INVESTIGATION ON MAPPING HIGHLY SENSITIVE AND TUNABLE HOLLOW CORE PHOTONIC CRYSTAL FIBER FACILITATED WITH ULTRA-SHORT PULSE FOR MULTIPURPOSE APPLICATIONS

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Certification of Approval

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Declaration of Authorship

We, Abdullah Al Mahmud Nafiz (190021221), Afra Anika Protiva (190021230) and Mohammad Tamim (190021302) declare that the thesis titled," **INVESTIGATION ON MAPPING HIGHLY SENSITIVE AND TUNABLE HOLLOW CORE PHOTONIC CRYSTAL FIBER FACILITATED WITH ULTRA-SHORT PULSE FOR MULTIPURPOSE APPLICATIONS**" that has been proposed are completely belong to us.

We also confirm that-

- This thesis has done as part of the requirements for the completion of our **Bachelor of Science in Electrical and Electronic Engineering degree at the Islamic University of Technology (IUT)**
- None of the content is submitted for the purpose of any other degree.
- We have always clearly attributed the sources when while referring to existing research
- Some portion of this thesis book is under peer review as a unique research article in "Optics and Lasers in Engineering" journal

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Acknowledgement

By the mercy of the Almighty Allah (SWT), we want to declare the accomplish of our thesis work which is having extra-ordinary outcomes, which will serve in the field of photonics and future research. We would be grateful to acknowledge our heartfelt appreciation and cordial thanks to our thesis supervisor Mr. Sheikh Montasir Mahbub, Lecturer, Department of Electrical and Electronic Engineering, Islamic University of Technology for his workaholic mindset and unwavering support. During the whole journey starting from conceptualization up to completion of thesis book we cannot ask more from him. His helpful demeanor and belief in our capabilities always boosted our nerves. Moreover, we are grateful to the respected Faculty members of the Electrical and Electronic Engineering Department for their guidance, evaluation, management and helpful attitude in case of understanding the OBE concept and constant support. Finally, there is no doubt to mention about that, our fellow batchmates and parents were always having patience and believe on us. Thus, a fruitful conclusive remark we can have right now.

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List of Acronyms

PCF – Photonic Crystal Fiber

HC-PCF – Hollow Core Photonic Crystal Fiber

USP- Ultra short Pulse

MUS- Material Under sensing

HC- Hollow core

NC- Normal Core

SC- Solid Core

SPR- Surface plasmon resonance

PBG- Photonic Bandgap

Neff- effective Refractive index

RI- Refractive Index

MIR- Mid Infrared Ray

NIR- Near Infrared Ray

NLSE-Nonlinear Schrödinger equation

SSFM- Split Step Fourier Method

SPM- Self-phase modulation

XPM- cross-phase modulation

TPA- Two-photon absorption

ThPA- Three-photon absorption

FWM- Four-wave mixing

FWHM- Full width half maximum

SHG- Second Harmonic Generation

CL- Confinement Loss

ABSTRACT

Over the years, researchers have proposed numerous designs for traditional PCFs, featuring various structures, sensitivities, and confinement losses. However, most of the designs proposed offer either high sensitivity with high confinement losses or low sensitivity with low losses and too much computations. After carefully reviewing several prior works and considering their problems, we have developed our sensors by analyzing changes in the shape of ultra-short pulses (USP) passed through Hollow Core Photonic Crystal Fiber (HC-PCF) using COMSOL Multiphysics 5.6. Nowadays, adulteration in fuel is a noteworthy concern due to its impact on engine performance, environmental pollution, and economic losses. Detecting adulteration in diesel fuel is a challenging task and it requires identifying adulterants without compromising safety or quality standards.

We introduced a novel approach to sense diesel adulteration levels by analyzing changes in the shape of USPs passing through HC-PCF. This method advantages are fiber characteristics, including nonlinear parameters, to see how the shape of ultra-short pulses changes as they travel through diesel-filled HC-PCF. With the proposed sensor, we achieved remarkable compression sensitivity and power increases for diesel samples with varying adulteration levels under different input configurations. The method demonstrated a minimum sensitivity of 16%, indicating that the pulse is compressed by a factor of six, and the maximum power increase observed was 648.072 W.

Thesis Framework

A brief overview of all the chapters in this book has been given below.

CHAPTER 1: Introduction

This chapter inaugurates with the proper reasoning and overview of choosing photonics as research topic and background knowledge. It discusses with Nano sensing techniques, photonics and optical fibers, the concept of photonic band gaps, and the significance of HC-PCFs. The introduction also covers ultra-short pulses and presents the problem statement for the thesis.

CHAPTER 2: Literature Review

This portion of the book deals with existing literature related to HCPCFs. Highlighting computational complexities and advantages of hollow-core fibers over non-conventional photonic crystal fibers (NC-PCFs). The chapter then addresses issues related to ultra-short pulse power efficiency and the interaction between nonlinear fiber characteristics, ultra-short pulses, and HCPCFs, supported by examples from various papers.

CHAPTER 3: Detailed Methodology

This chapter encompasses the overall procedure of working by covering theoretical explanation and technical knowhow. It begins with Maxwell's equations and progresses to the Split Step Fourier method. The chapter discusses fiber length considerations and pulse alteration, setting the stage for the explanation of resulting parameters in subsequent chapters.

CHAPTER 4: Computational Methods / Mathematical Interpretation

Computational Methods chapter provides an in-depth explanation of the computational methods and mathematical interpretations of various parameters. It contrasts traditional resulting parameters with proposed parameters, such as compression sensitivity and power upsurge soliton number, offering a detailed explanation of each.

CHAPTER 5: Design and Nonlinearity Analysis of Elliptical shape Hollow core Photonic crystal Fiber facilitated with Ultra-short Pulse

The chapter introduces the first proposed design specifically for petrochemical industries. It details the design considerations and tests for fiber characteristics, including V parameter, area effective, power fraction, and effective refractive index (n_{eff}) vs. wavelength. The chapter also presents resulting parameters like power upsurge and compression sensitivity, followed by a comparative analysis.

CHAPTER 6: Fabrication Compatibility

In this chapter the fabrication compatibility of the proposed designs is discussed. It explores the practical aspects of fabricating HCPCFs and their feasibility in real-world applications.

CHAPTER 7: Concluding Note with Future Scopes

The concluding chapter incorporates the findings overall sum up of the research and suggests future research directions. It reflects on the implications of the study and potential advancements in the field of HCPCFs and related technologies.

CHAPTER 8: CO-PO Alignment Based on Template

This chapter aligns the course related outcomes (CO) with the program-based outcomes (PO). It includes graphical representations and other visual aids to demonstrate the alignment, enhancing the understanding of how the research meets educational and professional standards.

Chapter 1

Introduction

1.1 Background Study and Motivation

Photonics is regarded as the branch of physical science focused on light waves, encompassing the generation, detection, and manipulation of light. The term "photonics" gained prominence in the 1960s following the revolutionary invention of the laser and subsequently the laser diode. Initially, it described a field aiming to use light for tasks typically handled by electronics, which explains its name. Most photonic applications are in the range of visible and NIR light [1].The concept became more widely recognized with the rise of fiber optic communications in the 1980s[2].

1.1.1 Why Photonics

Photonics spans a wide range of scientific and technical implementations, incorporating the generation of lasers, detection of biological and chemical substances, medical diagnosis and treatment, display technologies, and optical computing. If the continuing progress in silicon photonics proves successful, it is likely that photonics will see more expansion[2]. Photonic sensors are instruments that employ light to detect and measure a range of physical factors, including temperature, pressure, chemical composition etc. Fiber-optic sensors, frequently used in distributed sensing applications, measure parameters along their length by utilizing the propagation of light through optical fibers. Photonic sensing devices have gained significant importance across numerous sectors including agriculture, medicine, biochemical sensing, and manufacturing. Their heightened sensitivity allows for the precise detection and classification of even the smallest changes in material properties and also the properties of the surrounding environment. This high level of accuracy is inevitable for applications requiring precise measurements, such as medical diagnostics and environmental monitoring (pollution level analysis).

Photonics, combined with material science, offers a captivating field of study, especially at the nanoscale. As nanotechnology progresses, Moore's Law is increasingly supported by the advancements in photonic research, which emphasizes energy-efficient approaches. Compared to electronic devices, which face challenges like larger size and significant heat dissipation, photonic devices offer remarkable improvements. They are not only smaller but also more efficient in managing heat, making them superior for applications requiring high precision and performance. Plasmonic devices further enhance these benefits by manipulating light at the nanoscale, outperforming traditional electronics. Therefore, photonics emerges as a better solution in terms of adhering to Moore's Law, reducing device size, and minimizing heat dissipation.

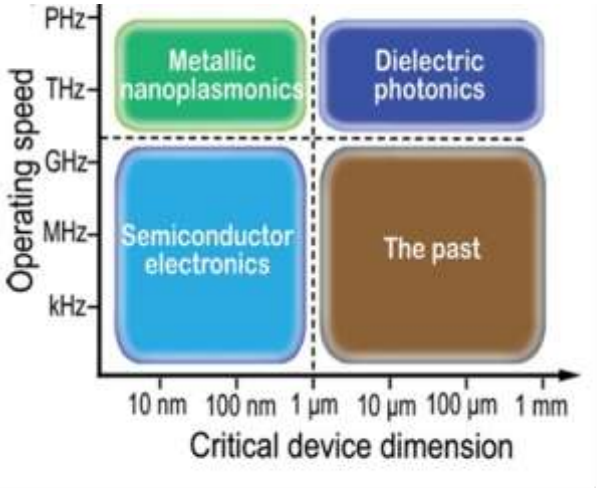


Figure 1.1: Speed vs Dimension of devices[3]

1.1.2 Why Optical Fibers

An optical fiber is a highly efficient medium for transmitting light signals over long distances. It is made of flexible glass or plastic, allowing for seamless transmission from one end to the other[2]. Progress in photonics relies heavily on optical fibers. The 19th-century discovery of complete internal reflection guides light in these fibers. Fiber optics started sending images via glass fiber bundles in the 1960s despite high signal losses. These losses dropped significantly in following decades. The 1970s saw attenuation drop to 20dB/km, and additional advancements replaced glass with silica, lowering losses to 0.2 dB/km by 1979. Nonlinear fiber optics and optical fiber communication advanced greatly due to these developments.

In 1973, a significant breakthrough occurred in the field of nonlinear fiber optics. Researchers discovered that optical fibers have the ability to sustain soliton-like pulses as a result of a precise equilibrium between dispersive and nonlinear effects. The experimental verification of optical solitons in 1980 was a significant breakthrough in this particular area of study. This breakthrough enabled major advancements in the generation and manipulation of very brief optical pulses throughout the 1980s, greatly improving the efficiency and efficacy of optical communication systems. Optical fibers have seen significant advancements, transforming from ineffective media to become the essential foundation of contemporary telecommunications. They now provide rapid and comprehensive transfer of data and promote the development of creative applications in the field of nonlinear optics.

Beginning in 1996, novel types of fibers were developed, known by various names including photonic crystal fibers, holey fibers, and microstructured fibers. Structural modifications in these fibers influence both their dispersive and nonlinear properties. The nonlinear properties are enhanced considerably inside them because of a relatively small core size. These advancements clearly indicate that the field of nonlinear fiber optics has significantly expanded over the past years and is anticipated to continue thriving in the foreseeable future.

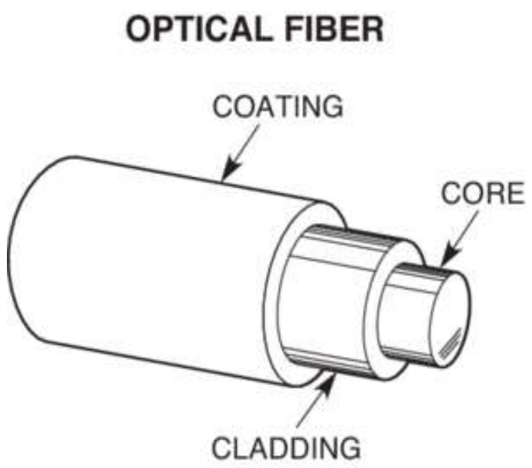


Figure 1.2 Optical Fiber[4].

1.2 Photonic Crystal Fiber

In 1996 PCFs were investigated at the University of Bath, UK. The ability of PCF to confine light gave it more advantages than any other type of optical fiber. The lowest reported attenuation of solid core photonic crystal fiber is 0.37 dB/km, and for hollow core is 1.2 dB/km[5]Photonic crystal fibers have a periodic arrangement of air holes surrounding a solid core or hollow core. PCF are being used in a wide range of applications starting from fiber-optic communication, fiber lasers, nonlinear devices, highly sensitive sensors and other areas[6]. PCF research has been guided two arenas on the structure of the fiber namely (a) Solid Core PCF and (b) Hollow core PCF.

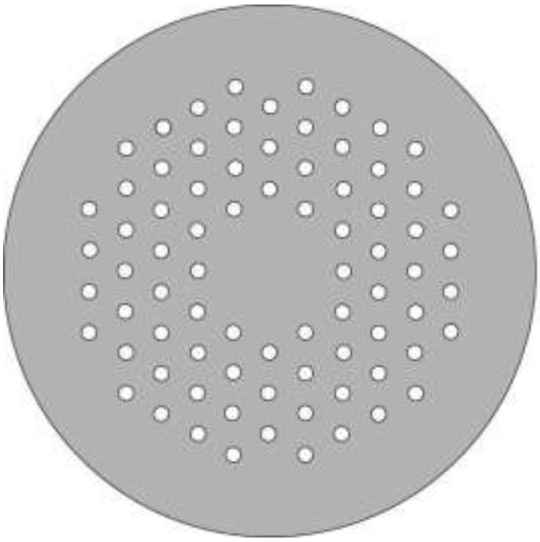


Figure 1.3 Solid Core PCF

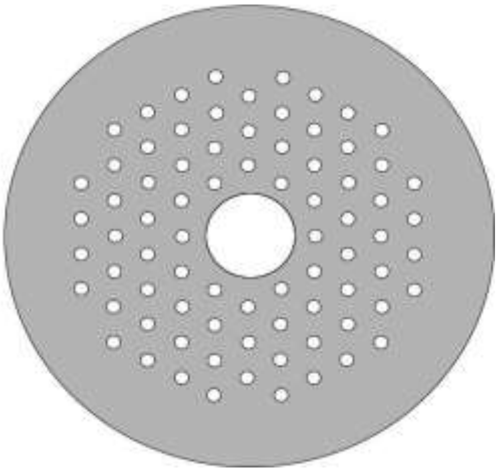


Figure 1.4 Hollow Core PCF

Photonic crystal fibers (PCFs) with a solid core feature a low-index cladding surrounding a core with a higher effective index. Conversely, hollow core fibers possess a core with a lower index compared to the cladding medium, where light confinement within the core is achieved through scattering and interference, resulting in the formation of an evanescent field in the cladding.

Despite the remarkable progress made in conventional optical fibers with solid cores and cladding since the seminal work of Kao and Hockham in 1966, and their subsequent dominance in wired transmission, with around 550 million kilometers installed globally by 2022, the field continues to innovate with the development of new fiber types for communication networks. These advancements are driven by the need for higher data rates, reduced latency, and improved signal integrity. Emerging fiber technologies, such as hollow-core photonic crystal fibers (HC-PCFs) and multi-core fibers (MCFs), promise to further revolutionize optical communication. HC-PCFs, for example, offer lower latency and reduced nonlinearity, while MCFs increase capacity by allowing multiple signals to be transmitted simultaneously within a single fiber. Such innovations underscore the ongoing evolution in optical fiber technology, ensuring that communication networks can meet the ever-growing demands of the digital age.[7].

The primary motivation for developing HCFs is to overcome the limitations inherent in fused silica (SiO_2). These limitations include:

- Minimum signal power attenuation of 0.14–0.16 dB commercially available laser (1550 nm).
- Low-loss bandwidth of 1250–1750 nm, or 68 THz at 0.40 dB/km.
- Latency and effective refractive index of neff = 1.45–1.47.
- Optical nonlinearities, particularly Kerr, Raman, and Brillouin effects.
- The maximum optical power that the fiber can carry without distortion.

HC fibers eliminate these constraints, as the majority of the guided radiation propagates through gas, reducing the interaction with glass by a factor of 100 to 100,000 compared to solid-core fibers, depending on the specific type of HCF[8].

1.2.1 Light Guiding mechanism

Conventional Optical fibers guided light through the fiber using index guiding but PCF's depending on their structure have different guiding mechanisms. Light is guided in 2 mechanisms in PCF depending on the type of structure being used. These mechanisms are (a) Index Guiding and (b)Photonic band gap.

Solid core photonic crystal fibers (PCFs) follow the index guiding principle of conventional optical fibers but feature a solid core surrounded by air-hole cladding, creating a higher effective refractive index contrast between core and cladding. This design enables significantly improved light confinement compared to traditional optical fibers.

In HC-PCF, photonic bandgap (PBG) mechanism is exploited. The hollow core in the center of the periodic microstructure of the air holes acts as a defect resulting in a band gap due to the lower RI of the core than the cladding. Thus, guiding light through the HC. Another possible advantage of a HC is the ability to dynamically introduce materials into the core, such as unknown gas substances, tissue or plasma specimens, petrochemical liquids etc.

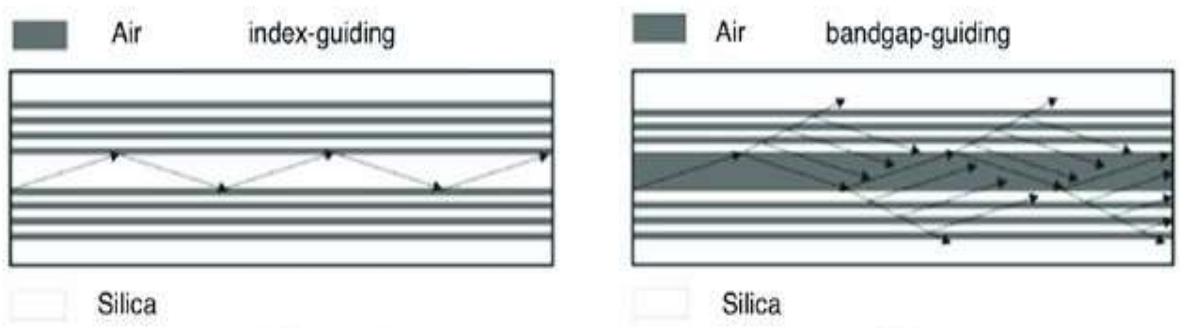


Figure 1.1 Guiding mechanisms (a) Index Guiding (b) Bandgap-guiding[9]

1.3 Ultra Short Pulse

Ultrashort laser pulses are defined as pulses of electromagnetic radiation with durations approximately ten of picoseconds (10^{-12} seconds). Pulses lasting a few picoseconds were first produced in the 1960s[10]. shortly after the invention of the laser. Throughout the following decade, advancements in pulse generation techniques and the use of large dye lasers with broad emission bandwidths reduced pulse durations to the scale of hundreds of femtoseconds (10^{-15} seconds). In the 1980s, dye lasers generated pulses shorter than 10 femtoseconds. The widespread availability of these systems in universities and research laboratories led to numerous applications of ultrashort laser pulses in various fields. Today, a wide variety of ultrashort pulse laser systems are available both commercially and in development, capable of generating pulses ranging from a few femtoseconds to hundreds of femtoseconds and picoseconds. These systems can produce energies from nanojoules to thousands of joules[11][12]. Ultrashort laser pulses, characterized by their picosecond to femtosecond durations and immense electric and magnetic fields, enable the study of ultrafast phenomena and induce significant material modifications through high-intensity nonlinear effects. These pulses, with peak powers in the tens of kilowatts, are pivotal in advanced detection techniques and high-energy electron acceleration. [13].

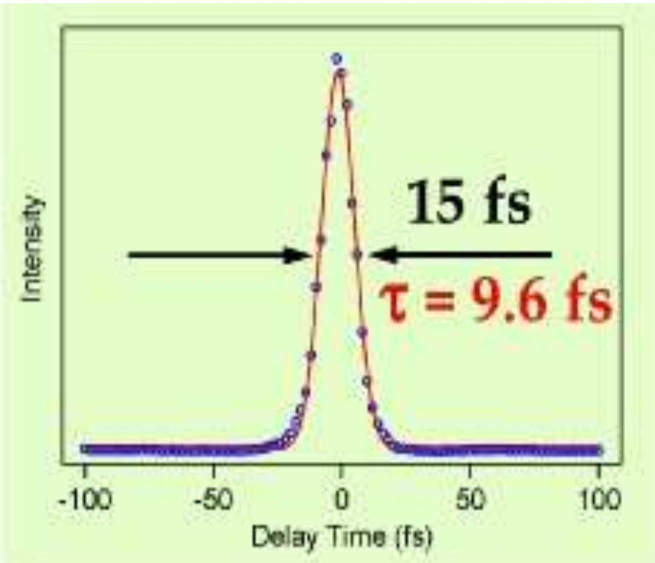


Figure 1.6 Ultra short pulse Intensity vs Delay time.[14]

1.4 Problem Statement

Diesel is highly regarded among fossil fuels for its efficiency, durability, and reduced emissions, making it a favored choice in many applications. However, in developing countries like Bangladesh, Pakistan, and India, fuel adulteration is a widespread issue. This involves mixing foreign substances such as kerosene, gasoline, or used engine oil with diesel to increase its volume. Such practices are carried out by both organized crime syndicates and individual distributors, affecting the entire supply chain from refineries to distribution networks. This adulteration not only worsens air pollution but also poses significant health risks. Detecting adulteration in diesel is particularly challenging due to the need to identify adulterants without compromising safety or quality standards.

Fuel adulteration detection employs advanced analytical techniques and specialized equipment, assessing properties like density and viscosity, and using methods such as gas chromatography and Fourier transform. Although traditional methods and optical fiber sensors, including Bragg grating sensors, provide high sensitivity, they encounter limitations such as accuracy, fragility, immobility, and cross-sensitivity issues.

Chapter 2

Literature Review

2.1 HC-PCF Literature Review

Optical fibers remain crucial across various fields, but HC-PCFs stand out due to their unique features, which have opened up significant applications in sensing, communications, and active optical devices. To effectively use HC-PCFs in these areas, it is essential to study and understand their operation in depth.

The paper "Simulation of Hexagonal HC-PCF With Circular Holes using COMSOL Multiphysics Software" presents a simulation of seven-cell HC-PCFs using COMSOL Multiphysics 5.5 software, employing finite element analysis. The step-by-step simulation process is detailed. The fiber characteristics were subsequently analyzed within the 1500–1600 nm wavelength range. Key aspects such as the fundamental mode profile, intensity, effective mode index, confinement loss, and the influence of pitch—the most critical structural parameter—were examined in detail[15].

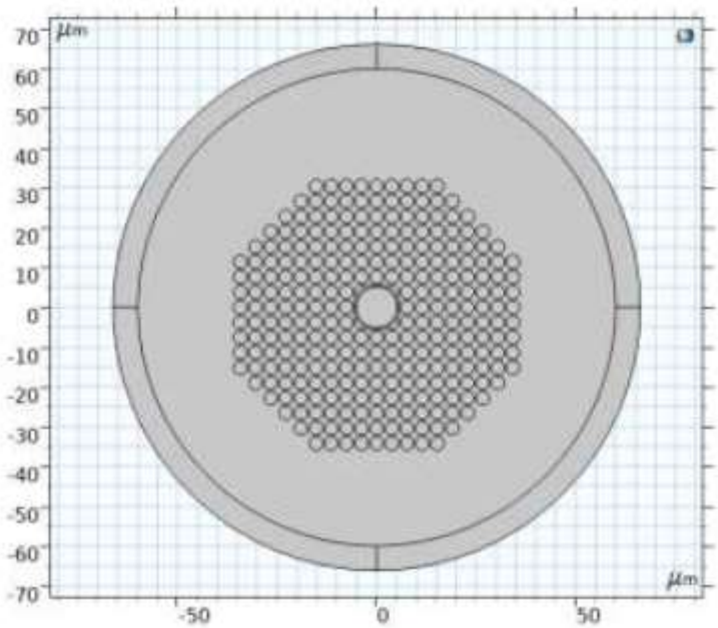


Figure 2.1 HC-PCF in Hexagonal Cladding Configuration[15]

In the paper "Efficient way for detection of alcohols using hollow core photonic crystal fiber sensor" Habib et al. proffers a HC-PCF for detecting and differentiating various alcohols. The sensor achieves a relative sensitivity of 87% and low CL of 10^{-10} dB/m. The RI and temperature-dependent properties of the alcohols are used to accurately simulate the sensor's performance. The sensor's geometry is simple and can be easily fabricated using cutting-edge technologies of very large-scale integration. The paper also analyzes other important properties of PCF-based sensors, such as numerical aperture and spot size. However, keeping track of 7 resulting Parameters at a time made the overall detection procedure computationally heavy and the experimental setup became complex. In this case, Nonlinear property analysis can come handy. Overall, this sensor offers a promising solution for alcohol detection with potential applications in various fields[16].

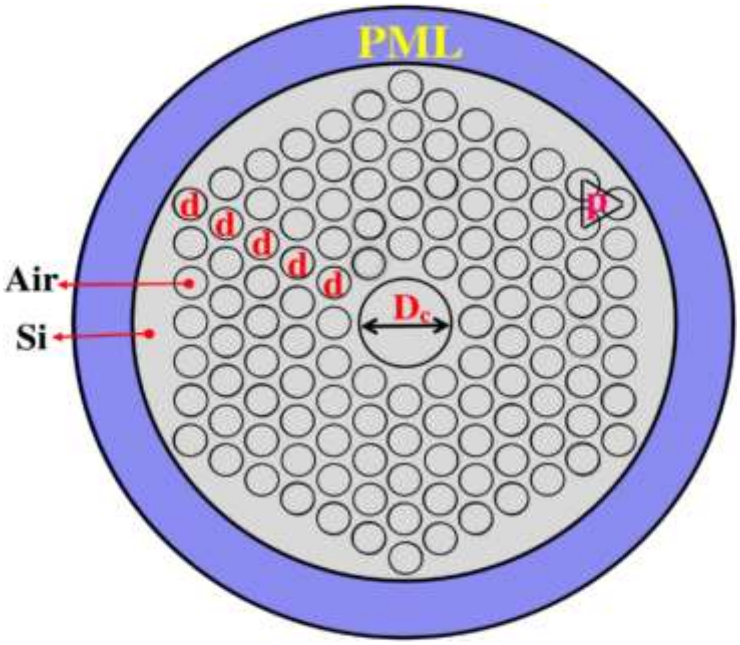


Figure 2.2 HC-PCF proposed by Habib et. al[16].

In the paper titled "Modeling and numerical analysis of a fabrication-friendly PCF-based biosensor: Milk sensing" by Abdullah Al-Mamun Bulbul et al. a unique HC-PCF based biosensor was modeled and numerically analyzed[17]. This biosensor is specifically designed to detect cow milk, camel milk, and water within the terahertz (THz) band (1-2 THz). The sensor's design includes a periodic arrangement of circular holes to enhance its fabrication feasibility using existing manufacturing methods. The study emphasizes the practical application of PCF-based biosensors in ensuring milk quality, an essential factor for the dairy industry. The proposed model achieves high sensitivity and low loss Overall, while this paper contributes valuable insights into the design and feasibility of HC-PCF-based biosensors, it is important to recognize its limitations in sensitivity and application breadth compared to more advanced nonlinear optics HC-PCFs.

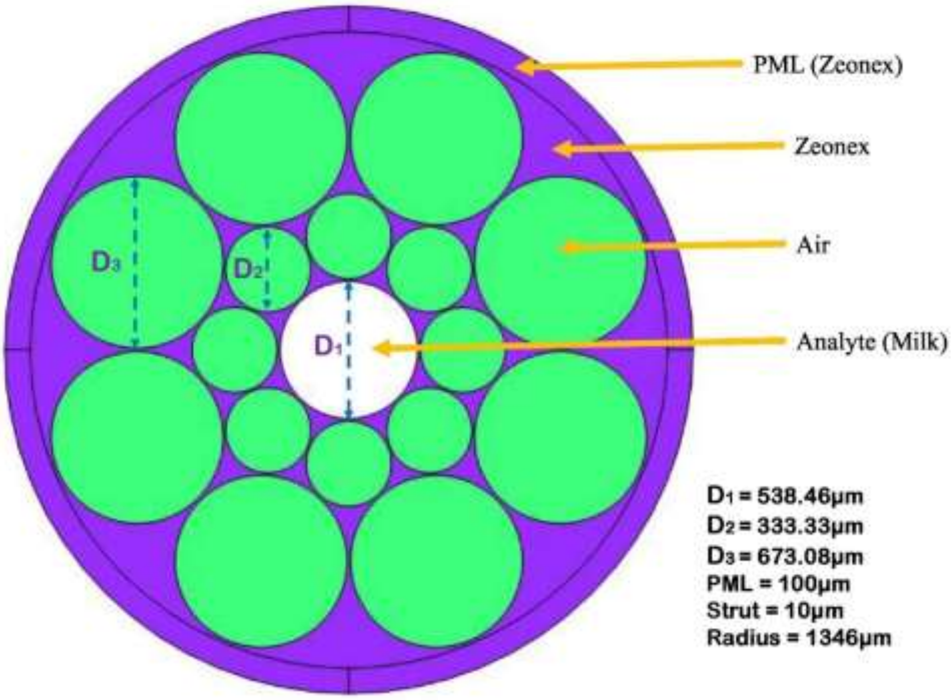


Figure 2.1 HC-PCF proposed by Abdullah Al-Mamun Bulbul et al.

Detecting changes in liquids using HC-PCFs is well-established in research. Mahmoud et al. designed a sensor for blood component detection using an HC-PCF with a single circular air hole in the core and four-quarter circular air hole rings in the cladding. Numerical analysis showed impressive relative sensitivity rates of 95.80%, 95%, 93.60%, 92.50%, and 91.40% for red blood cells (RBCs), hemoglobin, white blood cells (WBCs), plasma, and water, respectively, under optimal conditions. The sensor also demonstrated minimal optical loss (confinement loss) ranging from 3.80×10^{-11} dB/m to 8.30×10^{-9} dB/m for these biological components[18]

Additionally, Md. Ahasan introduced a new type of HC-PCF aimed at enhancing the detection of chemical analytes. This fiber features a hybrid cladding design with circular air holes and a central rectangular air hole within the core. Rigorous testing revealed a relative sensitivity of 89% and low confinement loss of 1.15×10^{-9} dB/cm at a frequency of 1.7 THz[19].

Existing HC-PCF methodologies as described above rely heavily on high sensitivity and low confinement loss, requiring complex setups and extensive mathematical computations. Their sensing capabilities depend on multiple variables such as relative sensitivity, effective area, confinement loss, effective material loss (EML), and numerical aperture. This reliance means that practical decision-making involves numerous experimental setups and devices, making the entire process computationally complex, cumbersome, and difficult to implement. By exploring non-linear optics of HC-PCF this cumbersome task can be made quite less complex and require less computation complexity.

2.2 Ultra Short Pulse Literature Review

Ultrashort pulse laser technology has significant potential for applications across various modern technological fields. The propagation of ultrashort pulses through different media leads to various intriguing phenomena, especially when optical nonlinearities are present. From previous work of Ultrashort pulse, we have seen High power being implemented in PCF also in HC-PCF without damaging the fiber. The alteration of a pulse refers to changes in its shape, duration, and intensity as it propagates through a medium. These alterations can be caused by dispersion and nonlinearity. Dispersion refers to the phenomenon where different frequency components of a pulse travel at different speeds, leading to pulse broadening or narrowing. Nonlinearity arises from the interaction between the intense electric field of the pulse and the material medium. It can cause SPM, XPM, FWM, and Raman scattering. The nonlinear parameter, denoted as γ, quantifies the strength of the nonlinearity and is determined by the Kerr coefficient and effective mode area of the fiber. Changes in the nonlinear parameter can occur due to variations in the fiber properties or changes in the pulse characteristics, such as variations in the fiber composition or geometry, peak power, pulse duration, or spectral width. Understanding these alterations and changes in the nonlinear parameter is crucial for accurately predicting and controlling the behavior of ultra-short pulses in optical fibers.

Mosley et al. (2010) investigate the transmission and compression of ultrashort pulses in a bandgap-guiding hollow-core photonic crystal fiber (HC-PCF) at 540 nm wavelength. The paper shows that HC-PCF can transmit high-power pulses with minimal distortion due to the significantly reduced nonlinearity compared to conventional solid-core fibers[20].

The paper titled "Study and Synthesis of the Propagation of Ultrashort Laser Pulses in Medias: Fused Silica, Photonic Crystal Fiber, Air Silica and Hollow Core" by Mounir Khelladi investigates the behavior of ultrashort laser pulses in various optical media[21]. It focuses on the effects of nonlinearities and dispersion, such as self-phase modulation, self-steepening, cross-phase modulation, and stimulated Raman scattering, during pulse propagation. The study compares the performance of fused silica, photonic crystal fiber, air silica, and hollow-core fibers, highlighting the advantages of hollow-core and air silica fibers for pulse compression and minimal nonlinear distortion.

Chapter 3

Methodology

Maxwell's equations are the magical ones to describe how a matter or medium behaves when it is under the operation of electric and magnetic field. This portion of the literature incorporates an all-out explanation of the research starting from basic optical events total internal reflection up to Nonlinear Schrödinger equation and its applicability based on the proffered sensor. As said earlier, Maxwell's equation helps to provide a detailed insight of light, working as an electromagnetic ray. Next, the relation between fiber characteristics and how the nonlinearity would help to find the alteration of pulse will be described through a granular analysis. Maxwell's equation can be readily application for multiple types of applications starting from designing sensors to extract Ultra-short pulse facilitated Photonic crystal fiber (PCF) applications.

3.1 Electromagnetic Wave

3.1.1 Maxwell's equation in a nutshell

In order to analyze the incident light and its alteration, Maxwell's equation is one of the most outstanding approaches. These equations can be expressed both in integral and differential form which will enhance the opportunity to utilize them in case of Split step Fourier Method. Differential representation of Maxwell's equation incorporated with nonlinear parameters time varying electromagnetic field can be described [22] .

$$\nabla\times E = -\frac{\partial B}{\partial t} \qquad 3.1.1$$

$$\nabla\times E = J + \frac{\partial D}{\partial t} \qquad 3.1.2$$

$$\nabla \cdot D = \rho_f \qquad 3.1.3$$

$$\nabla \cdot B = 0 \qquad 3.1.4$$

E and H denote the electric and magnetic field vectors, whereas D and B denote the corresponding electric and magnetic flux densities. The vector J, referred to as the current density, and the charge density ρf, serve as the sources of the electromagnetic field. When there are no free charges present in a medium, such as in optical fibers, the current density (J) and the charge density (ρf) are both equal to zero.

The equation $D = \varepsilon_0 E + P$ (3.1.5), establishes a relationship between the electric displacement field (D), the electric field (E), and the polarization of the material (P). This equation reveals that the electric displacement is the result of both the electric field and the polarizability of the material. Similarly, B will arise in response of electromagnetic wave propagating through the medium. It can be represented as $B=\mu_0(H+M)$ (3.1.6) where, vacuum permittivity and vacuum permeability can be epitomized as ε_0 and μ_0 respectively.

3.1.2 Modification for Light propagation

Some important conversion is done at first. $\nabla\times\nabla\times E \equiv \nabla(\nabla\cdot E) - \nabla^2 E = -\nabla^2 E$ (3.1.6.2)

The utilization of Maxwell's equations enables the derivation of the wave equation, which accurately characterizes the transmission of light across optical fibers. By applying the curl operator to Equation (3.1.1) and utilizing Equations (3.1.2), (3.1.5), and (3.1.6), it is possible to omit the variables B and D in favor of E and P, resulting in the following expression:

$$\nabla\times\nabla\times E = -\frac{1}{c^2}\frac{\partial^2 E}{dt^2} - \mu_0\frac{\partial^2 P}{dt^2} \qquad 3.1.7$$

This equation will come handy when the nonlinear Schrodinger equation will be utilized. At 1^{st}, all the portions of the equation should be described. C is supposed to be the speed of the light propagated through the vacuum which can be further defined by $\mu_0\varepsilon_0 = 1/c^2$. Equation 3.1.7 is needed to be solved further for the interpretation of Fiber modes, propagation constants and nonlinear effect description. In order to do so, a continues relation between induced P and E is a must. A quantum mechanical approach can be enhanced hypothetically to approach further.[23][24]

In case of optical fibers operating within a range of 500 nm to 2000 nm, a phenomenological equation can be used to describe the relation between P and E. It will also encompass the effect of nonlinearity as well.

3rd order nonlinear effect can be written as a summation of wave propagating polarization and nonlinear polarization with respect to time and space (r, t). (3.1.8)

$$P\,(r, t) = P_L\,(r, t) + P_{NL}\,(r, t) \qquad 3.1.8$$

Here, P_L stands for linear part and the NL part defines the nonlinear portion. Further rigorous mathematical manipulation and integration will help to find out the frequency and space dependent equation for a light propagating through a fiber considering the nonlinear effect as a whole.

$$\nabla\times\nabla\times \tilde{E}\,(r,\omega) = \varepsilon(\omega)\,\frac{\omega^2}{c^2}\,\tilde{E}\,(r,\omega) \qquad 3.1.9$$

Frequency dependent dielectric constant will turn into further derivation through the help of absorption coefficient and refractive index which can be expressed as:

$$n(\omega) = 1+\mathrm{Re}[\tilde{\ }\chi^{(1)}(\omega)]^{1/2}, \qquad \alpha\,(\omega)=\omega/nc\,[\mathrm{Im}[\tilde{\ }\chi^{(1)}(\omega)]],$$

In order to describe the fiber modes, the equation of Maxwell can be further manipulated and it will turn into a Helmholtz form:

$$\nabla^2 E + n^2(\omega)\,\frac{\omega^2}{c^2}\,E = 0 \qquad 3.1.10$$

3.2 Fiber Modes and its importance

For a particular frequency, ω, a finite number of guided modes can be found out. However, this particular research work emphasizes on the alteration of pulses having a wavelength of 1550nm only which can be supplied commercially by **Thorlabs** and **NKTphotonics (sometimes LASERGLOW also).** As a result, the light source giving dip or high absorption only on 1550 wavelength is point of concentration. However, multiple modes of fiber will create the problem of random linear coupling and it will eventually suffer from microbending. Also, it multimode will result in overlapping dip in case of transmittance vs wavelength graph. It basically prone to higher degree of modal dispersion which may create issues in case of decision making about the change of pulse.[25] Moreover, the multimode representation is having higher computational complexity and rigorous mathematical manipulations become much higher so as the time to execute the whole operation for one sample/analyte.

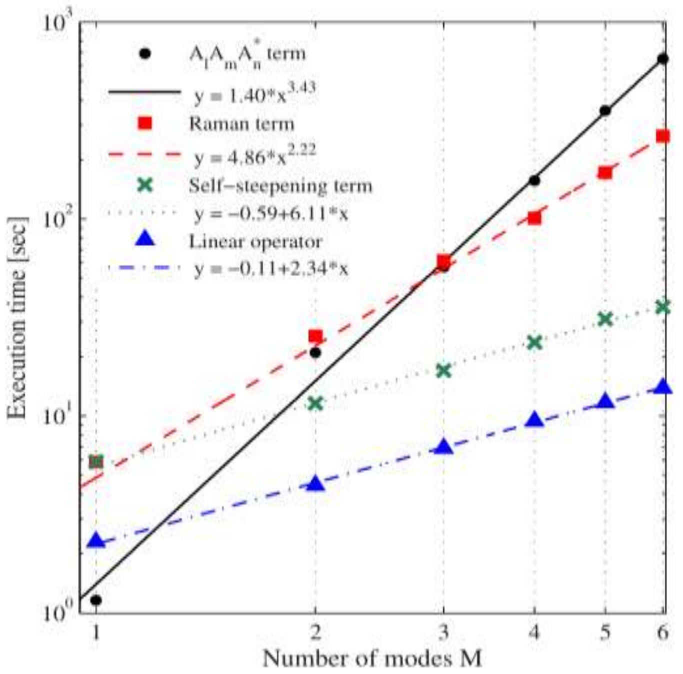


Figure 3.1: Execution time vs Number of Modes applied[26]

3.2.1 Eigen value Equation

It is visually evident that the ultra-short pulse will propagate through a cylindrical optical fiber region. As a result, the pulse propagation can be defined using Eigen Function. The equation can be defined as:

$$\frac{\partial^2 \tilde{E}}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial \tilde{E}}{\partial \rho} + \frac{1}{\rho^2}\frac{\partial^2 \tilde{E}}{\partial \Phi^2} + \frac{\partial^2 \tilde{E}}{\partial z^2} + n^2 k_0^2 \tilde{E} = 0 \qquad 3.2.1$$

Here, K_o is defined as $2\pi/\lambda$ and λ is 1550 in this research proceedings. Fourier transform will eventually result in

$$\tilde{E}(r,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \tilde{E}(r,\omega) e^{-i\omega t} \partial\omega \qquad 3.2.2$$

Method of separation of variable solution will result in an equation for electromagnetic Field found in Z axis, both E_z and H_z can be verified using the fundamentals of Maxwell's equation. After some modification and further analysis, the final equation will come up with:

$$\tilde{E}_z(r,\omega) = A(\omega)F(\rho)e^{il\varphi}e^{i\beta z} \qquad 3.2.3$$

Here, some important parameters have been extracted for the analysis of resulting parameters. When light is incident in a medium, penetrating through one medium to other (for convenience the analogy of Prism can be thought), dispersion of light will result in distinct wavelength of lights which can be visualized through different colors. Electromagnetic wave propagating through a medium will result in wave propagation constant, named as β. While defining the methodology both dispersion of light and nonlinear characteristics is needed to be taken into consideration[27][28].

3.2.2 Single mode Analysis

Equation 3.2.3 defines the Electric field on z direction, for H, z direction magnetic field can be calculated as well. Based on different values of l, the Bessel and Neumann function will come. All these theoretical derivations conclude up to a special Parameter to test the single mode of the Fiber.

$$V = \frac{2\pi a}{\lambda}\sqrt{{n_{core}}^2 - {n_{cladding}}^2} \quad [29] \qquad 3.2.4$$

Where a is the radius of the core portion where most of the light will be confined. The single-mode specific parameter is named as V depends on the value of frequency, ($k_0 = \omega/c = \frac{2\pi}{\lambda}$) having no dimension. Here, the tricky designing point is to be noted is that, the single moodiness of the fiber will be preserved if and only if the value of V is near or equal to 2.405.[28] . Hybrid Mode H_{11} is only supported by a single-mode fiber. As a result, this is also known as the fundamental mode of the fiber. The distribution of fields The HE_{11} mode, represented by E(r,t), contains three nonzero components: Eρ, Eφ, and Ez, or Ex, Ey, and Ez in Cartesian coordinates. Since, Ez is tiny for the HE_{11} mode, the fundamental mode may be approximated to a considerable degree. Depending on which predominate, Ex or Ey, is linearly polarized in the x or y direction. This means that even a single-mode fiber may accommodate two modes with orthogonal polarizations, therefore it is not really a single mode.

Defining proper V parameter is the crucial point of Designing a fiber. For a traditional case, $n_1 - n_c$ should have very low difference to get perfect "Defect" near 0.005, of the index difference, 1.2 µm to be the wavelength of light trapped in the core region and for a=4 µm, indicating that such a fiber supports a single mode only for λ>1.2 µm. In actuality, core radius should be below 2 µm for such a fiber to support a single mode in the visible region. In our case, after a lot of trial and error-based simulation, it is found that, for cutoff wavelength 1550nm, n_{silica}= 1.4444 and a range of applications like 1.41 to 1.438 (n_{core}) the V parameter is having the desired value. Some modifications on diameter will help to widen this range from 1.33 to 1.44 (based on 3.2.4 equation)

3.3 Pulse Propagation with Nonlinear effect

Ultrafast optics have brought revolutionary change in biomedical sectors and many other applications. This motto of this research endeavor is to design a Nano level sensor for Petrochemical industries, which will be further viable for other applications like biomedical, adulteration detection, disease analysis and detection etc. For this, nonlinear and dispersive effect of light will be a major takeaway to analyze. After having extensive literature review and background analysis we could come up to a conclusion that, an ultra-pulse having a duration from 10ns to 10fs (nanosecond and femtosecond) will have alteration or change in pulse and spectra if it is propagated through a single mode fiber. Based on this distinct change for each of the petrochemical sample, type of chemical, adulteration level can be analyzed.

Nonlinear form of Schrödinger can be derived using equation 3.6.1.2 and 3.1.7. After some modifications and mathematical manipulation, it will result into

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial E^2}{\partial t^2} = \mu_0 \frac{\partial^2 P_L}{\partial t^2} + \mu_0 \frac{\partial^2 P_{NL}}{\partial t^2} \qquad 3.3.1$$

Before deriving the equation for final version of application some major assumptions have been taken into consideration.

- P_{NL} is considered a minor disturbance to P_L. This is supported by the fact that the changes in the refractive index for silica fibers are relatively small, measuring less than 10^{-9}.
- the polarization of the optical field remains constant along the length of the fiber, allowing for a simplified scalar approach. It's not entirely accurate, unless you use polarization-maintaining fibers, but in practice, the approximation is quite effective.
- Additionally, it is important to consider that the optical field is assumed to be quasi-monochromatic, meaning that the pulse which is centered at ω_0, is assumed to have a spectral width ω such that $\Delta\omega/\omega_0 << 1$. For ω_0 of 10^{-15} s^{-1} the terminal assumption holds true for pulses as brief as 20 femtoseconds.

After a long derivation done by Mr. Schrodinger, finally it came up to an equation which encompasses both the dispersive effect (Propagation constant) and nonlinearity (Gamma)[25], [28]

$$\frac{\partial A}{\partial z} = -\beta_1 \frac{\partial A}{\partial z} - j\frac{\beta_2}{2}\frac{\partial^2 A}{\partial T^2} - \frac{\propto}{2} - j\gamma |A|^2 A \qquad 3.3.2$$

Here,

- A is the pulse amplitude which is input power in watt for this experiment.
- α is defined as the absorption coefficient, one of the major terms to define peak in Absorption vs wavelength Graph.
- γ is defined as the nonlinear parameter which can be defined with respect to Area effective.

Area effective defines the specific area where the light is confined compare to the whole area. It can be defined as modal volume. Using finite element numerical method, dispersion of the engineered waveguide/ photonic crystal fiber can be achieved[30].

$$Effective\ area,\ A_{eff} = \frac{(\int |E(x,y)|^2\, dxdy)^2}{\int |E(x,y)|^4\, dxdy} \qquad 3.3.3$$

$$\gamma = \frac{\omega_{0*} n_2}{c * A_{eff}} \qquad 3.3.4$$

In a nutshell, the pulse envelope travels at the group velocity vg, which is defined as 1 divided by β1. The impact of group-velocity dispersion (GVD) is determined by β_2. The GVD parameter β_2 might have a positive or negative value, depending on whether the wavelength λ is lower or higher than the zero-dispersion wavelength λ_D of the fiber. For wavelengths greater than λ_D, the value of β_2 is negative, indicating that a fiber of this type is capable of sustaining optical solitons. The value of β_2 in normal silica fibers is around 50 ps^2/km in the visible range. However, it becomes close to -20 ps^2/km at 1.5 µm, with the shift in sign occurring around 1.3 µm. The quantity appearing on the right side of Equation (3.3.2) corresponds to the nonlinear phenomena known as self-phase modulation (SPM).[25], [28]

3.4 Consideration of fiber length:

The length of the fiber should have some finite value to implement is as a practically applicable sensor. Keeping this in mind, for a instant pulse width and input power, the fiber length is tunable at a certain range, the minimum length of the fiber should be such that, the pulse should propagate through the fiber with alteration but not a continues breakdown. If the pulse is broken

or spiked up, then the compression or expansion of the pulse cannot be determined even if the experimental facilities of Autocorrelator and power meter is inserted properly.[31]
In order to analyze this, some major terms should be taken into consideration:

- **Optical solitons:**

Optical solitons are special light pulses that can travel long distances through optical fibers without changing shape or spreading out. This unique behavior happens because of a delicate balance between two effects:
Dispersion: Tends to spread the light pulse out over time.
Nonlinearity: Tends to compress the light pulse.

- **Length of dispersion**

The electromagnetic wave incident on core region of the HC-PCF will have dispersion property. Light should spread or propagate in such a way so that it is less than the fiber length. From this concept, a new term $\mathbf{L_{fission}}$ is introduced.

- **Thumb rule for Stable Propagation**

For minimum Number of soliton N> 1, the fission length should be greater than the length of the Fiber and it can be defined using the following equation:

$$L_{fission} = \frac{L_D}{N} \qquad 3.4.1$$

$$L_D = \frac{T_o^2}{abs(\beta_2)} \qquad 3.4.2$$

3.5 Split Step Fourier Method/ SSFM:

All the steps that has been discussed up to now is basically based on the nonlinearity and dispersion parameters calculation which should be continued in parallel with each other for each of the finite length of the fiber. However, FEM or finite element method can calculate any rigorous calculation like area, modal volume etc. which have only 1 parameter to consider usually. Split step Fourier method is a modification of normal Fourier transform where, each of the finite fiber length will be subdivided into two parts further. One portion will account for calculating Dispersion due to wave propagation and another part stands for Nonlinear parameter calculation.[28] Instead, the NLS equation may be solved using a finite-difference approach either in the time or frequency domain. Several often-used schemes include the Crank-Nicholson scheme and its variations, as well as the hopscotch system and its variations and the procedure known as leap-frog[32]

$$\frac{\partial A}{\partial z} = (\check{D}+\check{N})\, A \qquad 3.5.1$$

$$\check{D} = \frac{i\beta_2}{2}\frac{\partial^2}{\partial T^2} + \frac{\beta_3}{6}\frac{\partial^3}{\partial T^3} - \frac{\propto}{2} \qquad 3.5.2$$

$$\check{N} = i\,\gamma\,(|A|^2 \frac{i}{\omega_0}\frac{1}{A}\frac{\partial}{\partial T}\,|A|^2\,A - T_R\frac{\partial |A|^2}{\partial T}) \qquad 3.5.3$$

To implement the method, short-distance linear and nonlinear effects are applied at regular intervals. In order to linearly regulate dispersion, the pulse must first be translated into the frequency domain. Next, it is transformed back into the time domain so that nonlinear processes may be included. This operation is repeated over the whole fiber length to make it seem as though the pulse is subject to the full force of dispersion and nonlinearity. The remarkable efficiency and precision of SSFM in simulating complicated optical systems have earned it a lot of praise.

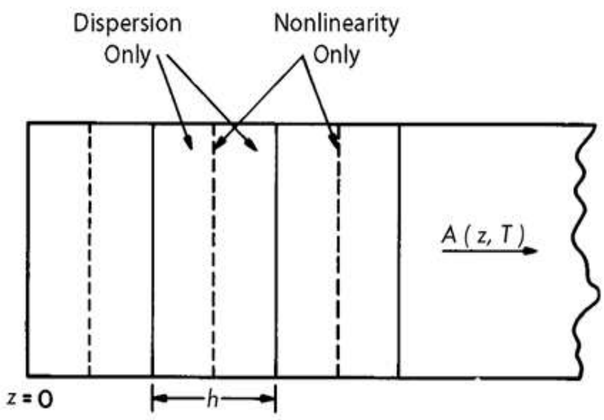


Figure 3.2: The symmetrized SSFM is depicted in the schematic figure, which is utilized for conducting numerical simulations. The fiber length is split into several segments, each with a width of h. The impact of nonlinearity is accounted for inside a certain section, shown by a dashed line at the midplane[27], [28].

3.6 Applicability of High-Power Input in a Nano Sensor

As per proffered statement, this research work will enable a computationally efficient and simpler way of detecting Petrochemical samples. However, there might be an intuitive question that, is it truly implementable? As the input power is having a high range of 300W to 1000W (tunable). Won't it burn the whole sensor as it is in Nano level fabrication and the power level is high? The answer is, it is obviously implementable. Ultrafast master oscillator power amplifier is such an example where input energy up to 75MW can be utilized with proper isolation setup, Also, for low power like 300 to 500W, overall work done is Nano joule range which is very small and energy efficient. To sum up, this 500W laser can be implementable using proper experimental setup and trial and error based Proffered PCF[33]

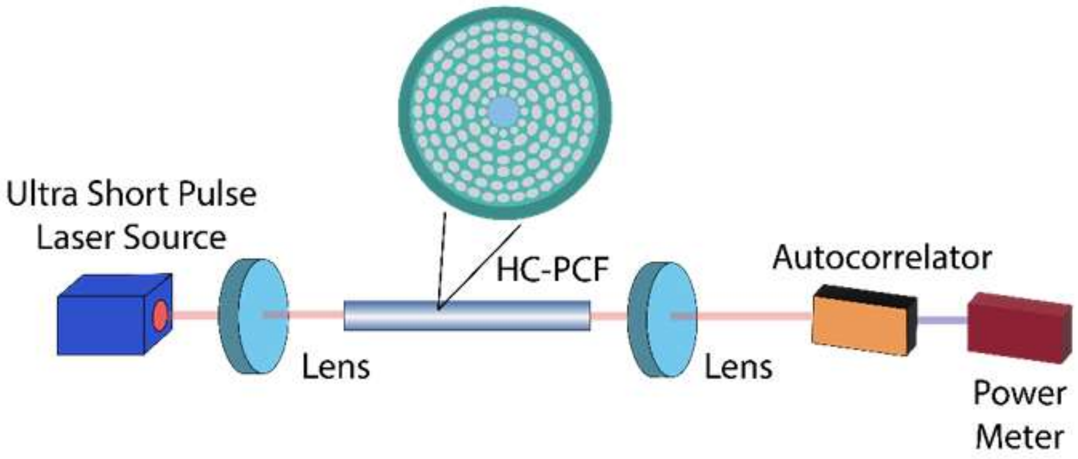


Figure 3.3: Proposed Experimental setup

Chapter 4

Computational Methods

4.1. Designing Parameter of the sensor

To design any sensor, some parameter needs to be thoroughly checked. In HC-PCF, the fiber has to be in single mode for light confinement. This can be verified using V-parameter value. Also, there should be a background material capable of establishing photonic bandgap. This bandgap prevents certain wavelengths propagating through the background material which helps to confine the light.

4.1.1.V parameter:

Single-mode operation checks that most of the light can be trapped in the core, eliminating modal dispersion caused by multiple modes traveling at different speeds. This gives a very stable signal, which is critical for high-precision applications like sensing. (ahmed2017.pdf) To ensure the single moodiness, the value of the V parameter should be less or equal to 2.405.

$$V=\frac{2\pi}{\lambda}\, a\sqrt{n_{core}^2 - n_{cladding}^2}$$

where,

a = core radius, (Dcore/2)

λ = 1550 nm (Commercially available Laser wavelength)

From the software simulation n_{eff} of core and cladding section needs to be carefully chosen[18].

4.1.2. Choice of background material:

Silica is used as background material because its property is already well understood and it is compatible with fiber optic manufacturing process. Its refractive index is changed with the variation of wavelength. This is calculated using Sellmeier's equation[34]-

$$\eta_{silica}=\sqrt{1+\frac{B_1\lambda^2}{\lambda^2\text{-}C_1}+\frac{B_2\lambda^2}{\lambda^2\text{-}C_2}+\frac{B_3\lambda^2}{\lambda^2\text{-}C_3}}$$

Coefficients	Values
B_1	0.696163
B_2	0.4079426
B_3	0.8974794
C_1	0.00467914826 μm^2
C_2	0.0135120631 μm^2
C_3	97.9340025 μm^2

Table-I: Sellmeier's coefficients for silica

The refractive index of Silica (η_{silica}) provides necessary contrast for light confinement within the hollow core. It has low optical loss and high efficiency of light transmission. That’s why, silica is a ideal choice as a background material in HC-PCF.

4.2. Traditional Resulting Parameter:

In Hollow Core Photonic Crystal Fibers, there are some resulting parameters which reflects that if the sensor is working properly or not. Area Effective, Power Fraction, Effective Refractive Index show linear trend with respect to wavelength due to its material and structural configuration.

4.2.1. Area effective:

Some of the light leaks into the cladding regions instead of staying confined to the central air hole in HC-PCF. To address the distribution of photon energy, Saitoh et al. introduced the concept of the effective area as a precise representation of the fiber’s mode field area calculated in the following way[35].

$$\text{Effective area, } A_{eff} = \frac{(\int |E(x,y)|^2 \, dxdy)^2}{\int |E(x,y)|^4 \, dxdy}$$

In this formula, E(x,y) represents the electric field intensity distribution of the fundamental mode of the optical fiber. To determine the effective area using finite element simulation, the electric field distribution E(x,y) is analyzed over the fiber's cross-sectional area. The process involves two main steps: First, the square of E(x,y) is integrated to obtain the numerator. Next, E(x,y) raised to the fourth power is integrated to get the denominator. The effective area is then found by taking the ratio of these two values.

4.2.2. Effective refractive index:

The effective refractive index goes beyond just representing the refractive index of the material within the core. It captures the complex interaction between the core and cladding structure It expresses the intricate interplay between the core and cladding structure. Effective refractive indices of the guided mode are calculated by solving Maxwell’s double curl equation[36]. The final solution can be-

$$\eta_{effpm} = \frac{c}{vp} = \frac{\beta pm}{ko}$$

c = speed of light in the vacuum

vp =phase velocity of the mode propagating in fiber

β_{pm}= propagation constant of light

Quantity of waves in a void = $k_o = \frac{\omega}{c} = \frac{2\pi}{\lambda}$

The effective refractive index determines the mode field distribution and the mode confinement within the hollow core. It determines how tightly the light is confined and how efficiently it travels through the fiber. Different wavelengths have different interactions with the light confinement. That is why, as the wavelength changes, the neff shows a linear trend.

4.2.3. Power fraction:

Power fraction, referred as the power confined in the core area compared to the total power can also be examined which is unique for each solvent. Power fraction helps in optimizing the design for better confinement and lower losses. The power fraction is calculated by

$$Power\ Fraction,\ P_f = \frac{\int_{sample} Re(E_X H_y - E_y H_x)\, dxdy}{\int_{total} Re(E_X H_y - E_y H_x) dxdy} \times 100\%$$

where *Ex*, *Ey* and *Hx*, *Hy* are the transverse component of electric field and magnetic field of the propagating mode in x and y direction and the light propagate at z direction. The integrals are taken over the total sample area(core) and the total area. (cross-section of the fiber). [18], [36]

The global computing module is used to solve Maxwell's equations in finite element simulation method. The process begins by defining the surface integral of all air hole sensing areas as well as the HC-PCF's cladding end-face are defined. Following that, the time-averaged power flow, specially the z-component of the electric field within these integral areas, is calculated. The final ratio is power fraction[35]. The behavior of Power fraction is unique for each refractive index used in the fiber, making it a critical parameter for the design and optimization of optical fibers for specific applications. A higher power fraction suggests better light confinement within the core, leading to lower losses of the fiber.

4.3. Nonlinear characteristics of the fiber:

The area effective, effective refractive index and power fraction are taken as resultant parameter in the traditional HC-PCF sensing applications. But in our work, we aim to identify the unknown samples using ultrashort pulse. The computational complexity will be decreased by using ultrashort pulse detection with HC-PCF which will be described in the following chapters. To achieve this, some non-linear parameters of the fiber must be found.

4.3.1. Dispersion of light:

The dispersion parameter D is a key quantity in fiber optics, providing understanding into how different wavelengths of light separate as they travel through a fiber. When light passes from one media to another, due to the change of the speed, the wavelength and refractive index are also changed. It can be described in various ways. However, to find the nonlinear characteristics of the optical fiber, it can be described in the following way-

$$D = \frac{d\beta_1}{d\lambda} = - \frac{2\pi c}{\lambda^2}\,\beta_2$$

- $\beta_1 = \frac{d\beta}{d\omega}$=group delay, which is the derivative of the propagation constant β with respect to angular frequency ω.Group delay refers to the time it takes for a pulse of light to travel a specific distance.
- $\beta_2 = \frac{d^2\beta}{d^2\omega}$= group velocity dispersion, which is the second derivative of β with respect to angular frequency ω..The dispersion that leads to pulse broadening that is, the different spectral components of a pulse traveling at different speeds is represented by GVD. It affects pulse broadening.
- A positive D parameter means shorter wavelength can travel faster than longer wavelength and a negative D parameter means longer wavelength can travel faster than shorter wavelength.
- The negative sign in the equation highlights that an increase in wavelength leads to a decrease in group delay for normal dispersion[37][38].

4.3.2. Propagation Constant:

The propagation constant, denoted as β is a one of the important parameters in the analysis of wave propagation in fibers. It is essential to comprehending how light flows through the fiber since it describes the phase change per unit length along the propagation direction.

$$\beta = \frac{\omega}{c}\, n_{\omega_0}$$

Here,n_{ω_0} is the refractive index as a function of angular frequency ω_0 and c is the speed of light in a vacuum. This equation shows that for a constant wavelength and c, the propagation constant is equal to the refractive index as a function of ω_0. The propagation constant β itself is a linear function of optical fibers.

$$\beta_n = \frac{d}{d\omega}\beta_{n-1}$$

According to the equation, the derivatives of propagation constant β should have unique value for different refractive indexes. In our case we limit our analysis with second and third derivative of β.

$\beta_2 = \frac{d^2\beta}{d^2\omega}$ = group velocity dispersion

$\beta_3 = \frac{d^3\beta}{d^3\omega}$ = Higher order dispersion

Second-order dispersion(β_2) describes how different spectral components of a pulse travel at different velocities. This leads to pulse broadening as different frequency components spread out over time. With positive β_2, known as normal dispersion, longer wavelengths travel faster than shorter wavelengths. Negative β_2 indicates anomalous dispersion, where shorter wavelengths travel faster than longer wavelengths.

β_3 captures third-order dispersion effects by causing the pulse to spread asymmetrically. This means that the front and back end of the pulse stretch out differently, leading to an overall asymmetrical shape.

In HC-PCF, both β_2 and β_3 need to be managed for optimizing pulse propagation. This balance helps in achieving minimal pulse distortion and ensuring the fiber performs effectively[37], [38].

4.3.3. Nonlinear parameter gamma:

Nonlinear optical effects, including second-order and third-order non-linearities, are crucial for developing high-speed, low-energy optical devices. Second-order nonlinearities like second-harmonic generation (SHG) and the Pockels effect have been observed in Photonic Crystal Fiber. Third-order nonlinearities, including self-phase modulation (SPM), cross-phase modulation (XPM), two-photon absorption (TPA), three-photon absorption (ThPA), and four-wave mixing (FWM), are vital for all-optical signal processing[39].

To measure these third-order effects in optical waveguides, γ (gamma) is widely used, defined in the nonlinear Schrödinger equation. Gamma can be calculated in following way-

$$\text{Nonlinear parameter: } \gamma = \frac{2\pi}{\lambda}\frac{\eta_2}{A_{eff}}$$

$\lambda = 1550$ nm

η_2 = Non-linear Refractive Index of the Silica = 3×10^{-20}

A_{eff}= Effective area of the fiber mode

For each of the sample, γ should be different as effective area of the fiber mode changes. If γ shows different value with the change of refractive index, it indicates that the nonlinear characteristics of the fiber are functioning properly allowing for detection using ultra-short pulses[37], [38], [40].

4.3.4. Nonlinear Schrödinger equation (NLSE):

Nonlinear Schrödinger equation defines both the propagation constants a nonlinearity based on which Split Step Fourier Method (SSFM) tries to manipulate the solution. The NLSE looks like:

$$\frac{\partial A}{\partial z} = -j\,\frac{\beta_2}{2}\,\frac{\partial^2 A}{\partial T^2} - \frac{\propto}{2} - j\,\gamma\,|A|^2\,A$$

Here A is the slowly varying component, α is the absorption property, β and γ are the dispersion and nonlinearity respectively. SSFM at first divides this equation in two parts while solving it. First part is Dispersion and loss term which is also known as linear part and second part is Nonlinear-term.

Dispersion term: $-j\,\frac{\beta_2}{2}\,\frac{\partial^2 A}{\partial T^2}$

Loss term: $\frac{\propto}{2}$

Nonlinear Term: $\gamma|A|^2\,A$

The linear part is solved using the Fourier transform in the frequency domain, while the nonlinear part is solved in the time domain[27], [41].

4.4. Proposed Resulting Parameter:

The ultra-short pulse is simply a brief burst of electromagnetic waves. The peak power of ultra short pulses has been changed when the refractive index changes. It occurs due to the nonlinear characteristics of the Hollow Core PCF.

4.4.1. Power Upsurge:

Power upsurge quantifies the difference between the peak power of transmission and receiving end. Variations of refractive index can alter the peak power of receiving end will be changed, creating the power upsurge distinct for each case.

Power Upsurge = Peak Power at The Receiving End **-** Peak Power at The Sending End

4.4.2. Compression Sensitivity:

Compression Sensitivity is one of the resulting parameters that compares the width of the input pulse to the width of the compressed pulse. It is a dimensionless ratio that evaluates the efficiency of pulse compression in the optical fiber. Full-Width at Half Maximum which measures specific pulse width at half of its maximum amplitude. It’s a Gaussian shaped filter and that can be easily manipulated using FWHM. By comparing FWHM value of both sending and receiving power, the compression sensitivity can be determined-

$$\textbf{Compression Sensitivity} = \frac{\text{FWHM of compressed pulse}}{\text{FWHM of input pulse}}$$

Chapter 5

Design and Nonlinearity Analysis of Elliptical shape Hollow core Photonic crystal Fiber facilitated with Ultra-short Pulse

5.1. Introduction:

Diesel, one of cornerstone fuel in the petrochemical industry, a cornerstone of this industry, is mainly used as a backbone in power station. It offers significant advantages such as enhanced efficiency, improved combustion efficacy, and reduced emissions of harmful pollutants like hydrocarbons, particulate matter, carbon dioxide, carbon monoxide, and nitrogen oxides[42]. Despite these benefits, fuel adulteration remains a pervasive issue in many developing countries such as Bangladesh, Pakistan, and India. Adulterants like kerosene are frequently mixed with diesel to increase volume, perpetrated by organized crime syndicates and individual distributors throughout the supply chain. This practice not only compromises fuel quality but also exacerbates environmental degradation by increasing emissions of hazardous pollutants, leading to heightened levels of air pollution and significant public health risks[43], [44], [45]. To solve this problem, petrochemical industry is in need of sensor which can easily detect any unknown analyte, adulteration level in refineries, quality control and aging effect mapping etc. These includes assessing properties such as density, viscosity, color, odor, and specific gravity, along with sophisticated techniques like gas chromatography, Fourier transform infrared spectroscopy, titration and ultrasonic measurements[46],[47]. Optical fibers, particularly Hollow Core Photonic Crystal Fibers (HC-PCF), have emerged as a promising technology due to their high sensitivity and ability to detect changes in liquids based on variations in their refractive indices.

Research in this field has shown that HC-PCFs can dynamically alter the shape of ultra-short pulses as they propagate through different substances, leading to unique responses based on the materials' optical properties. This approach highlights a novel and highly sensitive method for fuel sensing and underscores the potential of HC-PCFs in advancing fuel quality monitoring and environmental protection efforts globally.

5.2. Design Consideration Explanation:

A Hollow core PCF has been designed to detect any kind of fuel adulteration in diesel samples, providing a critical solution in energy sectors. This fiber is predominantly made of high quality silica glass, features sophisticated arrangement of air holes around the core . These air holes help to guide light within the core region, ensuring optimum sensitivity. The detection process introduces with the placement of the Diesel samples into the hollow core of the HC-PCF followed by transmission of ultra-short laser pulses through the fiber. The level of adulteration can be determined by closely examining how these pulses are altered. This advanced sensing technique takes advantage of the unique properties of HC-PCF and ultra-short pulse laser technology, resulting in precise and sensitive detection of fuel adulteration. The fiber designed for this sensing application was created with COMSOL Multiphysics. Its feasibility was confirmed by determining whether light is effectively trapped within the core.

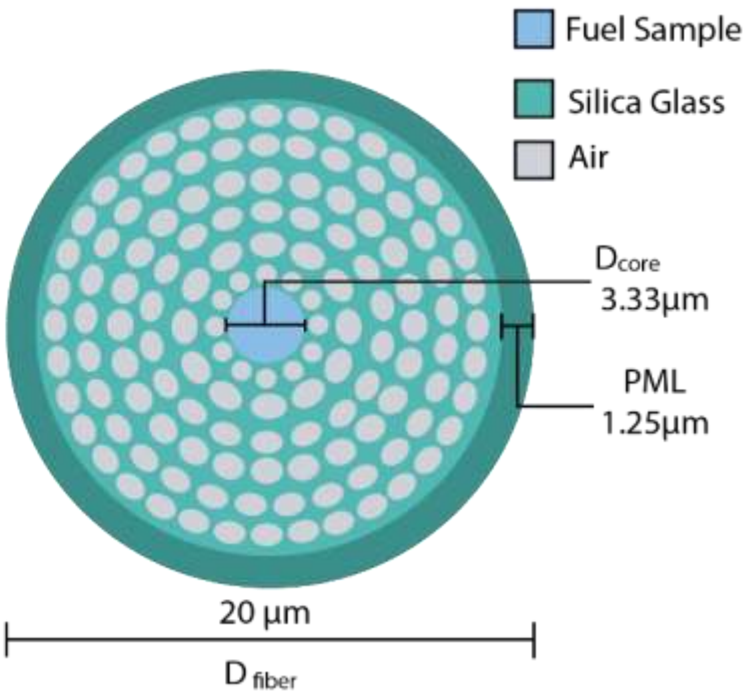


Figure 5.1: Proposed Hollow Core Photonic Crystal Fiber

The air holes in the HC-PCF are placed in six layers around the core. The first layer is composed of elliptical air holes each with a diameter of 0. 87µm.These holes are distributed in a circular pattern around the core, with each hole 30° apart from its neighbors. The first type of elliptical hole has a major axis length of 0.65μm and a minor axis length of 0.42μm. They are both used in the second and fourth layers. The elliptical holes in the second layer are 30° apart, while the holes in the fourth layer are 15° apart, resulting in a balanced structure surrounding the core. The second type of elliptical hole has a major axis length of 0.65μm and a minor axis length of 0.56μm. These are placed in the third, fifth, and sixth layers, with spacing of 15°, 12°, and 10° apart, respectively. Additionally, a perfectly matched layer with a width of 1.235μm has been introduced to prevent the applied light wave from reflecting back into the system.

5.3. Dataset:

The fuel samples with different adulteration level exhibit different values of refractive index.[48].

SL No	Concentration of kerosene in the fuel sample	Refractive index of the fuel sample
1	0%	1.455
2	20%	1.4516
3	40%	1.4482
4	60%	1.4448
5	80%	1.4414
6	100%	1.4380

Table-II: Refractive Index for Each Sample at a Constant Temperature 20^{0}C

5.4. Fiber Characteristics:

Area Effective, power Fraction, Effective Refractive Index are the conventional resulting parameters that reflects whether the optical are functioning correctly. In our research, we are extensively tested these parameters as a fiber characteristic. As we are connecting our work with ultra short pulse, so the nonlinear parameters like Propagation constants and gamma are also required to determine. These parameters play significant role to understand how the HC-PCF will interact with ultra short pulse.

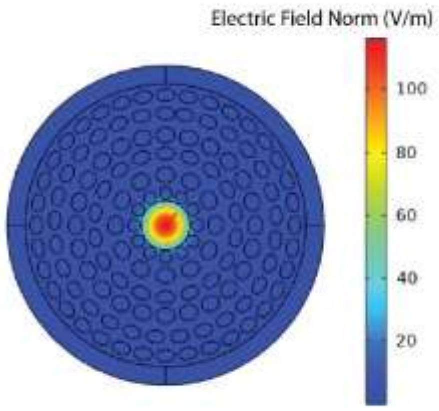


Figure 5.2: Light Confinement in the Proposed Sensor

5.4.1 Effective Refractive Index:

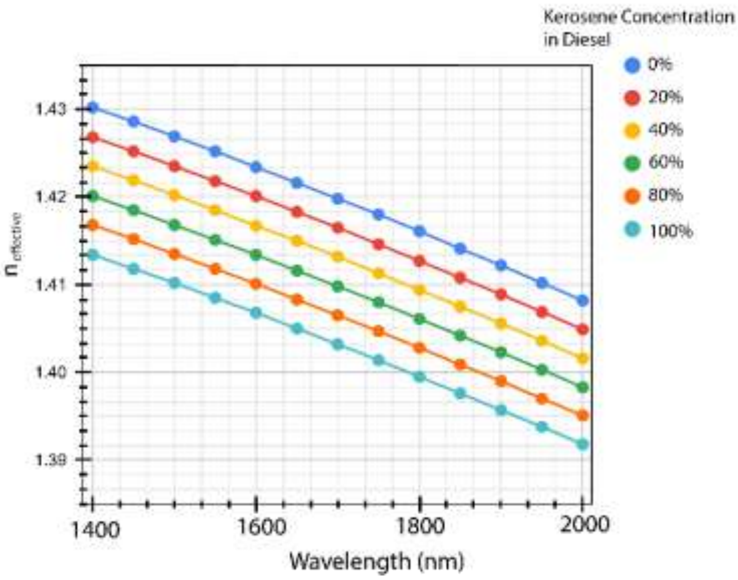


Figure 5.3: Effective Refractive Indices of HC-PCF for Diesel samples with different kerosene concentration level

The effective refractive index varies linearly with wavelength due to the fiber's dispersion properties. This dispersion is raised due to the material properties and structure of the PCF. The linear relationship means that the rate of change of the effective refractive index with respect to wavelength remains approximately constant over a given range of wavelengths.

5.4.2. Power Fraction:

The power fraction decreases because at longer wavelengths, the contrast between the refractive indices of the core and cladding becomes less effective at keeping the optical mode confined within the core. The decrease in power fraction with increasing wavelength follows a linear relationship because the spreading of light into the cladding is gradual and proportional to the wavelength change.

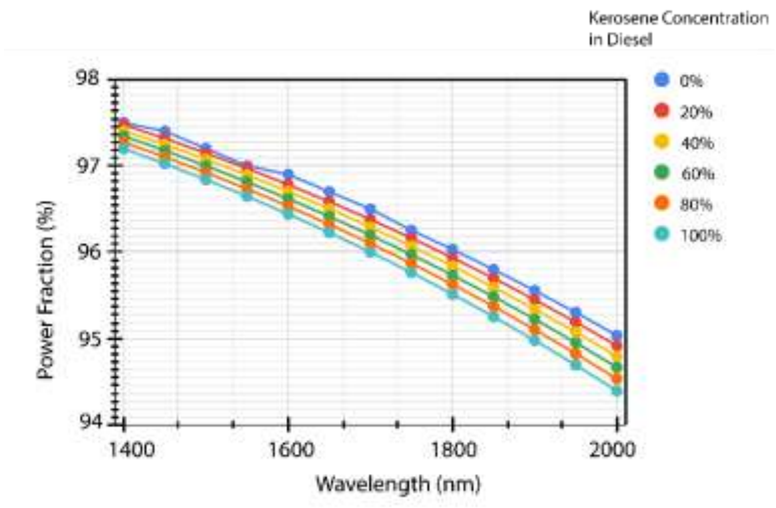


Figure 5.4: Power Fraction of the HC-PCF for diesel samples with different kerosene concentration. Levels.

From the graph of Power fraction assures that the model is working effectively as most of (94% to 98%) the power is confined within the core region. This depicts that the preferred sensor works well for traditional terahertz sensing mechanism. However, keeping the parameters existing sensor in mind, our motto is to develop a Ultra-short pulse facilitated HC-PCF.

5.4.3. Area Effective:

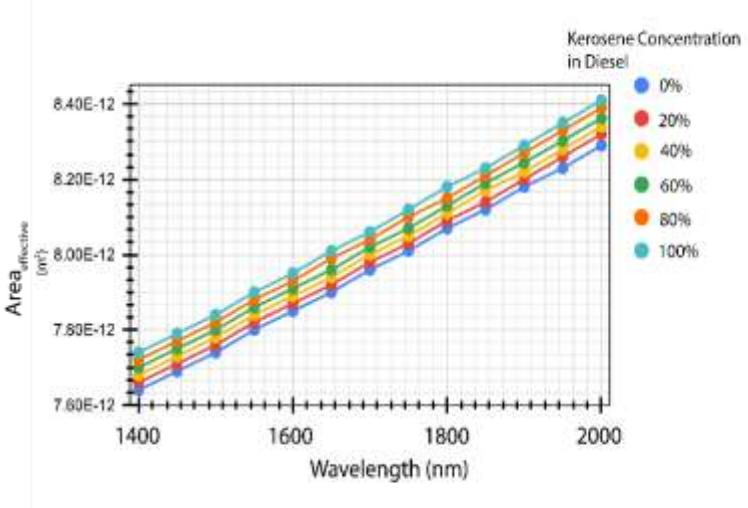


Figure 5.5: Area Effective of the HC-PCF for diesel samples with different level of kerosene concentration

As the wavelength of light increases in the fiber, the mode field diameter expands as a result of alternations of how the optical mode distributes within the fiber core. This expansion leads to a linear increase in the effective area. The relationship is governed by the wavelength-dependent nature of the mode field distribution, where longer wavelengths allowing the mode to spread out more broadly, thereby enhancing the effective area in proportion to the wavelength change.

5.5. Non-Linear Characteristics:

Each of the nonlinear parameter like derivatives of propagation constant and Gamma yields unique value for each sample demonstrates that HC-PCF will function correctly when ultra short pulse passes through it.

Concentration of kerosene in the fuel sample	Refractive index of the fuel sample	β_2 at 1550 nm (s^2/m)	β_3 at 1550 nm (s^2/m)	A_{eff} at 1550 Nm(m^2)	γ ($W^{-1}m^{-1}$)
0%	1.455	-6.08×10^{-26}	-3.71×10^{-40}	-7.80×10^{-12}	0.015591
20%	1.4516	-1.34×10^{-25}	-3.71×10^{-40}	-7.82×10^{-12}	0.015671
40%	1.4482	-9.87×10^{-26}	-1.83×10^{-40}	-7.84×10^{-12}	0.015512
60%	1.4448	-8.92×10^{-26}	-1.99×10^{-40}	-7.86×10^{-12}	0.015472
80%	1.4414	-7.78×10^{-26}	-4.63×10^{-40}	-7.88×10^{-12}	0.015433
100%	1.4380	-1.32×10^{-26}	-2.09×10^{-40}	-7.90×10^{-12}	0.015394

Table-III: Extracted Dispersion and Nonlinear Parameters for Each Diesel Sample

These fiber characteristic parameters and nonlinear parameter appears to be unique for each of the fuel sample, so if these fuel samples are put inside the hollow core of a PCF and exposed to ultra-short pulse, the shape of the pulse will change for each of the sample. It is verified using Schrodinger Nonlinear equation.

5.6. Resulting Parameter:

When ultrashort pulses were transmitted through the proposed hollow-core PCF, their shape was changed depending on the specific diesel sample employed. This suggests that refractive index can significantly effect propagation and form of the ultra-short pulses within the fiber. By varying the input power in 300W,400W and 500W while exploring width in 1ps, 2ps and 3ps a detailed analysis can be performed to understand how kerosene concentration characteristics impact pulse compression.

When the input power was 500W and pulse width was 1ps, the fiber length was taken as 0.6m meeting the requirements for soliton number. Fuel samples were observed with the same input power but the pulse width was changed to 2ps and 3ps.The power upsurge a compression sensitivity gave favorable outcome for detection of the chemical solvent which is given in Table-IV. The results can be seen from Figure 5.6, it is evident that for the input configuration, the detection of fuel adulteration can be accomplished conveniently.

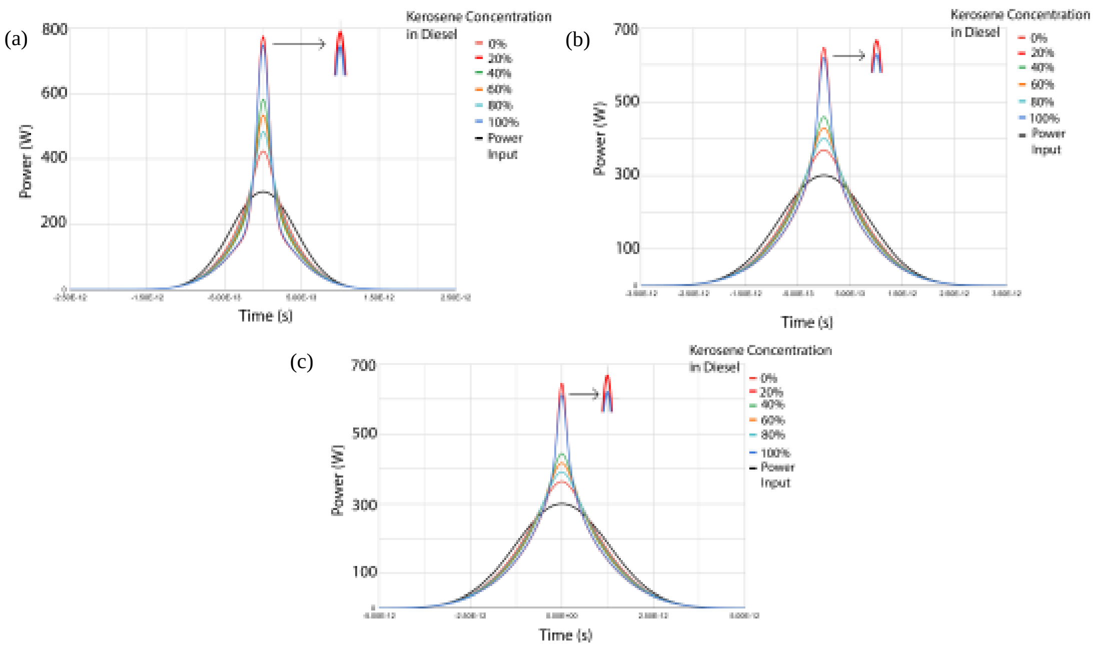


Figure 5.6: Shape of the pulse at the receiving end as it passed through HC-PCF filled with diesel sample with varying adulteration level for –a) input power

300W and pulse width 1ps, b) input power 300W and pulse width 2ps, c) input power 300W and pulse width 3ps.

Concentration of kerosene in the fuel sample	Input Power = 300W and Pulse width = 1ps			Input Power = 300W and Pulse width = 2ps			Input Power = 300W and Pulse width = 3ps		
	Peak Power Output (W)	Power Upsurge (W)	Compression sensitivity (%)	Peak Power Output (W)	Power Upsurge (W)	Compression sensitivity (%)	Peak Power Output (W)	Power Upsurge (W)	Compression sensitivity (%)
0%	422.753	122.753	60	369.33	69.33	74	362.67	62.67	76
20%	774.415	474,415	23	647.25	347.25	25	644.306	344.306	25.34
40%	581.119	281,119	33	459.72	159.72	52	443.267	143.267	56
60%	533.232	233.232	39	429.59	129.59	59	415.963	115.963	62
80%	481.97	181,97	44	400.659	100.659	65	390.377	90.377	66.67
100%	748.657	448.657	24	620.574	320.574	27	612.389	312.389	29.34

Table-IV: Compression Sensitivity and Power Upsurge at the receiving end of HC-PCF for the input pulse having 300W Input power and pulse width of 1ps, 2ps and 3ps respectively

The analysis was done for input power 400W as well, where the pulse width was varied from 1ps, 2ps and 3ps, where fiber length was chosen to be 0.45m, 0.8m and 1.1m respectively. The results of the compression sensitivity and power upsurge are tabulated in Table-V.

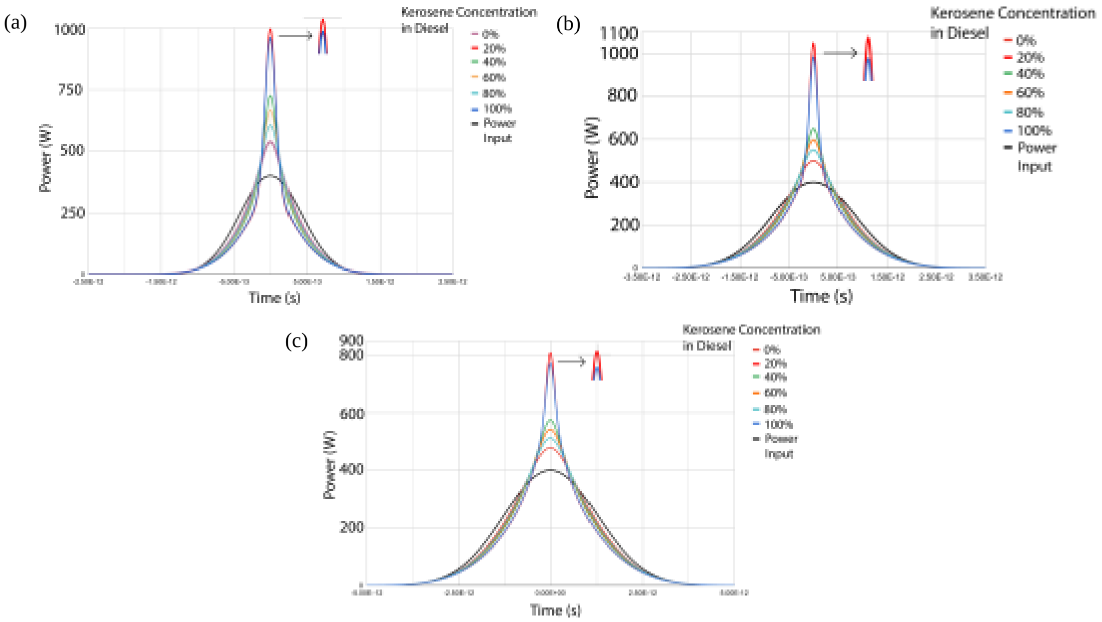
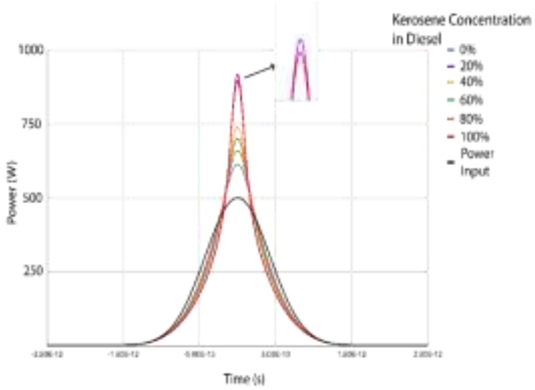


Figure 5.7: Shape of the pulse at the receiving end as it passed through HC-PCF filled with diesel sample with varying adulteration level for –a) input power 400W and pulse width 1ps, b) input power 400W and pulse width 2ps, c) input power 400W and pulse width 3ps.

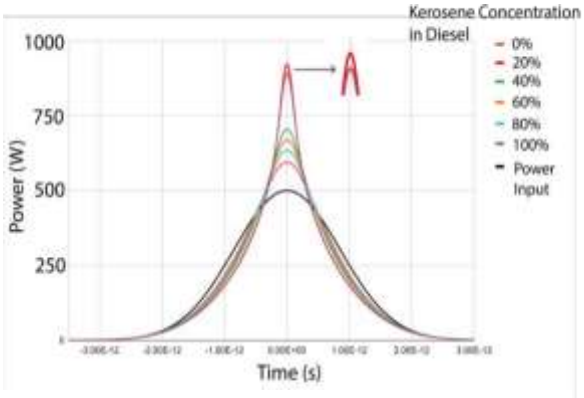
Concentration of Kerosene in Diesel	For Input Power = 400W and Pulse width = 1ps			For Input Power = 400W and Pulse width = 2ps			For Input Power = 400 W and Pulse width = 3ps		
	Peak Power Output (W)	Power Upsurge (W)	Compression Sensitivity (%)	Peak Power Output (W)	Power Upsurge (W)	Compression Sensitivity (%)	Peak Power Output (W)	Power Upsurge (W)	Compression Sensitivity (%)
0%	538.832	138.832	64.4	500.585	100.585	73	478.302	78.302	78
20%	996.719	596.719	22	1048.072	648.072	16	807.576	407.576	30.367
40%	725.62	325.62	37	648.64	248.64	47	574.58	174.58	58.67
60%	666.64	266.64	44	596.468	196.468	55	542.515	142.515	64.34
80%	606.204	206.204	50	549.16	149.16	63	511.946	111.946	70.34
100%	960.665	560.665	24	983.086	583.086	18	770.908	370.908	33.67

Table- V: Power Upsurge and Compression Sensitivity at The Receiving End of HC-PCF For The 400W Input Pulse and Pulse Width Of 1Ps ,2Ps, 3ps

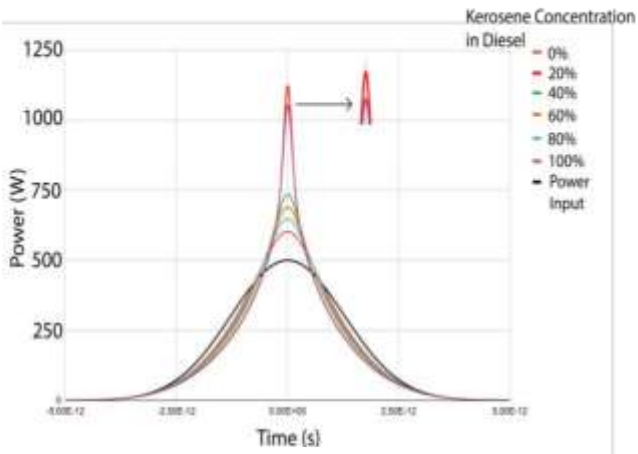
Again, the fuel samples are exposed to 500W power for 1ps, 2ps and 3ps.The lengths were chosen 0.5m and 0.92m for the respective pulse width with the input power 500W. e power upsurge a compression sensitivity gave favorable outcome for detection of the chemical solvent which is given in Table-VI.



(a)



(b)



(c)

Figure 5.8: Shape of the pulse at the receiving end as it passed through HC-PCF filled with diesel sample with varying adulteration level for –a) input power 500W and pulse width 1ps, b) input power 500W and pulse width 2ps, c) input power 500W and pulse width 3ps.

Concentration of kerosene in the fuel sample	Input Power = 500W and Pulse width = 1ps			Input Power = 500W and Pulse width = 2ps			Input Power = 500W and Pulse width = 3ps		
	Peak Power Output (W)	Power Upsurge (W)	Compression sensitivity (%)	Peak Power Output (W)	Power Upsurge (W)	Compression sensitivity (%)	Peak Power Output (W)	Power Upsurge (W)	Compression sensitivity (%)
0%	613.621	113.621	74	595.001	95.001	78	602.64	102.649	76.67
20%	918.405	481.405	36	922.867	422.867	36	1123.862	623.862	23.34
40%	739.365	239.365	54	705.518	205.518	60	735.878	235.878	56
60%	700.938	200.938	60	669.842	169.842	65	690.352	190.352	62.67
80%	660.714	160.714	66	634.632	134.632	71	648.031	148.031	68.67
100%	896.402	396.402	38	892.841	392.841	38	1055.095	555.095	54.67

Table VI: Power Upsurge and Compression Sensitivity at The Receiving End of HC-PCF For The 500W Input Pulse and Pulse Width of 1ps ,2ps, 3ps

5.7. Conclusion:

Our research work shows a unique approach of detecting kerosene concentration level using only two resulting parameters named power upsurge and compression
sensitivity.

- This approach significantly reduces the computational complexity while offering high sensitivity compared to other methods. Our approach has reported a notable minimum sensitivity of 16%, corresponding to 648.072W power upsurge.
- The exceptional sensitivity resulting from ultra-short pulse alteration proves commercially viable, promising substantial benefits for biosensing, atmospheric pollution measurement, and the broader scientific community.

Chapter 6

Fabrication Compatibility

A Nano level sensor without fabrication compatibility is of no use. For this reason, analysis of a proffered sensor through existing methods is a good practice. The sensor that has been proposed has three types of material primarily[49].

- Air
- Silica glass as background element
- Material Under sensing (MUS)

Air is readily available and it helps to create the "Defect" while mapping a hollow core based photonic crystal fiber. Now, modification of Silica glass according to the desired shape and characteristics is a bit tricky. The overall process is described below:

6.1 Background Material Processing:

For low-loss optical fibers, the material of choice is pure silica glass, which is developed through the process of fusing molecules together. It is possible to achieve the difference in refractive index that exists between the core and the cladding through the utilization of dopants when the fabrication process is being carried out.

GeO and P_2O dopants are appropriate for utilization in the core because they enhance the RI of pure silica. On the contrary, elements like as boron(B) and fluorine(F) are used for the cladding due to their capacity to lessen the refractive index of silica. However, some other dopants can be employed, depending on the particular applications under consideration. To enhance the generation of fiber amplifiers and lasers, rare-earth ions are added to the core of silica fibers by the use of dopants like $ErCl_3$ and Nd_2O_3[50].

6.2 Fabrication Process in a nutshell:

The practical implementation of optical fibers involves two distinct phases [51]. Initially, a vapor-deposition method is used to produce a cylindrical preform with the requisite refractive-index profile and the correct core-cladding dimensions. The dimensions of a normal preform are 1 meter in length and 2 cm in diameter. During the second phase, the preform undergoes a painstaking transformation into a fiber using a precision-feed mechanism. Afterwards, the material is placed into a furnace at the ideal speed. During this procedure, the dimensions of the core and cladding stay constant. The preform fabrication and fiber drawing operations utilize advanced technologies to maintain constant core size and index profile [51], [52] Various methodologies can be utilized to construct a preform. Some of the frequently used methods are modified chemical vapor deposition (MCVD), external vapor deposition, and vapor-phase axial deposition. The MCVD process is depicted in a schematic diagram in the figure. The process involves depositing successive layers of silicon dioxide (SiO2) onto the inner surface of a fused silica tube by reacting the vapors of silicon chloride (SiCl) and oxygen (O) at a temperature of around 1800 °C. To ensure uniformity, the multiburner flame is oscillated across the whole length of the tube. Fluorine is introduced into the tube to control the refractive index of the cladding layers. After applying many passes of the torch, a sufficiently thick layer of cladding is formed. Then, the vapors of GeCl or POCl are added into the vapor mixture to construct the core. After the deposition of all layers, the temperature of the torch is raised to induce the collapse of the tube, resulting in the formation of a solid rod known as the preform[51], [52], [53].

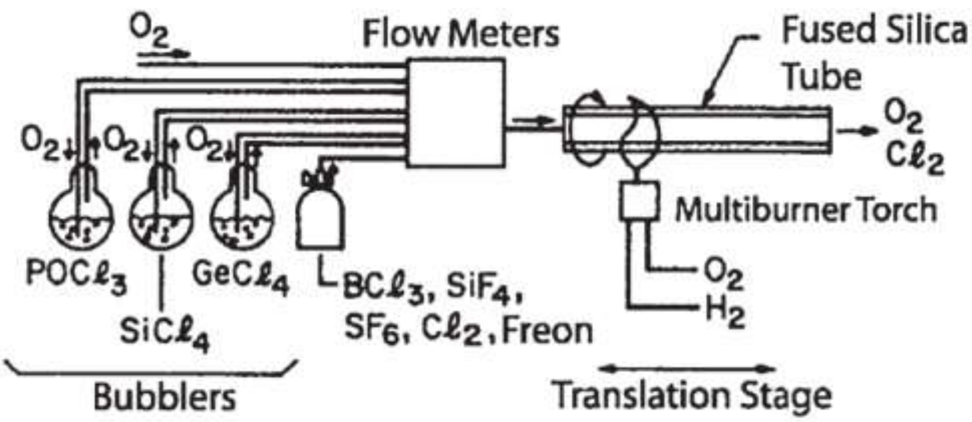


Figure 6.1: Schematic Diagram of CVD technique

Chapter 7

Concluding Notes with Future Scopes

Photonics along with the knowledge of material science is always an enchanting subject to discover. For Nano level research, continues advancement of Nano-technology, supportive Moore’s law and Energy efficient approaches have enabled the photonic research to flourish in a tremendous manner. All the electronic devices having higher size and heat dissipation issues are getting replaced by Photonic devices. The proffered sensor will have wide range of applications, starting from serving Petrochemical Industries to medical sectors for disease diagnosis, adulteration detection, sensing foreign body element, scanner etc. Insertion of ultra short pulse will pave the way of Laser based photonics research which is not only commercially available but also sustainable, energy efficient, computationally sound and simpler in case of arranging experimental setup.

7.1 Concluding Remarks:

Talking about the Laser optics-based work, this research endeavor introduces a novel method for detecting levels of adulteration in diesel samples. It utilizes the nonlinear optical characteristics of HC-PCF to acquire perfect results. The detection mechanism relies on analyzing the pulse shape change of ultra short pulse transmitted through HC-PCF in a meticulous and professional manner. An ultrashort pulse of picosecond has been transmitted through the HC-PCF using a total of nine different input configurations and three distinct fiber lengths. The study demonstrates the effective detection of adulteration levels in diesel using this method, as each sample exhibits distinct values for pulse compression and power upsurge. Significantly, a **compression sensitivity of 16%** has been achieved, with pulse compression reaching six times the input pulse width and a **maximum power upsurge of 648.072W**. The results emphasize the method's exceptional sensitivity and relatively lower complexity in comparison to alternative methods. Given the extensive use of diesel in numerous industries and automotive sectors, accurate detection of diesel and other petrochemicals become so much crucial. Introducing a fresh perspective significantly enhances the impact of this endeavor and sets the stage for future advancements in the industry.

7.2 Future Prospects

7.2.1 Analysis of soliton Numbers

The soliton number plays a pivotal role in determining the generation and behavior of optical solitons in a medium in the field of nonlinear optics. This represents the balance between dispersion, which leads to pulse broadening, and nonlinearity, which counteracts the broadening. The soliton number indicates whether a pulse will maintain its shape as a soliton, break into multiple solitons, or disperse. In ultrafast optics, solitons are particularly valuable because they enable the transmission of high-intensity pulses over long distances without distortion.[54] Real-world applications such as ultrafast laser technology and granular analysis in the biomedical industries greatly depend on its stability. Through the manufacture of meticulously designed HC-PCF, researchers in the field of nanotechnology can harness the unique capabilities of solitons. These remarkable entities have the remarkable ability to retain their shape and travel consistently through nonlinear materials. This highlights the immense value of solitons in the field of ultrafast optics, as they allow for precise manipulation of light pulses and reliable signal transmission[55].

7.2.2 High compression efficiency and power upsurge

Existing sensors are having outstanding result, obviously. However, there should be given more focus on Fiber length vs Pulse distortion possibilities. Yes, the fiber length is practical till now. However, improved compression factors along with lesser size can be a keynote point to deal. Then optimization of existing design will be there. A lot of trial and error-based simulation will be going on. Moreover, fiber length with Fabrication compatibility will be another takeaway for that research also.

7.2.3 Comparative analysis of design Flexibility between Normal Core and HC-PCF for area-specific applications

When comparing hollow-core photonic crystal fibers (HC-PCFs) to normal-core fibers for certain applications, design flexibility is a crucial consideration. The solid core of normal-core fibers, which direct light by complete internal reflection, provides strong performance for a variety of applications. Nevertheless, the design flexibility of these fibers is often limited by material restrictions and dispersion characteristics. However, HC-PCFs offer impressive flexibility as they guide light through a hollow core surrounded by a microstructured coating with a wide range of tunability as observed from our research work. They are ideal for applications that require precise control over light propagation, such as high-power beam delivery, ultrafast pulse shaping, and low-loss transmission across wide spectrum ranges. This is because they have the ability to adjust dispersion and modal characteristics by altering the microstructure. Due to their versatility, HC-PCFs are more suitable for specialized applications where regular fibers are not enough, providing enhanced performance tailored to specific operating needs. HC-PCFs offer significant advantages when it comes to design flexibility, allowing for innovative opportunities in the field of optical systems and specialized applications.[56] Keeping all those in mind, we will try to figure out the comparison of results and outcomings and limitations of each type of sensors

7.2.4 Exploration of emerging Optical devices of Photonics

Photonic research encompasses a vast number of optical devices for area specific applications. Starting from Bragg grating fiber, prism coupling up to optical switch, coupler, Filter of different types, Metamaterials etc. Graphene based metamaterials can be a large area of exploration to do. We will try to focus on these specific arenas as well as nonlinear optics.

Taking Moore's law in consideration we will try to explore some other optical devices in Photonics like:

Here's a table listing some Nano-level optical devices in photonics along with their typical sizes Table VII:

These sizes are approximate and can vary depending on the specific design and application.

Optical Device	**Size according to literature**
Plasmonic Nanoparticles	10-100 nm[57]
Photonic Crystals	Lattice constant ~200-500[58]
Metamaterials	Unit cell ~10-200 nm[59]
Nanowire lasers	Diameter ~50-200 nm[60]
Quantum Dots	2-10 nm [61]
Nanoantenna	Length 10-200nm[62]
Nanophotonic Waveguides	100-500 nm feature size[63]

Surface Plasmon Resonators (Filters Specifically)	10-100nm[64]
Nanocavities	100-300 nm[62]
Nanophotonic Switches	100-500nm[65]

Table VII: Optical devices with their size

We will grab the opportunity to have a detailed analysis on each of the optical devices on by one. We are optimistic to have certain devices for multidimensional applications, serving industries, Biomedical genre, telecommunication and Power sectors as well.

Chapter 8

Demonstration of Outcome Based Education (OBE)

Any technological advancement or scientific research needs a proper granular analysis and pinpoint installation to make it compatible for commercial production. As a result, a perfect mapping of outcomes enables the assurance of grabbing those. Outcome based Education system (OBE) has created an interconnection between the achievable program outcome from the project and the key takeaways that is practically attained from the project. Starting from acquisition of theoretical knowledge acquisition to Project Budget analysis, teamwork, Environmental and Human health issues, socio cultural Impact of the project etc. are taken into consideration. All these give a higher degree of confidence to the students who aim to be an Electrical and Electronic Engineer, a farsighted dream of us, since infancy. The problem statement titled with **"Investigation on Mapping Highly sensitive and tunable Hollow Core Photonic Crystal Fiber Facilitated with Ultra-Short Pulse for multipurpose applications."** Has gone through a detailed analysis of Literature review, Software and technical knowhow acquisition, consideration of Professional, ethical point of view, environmental effect and sustainability of the project, economic and socio-cultural impact consideration etc. The following pages will come up with a proper dissection of these portion one by one. Here goes a 4-step workflow process which incorporates the major key points of the project:

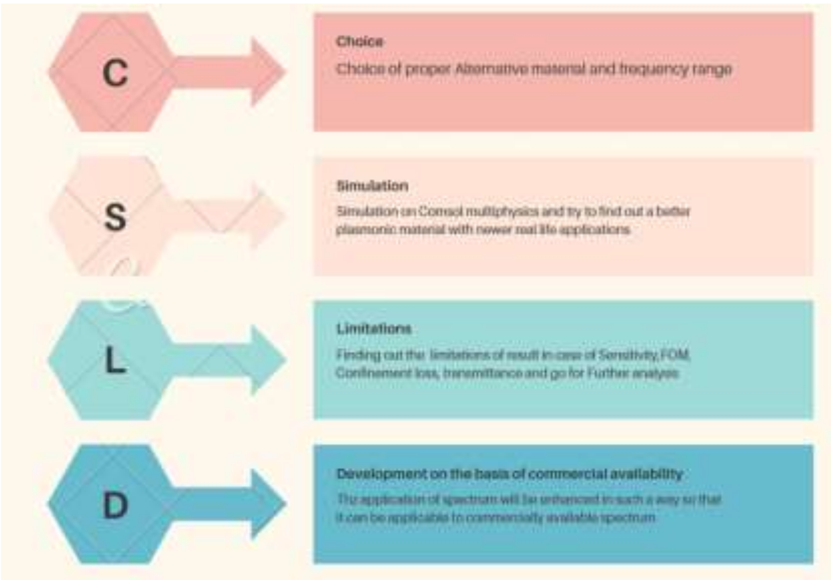


Figure 8.1 4-step workflow process (in a nutshell)

8.1 Course Outcome (CO)

COs	CO Statement	POs	Put Tick (√) EEE 4800
CO1	Petrochemical Industries need perfect detection of unknown analyte and also the level of adulteration for different important consumer end usage. So, having precise chemical detector is a modern day problem	**PO2**	√
CO2	Assess the experimental and technical requirements of the problem by carefully analyzing and synthesizing information, taking into account feasibility and efficiency.	**PO4**	√
CO3	Choose an appropriate solution and evaluate its approach while taking into account ethical considerations, industry codes, and established standards.	**PO8**	√
CO4	Utilize cutting-edge engineering facilities, modern experimental setup, softwares and acquisition of knowledge to address the issue.	**PO5**	√
CO5	Prepare management plan, however lack of Nano lab became a hindered for us, so it is not included	**PO11**	
CO6	Analyze the socio-economic cultural health environmental effect	**PO6**	√
CO7	Analyze the long- and short-term effect of the proffered solution which is environment friendly, green energy technologies and reusable.	**PO7**	√
CO8	Assure a realistic and fruitful long-term solution all the aspects of environment, religion and Human health	**PO3**	√
CO9	Have to give effort diligently as an individual and as a team player for the completion of the solution.	**PO9**	√
CO10	Try to arrange various finding as detailed reports, assignments, field visit reports, applicability test etc. As a part of it, we have produced capstone project proposal, Poster related to Capstone project, Presentation for Pre-defense and defense, thesis book etc.	**PO10**	√
CO11	Acknowledge the importance of ongoing research, knowledge and facilities: we have done it in a exquisite way	**PO12**	√

Table VIII: Alignment of CO-PO based on Ultra-short pulse facilitated Hollow core PCF project

8.1.1 Detailed explanation and reasoning behind each CO

CO1:

Proficiently Formulate and Analyze Complex Engineering Challenges in Designing a PCF Hollow Core with Commercial Light available: This specific laser is readily available in NKTphotonics, LASERGLOW and Thorlabs etc.

CO2:

Study of related papers and theories about Hollow core PCF design and check the previous works: Numerous papers have been analyzed and re-simulated which helped to assure the perfect initiation of thinking about problem statement of this project. For example, solving the adulteration issue in Food components like sugar, honey, Petrochemical industry related sensing (Octane, diesel etc.)

CO3:

Developing a design that optimizes usability and user-friendliness for the broader community: This portion encompasses the Fiber characteristics, design consideration and Applicability for specific arena (Biomedical, petrochemical etc.)

CO4:

A thorough understanding of COMSOL software, and the capacity for incorporating plasmonic techniques: In this project COMSOL Multiphysics 5.6 has been harnessed as prime software. However. MATLAB, origin etc. were also used time to time.

CO6:

Creating a design that will be useful for future research and may help various Fabrication companies like Neural Semiconductor, Ulkasemi, itest etc.

CO7:

Aiming for a structure that is readily available or further optimized and ensures the public safety and health

CO8:

Communicate complex electrical designs effectively in reports and presentations, demonstrating clear instructional communication for the sensors.

CO9:

Apply proper management planning, work as a better team and have problem-solving model, showcasing project management and financial proficiency in team and multidisciplinary settings.

CO10:

To solve the project's persistent problem, evenly distribute tasks among team members to use current advances in technology.

CO11:

In order to address modern issues and guarantee attendance at meetings and professional groups, such a model should undergo constant evaluation

8.2 Aspects of Program Outcomes (POs) Addressed:

	Statement	Different Aspects	Put Tick (√)
PO2	A rigorous on hand experimental approach has been followed using the simulation environment of COMSOL after acknowledging the problem statement about petrochemical industries. The information from mathematics, pure scientific law and formulation have been done		√
PO4	Investigation: ▪ Nonlinearity properties of a fiber ▪ Problem of traditional sensing ▪ Unique shape PCF design ▪ Better solution compares to existing work ▪ Limitations of proffered sensors	Designing software- COMSOL	√
		Analysis- Excel sheet, interpretation- Research papers and websites	√
		Information analysis form Literature review	√
PO6	The engineer and society: Evaluate society, health, safety, legal and cultural concerns and the related obligations important to professional engineering practice and solutions to difficult electrical and electronic engineering problems using reason informed by contextual knowledge.	Societal impact- Employment	√
		Health effect- No negativity	√
		Safety- should be done and taken into consideration	√
		Legal- MIR range is legal, no permission required	
		Cultural- Long term positive impact in Biomedical and petrochemical sectors	
PO7	Environment and sustainability: ▪ Low power usage ▪ Environment friendly ▪ Reusable	Societal	√
		Environmental	√
PO8	Ethics: ▪ Proper credit given ▪ Novel work ▪ Plagiarism issue- taken into consideration	Religious values	√
		Professional ethics and responsibilities	√
		Norms	√
PO9	Solo effort and teamwork: a diverse team combination was there. ▪ **190021221** had better resource analysis, software skill ▪ **190021230** helped with technical analysis, finding the loopholes of the project, went for mathematical manipulations perfectly. ▪ **190021302** compensate in both technical and software skillsets	Diverse teams	√
		Multi-disciplinary settings- done	√
PO10	Communication: Effective team game was there. 1^{st} one came up with drafting methodology, Future scopes, CO PO alignment, fabrication compatibility while writing thesis book. The 2^{nd} member came up with Design	Analytical writing, development of writing skill	√
		Design and documentation	√
		Better presentations	√

	consideration writing, referencing, Proffered sensors resulting parameter and visualization. Finally, the 3rd one went for Introduction, Problem statement writing, designing the Slides for presentation, documentation etc.	Give and receive clear instructions	√
PO11	Being able to show knowledge and comprehension of engineering management and financial choices, in addition to the ability to apply these concepts to self-work, as an employee and boss of a group, in order to manage initiatives that involve a variety of disciplines, is included in this ability.	Engineering management	√
		Financial decision-making	√
		Project management	√
		Diverse environment	√

Table IX- Addressed CO-PO in Ultra-short pulse facilitated HC-PCF design

Each of the POs are playing vital role in case of project mapping. As a result, minute analysis of these individually is a must. Here goes some detailed explanation and justification behind each of the POs considered for this project

8.3 Justification of Each Program Outcome

COs	POs	Explanation/Justification
CO1	PO2	Even with advancements in technology, both the petrochemical and biomedical industries still struggle with inefficient detection and diagnosis processes. Our goal is to create a Nano sensor that improves detection abilities, more energy efficient and commercially available
CO2	PO4	We have designed a novel experiment based on previously conducted experiments, made decisions by interpreting the obtained data.
CO3	PO8	Through utilization of the material properties of both the fiber (silica glass) and MUS, we have identified key parameters. Our solution, analyzed with COMSOL Multiphysics and MATLAB, is both computationally efficient and ethically sound, with fabrication feasibility, adaptable through THORLAB
CO4	PO5	We are using COMSOL Multiphysics and MATLAB software to simulateand verify the result which are modern engineering tools.
CO5	PO11	We have layout the steps on how we are going to solve the problem and a budget that we will require for solving it
CO6	PO6	If we are able to detect the different cancer and normal cells as well as different chemicals an impact will be made on health and society by improving overall public health outcomes and quality of life.
CO7	PO7	Our proposed solution, utilizing terahertz sensing, is non-ionizing and environment friendly. It consumes less power and its commercialproduction will reduce overall energy consumption.

CO8	PO3	Developing a viable solution for plasmonic crystal fiber and waveguide sensors involves ensuring considerations for human health and environmental affect. This includes designing sensors that are non-invasive and safe for use in medical diagnostics, addressingsocietal needs by providing accessible and affordable detection methods, and minimizing environmental impact through the use of sustainable materials and manufacturing processes. MIR range doesn't have mass impact as the heat dissipation and microcrack insertion is negligible
CO9	PO9	Efficiently contribute to solving challenges both independently and collaboratively with other members of the team by dividing our work and sharing the resources.
CO10	PO10	Upon completing this project, we will compile a comprehensive technicalreport, documentation and interact through presentation. These will provide a detailed overview of our solution, potential outcomes, and future opportunities for advancement.
CO11	PO12	Our project introduces a new method for any petrochemical detection and biomedical application by reducing energy consumption and rigorous calculation.

Table X- justification of each PO along with compatible CO

8.4 Addressing Knowledge Profiles Related Attributes (K3 – K8)

K	Knowledge-Profile related Attributes	Put Tick (√)
K3	Formulation of Engineering knowledge, here for our case this is Nonlinear optics with ultra short pulse analysis	√
K4	A complete theoretical framework has been mapped starting with terahertz sensing up to Propagation constant analysis with Nonlinearity which formulates the K4	√
K5	Lack of designing Machines and experimental setup like 3D Nano printer we could not avail K5	
K6	For same reason k6 has been excluded from our analysis	
K7	K7 is included as we see our sensor will serve petrochemical industry, Biomedical sensor and measurement genre, socio economic impact is clearly evident and further discussed. Also, no religious clash is existent. Moreover, serving Fabrication company will help to earn a lot of Revenue	√
K8	We got the opportunity to have a meet up with Mustafa Ordu, a renowned person in Photonics and Nano sensor research, we also went through lot of existing research as mentioned earlier	√

Table XI- justification of knowledge profiles for each of the K

Theoretical knowledge on nonlinear optics and ultrafast laser, its availability has been harnessed well. After an extensive literature review it came up with a real-life problem to be solved. For our case, Diesel Adulteration level detection based on specific sample has been utilized. Nano level research demands highly efficient softwares like COMSOL, MATLAB, Lumerical FDTD etc. Finally, the sensors high range of tunability have been inspected which is also sustainable, power efficient and Rapid sensing facilitated sensor.

8.5 Addressing the Attributes of Complex Engineering Problems

P	Explanation/Justification
P1	In designing sensors for detecting chemicals and cancer cells, we incorporate advanced engineering principles of k3, k4 and stay updated with the latest research in the field utilizing k8.
P2	Understanding the diverse refractive index ranges is crucial to determine which ones are compatible with our sensors, facilitating informed decision-making in our design and implementation.
P3	There are some solutions which are already developed for the problems we are tackling and our solution requires proper analysis, critical thinking and uniqueness to serve scientific faternity.
P4	RI sensors offer a variation of detection capabilities, yet achieving comprehensive coverage across all detection levels proves unattainable.
P5	Our problems and solutions completely fit into the rules and guidelines that engineers usually follow.
P6	Meeting all the different needs for sensors presents a formidable challenge as there are lot of parameters included to design a sensor
P7	There are some solutions which are already developed for the problems we are tackling and our solution requires critical thinking, uniqueness in analysis to formulate perfect area specific models.

Table XII- justification of Complex Engineering Problem

Environmental conflict, theoretical knowledge and the possibility of commercial production for multidimensional applications have been the sole factors that have been considered from Complex Engineering Problem Solving part.

8.6 Socio cultural and Environmental Effect

- **Socio Cultural:**
  - **To serve Petrochemical Industry through wide range of analyte detection (1.35-1.44)**

    For area specific application, the Refractive index of each sample will be unique. For proper light confinement and Fiber characteristics tests and Thumb rule, the design of the sensor (core diameter, PML layer, Circular and elliptical layer number and their width) should be optimized accordingly.[16], [66]

  - **Can be used in Biomedical Sectors for example:**
    - ➢ **Cancer cell detection** (Hela, Jurkat, MCF-7, MDA-MB-231 ranging from 1.36-1.40) [67]
    - ➢ **Diabetes detection** through Acetone Level Mapping (1.3572-1.4196) [18]
    - ➢ Blood Plasma related Diseases Like **Tuberculosis, Malaria** etc.
  - Creating the possibility to serve **VLSI Fabrication companies** like Neural, Ulkasemi etc. [49], [68]

- **Environmental:**
  - Ultra short pulse is using a Nano joule energy ranging from 0.05 nJ to certain picojoule. As a result, high power production is not required here which makes the system power efficient and sustainable.[69]
  - Minimum heat dissipation results in very small chance of macrocracks to be penetrated in the environment. Also, maximum portion of the beams is absorbed. So, chances of having mass pollution is tends to zero. As a result, it is certainly environment friendly.[70]

8.7 Addressing Attributes of Complex Engineering Problem Solving portion

Here goes the Complex engineering related portion for problem solving and the key takeaways that have been found to be relevant for this project are incorporated below:

P **Attribute**	**Range of Complex Engineering Problem Solving** Complex Engineering Problems have characteristic P1 and some or all of P2 to P7:	**Put Tick (√)**
Depth of knowledge required	**P1:** Cannot be resolved without granular engineering knowledge at the level of one or more of K3, K4, K5, K6 or K8which allows a sole but important, first principles analytical approach	√
Range of conflicting requirements	**P2:** Involve a vast range or conflicting technical, engineering and other issues	√
Depth of analysis required	**P3:** Have no one step or only solution and require abstract thinking, originality formulate suitable models	
Familiarity of issues	**P4:** Involve rarely encountered issues	
Extent of applicable codes	**P5:** Are outside problems, Not addressed or relevant to this project.	
Extent of stakeholder involvement and conflicting requirements	**P6:** Involve diverse groups of stakeholders or Commercially important person with widely varyingneeds	√
Interdependence	**P7:** Are higher level problems including many sub divisions of each problem	

Table XIII- justification and key takeaways for Complex Engineering Problem

The only things that have been taken into consideration by the Complex Engineering Problem Solving component are environmental conflicts, theoretical comprehension, and the possibility of commercial manufacture across a variety of applications.

8.8 Addressing Complex Engineering Activities (A1 – A5)

A	Range of Complex Engineering Activities	Put Tick (√)
Attribute	Complex activities refer to engineering activities or projects that exhibit one or more of the following characteristics:	
Range of resources	**A1**: Involve the utilization of a wide variety of resources (and for the sake of this, resources include people, money, equipment, materials, information, and technology).	√
Level of interaction	**A2:** It is necessary to find solutions to serious difficulties that have arisen as a result of interactions between a wide variety of technological, engineering, or other challenges that are in conflict with one another.	
Innovation	**A3:** Encourage innovative applications of engineering ideas and information derived from research in a variety of inventive methods	√
Consequences for society and the environment	**A4:** Have major repercussions in a variety of settings, and are defined by the difficulty of either predicting or mitigating their effects.	√
Familiarity	**A5:** The application of principles-based techniques allows for the possibility of going beyond prior experiences.	

Table XIV- Complex Engineering Activities

A	Explanation/Justification
A1	Making our sensors for real-world applications demands a robust blend of engineering expertise,financial resources, technical prowess, and access to necessary equipment.
A2	The proposed sensor has usage of wide range Wavelength starting from 1300nm to 2500nm whichis in Near Infrared Light range and also commercially available (Laser beam). It does not have conflicting technical issues that may affect another scientific genre.
A3	The sensors we aim to build are improving existing works completely.
A4	Our sensing strategy poses no threat to the environment, lacking any radiation or health risks,ensuring its eco-friendly implementation.
A5	We have explored the probable applications in various sectors like biomedical and petrochemicalindustry based on existing theoretical knowledge, however, expansion of existing principle-basedapproaches was not utilized by us.

Table XV- Justification for Complex Engineering Activities

8.9 Workflow aligned with CO PO

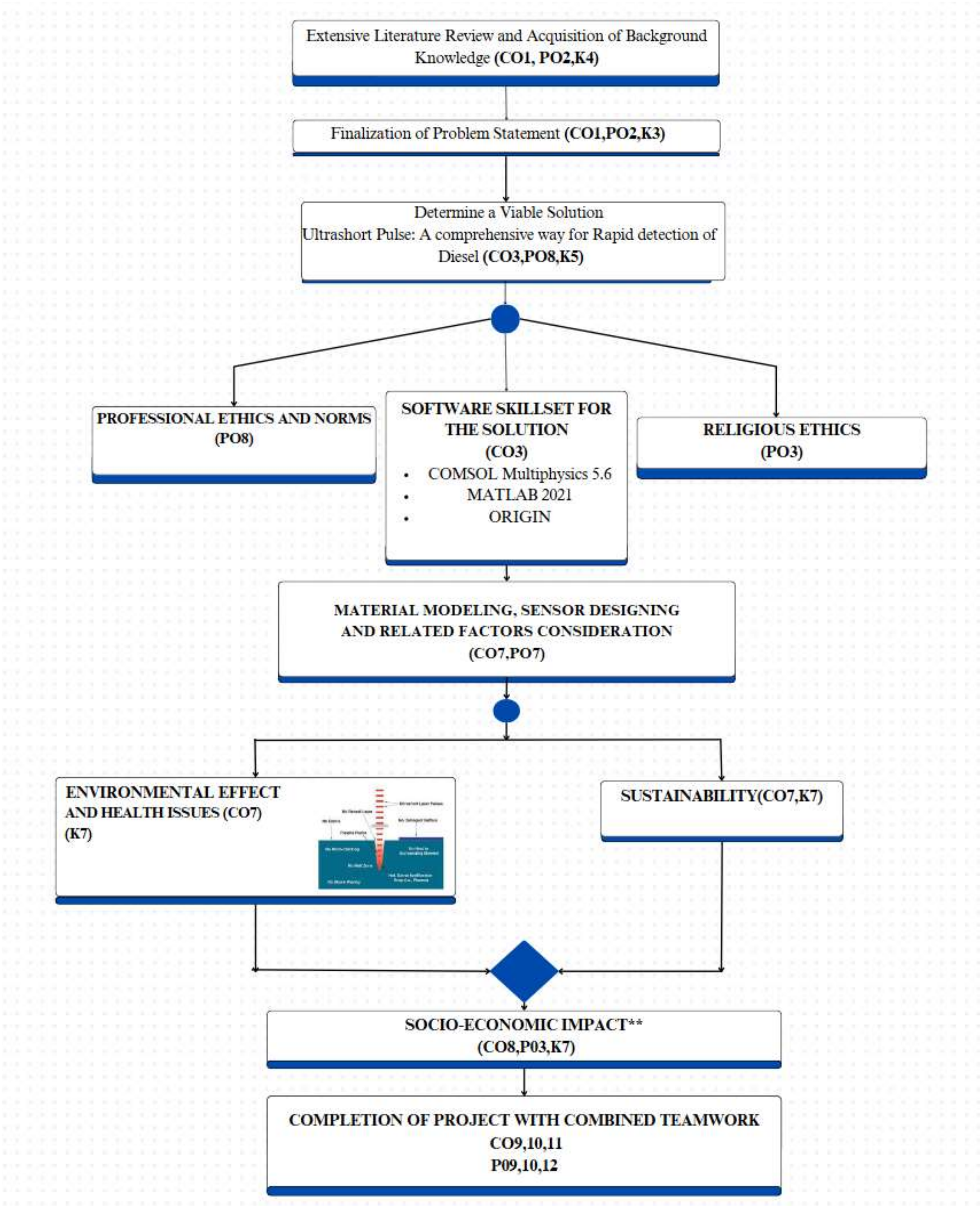


Figure 8.2 Visualization of CO PO in Flow diagram

8.10 Conclusion

This thesis book represents a unique approach for detection of Adulteration using Ultra-short pulse. The novelty remains in outstanding parameter values, less computational complexity and simpler experimental setup. Some error and trial basis modification will enable the sensor to work for wide range of area specific applications like Biomedical element analysis, disease detection, Measurement and sensing pressure, temperature etc. Another key takeaway from this research can be unique shape and outstanding compression sensitivity of 16%. In future, we will try to come up with more granular details about nonlinear optics and its probable applicability in different genres

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