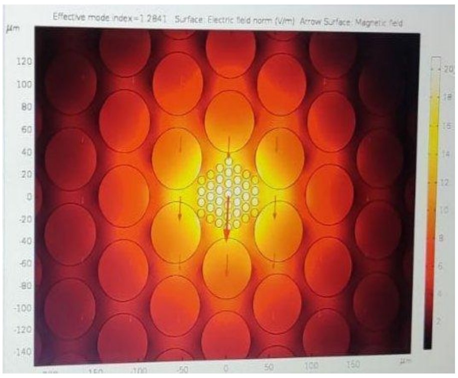


fig. (4.12): Thermal polarization (Y-pole)

4.8 Light propagation of alcohols compared with their particular refractive index

The refractive index of them is Methanol (n=1.326), Ethanol (n=1.354), Propanol (n=1.387), and Butanol (n=1.399) respectively.

Firstly, light propagates through the core of the proposed sensor for Methanol with the refractive index of Methanol (n=1.326) is shown in fig. (4.13):

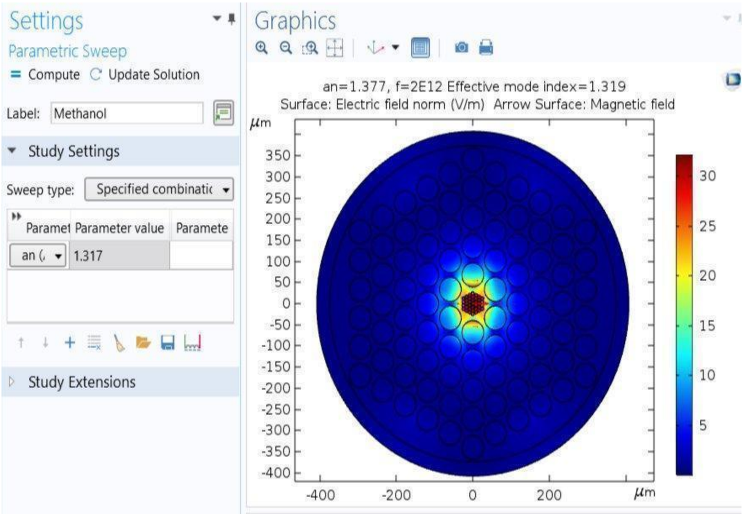


fig. (4.13): Light propagation through the core for Methanol (n=1.326)

Secondly, light propagates through the core of the proposed sensor for Ethanol with a refractive index of Ethanol (n=1.354) is shown below in fig. (4.14):

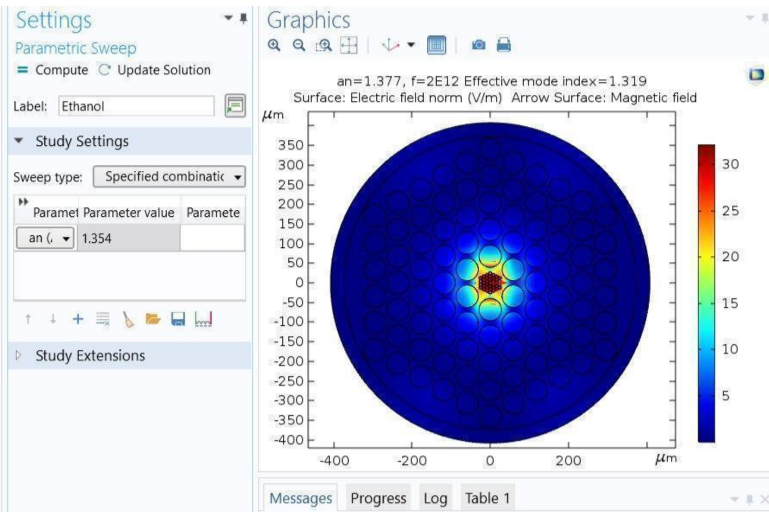


fig. (4.14): Light propagation through the core for Ethanol (n=1.354)

Thirdly, light propagates through the core of the proposed sensor for Propanol (n=1.387) with a refractive index of Propanol (n=1.387) is shown below in fig. (4.15):

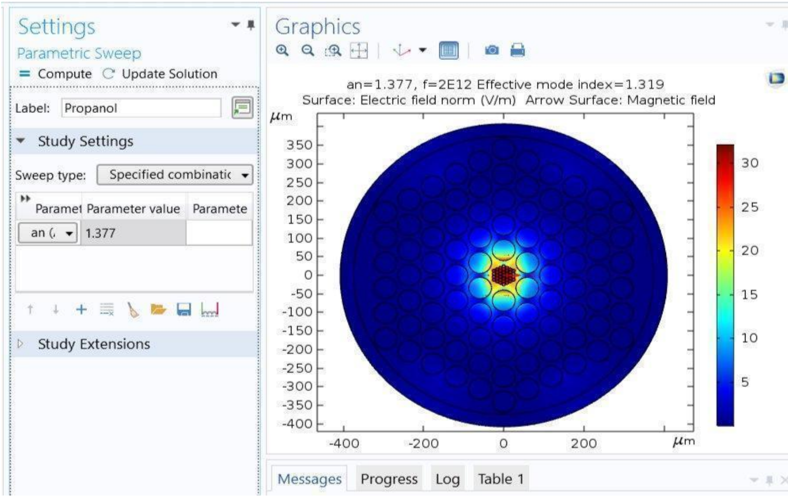


fig. (4.15): Light propagation through the core for Propanol (n=1.387)

Fourthly, light propagates through the core of the proposed sensor for Butanol with a refractive index of Butanol (n=1.399) is shown below in fig. (4.16):

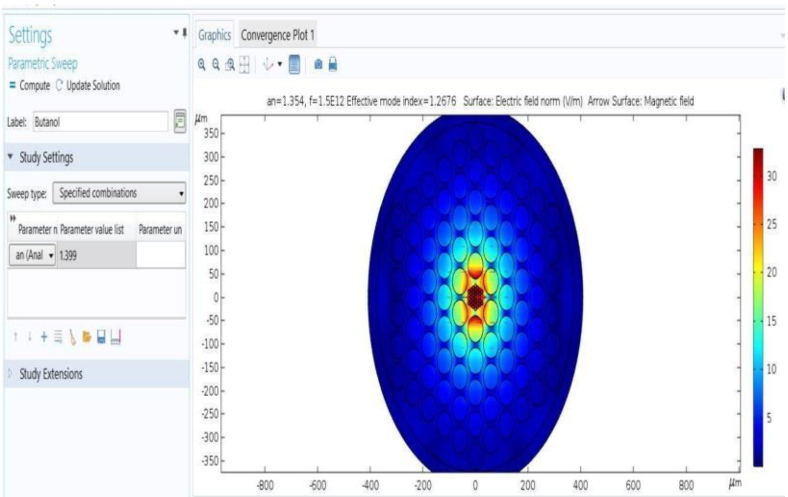


fig. (4.16): Light propagation through the core for Butanol (n=1.399)

4.9 Relative sensitivity

Relative sensitivity of alcohols like methanol, ethanol, propanol and butanol at the range of 1-3 THz has been plotted differently with MATLAB are given below in fig. (4.17), fig. (4.18), fig. (4.19) and fig. (4.20) respectively:

The relative sensitivity for Ethanol at a range of (1-3) THz, that we have got in our proposed sensor has been plotted in MATLAB shown in the following figure:

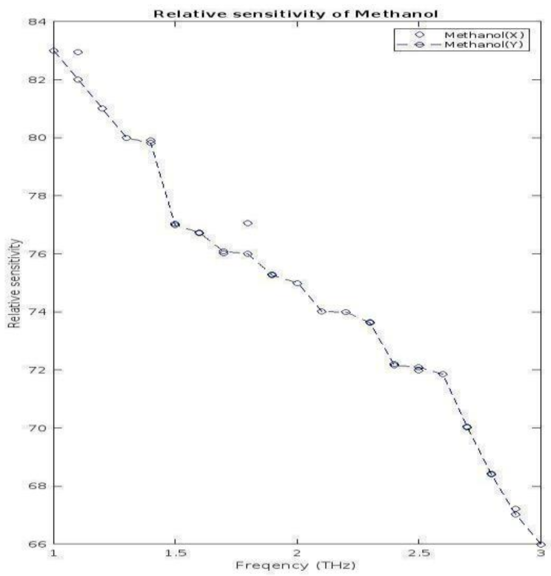


fig. (4.17): RS of Methanol at (1-3 THz

The relative sensitivity for Methanol at a range of (1-3) THz, that we have got in our proposed sensor has been plotted in MATLAB shown in the following figure:

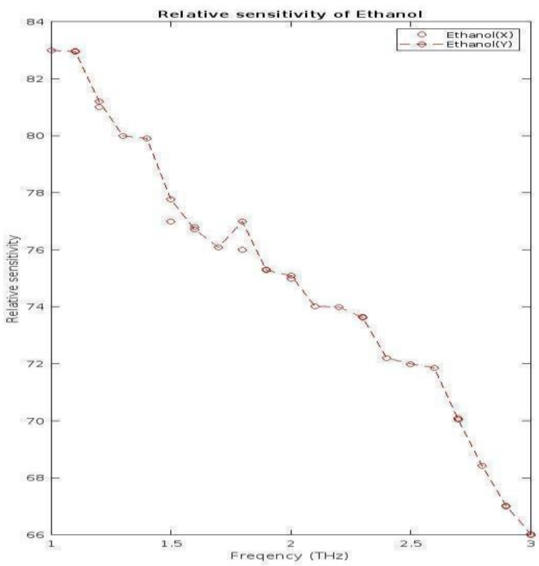


fig. (4.18): RS of Ethanol at (1-3 THz)

The relative sensitivity for Propanol at a range of (1-3) THz, that we have got in our proposed sensor has been plotted in MATLAB shown in the following figure:

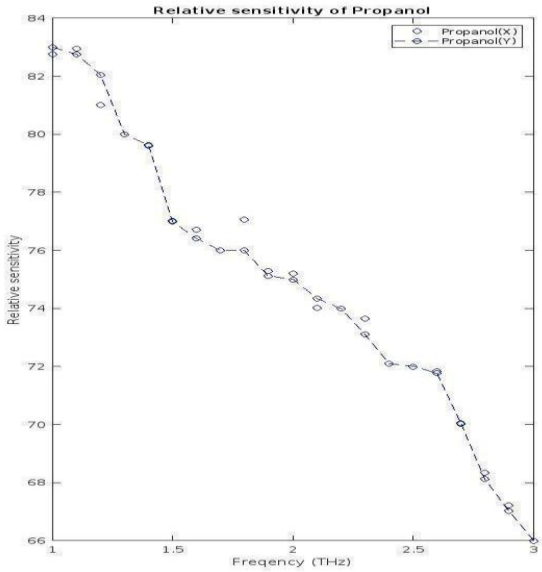


fig. (4.19): RS of Propanol at (1-3 THz)

The relative sensitivity for Butanol at a range of (1-3) THz, that we have got in our proposed sensor has been plotted in MATLAB shown in the following figure:

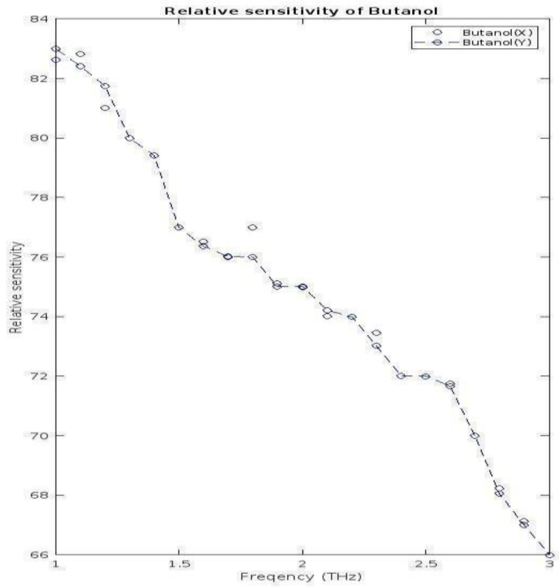


fig. (4.20): RS of Butanol at (1-3 THz)

4.9.1 Combined Relative Sensitivity of Methanol, Ethanol, Propanol and Butanol in MATLAB

Relative sensitivity for alcohols like methanol, ethanol, propanol and butanol at the range of 1-3 THz has been plotted combinedly with MATLAB are given below in the

Following fig. (4.21):

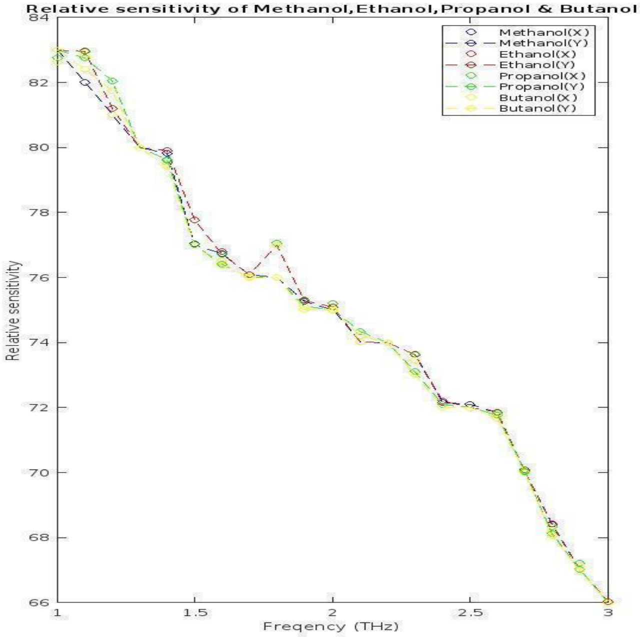


fig. (4.21): RS of Methanol, Ethanol, Propanol and Butanol at (1-3 THz)

4.10 Confinement loss

The optical waveguide confinement factor represents how well electromagnetic fields are confined to the core. It is found by the ratio of the electromagnetic fields within the core region to the electromagnetic fields within the entire waveguide structure. Calculating confinement losses in COMSOL Multiphysics involves simulating the guided modes within the photonic crystal fiber (PCF) structure and analyzing the power leakage due to confinement loss[3]. In the context of designed sensors in COMSOL Multiphysics, "confinement loss" refers to the amount of optical power that is lost from the guided modes within the sensor structure. This loss occurs when the electromagnetic field of a guided mode extends beyond the core region of the photonic crystal fiber (PCF) or waveguide, leading to radiation and energy leakage.

Some key details of confinement losses in Photonic Crystal Fiber (pcf) are given in the following points:

Guided Modes: Guided modes are electromagnetic waves confined within the core of the PCF or waveguide, propagating along its structure.

Confinement Loss Mechanism: Confinement loss occurs when the electromagnetic field of a guided mode extends into the cladding or surrounding medium, leading to radiation and loss of optical power.

Simulation in COMSOL: In COMSOL Multiphysics, the Wave Optics Module is used often to model guided modes within the PCF or waveguide structure. Confinement loss is calculated by analyzing the power distribution and monitoring the amount of power that escapes from the core.

Material Properties: The refractive indices and other optical properties of the core and surrounding medium play a crucial role in determining the extent of confinement loss.

Parameter Sensitivity: Confinement loss can be sensitive to changes in the refractive index of the materials involved. This sensitivity is often utilized in sensor designs to detect variations in the refractive index of the surrounding medium, such as those induced by the presence of analytes like alcohols.

Design Optimization: Minimizing confinement loss is a key aspect of designing efficient optical sensors. Optimizing the dimensions and properties of the PCF or waveguide helps enhance the confinement of light within the core.

Sensitivity to External Factors: Confinement loss can be influenced by external factors such as temperature changes. Therefore, in sensor designs where temperature variations are significant, it's essential to consider the impact of temperature on confinement loss[7]. In summary, confinement loss in designed sensors within COMSOL Multiphysics refers to the escape of optical power from the guided modes within the sensor structure. Understanding and controlling confinement loss is crucial for optimizing sensor performance, especially in applications where changes in the refractive index of the surrounding medium need to be accurately detected. We have showed how the imaginary part of the microstructure, which describes confinement losses not associated with absorption, varies with hole size, the number of rings of holes, and wavelength, and give the minimum number of rings of holes required for a specific loss for given parameters.

Here, we have calculated the low confinement losses (CLs) are 6.17×10^{-08} dB/m, 5.89×10^{-08} dB/m, 5.82×10^{-08} dB/m and 6.38×10^{-08} dB/m for four alcohols such as Methanol (n=1.326), Ethanol (n=1.354), Propanol (n=1.387), and Butanol (n=1.399) respectively at observed region of (1-3 THz), which are plotted in MATLAB. The CLs of these four alcohols at (1-3 THz) plotted in MATLAB is shown below in fig. (4.22):

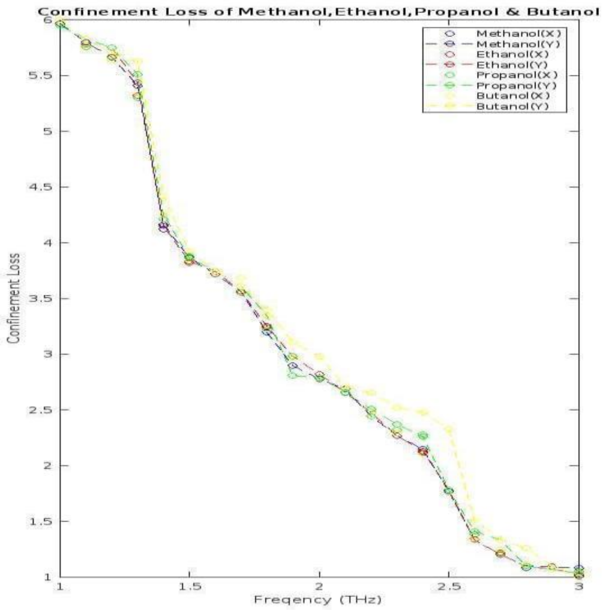


fig. (4.22): CLs of Methanol, Ethanol, Propanol and Butanol at (1-3 THz)

4.11 Effective Mode Index

In COMSOL Multiphysics, the effective mode index is a parameter that characterizes the propagation of guided modes within a waveguide or photonic structure[5]. It is a crucial parameter in optical simulations, especially when modeling the behavior of guided waves in devices such as photonic crystal fibers (PCFs) or optical waveguides. Here's a brief description:

Definition: The effective mode index (also known as the effective refractive index) represents the equivalent refractive index experienced by a guided mode in a waveguide or optical structure. It is an effective value that takes into account the confinement and guiding properties of the structure.

Calculation: In COMSOL Multiphysics, the effective mode index is typically calculated as part of optical waveguide or mode analysis simulations. The solver computes the effective mode index based on the geometry, refractive indices, and other optical properties of the materials involved.

Importance in Waveguide Design: The effective mode index is a key parameter in designing and optimizing waveguides and optical devices. It helps determine the mode profile, propagation characteristics, and how light is confined within the structure.

Sensitivity to Parameters: The effective mode index is sensitive to changes in the geometry and refractive indices of the materials. This sensitivity is often leveraged in sensor design, where variations in the refractive index of the surrounding medium can be detected through changes in the effective mode index.

Here, we have shown the effective mode index for our proposed design, which shows the data table in fig. (4.23):

1	f	Methanol (X)	Methanol (Y)	Ethanol(X)	Ethanol(Y)	Propanol(X)	Propanol(Y)	Butanol(X)	Butanol(Y)
2	0.5	1.1095	1.1096	1.1255	1.1262	1.1285	1.1295	1.1514	1.1573
3	0.6	1.1097	1.1098	1.1287	1.1289	1.1292	1.133	1.1608	1.1668
4	0.7	1.1099	1.1099	1.1292	1.1297	1.1824	1.1825	1.1711	1.1759
5	0.8	1.1239	1.1211	1.1445	1.1593	1.1989	1.1999	1.1789	1.1817
6	0.9	1.1401	1.1434	1.1622	1.1701	1.2111	1.2287	1.1855	1.1894
7	1	1.1621	1.1671	1.1895	1.1985	1.2223	1.2331	1.1937	1.1943
8	1.1	1.1901	1.1871	1.2095	1.2151	1.2262	1.2397	1.2025	1.2091
9	1.2	1.2104	1.2012	1.2245	1.2379	1.2422	1.2418	1.2187	1.2374
10	1.3	1.2378	1.2101	1.2405	1.2485	1.2533	1.2533	1.2494	1.2571
11	1.4	1.2401	1.2213	1.2545	1.2515	1.2594	1.2597	1.2617	1.2679
12	1.5	1.2451	1.2367	1.2655	1.2699	1.2697	1.2699	1.2714	1.2719
13	1.6	1.2519	1.2451	1.2745	1.2795	1.2787	1.2782	1.2786	1.2859
14	1.7	1.2672	1.2541	1.2861	1.2898	1.2875	1.2881	1.2899	1.2946
15	1.8	1.2711	1.2634	1.2931	1.2989	1.2975	1.2982	1.2997	1.3072
16	1.9	1.2862	1.2739	1.3065	1.3098	1.3079	1.3086	1.3147	1.3193
17	2	1.2921	1.2829	1.3142	1.3187	1.3182	1.319	1.3257	1.3296
18	2.1	1.3001	1.2914	1.3238	1.3286	1.3289	1.3298	1.3374	1.3397
19	2.2	1.3145	1.3019	1.3347	1.3393	1.3394	1.3403	1.3439	1.3481
20	2.3	1.3276	1.3121	1.3439	1.3492	1.3496	1.3505	1.3511	1.3571
21	2.4	1.3356	1.3244	1.3529	1.3587	1.3595	1.3604	1.3596	1.3628
22	2.5	1.3421	1.3339	1.3624	1.3681	1.369	1.3698	1.3653	1.3679
23	2.6	1.3528	1.2417	1.3707	1.3745	1.3781	1.3788	1.3695	1.3717
24	2.7	1.3576	1.2508	1.3788	1.3806	1.3867	1.3874	1.3756	1.3783
25	2.8	1.3623	1.2554	1.3833	1.3865	1.3949	1.3955	1.3799	1.3818
26	2.9	1.3678	1.2631	1.3898	1.3939	1.4027	1.4032	1.3856	1.3889
27	3	1.3721	1.2671	1.3985	1.3988	1.4101	1.4105	1.3933	1.3997

fig. (4.23): Data table for the effective mode index of Methanol, Ethanol, Propanol and Butanol.

We have also plotted all the effective mode index data for Methanol, Ethanol, Propanol and Butanol combinedly in MATLAB at the range of (0.5-3) THz.in the following in fig. (4.24):

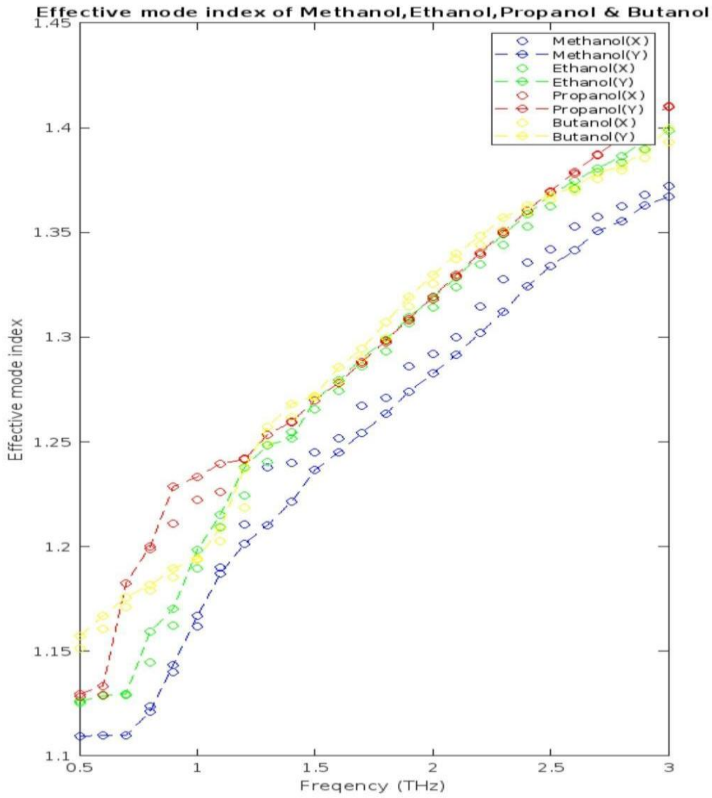


fig. (4.24): EMI chart of Methanol, Ethanol, Propanol and Butanol plotted in MATLAB.

4.12 Results obtained in this research

In this study, an optical sensor for detecting alcohols to prevent drunk driving in highways, made of circular air holes (CAH) in the cladding which is hexahedron in shape and a hexahedron core which is also very compact in size is suggested here. COMSOL Multiphysics software for developing and analyzing the sensing qualities of a PCF based sensor using particular elements technical as solution. In the THz frequency band, the described PCF structure has a high relative sensitivity of 83.05%, 82.96%, 82.75% and 82.64%. Low confinement losses (CLs) are 6.17×10^{-08} dB/m, 5.89×10^{-08} dB/m, 5.82×10^{-08} dB/m and 6.38×10^{-08} dB/m for four alcohols such as Methanol (n=1.326), Ethanol (n=1.354), Propanol (n=1.387), and Butanol (n=1.399) respectively at observed region of 1 THz.

4.13 Comparison with recent works

Here we have compared the results of our proposed design for alcohol detection with recent works. Which are given below in the following table:

TABLE I: COMPARISON WITH RECENT WORKS.

Prior in PCFs	Opera-ting region (f) THz	RS (%)	CL (dB/m)	(Structure design)	
				core	*cladding*
PCF[9]	1	60.05%	1.43×10^{-11}	Rotated Hexa-Circular holes	Heptagonal
PCF[10]	1	64.00%	1.12×10^{-11}	Elliptical holes	Quasi
PCF[11]	1	74.54%	7.72×10^{-08}	Slotted core	Quasi
PCF[12]	1	78.80%	2.19×10^{-09}	Elliptical holes	Quasi
PCF[13]	1	45.13%	5.58×10^{-05}	Circular holes	Hexagonal
PCF[14]	1	55.56%	1.00	Rhombic holes	Hexagonal
PCF[15]	1	80.93%	1.23×10^{-11}	Elliptical holes	Circular
PCF [proposed]	1	83.05%	6.17×10^{-08}	Hexagonal	Hexagonal

Chapter 05

Conclusion

5.1 Introduction

The exploration began with a comprehensive review of existing sensor technologies, scrutinizing their principles, advantages, and challenges. Subsequently, we embarked on the development and characterization of PCF-based alcohol sensors, leveraging the distinctive features of PCFs to enhance sensitivity, selectivity, and overall performance. Our investigation involved meticulous experimentation, data analysis, and comparison of results, providing valuable insights into the viability of PCF technology in the realm of alcohol detection. As we navigate through the concluding chapter, the synthesis of knowledge obtained from these diverse sensor technologies becomes apparent. The findings encapsulated herein not only contribute to the growing body of knowledge in sensor development but also offer practical implications for real-world applications, particularly in the context of alcohol detection.

5.2 Conclusion

The findings of this research contribute to the growing body of knowledge in the field of photonic sensors, providing valuable insights for the development of efficient and reliable sensing devices. Further experimental validation of the simulated results will be crucial for transitioning these simulations into practical, real-world implementations. This thesis sets the stage for continued exploration and innovation in the domain of compact-sized PCF sensors, paving the way for their integration into next-generation sensing technologies. In conclusion, the development and implementation of a compact-sized Photonic Crystal Fiber (PCF) sensor for the detection of alcohols, including methanol, ethanol, propanol, and butanol, represent a significant stride towards enhancing highway safety and preventing accidents. The utilization of PCF sensors in this context capitalizes on the unique properties of photonic crystal fibers, enabling precise and reliable detection of alcohol vapors. The compact size of the PCF sensor makes it particularly advantageous for integration into portable and cost-effective sensing systems, providing a scalable solution for widespread deployment in various highway environments. The ability to detect a range of alcohol types addresses the diverse nature of potential hazards on the road, contributing to a comprehensive safety strategy. By focusing on alcohol detection, the PCF sensor presented in this thesis offers a valuable tool for mitigating the risks associated with impaired driving.

Rapid and accurate identification of alcohol presence in the vicinity allows for timely intervention, promoting proactive measures to ensure public safety and reduce the incidence of accidents. Furthermore, the potential impact of this compact-sized PCF sensor extends beyond highway safety, with applications in diverse fields such as law enforcement, industrial safety, and environmental monitoring. The adaptability and sensitivity of the PCF sensor make it a versatile technology with far-reaching implications for creating safer and more secure communities. As we embrace innovative technologies to address contemporary challenges, the compact-sized PCF sensor developed in this research stands as a testament to the potential of photonics in shaping a safer and more connected world. As we look to the future, continued research and development in this field hold the promise of further advancements, ultimately contributing to a safer, more sustainable, and technologically advanced transportation landscape.

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