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Acknowledgement

I want to extend my heartfelt gratitude to my esteemed Supervisor, Dr. Ajeet Kumar, whose unwavering support, insightful guidance and invaluable mentorship has been instrumental at every stage of this research work on applications of Surface Plasmon Resonance phenomenon in Photonic Crystal Fibers. His expert advice has been invaluable in shaping the direction and success of this work. My deepest thanks to Prof. Vinod Singh, Head, Department of Applied Physics, for providing the essential facilities and a conductive environment for our research.

I am also deeply thankful to the committee members for their critical input and suggestions, which have significantly enhanced the quality of my research work. I gratefully acknowledge Delhi Technological University for offering me the opportunity to conduct this research and for the extensive resources and support provided.

A special note of thanks to Mr. Akash Khamaru and Mr. Deepak Garg, PhD scholars, for their constant motivation and invaluable assistance. Their encouragement and support have been a great source of inspiration throughout my research journey.

I am deeply thankful to my sister, Mahi Yadav, for her constant support. Lastly, my heartfelt gratitude to my friends and family. Their unwavering love and support have been my constant source of strength and motivation throughout this journey.

Nidhi Yadav

(24/MSCPHY/50)

ABSTRACT

19 This work suggests design and structural analysis of highly sensitive photonic crystal fiber (PCF) based on surface plasmon resonance for various sensing applications. The designed sensor operates as refractometric sensor and biosensor used for the detection of various diseases like Anemia. This work mainly investigates its applications in biosensor, while also studying and comparing the effects of various 2D Plasmonic materials in terms of Confinement Loss and Wavelength Sensitivity. The proposed fiber is stimulated computationally on COMSOL Multiphysics by using FEM. The proposed work examines the work of Black Phosphorus (BP), a 2D plasmonic material, in the detection of Anemia. Anemia is a blood disorder characterized by low hemoglobin level in blood. This work aims for early detection of this disease to enable effective treatment. The obtained wavelength sensitivity for gold PCF sensor is 5500nm/RIU and for BP layered gold PCF sensor is 12,000nm/RIU. The BP layered sensor achieved amplitude sensitivity of -252.28RIU^{-1}. The wavelength sensitivity achieved for 140g/L Hemoglobin concentration in blood by gold PCF sensor is 5500nm/RIU and by BP layered gold PCF sensor is 14,500nm/RIU. Hence, this work summarizes that 2D materials like Black Phosphorus are highly effective plasmonic enhancers when they are used in combination with any plasmonic material like Gold, Ta_2O_5 and exhibits high sensitivity for biosensing applications.

Table of Contents

Candidate's Declaration ii
Supervisor's Certificate iii
Acknowledgement iv
Abstract v
Table of Contents vi
List of Figures viii
List of Tables ix
List of Abbreviations x
Chapter-1 Introduction 11-13
1.1 Aim of thesis
1.2 Thesis organization
Chapter-2 Optical Fibres 14-16
2.1 Introduction
2.2 Types of Optical Fibre
Chapter-3 Photonic Crystal Fibres 17-19
3.1 Introduction
3.2 Types of PCFs
3.3 Key Properties of PCFs
Chapter-4 Surface Plasmonic Resonance 20-22
4.1 Introduction
4.2 Biological setup of SPR
4.3 History of SPR
Chapter-5 SPR and PCF 23-26
5.1 Introduction
5.2 Types of SPR based PCFs
5.3 Advantages of SPR based PCFs
5.4 Limitations of SPR based PCFs

Chapter-6 Plasmonic Materials **27-29**

6.1 Introduction

6.2 Black Phosphorus

Chapter-7 Numerical Analyses **30-33**

7.1 Introduction

7.2 Characteristics of PCF

7.3 COMSOL Multiphysics Software

7.4 Numerical Analyses

Chapter-8 Literature Review **34-35**

Chapter-9 Design and Computational Analysis of Black Phosphorus-Based D-Shaped PCF SPR Refractive Index Sensor **36-49**

9.1 Introduction

9.2 Design of Proposed Biosensor

9.3 Mathematical Modelling

9.4 Fabrication Feasibility

9.5 Results and Discussions

9.6 Performance of sensor-RI sensing

9.7 Performance of sensor-Anemia sensing

9.8 Conclusion

Chapter-10 Conclusion and Future Work **50-52**

10.1 Conclusion

10.2 Future work

REFERENCES **52-57**

List of Figures

Fig. No.	Title of the Figure	Page No.
2.1	Phenomenon of TIR	14
2.2	Structure of Optical Fibre	15
3.1	Types of PCFs	18
4.1	SPR Setup	20
5.1	Types of SPR-PCF Designs (1)	23
5.2	Types of SPR-PCF Designs (2)	24
7.1	COMSOL Multiphysics Software	32
9.1	(a) Cross section of proposed D-shaped PCF SPR Sensor (b) Proposed experimental setup	39
9.2	Electric field distribution for **(a)** core mode with y-polarization, **(b)** core mode with x-polarization, **(c)** SPP mode, **(d)** Dispersion relation of the optimized structure at RI of 1.34	43
9.3	Shifts in loss peak (a) with gold layer thickness (b) with Ta_2O_5 layer	43
9.4	CL spectra at n_a= 1.37 and 1.38 (a) for various radii of big air holes (r_1) (b) for various radii of medium air holes (r_2)	44
9.5	CL spectra at n_a= 1.37 and 1.38 (a) for various radii of small air holes (r_3) (b) for different numbers of BP layers	45
9.6	(a) Loss curve and (b) amplitude sensitivity curve for optimized parameters without BP (c) loss curve (d) amplitude sensitivity curve for optimized parameters with BP	46
9.7	a) Loss curves for different hemoglobin concentration without BP (b) Loss curves for different hemoglobin concentration with BP	49

List of Tables

Table No.	Tittle of the table	Page No.
9.1	Change in Sensitivities when BP is incorporated	46
9.2	Performance Comparison of proposed sensor with prior studies	47
9.3	Primary Classification of Anemia	47

turnitin Page 11 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

List of Abbreviations

Abbreviation	Full Form
SPR	Surface Plasmon Resonance
PCF	Photonic Crystal Fiber
TIR	Total internal reflection
2D	Two-Dimensional
BP	Black Phosphorus
RI	Refractive Index
CL	Confinement Loss
EMA	Effective Mode Area
PDE	Partial Differential Equation
FEM	Finite Element Method
FDTD	Finite Difference Time Domain
SMF	Single Mode Fiber
SPP	Surface Plasmon Polariton
IR	Infrared

1 Introduction

The integration of Surface Plasmon Resonance (SPR) with Photonic Crystal Fibers (PCFs) represents an advanced approach in photonic sensing technology. This report presents the theoretical design and simulation of SPR-based PCFs aimed at enhancing optical sensing performance. Using COMSOL Multiphysics software, the proposed PCF structures were designed with suitable material compositions. The interaction between guided light modes and surface plasmons was investigated with a focus on sensitivity and spectral characteristics. The obtained results indicate enhanced performance in biosensing and chemical detection applications when compared with conventional PCFs.

13 Surface Plasmonic Resonance is an optical technique, which occurs at dielectric medium (usually gold or silver) at the interaction of light. When the light strikes the metal interface at specific angle and wavelength, it excites the electrons, and they begin to resonate [1]. The interaction is sensitive to environment and also sensitive to changes in refractive index.

SPR-based sensing technology offers several notable advantages over conventional sensing methods which includes the capability for real-time analysis. It also enhances sensitivity for environmental variations and is label free. Due to its high sensitivity and broad applications potential, the SPR-based sensing approach has made itself a highly effective detection technique. Including utility in areas such as biosensing, food quality monitoring, and gas detection.

A biosensor is an analytical device used to identify and measure biological substances. It consists of two primary components. A biological recognition element, which can be tissues, microorganisms, enzymes, or antibodies, and a physicochemical detector. When the target analyte binds to the biological element change is produced that the detector captures and

turnitin Page 14 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

converts it into an electronic signal, thereby indicating the concentration of the substance being analysed.

Photonic crystal fibres (PCFs) are a special kind of optical fibre that contain tiny air holes running along their entire length. These air holes help control how light travels through the fibre, allowing for much more precise manipulation of light compared to standard optical fibres [2]. PCFs offer several advantages, such as high birefringence, strong nonlinearity, and flexible structural design. These fibres can be designed in different shapes and sizes to achieve specific light-handling properties.

In recent times, several SPR-based PCF sensor designs have been proposed. To replace the conventional prism-based approach [3], with metal-coated holes [4] and U-grooved structures [5] being studied in old studies. But these designs come with some practical limitations like fabrication complexity and the challenge of depositing metals uniformly inside the fibre holes [6]. For these issues D-shaped PCF structures have been proposed where the top portion of the fibre is polished flat. This design allows for a wide interaction area between the light guided through the core and the surface plasmons and leading to improved sensing sensitivity.

1.1 Aim of Thesis

- To design SPR based PCF sensor.
- To study the functions of plasmonic materials like Gold, Ta_2O_5.
- To study the functions of 2D plasmonic materials like Black Phosphorus (BP).
- To stimulate the optical properties of designed sensor in COMSOL Multiphysics using Finite element method (FEM).
- To analyse properties like Confinement loss (CL), Effective mode index, Sensitivity, Figure of merit (FOM).
- To optimize the fibre for low loss and high sensitivity by changing parameters.
- To check designed sensor's capability for sensing for a particular disease like Anemia.

turnitin Page 14 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 15 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

1.2 Thesis Organisation

This work contains 10 chapters

- Chapter-1 contains the introduction of all topics of thesis and aim of thesis and thesis organization.
- Chapter 2 explores optical fibres and its types.
- Chapter 3 explores PCFs in detail and its types.
- Chapter 4 explores the SPR in detail.
- Chapter 5 combines SPR and PCF and contains the advantages of SPR based PCFs.
- Chapter 6 explores the plasmonic materials.
- Chapter 7 is aimed to explore the optical properties and Numerical Analyses.
- Chapter 8 contains the Literature review.
- Chapter 9 contains the first main project on designing a refractometric sensor with BP for offering higher sensitivity.
- Chapter 12 contains conclusion and future scope.

turnitin Page 15 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

2 Optical Fibres

2.1 Introduction

Optical fibres are thin, flexible waveguides made of glass or plastic, which transmits light from one place to another and transfers information from one place to another by a phenomenon known as total internal reflection (TIR). In TIR when the light hits the interface of first and second medium it reflects back to first medium, it does not refract into the second medium as shown as in **Fig 2.1**. The necessary conditions for TIR to occur are light must travel from denser medium to rarer medium and the angle of the incidence at the interface must be greater than the critical angle.

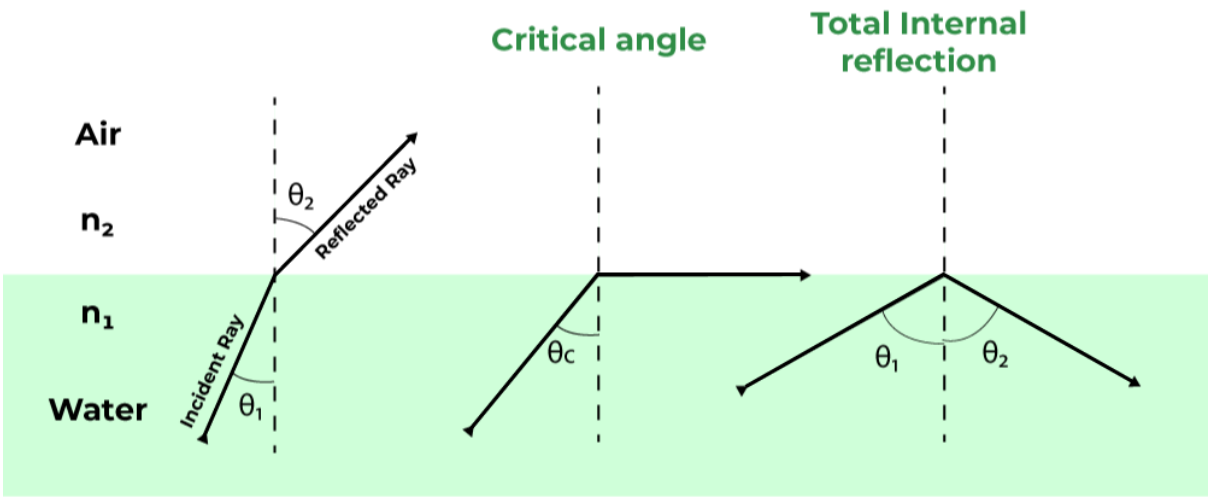


Fig 2.1 Phenomenon of TIR

An optical fibre is composed of two major parts **(Fig2.2):**

The inner core which has higher refractive index. It is mostly made up of silica and due to TIR, light propagation takes place here in the core region.

turnitin Page 17 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

The Outer cladding which has lower refractive index than core surrounds the core region in optical fibre. It is composed of an optically transparent material which has lower refractive index than core.

This structure of optical fibre helps in enhancing telecommunications by enabling high speed data transfer for long range applications with minimal attenuation.[7]

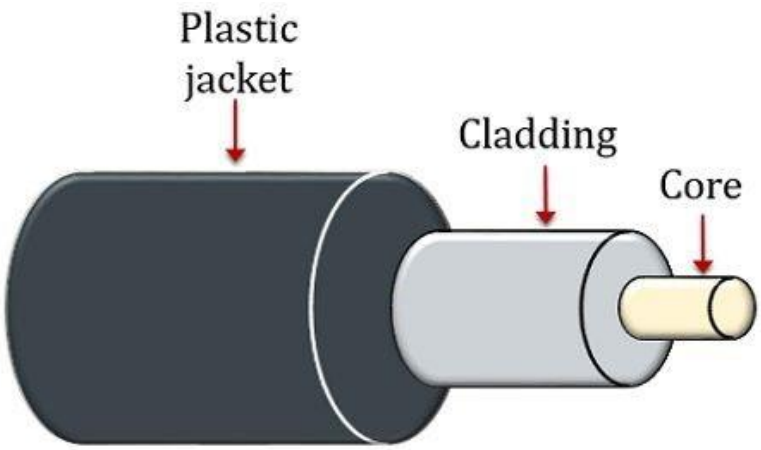


Fig 2.2 Structure of an Optical Fibre

2.2 Types of Optical Fibres

18

Based on no. of modes optical fibres can be classified in the following types:

a. **Single-mode fibre**

In single mode fibres, only one type of light can be propagated through them. The core diameter is smaller than the cladding diameter in range of few wavelengths as compared to the wavelength of light passing through it. Signal does not degrade or disperse, when travelling through these fibres. The light in single mode fibre can be passed through laser diodes.

b. **Multi-mode fibre**

In multi-mode fibres, many modes of light ray can be propagated through them. The relative difference of refractive index of core and cladding is also greater than single mode fibres. The diameter of core is larger than the wavelength of light which pass

turnitin Page 17 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 18 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

through it. Due to multimode, there is signal dispersion in these fibres. So, they are not suitable for long distance communication.

Based on refractive index optical fibres can be classified in following types:

a. **Step index optical fibre:**

   In this type of fibre, the refractive index of core is constant and the refractive index of cladding is slightly lower but also constant. The light rays propagate in this fibre as meridional rays i.e. cross the axis of core after every reflection from interface of core and cladding.

b. **Graded index fibre:**

   In this type of fibre, the refractive index of core is not uniform but it continuously decreases from centre towards core-cladding interface. The refractive index of cladding is uniform. The light rays propagate in this fiber as helical rays i.e. they do not cross fibre axis.

turnitin Page 18 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 19 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

23

3 Photonic Crystal Fibres

3.1 Introduction

Photonic crystal fibres (PCFs) are a speciality fibre (optical fibre with special design or materials) that contain tiny air holes running along their entire length. These air holes help control how light travels through the fibre, enables formation of guided waves with physical mechanisms different than the conventional fibres. Such air holes in PCFs are created by stacking capillaries or solid tubes and inserting them into a larger tube. Mostly, pure silica is used to make PCFs which makes them compatible for the fabrication technique given above.

1

PCFs offer several advantages, such as high birefringence, strong nonlinearity, and flexible structural design. Because of these features, they are used in many areas, including terahertz communication [8], terahertz sensors [9], refractive index sensing [10], pressure sensing [11], electric and magnetic field sensing [12], supercontinuum generation, high-power fibre lasers, and various metrology and spectroscopy applications.

Today, PCFs are manufactured in many research labs using different methods like stacking capillaries and rods, extrusion, sol-gel casting, and drilling. They can be made from materials such as silica, fluoride glasses, polymers, and chalcogenide glasses [2].

PCF-based SPR sensors are used to detect very small amounts of substances in areas like biology, environmental monitoring, and medicine. They have several advantages—such as compact size, single-mode light propagation, easy light coupling, and good control over the evanescent field—which make them highly suitable for sensing applications.

In these sensors, light travels through the core of the photonic crystal fibre. When this light reaches the plasmonic layer (usually silver or gold), it causes the metal's free electrons to oscillate. When the oscillation of these electrons matches the incoming light,

turnitin Page 19 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 20 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

a strong interaction occurs, known as resonance. If the conditions around the fibre change For example, if the analyte's refractive index varies—the resonance point also shifts. This shift alters the wavelength of the incident light, and the PCF-SPR sensor detects this change.

3.2 Types of PCFs

1) **Index guiding Photonic crystal fibres:**

   In this type of PCF, light stays confined in the core through total internal reflection. The core is solid, while the surrounding region contains air holes that act as the cladding. This structure is enclosed by pure silica, which has a refractive index of about 1.462. The air gaps help guide and control how the light moves through the fibre.

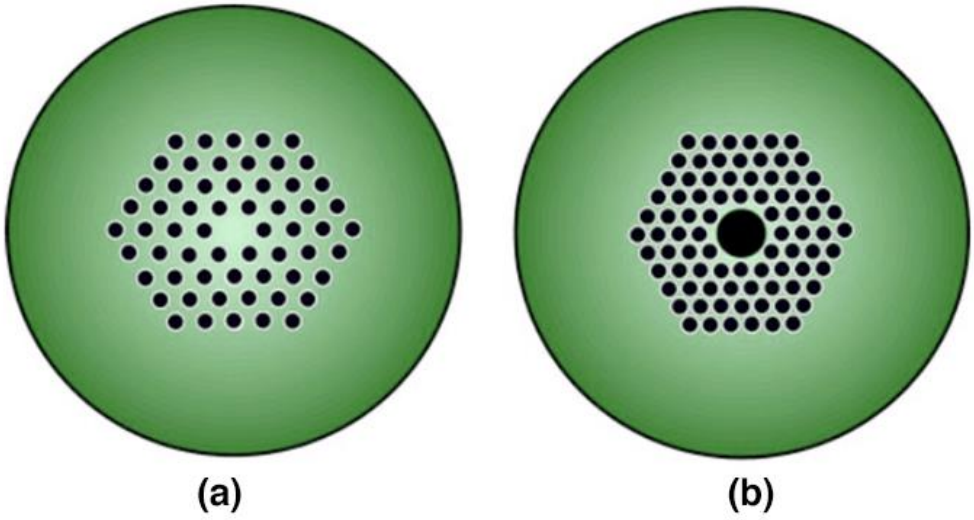


Fig.3.1 Types of Photonic crystal fibres a) Index guiding PCF
b) Photonic band gap fibre

2) **Photonic Band gap fibre:**

   In **Fig.3.1(b)** one of the air holes in the central region is replaced with a much larger air hole compared to the surrounding ones. This larger central hole forms the core, and light is guided through it by the photonic band-gap effect rather than total internal reflection.

turnitin Page 20 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 21 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

PCFs are special type of fibres because they have exclusive properties which makes them valuable in various applications across different fields like Telecommunications, Sensing and Measurements, Light generation and manipulation and Quantum Optics.

3.3 Key Properties of PCFs:

1) **Tailorable dispersion:** One of the most remarkable properties of photonic crystal fibres are their ability to precisely control the dispersion.[13] Unlike in standard fibres where dispersion is fixed, in PCFs there is tuneable dispersion characteristics due to its design.
2) **Enhanced nonlinear effects:** The unique microstructures of PCFs result in considerably enhanced nonlinear optical effects compared to conventional optical fibres.
3) **Endlessly single mode operation:** The exceptional feature of PCFs to maintain single mode operation throughout the fibre, unlike standard fibre which become multimode at shorter wavelengths. [14]
4) **Flexible Birefringence Control:** PCFs offer remarkable control over birefringence by their irregular air hole designs. By using different sized or shaped air holes like elliptical or circular we can create fibres with precisely tailored birefringence properties.[15]

turnitin Page 21 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 22 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

4 Surface Plasmonic Resonance

4.1 Introduction

Surface plasmon resonance (SPR) is a widely used optical method, especially in photonic crystal fibres (PCFs). SPR works by exciting surface plasmons—these are electromagnetic waves that move along the boundary between a metal and a dielectric material. When light hits the metal layer, the surface plasmons interact with it and cause a noticeable dip in the reflected light. This change happens very quickly, making SPR extremely sensitive to even small shifts in the surrounding refractive index. Because of this high sensitivity, it can detect tiny amounts of biological substances.

4.2 Biological setup of SPR

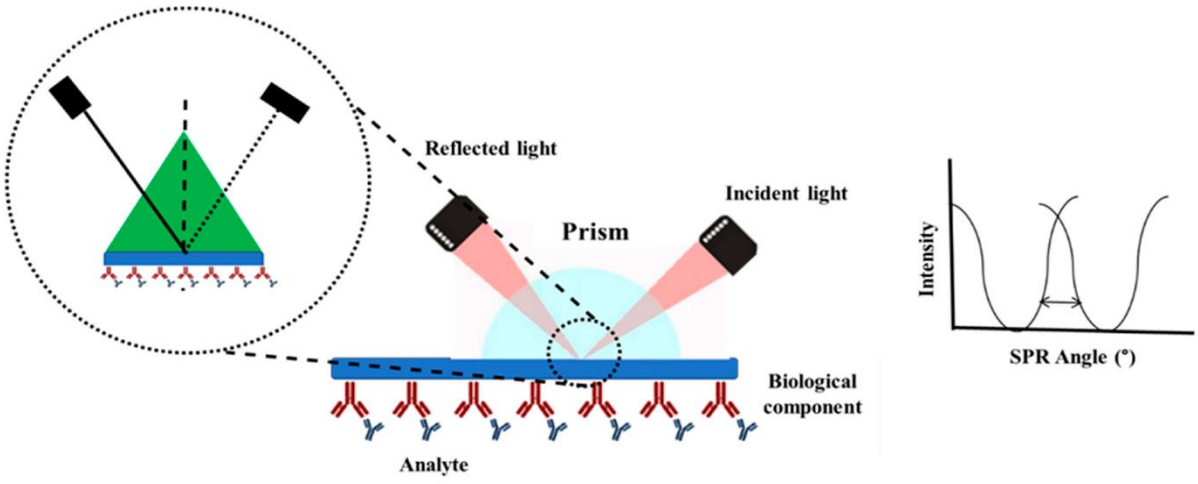


Fig.4.1 SPR Setup

A typical SPR sensor model is composed of several essential components, which works together to enable real time biochemical sensing and signal analysis. It generally includes an optical system responsible for generating and directing light toward the sensing region.

turnitin Page 22 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 23 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

It also contains a transducing medium that acts as an interface between the biochemical environment and the optical domain. It lastly contains an electronic unit that manages the optoelectronic components of the sensor.

The optical device plays a crucial role in exciting surface plasmons and monitors the changes in optical properties which are caused by interactions occurring at the sensor surface. The transducing medium converts biochemical interactions, like molecular binding or changes in measurable optical signals. Together all these components allow the SPR sensor system to achieve highly sensitive, real-time detection for a wide range of chemical and biological sensing applications. The SPR biosensor is classified as refractometric sensor. The interaction of analytes with ligands (as shown in **Fig.4.1**) causes change in the refractive index and then variation in light propagation constant which results in a label free real time signal. [15] When the refractive index changes, we'll notice that the reflected light intensity drops at specific angle to minimum.

4.3 History of SPR

Surface plasmons are waves formed when the free electrons in a metal start moving in response to incoming light. This interaction causes a drop in the reflected light intensity, creating a noticeable dip.

The idea of surface plasmons was first introduced by Ritchie in the 1950s [16]. Building on this concept, Otto studied a prism-coupled SPR setup in which the prism and the plasmonic layer were separated by a dielectric medium. Later, Kretschmann improved the design by placing the prism directly in contact with the metal. This upgraded configuration made it easier to generate surface plasmon waves by matching the frequency of the incoming light with the movement of the metal's free electrons.

By the 1980s, these configurations were being used to build SPR sensors for biological and chemical detection. The traditional prism-based Kretschmann setup is still widely used, where a prism is coated with a thin plasmonic layer. Any change in the refractive index shifts the propagation constant of the surface plasmon mode, which in turn alters the coupling conditions. However, prism-based SPR systems are bulky because they rely on several optical and mechanical components, and they are also relatively expensive. This makes them unsuitable for portable or field applications.[17]

turnitin Page 23 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 24 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

These drawbacks led to the development of optical-fibre-based SPR sensors in the 1990s. Fiber-based SPR sensors offered a broader operating range and improved resolution. Still, traditional PCF-based SPR sensors had a major limitation—they needed light to strike the metal layer at a very specific, narrow angle. To address issues like this, photonic crystal fibres (PCFs) were introduced in the 2000s, making SPR detection more flexible and practical.

turnitin Page 24 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 25 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

5 SPR and PCF

5.1 Introduction

Recently, SPR has been combined with PCFs, creating new possibilities in biosensing. This setup allows real-time, label-free detection, which is very useful in many applications. PCFs, with their air-hole structure running along the length of the fibre, act as cladding and are commonly used for things like supercontinuum generation, terahertz communication, and various sensing purposes. Plasmonic materials like gold, silver, and copper make it possible for SPR to occur. Among them, gold is usually preferred because it is chemically stable and safe to use in biological applications.

5.2 Types of SPR based PCFs

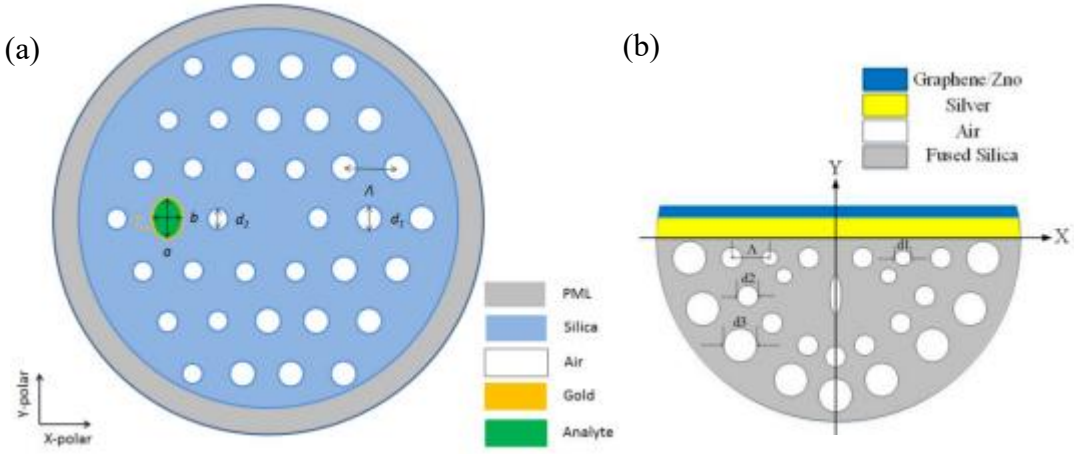


Fig.5.1 Types of SPR-PCF designs (a) Circular shaped (b) D-Shaped

1) **Circular shaped design –** In this model **(Fig.5.1 (a)),** a PCF design in which air holes, core and sensing region are arranged in a circular geometry. It is then coated

turnitin Page 25 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 26 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

with plasmonic material and a PML layer. This design provides symmetrical light confinement and improved optical performance [18].

2) **D-shaped design-** To form d- shaped design as shown in **Fig.5.1(b)**, polishing of upper portion of PCF with air holes is done. The flat surface of the PCF is then layered with plasmonic metal. Due to D-shaped structure there is larger interaction area between the core guided light and plasmons which enhances sensitivity [19].

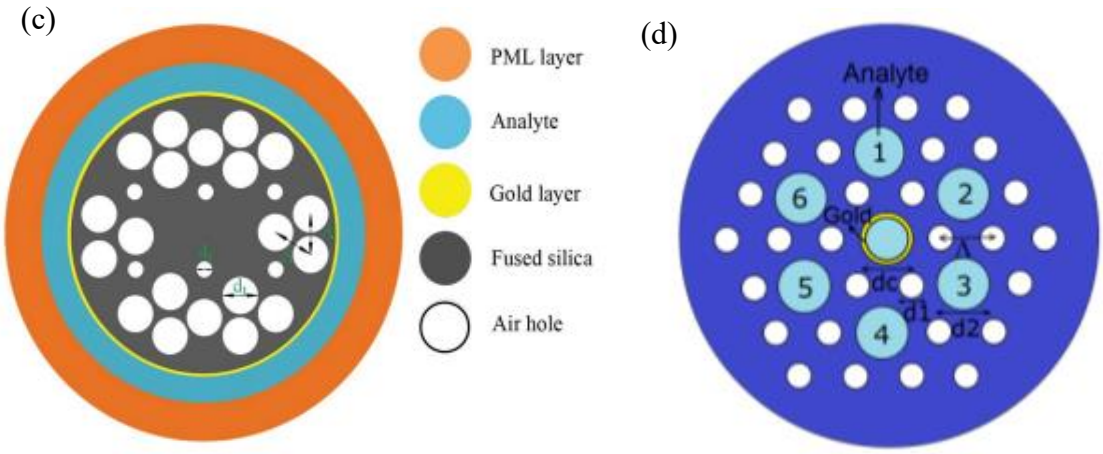


Fig.5.2 (c) External metal coating (d) Internal metal coating

3) **External metal coating:** In this design **Fig.5.2(c)**, a thin layer of plasmonic material like gold, silver is coated on the upper surface of PCF, which has easy fabrication. It also enhances sensitivity by providing interaction between plasmonic wave and surface plasmons. [20]

4) **Internal metal coating:** In this design **Fig.5.2(d)**, a thin plasmonic material layer is deposited on selective air holes inside the PCF. This method is somewhat challenging due to its fabrication process.[21]

5.3 Advantages of SPR based PCFs

turnitin Page 26 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 27 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

1. **High Sensitivity:** SPR based PCFs have high sensitivity because the evanescent field of light strongly interacts with analytes and a small change in refractive index can provide a noticeable change in resonance wavelength.
2. **Compact Structure:** These sensors have small and lightweight structure. It allows easy integration photonic and biomedical devices.

3. **Real time detection:** SPR-PCF sensors allow rapid and real-time monitoring of biochemical and chemical changes. It does not require lengthy processing.

4. **Label free sensing:** They do not require fluorescent or radioactive labelling of samples. It makes the sensing process faster, simpler and cost-effective.

5. **High accuracy and Resolution:** The sharp resonance peaks in SPR- PCF sensor provides precise measurement and improved detection resolution.

6. **Enhanced light matter interaction:** The unique structure of PCFs enhances confinement of light which increases the interaction between light and the plasmonic layer. Due to this, sensing efficiency increases.

7. **Wide range of applications:** They are used in biosensing, chemical sensing, environmental monitoring, medical diagnostics, food safety analysis, and gas detection.

5.4 Limitations of SPR based PCFs:

1. **Complex fabrication process:** The fabrication of SPR-based PCFs is challenging because of their complex micro structured geometry and metal coating requirements. Advanced fabrication techniques such as the sol–gel method and stack-and-draw methods are used.
2. **High manufacturing cost:** The use of noble metals such as gold and silver as well as advanced fabrication techniques. It increases the overall cost of sensor production.

turnitin Page 27 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 28 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

3. **Metal oxidation and stability issues:** Plasmonic materials like silver undergo oxidation which reduces sensors performance and stability with time.

4. **Limiting operating range:** Some SPR-PCF sensors can operate effectively only within a specific refractive index range and limits their versatility.

5. **Temperature dependence:** The variations in temperature of analytes may alter the refractive index and resonance conditions, affecting sensing accuracy.

6. **Limited metal choices:** Gold and silver are the most widely used metals for SPR applications but other metals such as aluminium and copper exhibit lower plasmonic efficiency so they restrict material flexibility. By Exploring more plasmonic materials may provide improved tunability and more stable alternatives for sensing applications.

turnitin Page 28 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

6 Plasmonic Materials

6.1 Introduction

Surface plasmon polaritons (SPPs) are electromagnetic waves generated by the collective oscillation of free electrons at the interface between a metal and a dielectric medium. The excitation of SPPs is significantly enhanced by the high electron density present in metallic thin films, which act as plasmonic materials.

So, it is very important to select good plasmonic material for a SPR-PCF sensor. The ideal choice of plasmonic metal is, which provides a high density of free electrons within the evanescent field region. Commonly used plasmonic materials are Gold, Silver, TiO_2 etc.

- **Gold as a Plasmonic material**

Gold is one of the most widely used plasmonic materials because of its properties like chemical stability, high free electron densities and strong surface plasmon resonance characteristics. It is highly resistant of corrosion and oxidation due to which it is reliable and have long term performance in plasmonic sensors. Gold also has favourable optical characteristic with low optical losses, which makes it a very good plasmonic material.

- **Silver as a Plasmonic material**

Silver is also considered as an efficient plasmonic material due to its optical properties and SPR characteristics. It also has high electron density and low optical loss compared to many other metals. Silver provides sharp and more enhanced resonance peaks which increases sensitivity of sensor.

- **Other Plasmonic Materials**

turnitin Page 30 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

Aluminium and Copper are also used as plasmonic materials due to their electrical and optical properties. Aluminium is considered as a promising plasmonic material because of its low cost, abundance and good plasmonic behaviour in UV region. But it has limitations that it forms oxide layer and have high optical losses.

Copper, on the other hand also possesses a high density of free electrons and exhibits plasmonic behaviour similar to gold in the visible and near-infrared regions. It is relatively inexpensive and offers good electrical conductivity but despite these advantages, copper is highly prone to oxidation and corrosion, which affects its plasmonic efficiency and long-term stability.

- **TiO_2 as a Plasmonic material**

Thin TiO_2 layer is used to provide an adhesion between gold and the fibre surface. Adding a layer also supports excitation of plasmons between Au and dielectric interface which causes an increase in the evanescent field which further increases the interaction between plasmon polariton with its surrounding medium i.e. analyte.

- **Ta_2O_5 as a Plasmonic material**

Another useful plasmonic material is tantalum pentoxide (Ta_2O_5). Its high refractive index and strong environmental stability make it a good choice for SPR generation and sensing that depends on the evanescent field. Because near-infrared light can pass through biological tissues, the evanescent wave created in this region helps improve the sensor's ability to detect biological macromolecules without harming the sample. Adding a Ta_2O_5 layer not only boosts the sensor's sensitivity but also helps protect the underlying gold layer. Ta_2O_5 is also known for its excellent thermal and chemical stability, along with good biocompatibility. This makes optical fibres coated with a Ta_2O_5 layer suitable for a wide range of chemical and biological sensing applications.

6.2 Black Phosphorus as a 2D Plasmonic material

Black Phosphorus (BP) is used as an additional plasmonic material in this proposed biosensor. BP is an emerging 2D plasmonic material that significantly increases sensor sensitivity. BP has a layer-dependent band gap ranging from 0.3 eV to 2 eV [21]. Its bandgap

turnitin Page 30 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 31 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

tuning range is exceeding than many other 2D materials, making it suitable for electronic or photonic applications. BP is attracting researcher's attention for its electrical and optical characteristics, including a direct band gap, high charge-carrier mobility, a lower work function, and stronger molecular interaction at the sensing surface. The presence of direct band gap allows BP to interact with light at particular wavelengths, thereby improving sensing performance [22]. The detector transmits signals quickly and efficiently due to its high charge-carrier mobility, resulting in high sensitivity and rapid response. The strong molecule binding capability of BP at the surface makes it suitable for biological and chemical sensing applications [23]. Black Phosphorus can be incorporated into a SPR sensor by incorporating several thin layers, each of 0.53 nm thickness, on the surface. Therefore, selected plasmonic material is arranged as a multilayer stack to analyse the influence of each layer on the SPR phenomenon.

turnitin Page 31 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 32 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

7 Numerical Analyses

7.1 Introduction

The field of optics is progressing rapidly due to the numerous advantages optical systems offers high bandwidth, improved sensitivity, greater efficiency and enhanced security. This advancement is driven by researchers worldwide who are actively engaged in extensive research activities. But conducting research through experimental setups involves significant costs and makes it economically challenging. To overcome this issue, various optical simulation software tools based on numerical techniques have been developed. These software applications simplify calculations reduce errors and make analysis more convenient. They are also capable of determining important properties of photonic crystal fibres (PCFs), including effective mode index, confinement loss (CL), effective mode index, birefringence (B), nonlinearity, and other related parameters.

7.2 Characteristics of PCF

1. **Effective mode index (n_{eff})**

   The effective mode index tells us how light actually behaves while travelling inside an optical fibre or waveguide. Inside an optical fibre, light does not stay completely inside only core. Part of the light spreads into the cladding also. Therefore, the mode experiences an effective refractive index instead of only the core index. This average is known as the effective mode index, and it can be evaluated using- [24]

$$n_{eff} = \frac{\beta\lambda}{2\pi} \tag{7.1}$$

2. **Confinement loss**

   Confinement loss (Cl), in a PCF refers to the loss of light that leaks from the core region due to the finite number of air holes surrounding it. It can be evaluated as [25]

turnitin Page 32 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 33 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

$$\alpha_{loss}\left(\frac{dB}{cm}\right) = 8.686 \times \frac{2\pi}{\lambda} \times Imag\left(n_{eff}\right) \times 10^4 \quad (7.2)$$

Here, α_{loss} is confinement loss, λ represents the wavelength, and Imag(n_{eff}) denotes the imaginary part of the effective mode index.

3. Birefringence

Birefringence in a PCF refers to the phenomenon where the two polarization components of the guided light x-polarized and y-polarized travel with different effective refractive indices due to the asymmetric arrangement of air holes in the fibre structure [26]. This difference in propagation characteristics between the two polarization modes is what defines the birefringence of the fibre [27].

$$B = \left|n_{eff}^{x} - n_{eff}^{y}\right| \quad (7.3)$$

4. Sensitivity

The performance of sensor can be calculated in two ways, wavelength sensitivity and Amplitude sensitivity. Wavelength sensitivity can be evaluated using the equation given below [28]

$$S_\lambda\left(\frac{\text{nm}}{\text{RIU}}\right) = \frac{\Delta\lambda_{\text{peak}}}{\Delta n_\alpha} \quad (7.4)$$

Here, $\Delta\lambda_{peak}$ refers to the change in the peak wavelength caused by a change in refractive index and Δn_α is change in the analyte's refractive index.

Amplitude Sensitivity can be evaluated using the following equation [29].

$$S_A(\lambda) = -\frac{1}{\alpha(\lambda,n_\alpha)}\frac{\partial\alpha(\lambda,n_\alpha)}{\partial n_\alpha}[RIU^{-1}] \quad (7.5)$$

turnitin Page 33 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 34 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

Here, $\alpha(\lambda, n_\alpha)$ denotes the confinement loss at a particular wavelength, $\partial\alpha(\lambda, n_\alpha)$ denotes the difference between losses at different wavelengths and ∂n_α denotes the change in the analyte's refractive index.

7.3 COMSOL Multiphysics Software

COMSOL Multiphysics is a simulation and finite element analysis software. Which is widely used across engineering and scientific fields especially for problems involving coupled and Multiphysics phenomena. It works by solving coupled systems of partial differential equations through user-friendly physics-based interfaces. This platform offers a unified workflow that spans electrical, mechanical, fluid, acoustic, optical, and chemical domains.

With its key analytical capabilities COMSOL also can be used for -

- Linear and nonlinear analysis
- Stationery and time-dependent studies,
- Frequency domain, modal, Eigenfrequency, and boundary mode studies

In the field of optics, COMSOL Multiphysics can be used for both ray optics and wave optics analyses by using its built-in modules. These capabilities make it a highly effective tool for designing and simulating a wide variety of optical structures. Which includes antennas, optical fibres, metamaterials, and photonic waveguides.



Fig 7.1 COMSOL Multiphysics Software

turnitin Page 34 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 35 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

7.4 Numerical Analyses

Simulation software used in fibre optic research includes specialized computational algorithms. Which enables researchers to numerically analyse and evaluate the performance of proposed fibre designs. For a detailed and accurate investigation of fibre structures, these software tools rely on various mathematical techniques. Some of which are discussed in the following sections.

7.4.1 Finite Element Method

The finite element method is a numerical technique used to solve complex engineering and physics problems. By dividing the problem domain into smaller subregions known as finite elements. The behaviour of each element is analysed individually and the results are assembled together to obtain the overall solution for the entire structure. This process is also known as meshing.

7.4.2 Finite difference time domain method (FDTD)

The finite difference time domain method takes a slightly different approach compared to other numerical techniques. It does not solve electromagnetic problems in the frequency domain. FDTD works directly in the time domain, it tracks how electric and magnetic fields evolve over time as an electromagnetic wave travels through the structure. This method achieves this by dividing the computational space into a fine grid and updating the field values at each grid point step by step in time. It follows Maxwell's equations. One of the most attractive features of FDTD is that a single simulation can provide results across a broad range of frequencies simultaneously. It makes it a highly efficient tool for analysing the wideband optical response of complex fibre structures like PCFs.

turnitin Page 35 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 36 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

8 Literature Review

In recent years, a large number of studies have focused on improving the performance of SPR-based sensors by exploring new materials and structural designs. In 2024, a D-shaped SPR PCF sensor was introduced that could accurately measure analyte refractive indices from 1.34 to 1.41 and achieved a maximum wavelength sensitivity of 25,000 nm/RIU as in. Another SPR PCF sensor coated with gold, also reported in 2024, reached a wavelength sensitivity of 14,100 nm/RIU. In another study, Mengqi L. et al. proposed a highly sensitive SPR PCF RI sensor using a composite micro-grating made of gold and tantalum pentoxide (Ta_2O_5) and it too reported a peak sensitivity of 25,000 nm/RIU. Several other Ta_2O_5-coated SPR PCF sensors have also been presented in recent research, including a 2023 design aimed at detecting biological tissues. Haoran Jiang and colleagues additionally introduced a novel D-shaped SPR PCF RI sensor with an impressive wavelength sensitivity of 20,000 nm/RIU at an analyte refractive index of 1.41.

Hasan Masud Khan and colleagues introduced an ultra-highly sensitive PCF-based SPR biosensor that can detect a range of analytes, including malaria and different types of cancer cells. The design is simple and well-balanced, featuring only eight circular air holes arranged in two rings. To enhance SPR excitation, improve adhesion, and reduce the amount of gold required, the sensor uses a combination of Ta_2O_5 and gold as the plasmonic layer. The device shows an impressive maximum wavelength sensitivity of 65,000 nm/RIU for refractive indices between 1.28 and 1.42. It was also tested for malaria detection, achieving a maximum sensitivity of 10,000 nm/RIU in the ring phase. Additionally, the sensor demonstrated the ability to detect six different types of cancer cells, with a maximum sensitivity of 7857.14 nm/RIU.

turnitin Page 36 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 37 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

Recent studies on SPR sensors using photonic crystal fibers (PCFs) combined with tantalum pentoxide (Ta_2O_5) and gold show notable improvements in sensitivity and overall performance. Ta_2O_5 helps enhance the coupling between light and plasmon modes, which boosts the sensor's responsiveness, especially in the near-infrared region. For example, Tonmoy Malakar and colleagues introduced a highly sensitive D-shaped, butterfly-core PCF-SPR sensor capable of detecting analyte refractive indices between 1.34 and 1.43, achieving a maximum wavelength sensitivity of 34,000 nm/RIU.

turnitin Page 37 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

9 Design and Computational Analyses of Black Phosphorus-Based D-Shaped PCF SPR Refractive Index Sensor

9.1 Introduction

Surface plasmon resonance (SPR) is a widely used optical method, especially in photonic crystal fibres (PCFs). These fibres are an advanced form of optical fibre that contain a regular pattern of tiny air holes, which helps trap and guide light more effectively. SPR works by exciting surface plasmons—these are electromagnetic waves that move along the boundary between a metal and a dielectric material. When light hits the metal layer, the surface plasmons interact with it and cause a noticeable dip in the reflected light. This change happens very quickly, making SPR extremely sensitive to even small shifts in the surrounding refractive index. Because of this high sensitivity, it can detect tiny amounts of biological substances. Recently, SPR has been combined with PCFs, creating new possibilities in biosensing. This setup allows real-time, label-free detection, which is very useful in many applications. PCFs, with their air-hole structure running along the length of the fibre, act as cladding and are commonly used for things like supercontinuum generation, terahertz communication, and various sensing purposes. Plasmonic materials like gold, silver, and copper makes SPR possible to occur. In these metals gold is usually preferred because it is chemically stable and safe to use in biological applications. Silver and copper also have good properties like high electrical conductivity but they tend to oxidize easily, which makes them less practical for real-time sensing devices.

To improve sensitivity researchers usually combines gold or silver with certain 2D materials like TiO_2, Ta_2O_5, MoS_2 or black phosphorus. These materials can enhance plasmonic performance but they also come with drawbacks like lower conductivity, poor biocompatibility, and weak adsorption.

turnitin Page 39 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

Another useful 2D material is tantalum pentoxide (Ta_2O_5). Its high refractive index and strong environmental stability make it a good choice for SPR generation and sensing that depends on the evanescent field. Because near-infrared light can pass through biological tissues, the evanescent wave created in this region helps improve the sensor's ability to detect biological macromolecules without harming the sample. Adding a Ta_2O_5 layer not only boosts the sensor's sensitivity but also helps protect the underlying gold layer. Ta_2O_5 is also known for its excellent thermal and chemical stability, along with good biocompatibility. This makes optical fibres coated with a Ta_2O_5 layer suitable for a wide range of chemical and biological sensing applications.

SPR-based PCF refractive-index biosensors have become promising diagnostic tools in medicine. They have been used to detect diseases such as cancer, malaria, tuberculosis, and even coronavirus. These detections rely on the differences in refractive index between normal and infected blood cells, as the sensors are extremely sensitive to small RI changes. The proposed SPR-based PCF refractive index biosensor seems to outperform many traditional detection methods. It offers label-free detection, can reach very low detection limits, and provides much higher sensitivity overall.

9.2 Design of Proposed Biosensor

The cross-sectional and magnified view of the proposed D-shaped SPR-PCF biosensor is shown in **Fig.9.1(a).** and **Fig. 9.1(b)** represents the schematic diagram for the proposed experimental setup. Different geometric parameters were chosen and arranged to facilitate the interaction between the SPP mode and the core mode of the sensor. Two types of air holes are used in this sensor: circular and elliptical.

The sensor consists of two sets of ellipses (Horizontal and Vertical) with a = 3 µm, b=1.8 µm, form a conjugate pair, where the major axis of one ellipse is equal to the minor axis of the other one and vice versa. On the introduction of elliptical air holes in the PCF body increases the confinement of core field [30]. The PCF structure contains three different types of circular air holes. The bigger air holes which have radius $r_1 = 1.8\ \mu m$ forms a rectangular lattice with elliptical air holes in the cladding region. The medium air holes with radius r_2 =

turnitin Page 39 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 40 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

1 μm are positioned close to the fiber core, forming a rectangular core structure. The smaller air hole with radius $r_3 = 0.25$ μm is associated between the rectangular lattice to direct the evanescent field to plasmonic layers (Ta_2O_5 + Gold).

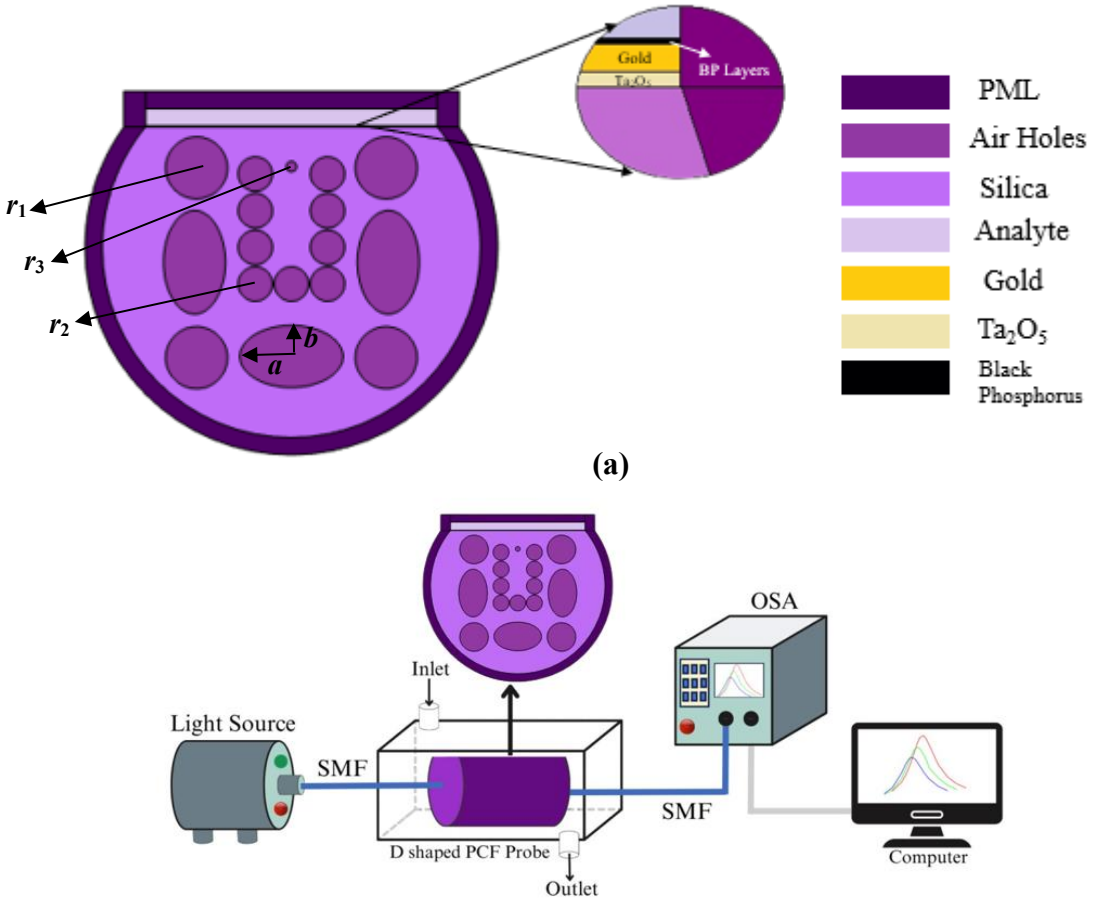


Fig.9.1: (a) Cross-sectional view of designed D-shaped PCF-SPR sensor (b) Proposed experimental configuration

A Gold layer of thickness t_g = 30 nm, is coated on the flat surface of the D-shaped PCF Sensor. A layer Ta_2O_5 layer with a thickness of t_{ta} =23 nm is used as an adhesive and a sensitivity enhancer between the gold layer and the PCF. 17 layers of BP are also added, with thickness of a layer as 0.53 nm, which creates a total thickness of 9.01 nm to enhance

turnitin Page 40 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 41 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

the sensitivity of PCF sensor. The PCF is coated with plasmonic layers in sequence of Ta_2O_5, Gold (Au) and 17 thin layers of BP. The bio-sample analyte layer of thickness 1 μm is introduced over the gold layer, after which a Perfectly Matched Layer (PML) is applied of thickness 1 μm. The inclusion of the PML helps to absorb outgoing waves and prevents reflection.

9.3 Mathematical Modelling

Fused Silica is employed as the background material in photonic crystal fibre. Therefore, it is important to determine the refractive index (RI) of fused silica, which is calculated using the Sellmeier Equation. The Sellmeier equation makes it easier to relate wavelength and refractive index and is used to find the appropriate refractive index for different wavelengths. The equation is given below [31].

$$n^2(\lambda) = 1 + \frac{0.696163\lambda^2}{\lambda^2 - 0.0046791486} + \frac{0.4079426\lambda^2}{\lambda^2 - 0.013520631} + \frac{0.897479\lambda^2}{\lambda^2 - 97.934003} \quad (9.1)$$

Here, n(λ) represents the RI of fused silica and λ represents the wavelength of incident light in micrometres.

The Drude–Lorentz model is employed to express the dielectric constant of gold. The expression of Drude-Lorentz model is as follows [32]

$$\varepsilon_{Au} = \varepsilon_\infty - \frac{\omega_D^2}{\omega(\omega - j\gamma_D)} - \frac{\Delta\varepsilon.\Omega_L^2}{(\omega^2 - \Omega_L^2) - j\Gamma_L\omega} \quad (9.2)$$

Here ε_{Au} is the permittivity of Gold, ω is angular frequency, ε_∞= 5.9673, $\Delta\varepsilon$ is the weight factor and ω_D and γ_D are defined as plasma frequency and damping frequency, where $\omega_D = 4227.2\pi$ THz and $\gamma_D = 31.84\pi$ THz. Furthermore, Ω_L and Γ_L are the frequency and width of Lorent'z oscillator with $\Omega_L = 1300.14\pi$ THz and $\Gamma_L = 209.72\pi$ THz.

The refractive Index of Tantalum Pentoxide (Ta_2O_5) is determined by the following equation [33]

$$n_{Ta_2O_5} = 1.88 + \left(178.4 \times \frac{10^2}{\lambda^2}\right) + \left(52.7 \times \frac{10^7}{\lambda^4}\right) \quad (9.3)$$

turnitin Page 41 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 42 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

Here, $n_{Ta_2O_5}$ is the RI of Ta_2O_5 and λ is the incident wavelength.

The RI of BP employed in this sensor is determined by the Cauchy absorbent model [34]

The light leakage from the PCF core to the plasmonic material layers can be evaluated as Confinement Loss (CL). It can be calculated using the equation given below [35]

$$\alpha_{loss}\left(\frac{dB}{cm}\right) = 8.686 \times \frac{2\pi}{\lambda} \times Imag(n_{eff}) \times 10^4 \quad (9.4)$$

Here, α_{loss} is confinement loss, λ represents the wavelength, and Imag(n_{eff}) denotes the imaginary part of the effective mode index.

The performance of the sensor can be evaluated in terms of Wavelength Sensitivity and Amplitude Sensitivity. Wavelength sensitivity can be evaluated using the equation given below [36]

$$S_\lambda\left(\frac{nm}{RIU}\right) = \frac{\Delta\lambda_{peak}}{\Delta n_\alpha} \quad (9.5)$$

Here, $\Delta\lambda_{peak}$ refers to the change in the peak wavelength caused by a change in refractive index and Δn_α is change in the analyte's refractive index. Amplitude Sensitivity can be evaluated using the following equation [37]

$$S_A(\lambda) = -\frac{1}{\alpha(\lambda, n_\alpha)} \frac{\partial\alpha(\lambda, n_\alpha)}{\partial n_\alpha} [RIU^{-1}] \quad (9.6)$$

Here, $\alpha(\lambda, n_\alpha)$ denotes the confinement loss at a particular wavelength, $\partial\alpha(\lambda, n_\alpha)$ denotes the difference between losses at different wavelengths and ∂n_α denotes the change in the analyte's refractive index.

9.4 Fabrication Feasibility

The fabrication of D-shaped PCFs typically involves polishing techniques combined with the conventional stacking and stretching of standard PCFs, which helps reduce production costs. Even complex microstructures can now be manufactured using 3D

turnitin Page 42 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 43 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

printing. Composite micro gratings are generally created through processes such as high-pressure microchemical deposition, Electron-beam etching and chemical vapor deposition (CVD) are key techniques used in the fabrication process. High-pressure chemical deposition helps create thin films on the surface of D-shaped PCF structures, while the Au–Ta_2O_5 composite micro-grating is formed using electron-beam etching.

For the D-shaped fibres described in this work, roller-side polishing is employed to precisely control the polishing depth. Initial preforms are prepared using quartz rods, capillaries, and quartz casing through a stacking and drawing process, which allows accurate control over the dimensions of the inner and outer air holes. Finally, the gold and Ta_2O_5 thin films are deposited using CVD or magnetron sputtering techniques.

The experimental setup includes four key parts: a supercontinuum broadband source (SBS) that provides the light, and an optical spectrum analyzer (OSA) that records and examines the signal. When the analyte enters the fiber and interacts with the structure, it alters the effective refractive index of the surface plasmon polariton (SPP) mode. As a result, the resonance wavelength shifts. This shift can be viewed instantly on the spectrometer, and the waveform can be monitored and processed on a computer.

9.5 Results and Discussions

The proposed sensor is analysed using COMSOL Multiphysics software, and various combinations of structural parameters optimized to enhance the sensing sensitivity are presented and discussed.

Fig.9.2(a), (c) shows Core mode and SPP mode respectively. Fig.9.2 (d) shows loss curve and dispersion relation of biosensor at refractive index 1.34. The RI of core mode and spp mode intersect with each other, at resonance point. Here, maximum light gets coupled with plasmonic materials, which indicates coupling between two modes.

turnitin Page 43 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 44 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

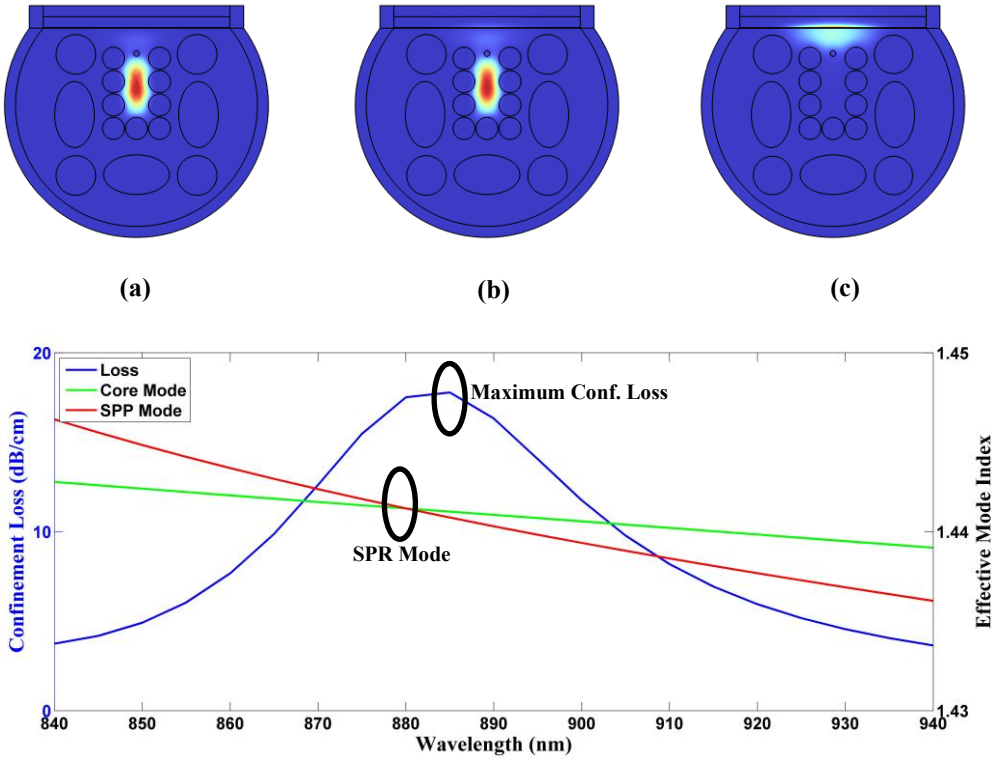


Fig.9.2: Electric Field profile for **(a)** core mode with y-polarization, **(b)** core mode with x-polarization, **(c)** SPP mode, **(d)** Dispersion relation of the optimized structure at RI of 1.34

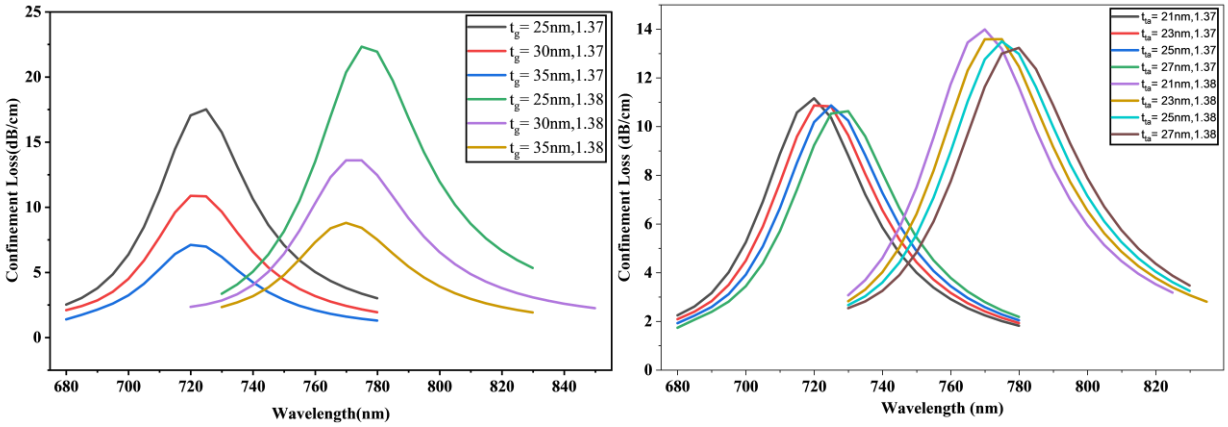


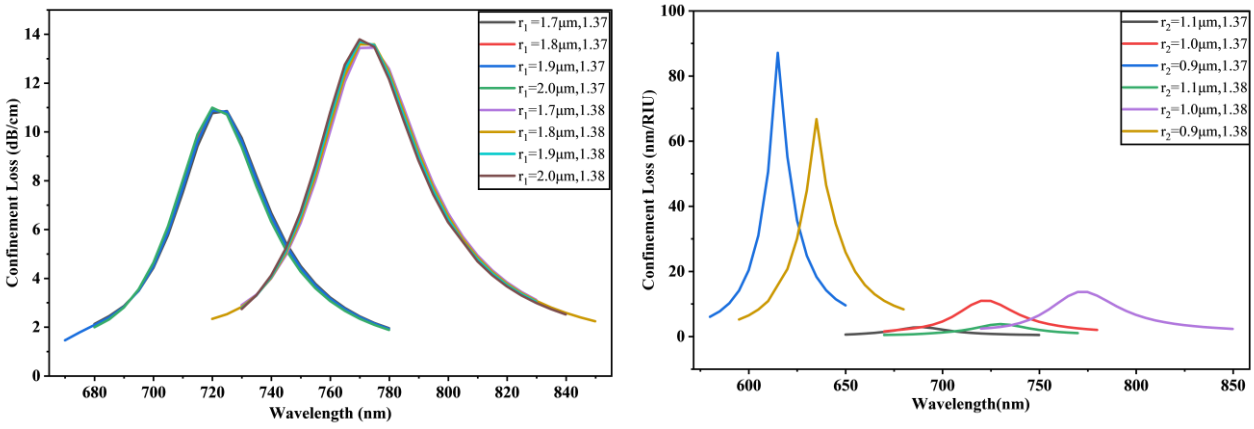
Fig. 9.3: CL spectra at n_a= 1.37 and 1.38 **(a)** for various thicknesses of gold layer **(b)** for various thicknesses of Ta_2O_5 layer

turnitin Page 44 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 45 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

The optimal thickness of the gold layer is determined by varying the gold layer thickness from 25 nm to 35 nm in increments of 5 nm by keeping all other parameters unchanged. No BP layer is incorporated this time, analyses with BP layers is done later. Fig. 9.3(a) illustrates the graphical representation of confinement loss versus wavelength for varying thicknesses of the gold layer (t_g). From the figure, it can be observed that on increasing the thickness of the gold layer, peak loss decreases for each analyte, because the interaction between the incident light and the analyte decreases. So, the ideal thickness of Gold is 30 nm.

The optimal thickness of the Ta_2O_5 layer is determined by varying its thickness from 21 nm to 27 nm in increments of 2 nm by keeping all other parameters unchanged. Fig. 9.3(b) illustrates the graphical representation of confinement loss versus wavelength for varying thicknesses of the Ta_2O_5 layer (t_{Ta}). Here, Ta_2O_5 is employed as an adhesive, its effect on confinement loss is minimal. From the figure, it can be seen that a slight decrease is in confinement loss with increasing thickness of Ta_2O_5 layer. Therefore, the optimum thickness of Ta_2O_5 for further analysis is chosen as 23 nm.



(a) **(b)**

Fig.9.4 CL spectra at n_a= 1.37 and 1.38 **(a)** for various radii of big air holes (r_1) **(b)** for various radii of medium air holes (r_2)

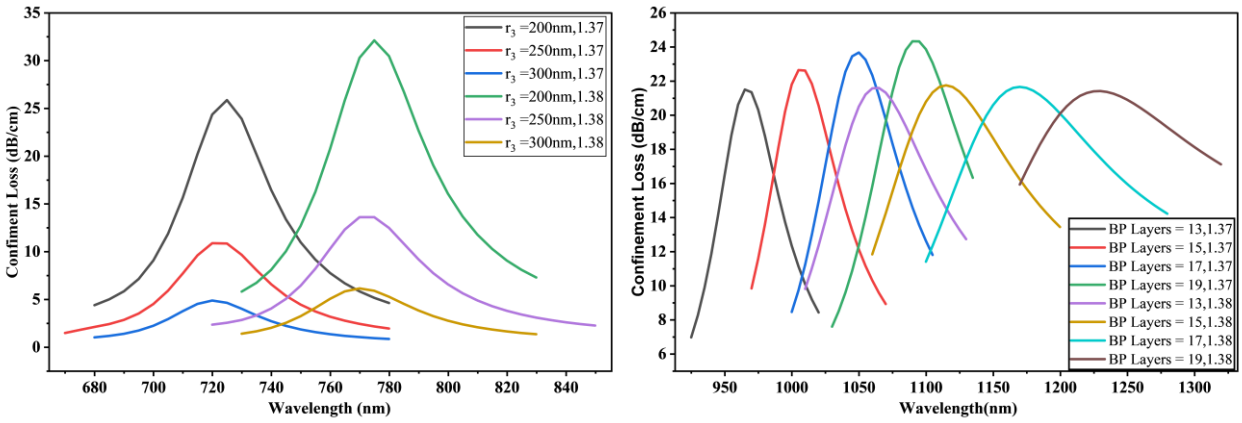
The optimal radius of the big air holes (r_1) is determined by varying its radius from 1.7–2 μm with a step size of 0.1μm by keeping all other parameters unchanged. Fig.9.4(a) shows the variation in the confinement loss as a function of the radius of big circular air hole. As we can see from the figure big air holes do not play major role in interaction light with

turnitin Page 45 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 46 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

plasmonic material. Therefore, the optimum radius of big air holes for further analysis is chosen as 1.8 µm.

The optimal radius of the medium air holes (r_2) is determined by varying its radius from 0.9 to 1.2 µm with a step size of 0.1µm by keeping all other parameters unchanged. Fig.9.4(b) shows the variation in the confinement loss as a function of the radius of medium circular air hole. As we can see the effect of the role of medium air holes is more prominent than big



(a) **(b)**

Fig.9.5: Confinement loss **(**CL) spectra at n_a= 1.37 and 1.38 **(a)** for various radii of small air holes (r_3) **(b)** for different numbers of BP layers

air holes because the play major role in interaction of light. Therefore, the optimum radius of medium air holes for further analysis is chosen as 1 µm.

The optimal radius of the small air holes (r_3) is determined by varying its radius from 200 to 300 nm with a step size of 50nm by keeping all other parameters unchanged. Fig.9.5(a) shows the variation in the confinement loss as a function of the radius of small circular air hole. As we can see the variation in peak loss at different radii of the small air holes follows a trend similar to that observed for the medium air-hole radius Therefore, the optimum radius of small air holes for further analysis is chosen as 250 nm.

BP layer optimization

As the thickness of each layer of BP is very thin, the thickness range employed is 13-19 layers at a difference of 2. Fig. 9.5(b) shows the variation of confinement loss versus wave

turnitin Page 46 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 47 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

length with varying BP layers. From the figure, it is interpreted that when the count of BP layers increases, sensitivity of the proposed sensor increases quickly but the confinement loss and FWHM also increases. So, 17 BP layers are taken as optimized configuration to achieve moderate FWHM and improved wavelength sensitivity.

9.6 Performance of sensor: Refractive index sensing

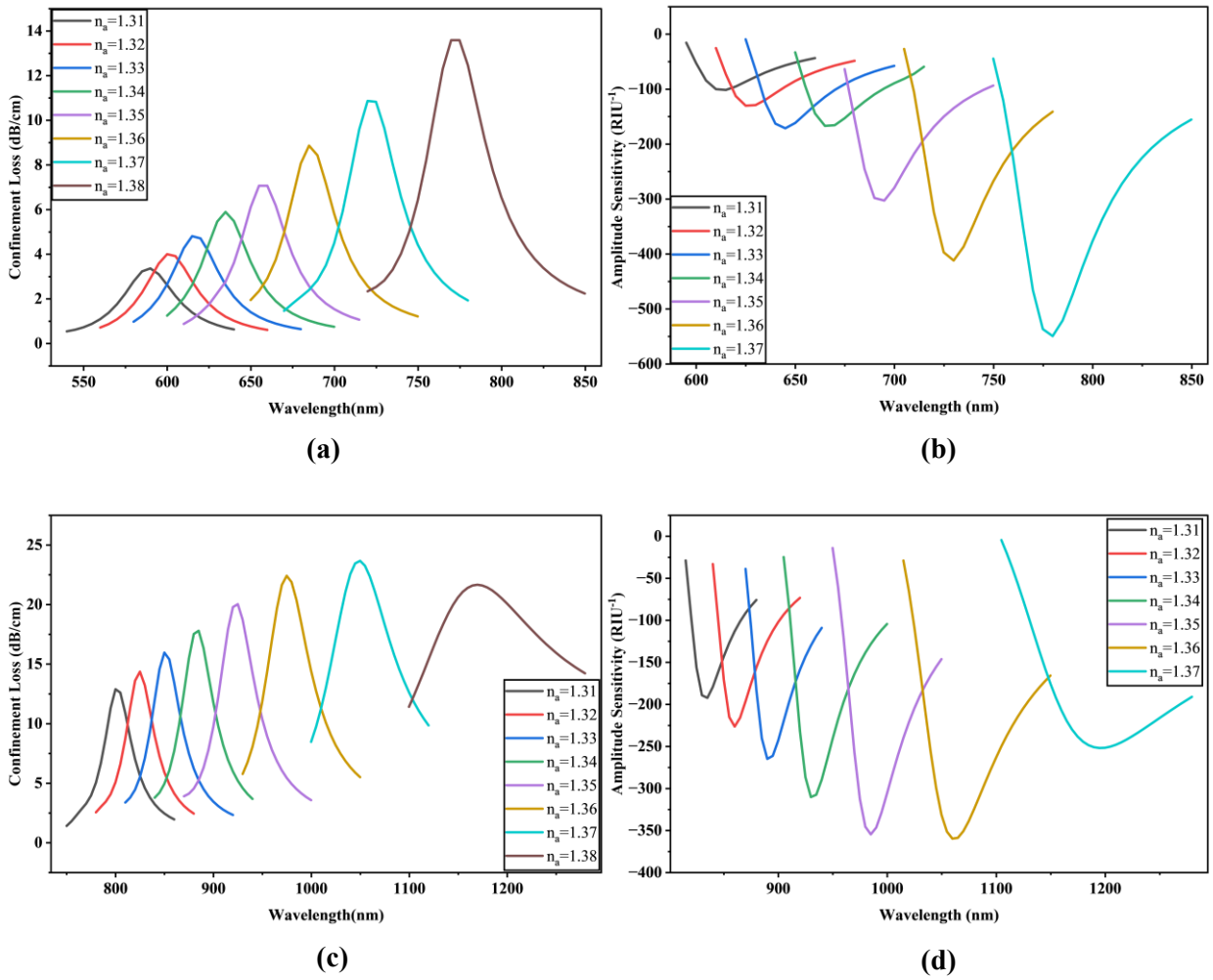


Fig.9.6: (a) loss curve and **(b)** amplitude sensitivity curve for optimized parameters without BP **(c)** loss curve **(d)** amplitude sensitivity curve for optimized parameters with BP

turnitin Page 47 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

Now, the confinement loss and wavelength sensitivity are calculated by keeping the parameters fixed at their optimized values for analytes with refractive index ranging from 1.31 to 1.38 RI. Fig.9.6 shows the confinement loss profiles for different refractive indices of analytes ranging from 1.31 to 1.38 at a difference of 0.01. The wavelength sensitivity without incorporating black phosphorus came up as 5500 nm/RIU, and after incorporating BP layers, the wavelength sensitivity advances to 12000 nm/RIU. Fig.9.6 (a) and (b) illustrates the confinement loss curves and amplitude sensitivity, respectively, for the proposed sensor in absence of BP, whereas Fig.9.6 (c) and (d) discuss the same analyses for the sensor with BP.

Table 9.1 illustrates the sensor's performance, which shows the difference in wavelength and amplitude sensitivity with or without using black phosphorus for the refractive index ranging from 1.31-1.38. The wavelength sensitivities are constantly increased by an average of 100%, after addition of black phosphorus.

Table 9.1 Change in Sensitivities when BP is incorporated

Analyte's Refractive Index	Proposed Sensor in absence of BP layers			Proposed Sensor with BP Layers		
	Resonant wavelength (nm)	Wavelength Sensitivity (nm/RIU)	Amplitude Sensitivity (RIU^{-1})	Resonant wavelength (nm)	Wavelength Sensitivity (nm/RIU)	Amplitude Sensitivity (RIU^{-1})
1.31	590	1000	-101.67	800	2500	-192.55
1.32	600	1500	-130.25	825	2500	-226.7
1.33	615	2000	-171.52	850	3500	-265.18
1.34	635	2000	-167.2	885	4000	-310.7
1.35	655	3000	-303.24	925	5000	-355.14
1.36	685	3500	-412.37	975	7500	-360.25
1.37	720	5500	-550.37	1050	12000	-252.28
1.38	775	--	--	1170	--	--

turnitin Page 49 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

Table 9.2 shows the comparison of the proposed SPR based PCF biosensor with previous literature works.

Table 9.2 Performance Comparison of proposed sensor with prior studies

Design	Refractive Index range	Wavelength Sensitivity (nm/RIU)
Hollow structured [38]	1.30-1.39	9900
AZO coated PCF [39]	1.32-1.34	5000
D shaped PCF [40]	1.36-1.42	8000
Dual core PCF [41]	1.30-1.40	5000
U shaped PCF [42]	1.36-1.43	5900
D shaped PCF [43]	1.33-1.40	10,300
Proposed work (without BP)	1.31-1.38	5500
Proposed work (with BP)	1.31-1.38	12,000

9.7 Performance of sensor: Anemia sensing

Anemia, a condition in which the body does not have enough red blood cells or Hemoglobin (Hb) to supply sufficient oxygen to body tissues. It can be indicated by low hemoglobin level. The standard hemoglobin level for a human body is H_{Normal} = 140g/L, which corresponds to a refractive index of 1.38 [44]. Table 9.3 illustrates about the classification of anemia when Hb concentration become less than H_{Normal} value [45].

Table 9.3 Primary classification of Anemia

Condition	Range	Refractive Index
Healthy	>120g/L	>1.376
Minor	100-120g/L	1.373-1.376
Moderate	80-100g/L	1.379-1.373
Acute	<80g/L	<1.369

Fig 9.7 (a) shows the confinement loss curves for different hemoglobin concentration without BP and Fig. 9.7(b) shows the confinement loss curves for different hemoglobin concentration with BP. As we can see all concentrations have gone through a wavelength shift, but the variation in confinement loss is minimal. The wavelength shift for 120g/L concentration is 22nm, 100g/L concentration is 36nm, for 80g/L concentration is 54nm

turnitin Page 49 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 50 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

without BP layers. The former data provides wavelength sensitivities of 5500 nm/RIU, 5142.85 nm/RIU, 4909.1nm/RIU. After incorporating BP layers, the resultant peak wavelength shifts provide enhanced wavelength sensitivities of 14500nm/RIU, 13000nm/RIU, 11818.2nm/RIU, respectively. The BP layers increase the sensitivity by an average of 100%, as similar to refractive index sensing. This indicates that the proposed biosensor is well-suited for Anemia detection.

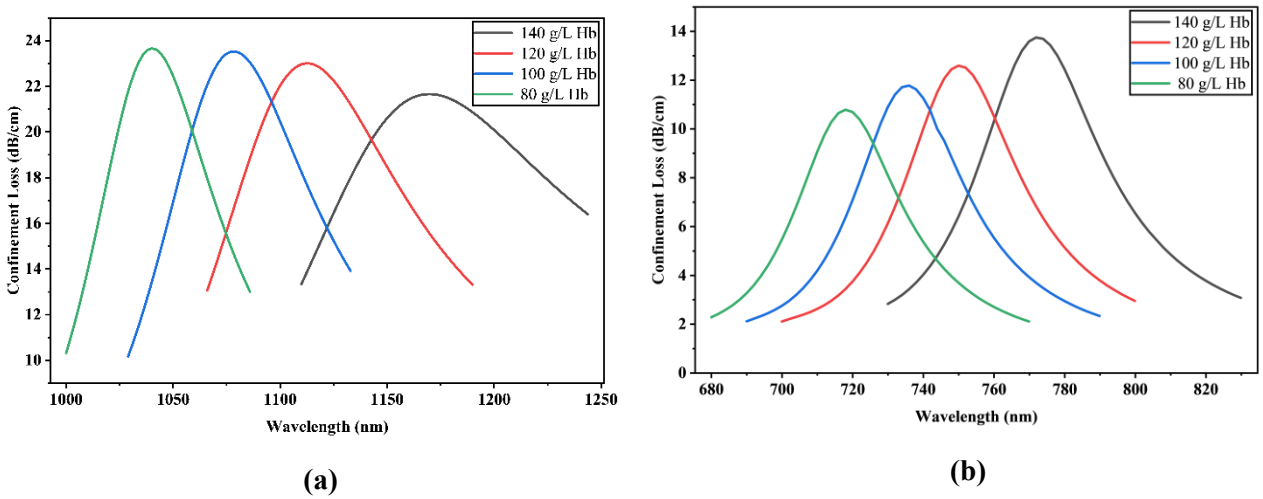


Fig. 9.7 (a) Loss curves for different hemoglobin concentration without BP **(b)** Loss curves for different hemoglobin concentration with BP

9.8 Conclusion

In summary, this research presents a D-shaped SPR-PCF Sensor incorporating Ta_2O_5, Gold and black phosphorus, which is also used for Anemia detection. Black Phosphorus, a 2d plasmonic material which is used to improve the sensor's sensitivity from 5500nm/RIU to 12000nm/RIU and achieving an amplitude sensitivity of -360.25 RIU^{-1}. All stimulations are performed using Finite Element Method (FEM), which is implemented in COMSOL Multiphysics. For enhanced sensitivity, all the structural parameters are optimized such that the radii of big, medium and small air holes are optimized at 1.8µm, 1µm, 250nm, respectively. Similarly gold layer at 30nm, Ta_2O_5 layer at 23nm and 17 layers of BP are optimized to attain high sensitivity. Due to these improvements, the sensor is capable of

turnitin Page 50 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 51 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

detecting small variations in the surrounding environment and is able to operate over wider RI sensing range, i.e., from 1.31 to 1.38. Hence, the sensor is applicable for wide range of applications such as medical diagnostics and chemical sensing.

turnitin Page 51 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 52 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

10 Conclusion and Future Work

10.1 Conclusion

In this thesis, we have studied about Optical fibre, Photonic Crystal fibre, Surface plasmonic resonance and we have successfully proposed and investigated SPR-based photonic crystal fibre sensors. Which can be used for high-speed and highly sensitive sensing applications. This designed sensor includes a refractive index sensor, an anemia detection biosensor and these all operate on the fundamental principle of detecting little variations in the refractive index of the analyte under examination.

All sensor geometries were modelled and evaluated using COMSOL Multiphysics. The parameters which play key role like confinement loss, wavelength sensitivity, and amplitude sensitivity were calculated in the research.

The refractive index sensor shows an admirable sensing range of 1.31to1.38 RIU. This range makes it well-suited for both medical diagnostics and chemical analysis. With a wavelength sensitivity reaching up to 12,000 nm/RIU and an amplitude sensitivity of -252.28 RIU^{-1}. The sensor proves its capability to detect even the most minute environmental change with accuracy.

For the anemia detection sensor, the results were equally promising because the sensor recorded wavelength sensitivities of 5500 nm/RIU, 5142.85 nm/RIU, 4909.1nm/RIU. After incorporating BP layers, the resultant peak wavelength shifts provide increased wavelength sensitivities which are 14500nm/RIU, 13000nm/RIU, 11818.2nm/RIU respectively.

These sensitivities highlight that the sensor is practical relevant for early-stage diseases detection. Overall, the findings of this study confirms that the sensor we purposed holds strong potential for next-generation biomedical and chemical sensing platforms. Which is a reliable and sensitive approach for disease detection and environmental monitoring.

turnitin Page 52 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

10.2 Future work

The results of this research open several exciting offers for further exploration and development of SPR-based PCF biosensors. The proposed designs have demonstrated good performance in numerical simulations. It remains to be done to bridge the gap between theoretical design and practical deployment. The following directions are identified as meaningful extensions of the current work:

1**. Experimental Fabrication and Validation**:

The sensors proposed in this study have been numerically analysed using COMSOL Multiphysics. But physical fabrication and laboratory testing is also an important next step. Future work should focus on converting these designs into real devices using advanced fibre drawing techniques such as stack-and-draw or sol-gel methods. Experimental results will help us to confirm the simulated results and reveal any fabrication-related challenges that must be addressed before clinical or industrial deployment.

2**. Integration with Machine Learning for Intelligent Sensing**:

The sensitivity data which is coming out from these sensors could make a valuable dataset when it comes to training machine learning models. Other future work would be looking at how SPR sensor outputs should be paired with AI-driven algorithms, not by identifying analytes automatically. We should keep the tabs in real time and pick up the patterns across more complex biological samples. Bringing these two things together we could meaningfully improve how well the sensing system handles the decision-making, particularly in situations where multiple analytes are present at once.

3. **Extension to Detection of Viral and Neurological Biosensors**:

This work focused on bacterial detection in the context of Anemia. We should extend it toward viral pathogens like influenza, hepatitis etc. or we can think of neurological conditions like Alzheimer's and Parkinson's these are natural next step. A lot of these come down from how the fibre surface is functionalised by engineering analyte-specific coatings. The sensor could be tuned to recognise these more varied targets with the kind of selectivity that clinical or diagnostic applications would actually demand.

turnitin Page 54 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

4. **Development of Multi-Analyte and Multiplexed Sensing Platforms:**

The current sensor we made are designed to target one specific analyte individually. A meaningful future direction would be to develop a single integrated PCF platform which is capable of simultaneously detecting multiple analytes. By engineering multiple plasmonic channels within the same fibre structure. We could achieve multiplexed sensing. It will reduce the need for multiple separate tools and it will enable faster and it will give more comprehensive analysis.

turnitin Page 54 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

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turnitin Page 60 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 61 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993

turnitin Page 62 of 62 - Integrity Submission Submission ID trn:oid:::27535:140681993