MXENE COATED SURFACE PLASMON RESONANCE BASED PHOTONIC CRYSTAL FIBER SENSOR FOR THE DETECTION OF HIV AND SICKLE CELL ANAEMIA

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

MASTER OF SCIENCE
IN
PHYSICS

Submitted by:
PREETHI KRISHNAN
2K23/MSCPHY/68

Under the supervision of
DR AJEET KUMAR
Associate Professor

DEPARTMENT OF APPLIED PHYSICS
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Bawana Road, Delhi 110042
June, 2025
DEPARTMENT OF APPLIED PHYSICS

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)
Bawana Road, Delhi 110042

CANDIDATE DECLARATION

I, **Preethi Krishnan**, hereby certify that the work which is being presented in the thesis entitled "**MXene coated surface plasmon resonance based photonic crystal fiber sensor for the detection of HIV and Sickle Cell Anaemia**" in partial fulfilment of the requirements for the Degree of Master of Science, submitted to the Department of Applied Physics, Delhi Technological University, is an authentic record of my own work carried out during the period from August 2024 To May 2025 under the supervision of Dr. Ajeet Kumar. The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other institute. The work has been published in the SCIE indexed journal 'Optical and Quantum Electronics'.

Title of the paper: MXene coated concave shaped microchannel PCF SPR biosensor for the detection of HIV and Sickle cell anaemia

Author names: Preethi Krishnan, Akash Khamaru, Ajeet Kumar

Journal Name: Optical and Quantum Electronics, Springer

Status of paper: Published

Date of paper communication: 11th December 2024

Date of paper acceptance: 19th February 2025

Date of paper publication: 20th April 2025

Place: Delhi **Preethi Krishnan**

Date: 09/06/2025

SUPERVISOR CERTIFICATE

To the best of my knowledge, the above work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere. I, further certify that the publication and indexing information given by students is correct.

Place: Delhi **Dr Ajeet Kumar**

Date: 09/06/2025 **Supervisor**

DEPARTMENT OF APPLIED PHYSICS

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)
Bawana Road, Delhi 110042

ACKNOWLEDGEMENT

I would like to extend my heartfelt gratitude to my esteemed Supervisor, Dr. Ajeet Kumar, whose unwavering guidance and insightful advice has been instrumental at every stage of this research work. His mentorship has been invaluable in shaping the direction and success of this work. My deepest thanks to Prof. Vinod Singh, Head of the Department of Applied Physics, for providing the essential facilities and a conducive environment for our research. I am profoundly grateful to committee members for their critical input and suggestions, which have significantly enhanced the quality of my research work. My sincere appreciation goes to Delhi Technological University for offering me the opportunity to conduct this research and for the extensive resources and support provided.

A special thankyou to Mr. Akash Khamaru, my mentor and PhD scholar in our lab, for his constant motivation and support. His encouragement and help have been a great source of inspiration throughout my research journey. A special thanks to Mr. Deepak Garg for his thoughtful insights. I also extend my deepest gratitude to Mr. Sree Hari B Lal, whose guidance helped me throughout the work, and also to my lab mates Devi Kangan B S, Arhee Bhuyan and Plakshi Gupta. Extending 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.

Preethi Krishnan

ABSTRACT

This work suggests the design and structural analysis of Surface Plasmon Resonance (SPR) Based Photonic Crystal Fiber (PCF) Refractive Index Sensor, which has found applications in various domains. The work mainly explores its potential in bio-sensors and also the effect of v 2D plasmonic enhancers are studied and are compared on the basis of Confinement Loss and Wavelength sensitivity. The proposed work explores the potential of MXene, another class of 2D materials, in the detection of Human Immuno-deficiency (HIV) Virus and Sickle Cell Anaemia. HIV and Sickle cell anaemia are two of the most dangerous conditions existing in our world. The work is an effort to encourage early detection of these diseases to facilitate effective treatment. The obtained wavelength sensitivities are 10,571.43 nm/ RIU and 3500 nm/RIU for the Gold PCF sensor, and 14,142.86 nm/RIU and 4000 nm/RIU for MXene-Gold PCF sensor for HIV-infected cell and Sickle cell anaemia, respectively. The work thus concludes that 2D materials, specifically MXenes are highly effective plasmonic enhancers when used in combination with any plasmonic material like gold, showcases high sensitivity for the application in bio-sensors.

LIST OF PUBLICATIONS

Publication(s) related to Thesis:

Journal Publication

Preethi Krishnan, Akash Khamaru, Ajeet Kumar, "**MXene coated concave shaped microchannel PCF SPR biosensor for the detection of HIV and Sickle cell anaemia**", Vol. 57, No. 5, p. 270 **Published in Optical and Quantum Electronics by Springer (SCIE-indexed Journal, IF: 3.3) on 20th April 2025.**
https://doi.org/10.1007/s11082-025-08123-1

Publication(s) out of the Thesis:

Conference publication

Preethi Krishnan, Devi Kangan B S, Akash Khamaru, Ajeet Kumar, "**A side polished gold-TiO_2 coated Surface Plasmon Resonance based PCF RI Sensor**", PHOTONICS 2024, 12-15th December 2024, IIT Kharagpur, West Bengal, India **(Poster Presented and full-length paper communicated).**

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1. Overview

Conventional optical fibers have proven to be a huge success in the field of telecommunications, industrial and medical applications, biosensing etc. [1,2]. Extensive study and research in the optical fiber realm has led to a more sophisticated version of optical fiber called Photonic Crystal Fiber (PCFs) having an innovative design consisting of periodically arranged air holes running along the fiber's length, which offers enhanced control over the light propagation. PCFs employ various optical techniques to boost sensitivity [3]. One such technique is the Surface Plasmon Resonance (SPR) effect, which involves excitation of surface plasmons at a metal-dielectric interface. When light strikes at this interface, it resonates with the surface plasmons causing a dip in the reflected light intensity. This resonance condition is highly sensitive to changes in refractive index near the surface [4]. The integration of SPR technology into the PCF sensors has maximized sensitivity by detecting even a small refractive index change in the surrounding analyte [1]. This technique is mostly exploited in the biomedical field for the detection and early diagnosis of various diseases like Cancer, Malaria, COVID, Tuberculosis etc. The detection is purely reliant on the refractive index differences between the bio-analytes of the normal and infected cells [5,6].

The sensing mechanism is facilitated by the addition of certain plasmonic materials, which can be combined with plasmonic enhancers for better and enhanced results. The former includes materials like Gold, Silver and Copper, with gold being the most commonly used material given its excellent chemical stability and unique optical properties. The latter encompass a wide variety of materials like the 2D materials- Black Phosphorous, MXene, Germanium-antimony-telluride ($Ge_2Sb_2Te_5$), MoS_2, Graphene etc. [7,8]. The material used in the suggested sensor is TiO_2 and MXene, which are also 2 D materials. Both these play a pivotal role in maximizing the wavelength sensitivity by ensuring strong light-matter interaction. A betterment in the resonance condition is observed due to enhanced confinement of the plasmonic field. Moreover, its unique adhesive property makes it an excellent choice for combining with other plasmonic material like gold. Its durability and chemical stability have widened its applications to various fields, including the biomedical sensors [9].

1.2. Objective of the study

The main aim of this work is focused and extensive research on Photonic Crystal Fiber based on an optical technique called Surface Plasmon Resonance. This device is mainly exploited for its sensing applications like environmental pollutant detection, chemical analyte detection or bio-analyte detection. This work predominantly relies on the Refractive index differences of the analyte to be detected for sensing application of bio-analytes of various diseases. The suggested sensor is designed on such a way that it shows enhanced wavelength sensitivity, for the detection of Human Immunodeficiency virus causing AIDS and Sickle cell anaemia. Moreover, the effect of various plasmonic enhancers to be used along with the plasmonic material, gold in the suggested work, is also explored. The 2D class of plasmonic enhancer materials are used for the detection of various analytes. A class of 2D materials called MXene is used, with an aim of increasing the wavelength sensitivity for the detection of HIV and Sickle Cell Anaemia.

1.3. Research methodology

1.3.1. COMSOL Multiphysics software

The simulation software COMSOL Multiphysics was used for analyzing the sensor performance of the proposed biosensor. Modelling and simulation are done using a numerical approach called Finite Element Method (FEM) using a finer mesh design.

Figure 1: COMSOL software

(Image courtesy: www.automation-mag.com)

The process involves sensor design, simulation, mathematical modelling, and parameter evaluation to assess performance for various applications. A PCF structure is designed with specific geometrical parameters such as air-hole diameters, pitch, and core dimensions.

1.3.2. Mathematical modelling

The sensor performance, is quantified by obtaining the value of wavelength sensitivity and also by considering a moderate loss spectrum. Wavelength sensitivity ($S\lambda$) is demonstrated by the equation [10],

$$S_\lambda\left(\frac{nm}{RIU}\right) = \frac{\Delta\lambda_{peak}}{\Delta n_a} \tag{1}$$

Confinement loss (CL) can be defined as [11],

$$C_L = 8.686 \times \frac{2\pi}{\lambda} \times I_m\left(n_{eff}\right) \times 10^4 \frac{dB}{cm} \tag{2}$$

The refractive index of Silica is given by the wavelength dependent Sellmeier equation [12],

$$n_{si} = \sqrt{\left(1 + \frac{(B_1 \times \lambda^2)}{\lambda^2 - C_1} + \frac{(B_2 \times \lambda^2)}{\lambda^2 - C_2} + \frac{(B_3 \times \lambda^2)}{\lambda^2 - C_3}\right)} \tag{3}$$

Where $B_1, B_2, B_3, C_1, C_2\ and\ C_3$ are Sellmeier coefficients bearing values of 0.69616300, 0.407942600, 0.897479400, $4.67914826\times10^{-3}\mu m^2$, $1.35120631\times10^{-2}\mu m^2$, $97.934002\mu m^2$ respectively.

The refractive index of gold is obtained using Drude-Lorentz model [13],

$$\varepsilon_{Au}=\varepsilon_\infty + \frac{\omega_D^2}{\omega(\omega+i\gamma_D)} - \frac{\Delta\varepsilon\Omega_L^2}{(\omega^2-\Omega_L^2)+i\Gamma_L\omega} \tag{4}$$

Where ε_∞ is given by 5.9673 and ω_D, γ_D and $\Delta\varepsilon$ are the plasma frequency, decaying frequency and weighting factor respectively.

$$n_{Au} = \sqrt{\varepsilon_{Au}} \tag{5}$$

The RI of the 2-D plasmonic enhancer MXene can be determined by fitting the curve using the experimental data of the real and imaginary part of permittivity as a function of wavelength. The data specifically represents the permittivity of Ti3C2Tx, where T is the surface termination element. Fluorine is taken for this proposed case. We obtain two sets of sixth-order polynomial equations representing the real and imaginary parts of permittivity, ε_1, and ε_2, respectively [14],

$$\varepsilon_1 = p_1 \times (\lambda^6) + p_2 \times (\lambda^5) + p_3 \times (\lambda^4) + p_4 \times (\lambda^3) + p_5 \times (\lambda^2) + p_6 \times (\lambda) + p_7 \tag{6}$$

$$\varepsilon_2 = q_1 \times (\lambda^6) + q_2 \times (\lambda^5) + q_3 \times (\lambda^4) + q_4 \times (\lambda^3) + q_5 \times (\lambda^2) + q_6 \times (\lambda) + q_7 \tag{7}$$

The real and imaginary part of MXene's refractive index can be obtained from the following equation,

$$n^2 = \frac{\sqrt{\varepsilon_1^2+\varepsilon_2^2} + \varepsilon_1}{2} \tag{8}$$

$$k^2 = \frac{\sqrt{\varepsilon_1^2-\varepsilon_2^2} - \varepsilon_1}{2} \tag{9}$$

where n and k are the real and imaginary part of the RI. The validity for these equations extends up to around 1770 nm wavelength and is applicable exclusively for 14 nm thickness of MXene.

1.4. Thesis organization

- Chapter 1: This chapter provides an overview of the research work, its significance, and objectives of the study. It also includes the Research methodology, which includes the simulation software that was used for the purpose – COMSOL and the mathematical equations necessary for the suggested work

- Chapter 2: This chapter explains the basics of Photonic Crystal Fiber and its types. A clear description of the fabrication of PCF is also included, along with its applications.

- Chapter 3: In this chapter we discuss the phenomenon of Surface Plasmon Resonance, its history and use in Prism based sensors and the gradual transition to PCF based SPR sensors.

- Chapter 4: This chapter highlights the plasmonic materials and plasmonic enhancers so as to maximize sensitivity of the sensors.

- Chapter 5: This chapter is an elaborate discussion on the suggested SPR PCF RI sensor for the detection of HIV and Sickle cell anaemia. It includes the structural design and the results and analysis are also discussed with the help of various graphs and figures.

- Chapter 6: This includes conclusion and the future work scopes in the SPR PCF domain.

CHAPTER 2

PHOTONIC CRYSTAL FIBER

Photonic crystal fibers are a type of optical fiber composed of an array of micro structured arrangement of air hole or dielectric elements along its length [15]. Introduced in the 1990s, the most prevalent form of PCF today is made from purified silica glass with air holes [16]. The region of silica embedded with the array of holes form the core of the fiber, while the region containing the air holes along the length of the fiber is called cladding [15,17]. PCFs operate as waveguide, with light guiding controlled by the periodic arrangement within the cladding. PCFs are further categorized into two distinct types: Index-guiding and photonic band gap. The classification is based on their light-guiding mechanism. There are three types of PCFs:

i. Index-Guiding PCFs
ii. Step-Index Fiber
iii. Photonic Bandgap (PBG) PCFs

2.1.Index-guiding PCFs

They work on the same mechanism as the conventional step-index fiber. They operate on the principle of total internal reflection. Light is confined with the core, with guidance occurring because of the refractive index (RI) difference between the core and the cladding [18]. Due to the low R.I of the air holes, the core has comparatively higher R.I than cladding [19]. Figure 2 illustrates the typical two-dimensional cross-section of an index-guiding photonic crystal fiber, where the center part contains the diameter of the core, diameter of the air holes is denoted by 'd', and the pitch is the distance between the air holes, shown by Λ.

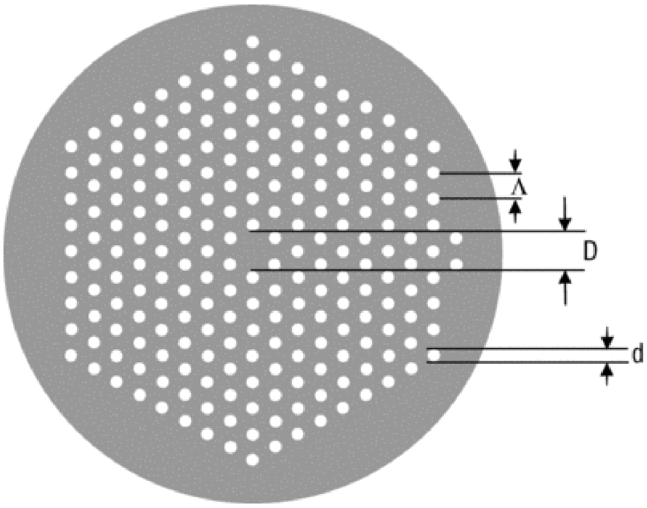

Figure 2: Index Guiding PCF

(Image courtesy: www.newport.com)

2.2.Step-index fiber

Step-index fibers are a type of conventional optical fiber distinguished by a constant R.I profile in both core and cladding regions. This traditional fiber setup functions according to the principle of total internal reflection, whereby light undergoes reflection at the

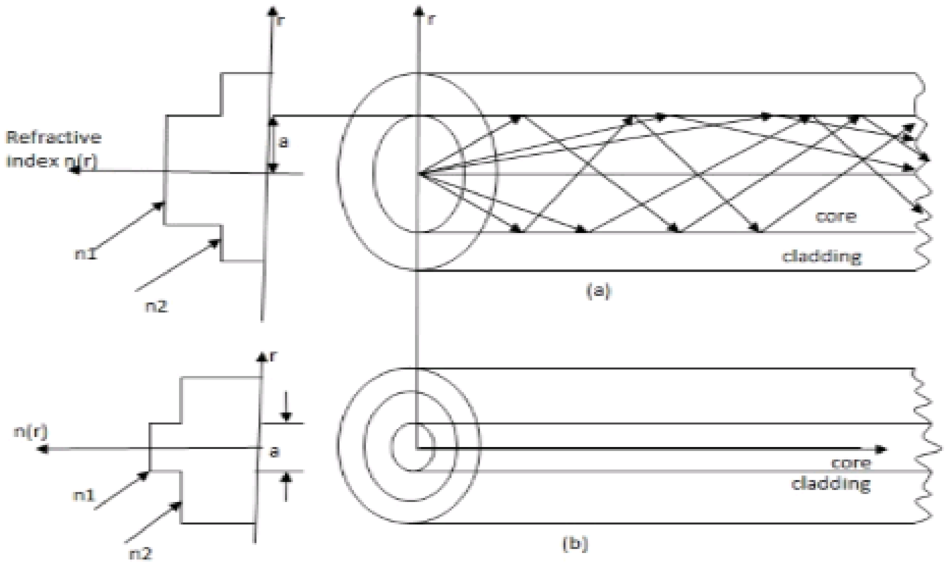

Figure 3: (a) Multimode step index fiber (b) Single mode step index fiber

(Image courtesy: www.ques10.com)

interface of two surfaces with different refractive indices [20]. The refractive index of the core is higher than that of the cladding, leading to steep decline in refractive index at the interface between the two regions. When the incidence angle exceeds the critical angle, a portion of the light is refracted into the medium. In step index fibers, the refractive index (n1) of the core is higher than the refractive index (n2) of the cladding [21].

2.3.Photonic-bandgap (PBG) PCFs

Photonic bandgap fibers are a type of hollow-core PCF that works on the mechanism analogues to the principle of a periodic crystalline lattice in a semiconductor that restricts electron from occupying a bandgap region [21]. These PCFs prevent the light of a certain frequency or wavelength from propagating away from the core, holes in the cladding are arranged in a way that it reflects the light back into the core, thus confining it. These fibers provide a significant advantage by minimizing losses attributed to dielectric materials and can be employed in applications such as gas-laser transmission, pulse compression, and more [22].

2.4.Applications of PCFs

While traditional optical fibers excel in both telecommunications and non-telecommunications applications; however, they come with their own set of limitations associated with their structures [17]. These fibers adhere to strict design criteria, including a restricted core diameter in the single-mode regime, a modal cut-off wavelength, and limited options in material as they require identical thermal properties for both the core and cladding glasses [23]. Unlike the conventional optical properties, PCFs have better guiding properties, low-loss guidance, non-linearity, higher sensitivity, high power delivery, and dispersion property. The unique geometrical structure of PCFs gives us the ease and flexibility to obtain different stomata arrangement that results in different optical properties. By manipulating the parameters like the diameter of the air holes or core, pitch, refractive index, number of air holes, we can fabricate the PCFs to obtain the optimum output. Moreover, we can also design different geometrical shapes such as circle, hexagon, triangular, spiral depending upon our studies [24].

Apart from their traditional use in telecommunication, PCFs provide a wide range of application. It has been proven invaluable in the field of sensing and measurement. PCFs are widely used in making sensors of all kinds. Additionally, they are used in imaging, spectroscopy, astronomy, and more [25]. The structure is also employed in the design of optical logic gates, combinational circuits, and optical absorbers [26].

2.5.Fabrication feasibility

For the practical execution of the suggested sensor various approaches are adopted, first one being the Stack-and-Draw technique for the precise creation of the intended PCF. It is an economical approach involving several steps like preform preparation, consolidation by applying the required temperature and pressure, followed by Drawing process and cooling. This process enables the incorporation of the nano meter ranged airholes into the PCF with ease. For the homogenous integration of the plasmonic metal layer of gold with the PCF, there exists many methods like atomic layer deposition (ALD), Sol–Gel method, Physical vapour deposition (PVD), Thermal evaporation and Chemical vapour deposition (CVD). However, CVD is the most commonly used technique for the nano-scale range deposition of gold. In this fabrication technique, gaseous precursors or reactants are first introduced to a reaction chamber, which is the made to undergo reaction and deposition onto a glass substrate. This procedure is always done at high temperature settings to facilitate smooth and homogenous deposition. In this case, the plasmonic enhancer MXene is prepared from its precursor MAX phase and it is coupled with gold nanoparticle layer by employing ultrasonication for obtaining uniform integration. This hybrid layer is then attached to the PCF using physical vapour deposition. Since both the plasmonic materials, gold and MXene are biocompatible, the bio-analyte can be passed in through the PCF with ease, facilitating easy analysis. Therefore, the fabrication of the suggested sensor is in accordance with the existing advanced innovations [27].

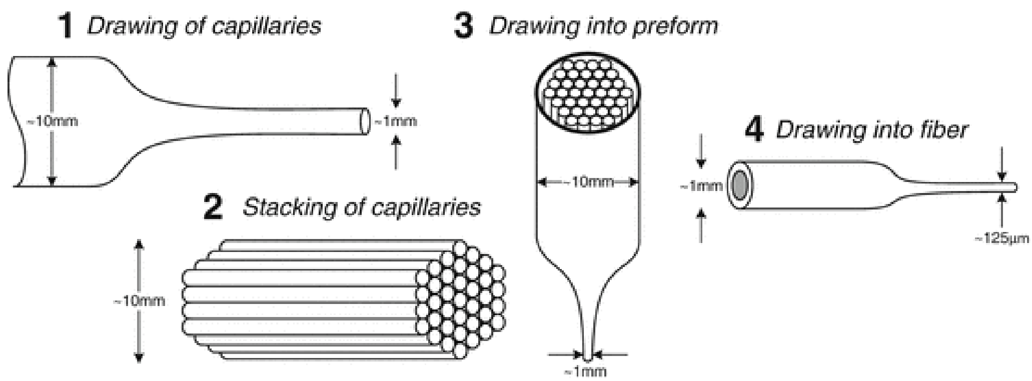

Figure 4: Fabrication of PCF [28]

Figure 4 shows how Photonic Crystal Fiber (PCF) is made using the popular stack-and-draw method. This technique allows for the creation of fibers that have a unique arrangement of air holes running along their length. It all starts with the drawing of individual capillaries (Step 1). Here, hollow glass tubes, about 10 mm in diameter, are heated and stretched into thin, uniform tubes that are roughly 1 mm wide. These capillaries will eventually create the air-hole structure in the finished fiber. In Step 2, these drawn capillaries are carefully stacked in a specific geometric pattern, usually a hexagonal lattice, to form the cladding structure we want. If we're making a solid-core PCF, this stack might also include a solid rod in the center, or we might leave out a capillary at the center to create a hollow-core PCF. Next, in Step 3, this stacked structure is placed inside a larger glass tube and fused into a preform by heating it and slightly drawing it into a solid rod about 10 mm in diameter, all while keeping the internal arrangement intact. Finally, in Step 4, this preform is heated again and drawn into a thin optical fiber of standard size (around 125 μm in diameter), during which the internal microstructure is uniformly scaled down. The end result is a fiber that features a periodic array of tiny air holes along its length, giving it remarkable light-guiding properties like endlessly single-mode transmission, high nonlinearity, and engineered dispersion. This precise control over geometry and refractive index contrast is what makes PCFs incredibly versatile for uses in sensing, nonlinear optics, telecommunications, and biomedical diagnostics.

CHAPTER 3

SURFACE PLASMON RESONANCE

3.1. History of SPR

Surface Plasmon Resonance (SPR) emerged from the field of Optical Physics early in the 20th century. Robert W. Wood noticed unexpected irregularities in the diffraction of light on metallic gratings back in 1902; these observations would later be associated with what today are surface plasmons. A formal theory for surface plasmons was put forward by R.H. Ritchie in 1957; surface plasmons were considered as collective oscillations of free electrons at a metal-dielectric interface. SPR, therefore, is essentially the excitation of these oscillations by incident electromagnetic waves under specific conditions.

By the late 1960s, experimental arrangements had been devised by the likes of Otto and Kretschmann-Raether employing prism coupling methods to excite surface plasmons. This permitted light to interact with a thin metal layer, typically silver or gold, so as to create an evanescent wave that matches the momentum of the surface plasmons [29,30].

3.2. SPR in prism

Surface Plasmon Resonance (SPR) is an optical effect observed when a polarized light falls upon a metal-dielectric interface, giving rise to the dynamical configuration of free electrons at the metal surface—the vibrations termed surface plasmons. These vibrations are so sensitive that any change to the refractive index in proximity to the surface renders the resonance phenomenon ideal for sensing applications. However, to achieve perfect resonance and generate surface plasmons, a certain mechanism has to be in place that can match the momentum of the incident photon to that of the surface plasmon waves. Because surface plasmons hold more momentum than free-space photons, there exists no such mechanism under direct light incidence. These configurations are crafted purposely to remove this mismatch, of which one of the most popular setups is the Kretschmann configuration, proposed in the year 1968 [31].

In this Kretschmann configuration, the metal film is often composed of gold or silver — metals generally recognized for their plasmonic properties — and is deposited directly onto the base of the high refractive index prism. p-polarized light is incident upon the prism such that the angle of incidence is higher than the critical angle for total internal reflection (TIR). At the interface, rather than penetrate through, the light is totally internally reflected, thereby generating an evanescent wave that extends into the thin metal film. The evanescent wave represents a field that cannot propagate, decaying exponentially with distance yet has enough strength to interact with the opposite surface of the metal film (metal–dielectric interface, usually exposed to air or sensing medium). Provided the metal layer is thin enough (on the order of 40 to 50 nm) and the angle of incidence is tuned appropriately, this evanescent field couples resonantly to surface plasmons-the coherent oscillations of free electrons confined at the metal-dielectric interface. It is important to note that the resonance condition is very stringent: it occurs only if the wavevector component of light parallel to the surface equals that of the surface plasmon. At resonance, there is efficient energy exchange from the light to the surface plasmon mode, which is manifested in a very steep reduction in the intensity of light being reflected: a feature of SPR [32, 33].

Resonance happens when the wavevector component of the evanescent wave aligns perfectly with that of the surface plasmon along the interface. At this specific angle of incidence, energy from the incoming light is effectively transferred to the surface plasmon mode, leading to a significant absorption of light at the metal surface. Consequently, we see a sharp drop in the intensity of reflected light at this angle — known as the SPR angle. This dip's position is incredibly sensitive to any changes in the local environment around the metal surface, particularly the refractive index of the dielectric medium. Even the attachment of just a few molecules can alter the refractive index enough to create a noticeable shift in the SPR angle, which makes SPR a fantastic tool for monitoring molecular interactions in real time.

The prism plays a crucial role in both the Kretschmann and Otto configurations, but there's a key difference in their designs. In the Otto setup, the metal film isn't placed directly on the prism; instead, there's a small air gap or a low-index dielectric that separates the prism from the metal surface. When p-polarized light hits the prism–air boundary and reflects totally, it creates an evanescent wave that can penetrate the gap and interact with the metal surface, exciting surface plasmons. This Otto configuration offers better control over the distance between the prism and the metal, which can boost sensitivity in certain situations. However, keeping that air gap consistent and precise—usually just a few hundred nanometers—can be quite tricky, especially when it comes to making practical sensors. Still, the Otto configuration is frequently used in fundamental SPR studies where fine-tuning the coupling distance is essential, and it's particularly useful for analyzing thicker metal films or dielectric layers that can't be directly coated onto a prism [34, 35].

Today, the Kretschmann configuration is still the go-to choice for commercial SPR biosensors, and it’s easy to see why. Its simplicity, durability, and seamless integration with microfluidic systems make it a favorite. This setup is at the heart of instruments that explore real-time biomolecular interactions—think protein-ligand binding, DNA hybridization, and drug-receptor kinetics—all without needing fluorescent or radioactive labels. On the flip side, the Otto configuration remains a key player in optical physics research, particularly when it comes to examining intricate multilayer structures or scenarios that require non-contact excitation of plasmons. Both configurations showcase how smartly designed optical systems can tackle fundamental physical challenges, and together, they’ve fueled decades of advancements in Plasmonics, sensor technology, and Nano photonics [36].

Figure 5 showcases the Kretschmann configuration, a key player in Surface Plasmon Resonance (SPR) biosensing. In this setup, a light source shines p-polarized light onto a high-refractive-index prism that’s been coated with a thin layer of metal, usually gold. When the light strikes the metal-dielectric boundary at a specific angle—one that exceeds the critical angle for total internal reflection—it creates an evanescent wave that seeps into the metal film. At a particular angle, known as the SPR angle, this evanescent wave syncs up with the surface plasmons, which are the coherent oscillations of free electrons at the metal-dielectric interface. This interaction leads to a noticeable drop in the intensity of the reflected light, which is then picked up and analyzed by a detector. The top layer of the metal is treated with a dextran coating, providing a platform for attaching conjugated ligands like antibodies or receptors. These ligands specifically bind to target analytes, such as proteins or DNA, as they flow through a flow cell. When these binding events happen, they alter the local refractive index at the metal surface, causing a shift in the SPR angle.

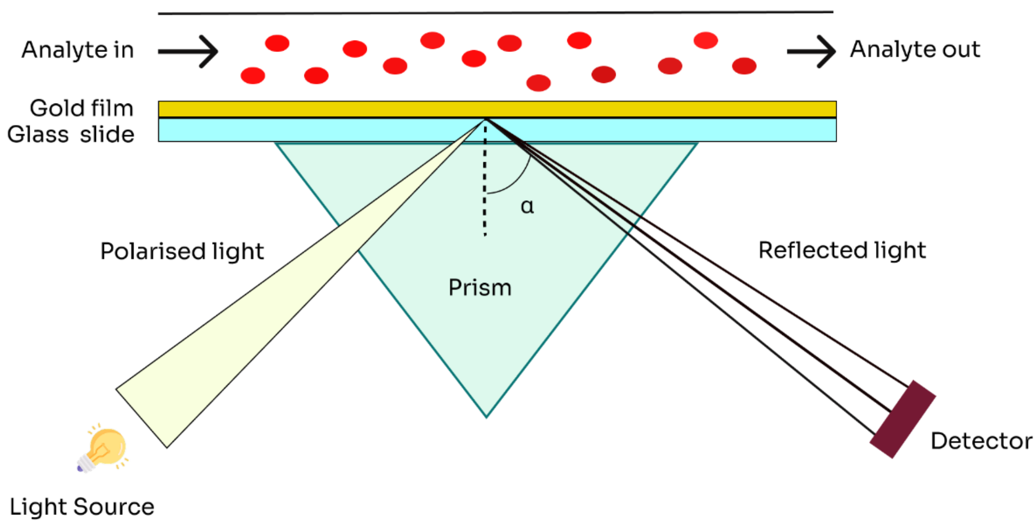

Figure 5: SPR in a Prism

This shift is tracked in real time and directly relates to the binding kinetics and concentration of the analyte, enabling highly sensitive, label-free detection of biomolecular interactions without needing fluorescent tags or dyes.

3.3. Limitations of prism based SPR sensors

Prism-based SPR sensors and Photonic Crystal Fiber (PCF)-based SPR sensors are both impressive tools for biosensing and chemical detection, but they have some notable differences in their design and performance. Traditionally, prism-based setups like the Kretschmann or Otto configurations have been used, but they come with several drawbacks when compared to their fiber-based alternatives. Here are the main limitations of prism-based SPR sensors in relation to PCF-based SPR sensors [37]:

- Bulky and Rigid Setup Prism-based SPR sensors need a large optical bench setup that requires precise angular alignment and bulky optical components, such as prisms, mirrors, and detectors. This makes them less suitable for portable or field applications, while PCF-based SPR sensors are compact, flexible, and can easily integrate with optical fiber systems.

- Limited Integration and Miniaturization Because of their design, prism-based systems are challenging to miniaturize or incorporate into lab-on-a-chip devices. In contrast, PCF-based SPR sensors are highly compatible with microfluidic systems, making it much easier to integrate them into portable or wearable biosensing platforms.

- Lower Sensitivity and Tuning Limitations PCF-based sensors allow for precise adjustments of structural parameters like air-hole diameter, pitch, and core shape, which leads to higher sensitivity and better tunability. On the other hand, prism-based sensors provide less control over field confinement and resonance conditions, making it trickier to optimize their performance for specific applications.

- Fixed Optical Path and Alignment Issues Prism configurations depend on angular interrogation, which requires careful control of the incidence angle to excite surface plasmons. This reliance makes them vulnerable to misalignment and mechanical drift. In contrast, PCF-based sensors often operate in wavelength interrogation mode, which is more stable and easier to implement with standard spectrometers.

- Sample Handling Constraints In prism-based setups, the sensing area is located on a flat metal-coated surface, which limits the interaction length and complicates sample handling.

3.4. SPR based PCF sensors

Surface Plasmon Resonance (SPR) in Photonic Crystal Fiber (PCF) sensors is an impressive technique that merges the unique light-guiding abilities of PCFs with the sensitivity of SPR, making it a go-to method for detecting changes in the refractive index of surrounding media. This is particularly useful in the realms of chemical and biological sensing. In a PCF-based SPR sensor, the optical fiber features a series of air holes arranged in a periodic pattern along its length, creating a micro structured cladding. These holes can be filled or coated with metallic layers—typically gold, silver, or even innovative materials like MXene—that can support surface plasmon waves, which are collective oscillations of conduction electrons at the interface between the metal and dielectric. As light travels through the core of the PCF, part of the evanescent field seeps into the metal-coated area. When the right resonance condition is met, energy from the guided light transfers to the surface plasmons, leading to a sharp dip in the transmission spectrum. The resonance condition is influenced by the refractive index of the analyte (the substance being detected) that surrounds the metal layer. Any change in this index—whether from binding events or chemical interactions—shifts the resonance wavelength, which can be monitored with precision. This shift is the foundation for highly sensitive, label-free detection of biomolecules, gases, or chemicals. PCFs bring several advantages to SPR sensing: they enable customization of the mode-field distribution, enhance light-matter interaction, and offer flexibility in sensor design. Different PCF geometries (like solid-core, hollow-core, D-shaped, etc.) and fabrication techniques (such as stack-and-draw or coating inside holes) can be employed to optimize sensitivity, selectivity, and spectral performance. Consequently, PCF-based SPR sensors are being actively researched for applications in biomedical diagnostics, environmental monitoring, and industrial process control, effectively combining the strengths of fiber optics and plasmonic sensing into one cohesive platform [38].

CHAPTER 4

PLASMONIC MATERIALS AND PLASMONIC ENHANCERS

4.1. Plasmonic materials and plasmonic enhancers

The utilization of plasmonic materials like Gold, Silver or Copper facilitates and provide a platform for the occurrence of SPR. Gold is the often-favoured plasmonic material due to its excellent chemical stability and biocompatibility. The efficient sustainment of the oscillation of the conduction electrons is made possible due to gold's electron density and band structure [39,40,41]. The relatively lower intrinsic losses like less scattering or absorption also makes gold a good plasmonic material. Silver and Copper also exhibit certain qualities like high conductivity which make it good plasmonic materials but in view of real-time fabrication, silver and copper suffers from environmental oxidation. The sensitivity can be further enhanced by using certain 2-D materials like Titanium dioxide (TiO_2), Germanium-antimony-telluride ($Ge_2Sb_2Te_5$), Molybdenum Disulphide (MoS_2), black phosphorous which are known as plasmonic enhancers. These materials, when coupled with the plasmonic material such as gold or silver, yield enhanced sensitivity [42,43,44]. Nonetheless, these 2D materials put forward certain constraints like reduced conductivity, low adsorption stability, poor biocompatibility and high hydrophobicity. However, there is a class of 2D materials called MXene, which has excellent conductivity, flexibility in functionalization, large surface area and hydrophilic in nature, allowing for uniform dispersion of plasmonic material [45].

4.2. MXene: A 2D plasmonic enhancer

MXenes are a group of 2D materials discovered by Naguib et al. in 2011 consisting of a transition metal carbide or nitride or carbonitride in a honey-comb like structure. MXenes are synthesized from its precursor MAX phase by selective etching using Hydrofluoric acid etchants and delamination. Further, MXene's properties can be altered based on our objective by changing the surface functional groups [45]

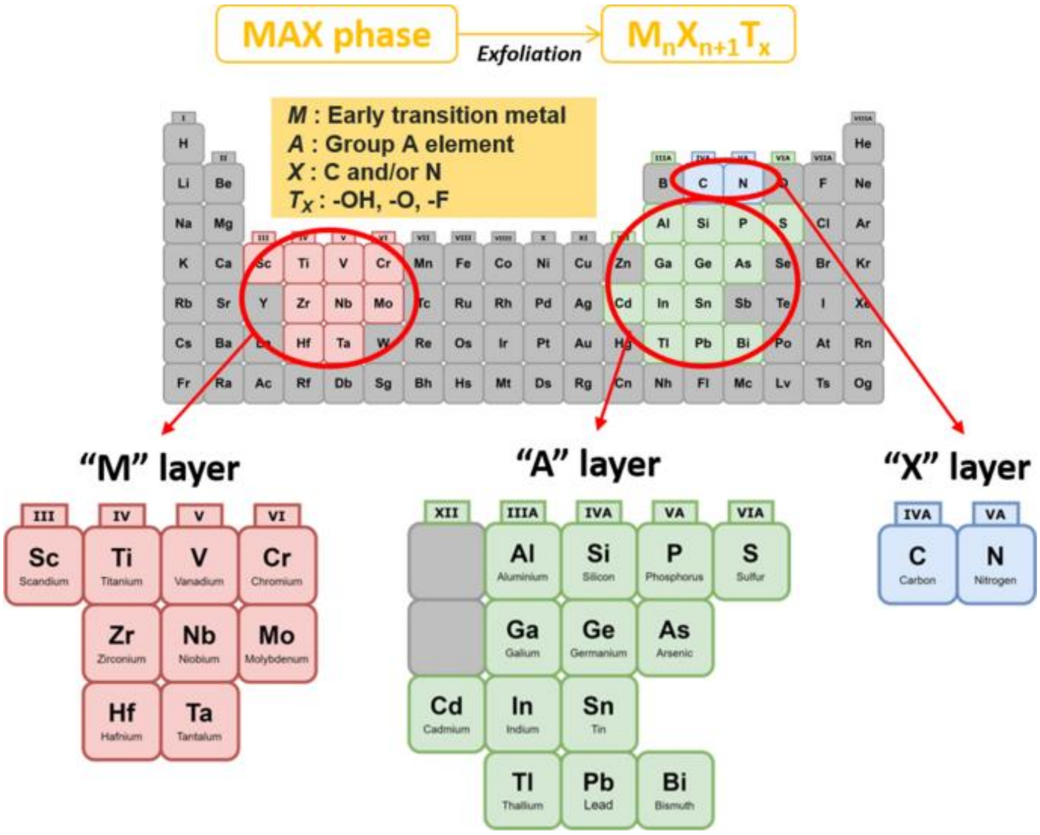

Figure 6: Elemental breakdown of MXene

(Image courtesy: biomedical-engineering-online.biomedcentral.com)

The figure 6 offers a straightforward visual breakdown of MAX phase materials and their role in creating MXenes, a fascinating new category of 2D materials known for their impressive electronic, mechanical, and sensing capabilities. MAX phases are essentially layered ternary carbides or nitrides, represented by the general formula $M_{n+1}AX_n$, where: M stands for an early transition metal (highlighted in red, like Ti, V, Cr, Zr, or Nb),

- A refers to an element from groups 13–16 (mostly from the p-block, shown in green, such as Al, Si, Ga, or In),
- X can be either carbon (C) or nitrogen (N) (marked in blue), and
- T_x indicates surface termination groups like –OH, –O, or –F that are added during the exfoliation process.

At the top of the image, you can see the structure of the MAX phase and how it undergoes exfoliation to produce MXenes, which have the formula $M_{n+1}X_nT_x$. This exfoliation selectively removes the A-layer (typically using HF or other etchants), resulting in a 2D layered structure made up of M and X atoms, now capped with T_x groups. Just below the periodic table, the image categorizes the elements suitable for each layer:

- The M-layer is made up of early transition metals that provide strong metallic conductivity and a solid structural framework.
- The A-layer elements are generally eliminated during the chemical exfoliation process.
- The X-layer elements (C, N) ensure chemical stability and shape the bonding characteristics within the MXene sheets.

This relationship between structure and properties enables MXenes to merge the metallic conductivity of transition metals with the chemical adaptability of 2D materials, positioning them as exciting candidates for uses in energy storage, electromagnetic shielding, catalysis, and sensing [14].

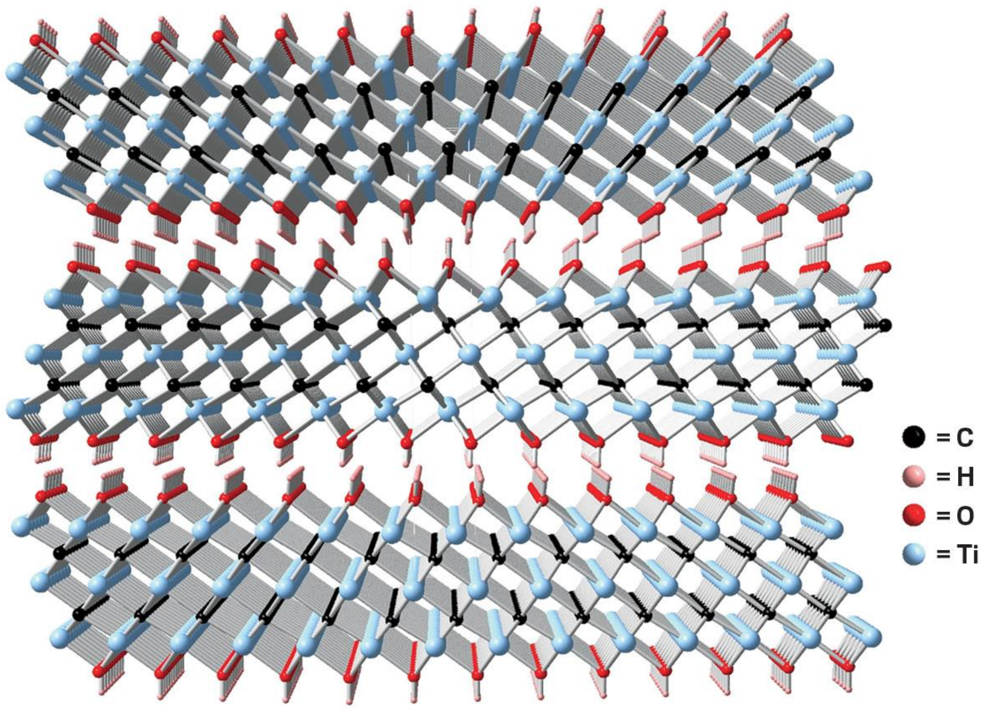

Figure 7: MXene structure

(Image courtesy: cen.acs.org)

The honeycomb-like structure of MXene is all about how the atoms are arranged in a hexagonal lattice at the atomic level, especially in those 2D planes that come to life after exfoliating from MAX phases. In this setup, transition metal atoms (M) create a hexagonal framework, while carbon or nitrogen atoms (X) nestle into the octahedral voids between the M atoms. This results in a beautifully ordered, layered structure. You can think of this hexagonal arrangement as similar to the honeycomb lattice of graphene, but with alternating layers of heavier atoms that add a touch of chemical versatility. What really sets MXenes apart is the functionalization of their outer surface with –O, –OH, or –F groups, which pop up during chemical etching, giving the structure both hydrophilicity and chemical reactivity.

This honeycomb configuration not only boosts mechanical strength and flexibility but also enhances electrical conductivity, thanks to the delocalized electrons from the transition metal layers. The periodic atomic arrangement allows MXenes to support plasmonic excitations, making them perfect for applications like SPR sensing. Plus, the uniform 2D layers offer a larger surface area for analyte adsorption and biomolecular interactions, which is crucial for improving sensitivity in sensing platforms. With their high aspect ratio, tunable chemistry, and strong electronic properties, the honeycomb-like structure of MXenes serves as an excellent foundation for the next generation of nanodevices, energy systems, and biosensors.

4.3. Why MXene over other 2D materials?

In the world of SPR-based Photonic Crystal Fiber (PCF) refractive index sensors, researchers have been exploring a range of 2D materials like graphene, MoS_2, WS_2, and black phosphorus (BP) for their potential to enhance plasmonic effects. However, these materials come with their own set of challenges. Take graphene, for example: while it boasts impressive electronic mobility, it has a very low intrinsic plasmonic resonance in the visible spectrum and only weak light absorption per layer (around 2.3%). This means that to achieve significant interaction, you need to stack multiple layers, which complicates the fabrication process and can even lower the sensing resolution. Transition metal dichalcogenides (TMDs) like MoS_2 and WS_2, although they are optically active, are semiconductors with relatively poor electrical conductivity compared to metals, which limits their ability to support strong plasmon resonance. Black phosphorus, another intriguing 2D material, faces rapid degradation when exposed to air and moisture, making it less stable for practical or long-term sensing applications. Additionally, the surface chemistry of these materials tends to be quite inert, which restricts opportunities for bio-functionalization or surface engineering—both of which are crucial for improving a sensor's selectivity and sensitivity [14].

On the other hand, MXenes (like $Ti_3C_2T_x$) rise above many of these hurdles and emerge as exceptional plasmonic enhancers in PCF-SPR sensors. They possess metallic or quasi-metallic conductivity, allowing them to support stronger and more tunable plasmonic resonances even at optical frequencies. Their unique surface terminations (such as –OH, –O, and –F) not only make them highly hydrophilic and chemically reactive but also facilitate easy surface functionalization for targeted sensing, which is vital in biosensing applications. Unlike BP or TMDs, MXenes show relative stability in aqueous environments, especially when treated properly, making them ideal for dependable, reusable, and long-lasting sensing platforms. Their high refractive index further enhances their appeal in this field.

CHAPTER 5

MXENE COATED CONCAVE SHAPED MICROCHANNEL PCF SPR BIOSENSOR FOR THE DETECTION OF HIV AND SICKLE CELL ANAEMIA[1]

This work presents the first-time analysis and discussions on a Surface Plasmon resonance-based Photonic Crystal Fiber Refractive index (RI) Bio-sensor, designed specifically to detect two of the most widespread diseases - HIV-caused AIDS and Sickle cell anaemia. While HIV is a highly transmissible disease, invading our body's immune system, Sickle cell anaemia is an inherited genetic disorder, both affecting blood cells. The detection is purely dependent on the refractive index of the affected cells (1.42 for HIV and 1.38 for Sickle cell anaemia), compared to 1.35 for normal cells. The highlight of the design is the appropriate use of the bio-compatible, 2D plasmonic enhancer MXene along with a layer of gold for maximizing the wavelength sensitivity.

Human Immunodeficiency Virus or HIV is an infection that invades our body's immune system. The extreme stage of infection leads to an extremely dangerous condition called Acquired Immuno-Deficiency Syndrome (AIDS). Globally, around 40 million people are currently affected with this infectious disease among which 1.4 million are children. The death toll ranges up to 50 million in the past 40 years [28]. The high mortality rate is the consequence of the fact that it has no definite cure. However, there exists many treatment approaches like antiretroviral therapy (ART) that has potentially expanded the life span of the infected individuals by reducing the viral load content in the body. But this is only effective in the early stages of infection, which necessitates the early diagnosis of the HIV infection. There are several diagnostic tools for detecting HIV, such as Enzyme-Linked Immunosorbent Assay (ELISA) and rapid antibody tests. But these techniques pose certain constraints like limited sensitivity (during acute infection stage), need for labelled antibodies and failure to detect HIV subtypes [46,47]. The proposed SPR PCF RI biosensor appears to be a superior detection technique in comparison with most conventional techniques, as it provides a label-free detection with

[1] A part of the results presented in this chapter have been reported in a research publication
Krishnan, P., Khamaru, A., & Kumar, A. (2025). MXene coated concave shaped microchannel PCF SPR biosensor for the detection of HIV and sickle cell anaemia. *Optical and Quantum Electronics*, *57*(5), 270.

a potential of achieving lower detection limits giving higher sensitivity. Another benefit of using SPR PCF RI Biosensor includes its broad specificity, which allows for the detection of multiple HIV subtypes (HIV1 and HIV2). HIV1 and HIV2 are the subtypes of HIV. This paper focusses on HIV1 because it is more common and more easily transmitted compared to HIV2, which is rarer. The RI of normal blood cell bears a value of 1.35, while that of HIV1 is 1.42. This increment in the RI of blood cell after infection occurs as a result of viral load accumulation in the cell, leading to the alteration of the cellular composition (altered protein and lipid concentration) [48].

Another suitable application for the proposed sensor is the detection of Sickle Cell Anaemia. It is an inherited disorder resulting in abnormal haemoglobin which in turn alters the appearance of the red blood cells to C or sickle shaped cell. The sickle cell leads to constricted blood flow causing further complications like anaemia and infection. The treatment involves only oral medications to reduce pain and further damage of the cell. It doesn't have a definite cure. However, there are several diagnostic techniques like genetic testing, haemoglobin electrophoresis, Complete blood count (CBC) etc. However, SPR PCF RI Biosensor offers much more promising results as it is a label-free technique providing higher sensitivity. The normal cell RI is, again, 1.35. But the RI of sickle cell anaemia is found to be 1.38. The change RI occurs due to the sickling of cells as it causes Haemoglobin S (HbS) polymerization [50,51].

5.1.Structural design

The structural design contains dual sets of airholes arranged in a concentric semi-circular pattern on both the halves of the circular PCF sensor of radius 4200nm. The radii of the small and big airholes are defined as r_1 and r_2 respectively. To ensure enhanced

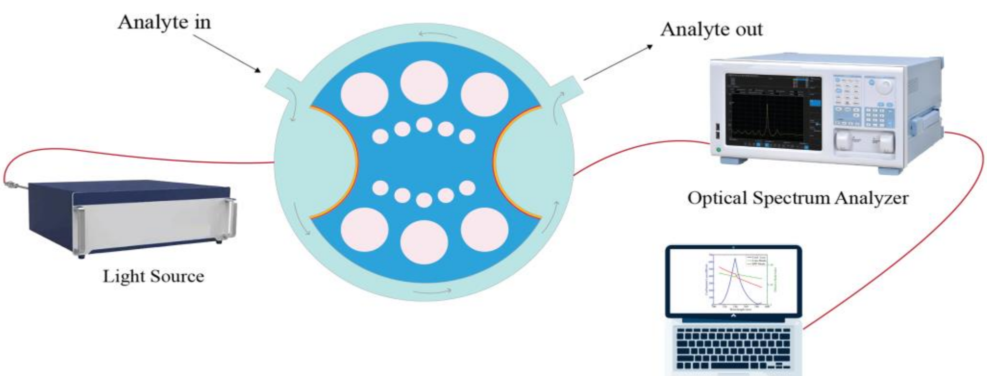

Figure 8: Experimental arrangement

interaction of the core mode with plasmonic material, few airholes from both the semicircular concentric sets are eliminated for the incorporation of the concave shaped microchannels on either side of the PCF. The arrangement of these airholes is done against a fused silica material background, which forms the core of the PCF. The plasmonic material, gold (t_g) is coated on the concave shaped microchannel on either side of the PCF, which lies in contact with the analyte layer. Additionally, a 14nm (t_m) layer of MXene (plasmonic enhancer) is sandwiched between silica and gold film of the concave shaped microchannel. This hybrid layer of gold and MXene promotes a more effective coupling and also enhances the field interaction with the analyte. Consequently, this results in an elevated sensitivity with lower detection limits. The analyte layer has a thickness of 0.5 μm and it contains the bio-analytes of HIV infected cell and Sickle cell

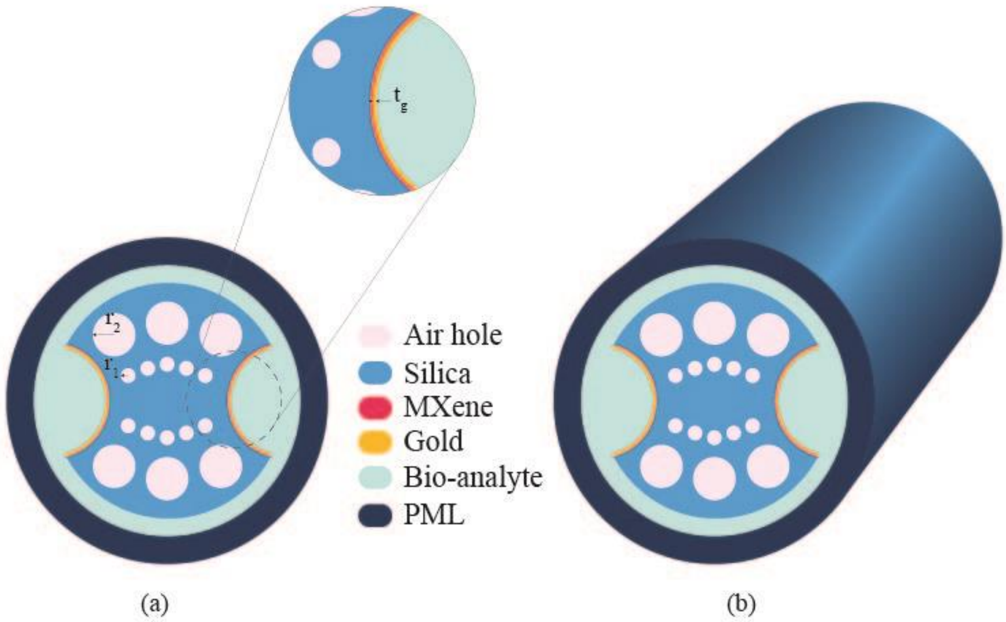

Figure 9: (a) 2D view of the Microchannel MXene coated sensor
(b) 3D view

anaemia affected blood cells, with a RI of 1.42 and 1.38 respectively. Lastly, a Perfect Matching Layer (PML) of 0.7μm thickness is added to minimize the electromagnetic wave reflections and for the absorption of radiation energy.

5.2.Simulation results and analysis

The simulation software COMSOL Multiphysics was used for analyzing the sensor performance of the proposed bio-sensor. Modelling and simulation are done using a numerical approach called Finite Element Method (FEM). As demonstrated in the Figure 13, the phase matching condition is observed when the effective mode indices of both SPP mode (red line) and the core-guided mode (green line) intersects with each other. Here, we observe the dispersion relation corresponding to an analyte refractive index of 1.38, whose resonant wavelength is observed at 740 nm. Consequently, a sharp confinement loss peak occurs at this resonant point, which corresponds to maximum energy transmission between the core-guided mode and SPP mode in the bio-sensor.

The suggested sensor is found to offer promising results in the detection of HIV cell and Sickle cell anaemia. The sensor performance is further amplified by optimization of the structural parameters. Those parameters are optimized which plays an essential role in deciding the sensor's sensitivity and loss spectrum. In this work, three of the parameters are chosen and are subjected to variations .

Firstly, the gold layer thickness parameter (t_g) is varied, keeping others constant. An optimized magnitude t_g is obtained and fixed for the further optimization of the radius of small and big air holes. The sensor performance, is quantified by obtaining the value of wavelength sensitivity and also by considering a moderate loss spectrum.

.

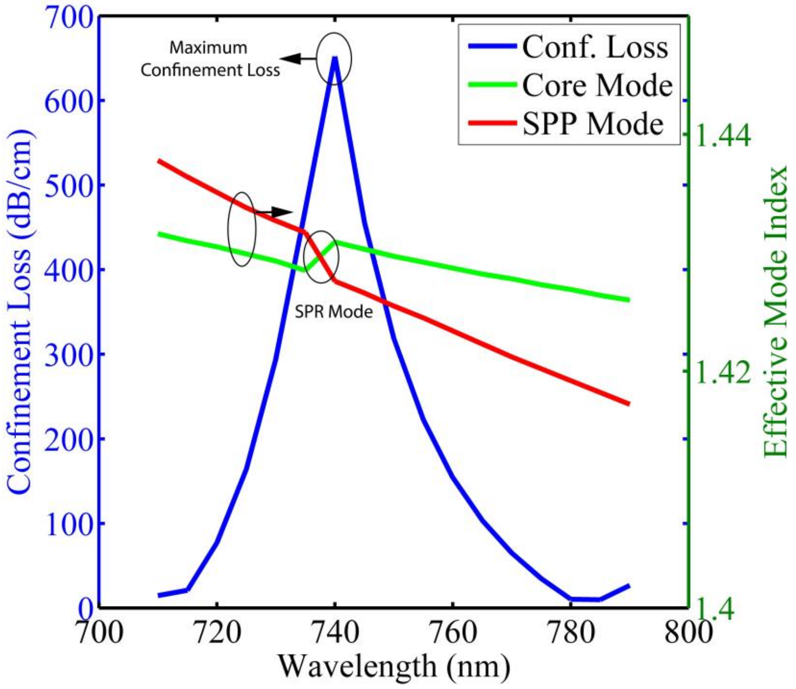

Figure 10: Dispersion relation of analyte of 1.38 and loss spectrum

The optimization of three key parameters—gold layer thickness, small air hole radius, and large air hole radius—revealed that the highest sensitivity is achieved when the gold layer thickness is set to 40 nm, the small air hole radius is 250 nm, and the large

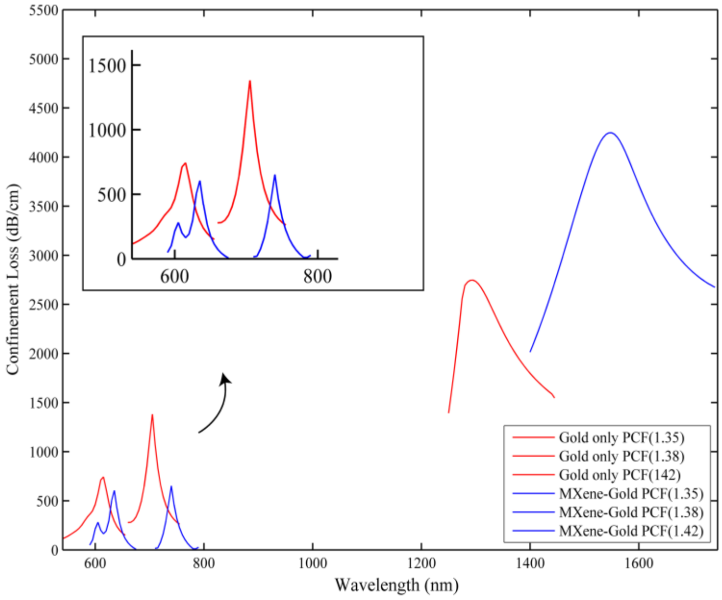

Figure 11: Comparison of gold only PCF and MXene-Gold PCF

air hole radius is 525 nm. These optimized values result in the most effective performance in terms of sensitivity and loss profile.

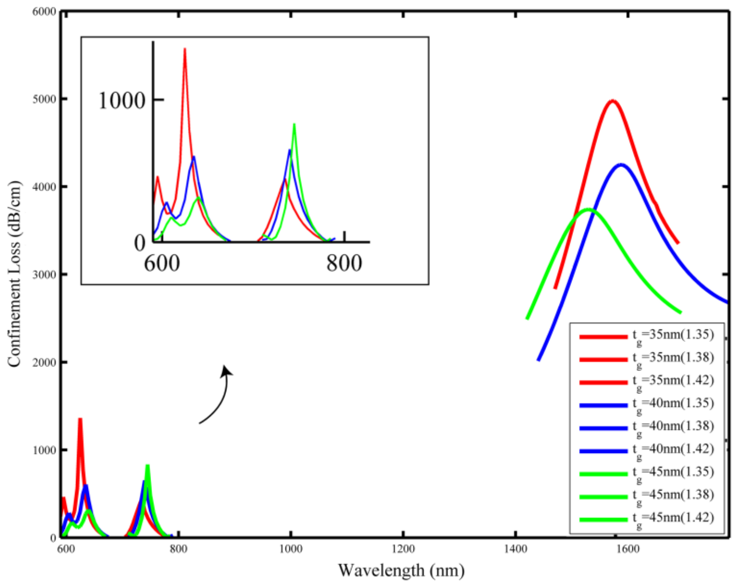

Figure 12: Thickness optimization of the MXene-gold

5.3. Influence of the thickness of gold layer

The gold layer thickness is carefully optimized to elevate the sensor performance. In view of initial study, a 40 nm thickness of gold layer and 14 nm MXene layer, a maximum sensitivity of 13,071.42 nm/RIU and 3500 nm/RIU and a loss of 4246.6 dB/cm and 652.06 dB / cm is obtained for HIV infected cell and sickle cell anaemia respectively. A slight elevation in wavelength sensitivity to 13,571.42 nm/RIU and 3666.66 nm/RIU for HIV and Sickle cell anaemia respectively is noticed when a 35 nm thick gold layer is used. However, the thinner gold layer leads to a higher loss spectrum due to the reduced excitation of the surface plasmon polaritons (SPPs). On employing a thicker gold layer (45 nm), a significant reduction in the wavelength sensitivity to 12,714.28 nm/RIU and 3500 nm/RIU is detected. As the thickness of gold layer rises, the evanescent field produced by the SPPs penetrates lesser into the surrounding analyte. This reduced interaction with the bio-analyte makes it less responsive to the RI variations, resulting in lower sensitivity. In view of the moderate loss spectrum and an elevated wavelength sensitivity, optimized sensor performance is obtained at a thickness of 40 nm gold layer. The graphical summary of the gold layer thickness optimization is demonstrated in the Figure 12.

5.4. Influence of the radius of smaller air holes

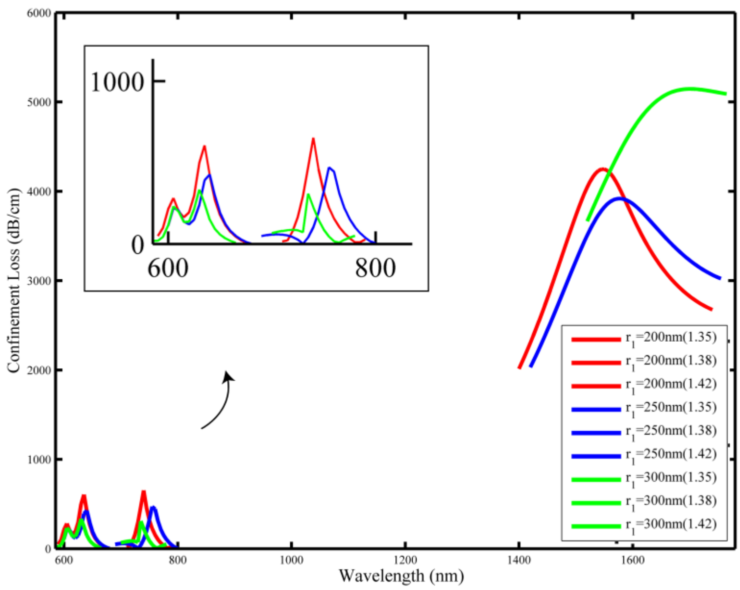

Figure 13: Small airhole optimization

The air holes in vicinity to the core plays a pivotal role in ensuring efficient coupling between the core mode and SPP mode. The radius is varied and assigned three different values (200 nm, 250 nm and 300 nm) as shown in the Figure 13. The wavelength sensitivity of HIV infected cell and sickle cell anaemia increased from 13,071.43 nm/RIU and 3500 nm/ RIU to 13,357.14 nm/RIU and 3833.33 nm/RIU when the radial parameter was varied from 200 to 250 nm with the increment of 50 nm. The sensitivity of HIV cell could be further increased to 15,825.71 nm/RIU for a radius of 300 nm. However, its loss spectrum reaches a very high and undesirable value of 5144.80 dB/cm. This is due to the fact that bigger air holes near the core causes leakage of optical energy to the cladding and plasmonic metal layers leading to radiative losses. Moreover, it curtails the RI contrast between the core and cladding. This degradation in the sensor performance cannot be encouraged and hence, the airhole of radius 250 nm is opted as the optimized parameter.

5.5.Influence of the radius of bigger air holes

The size of the outer set of bigger airholes can largely influence sensor performance by altering the sensitivity and confinement loss. A boost in wavelength sensitivity to 14,142.86 nm/RIU and 4000 nm/RIU for HIV cell and sickle cell anaemia respectively, is observed at a radius of 525 nm, in comparison to both 475 nm and 575 nm.

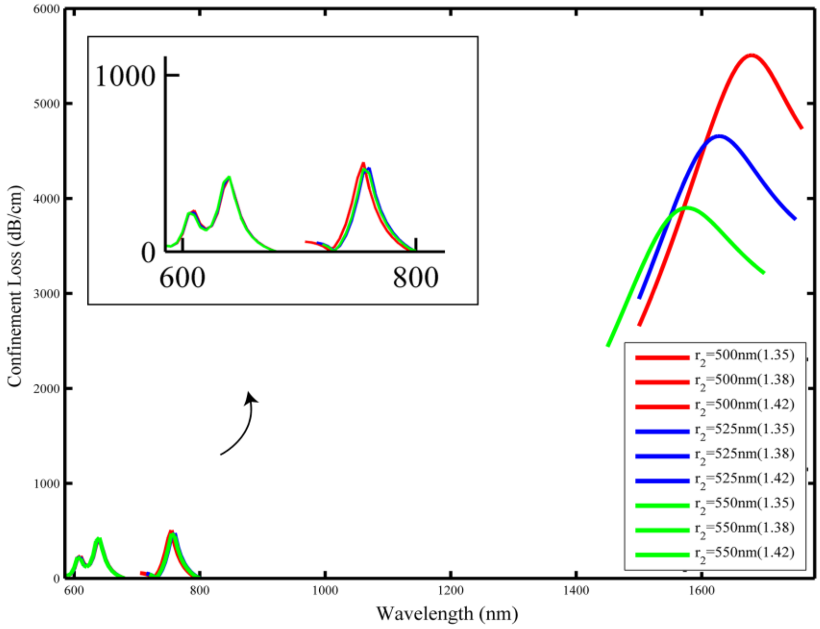

Figure 14: Big airhole optimization

On inspecting the loss peaks given in the Figure 14, we can conclude that moderate loss is also obtained at 525 nm radius, bearing a value of 4655.3 dB/cm and 475.37 dB/cm for HIV and sickle cell respectively. We can also observe that the smaller airhole (475 nm) gave a much higher confinement loss as they diminish the effective mode index contrast between the core and cladding. Moreover, inefficient coupling caused by smaller airholes results in inadequate energy transmission, resulting in higher loss. Therefore, optimized sensor performance is obtained at a radius of 525 nm. The analysis using the initial parameters revealed how the utilization of MXene along with gold reflected in an increase in wavelength sensitivity of the PCF sensor. The optimized parameters are tabulated at Table 1. After optimization of thickness of gold and radii of both big and small air holes, we can observe a significant hike in both Gold only and MXene-Gold PCF. The wavelength sensitivity of gold only PCF for HIV cell and Sickle cell anaemia extracted as 13,071.42 nm/RIU and 3500 nm/RIU, on using the optimized structural parameters as shown. A surge is observed in MXene-gold PCF also, wherein the sensitivity increased to 14,142.85 nm/RIU and 4000 nm/RIU for HIV and sickle cell anaemia respectively. The comparative study is also tabulated in Table 2. The HIV and sickle cell anaemia are first detected through photonic crystal probe by britto et al. In comparison to previous sensor, the proposed sensor offers an advanced sensitivity.

Table 1: Optimized parameters

Parameters	t_m	t_g	r_1	r_2
Values	14 nm	40 nm	250 nm	525nm

5.6. Comparative analysis of gold only and MXene-gold PCF using optimized parameters

The analysis using the initial parameters revealed how the utilization of MXene along with gold reflected in an increase in wavelength sensitivity of the PCF sensor. After optimization of thickness of gold and radii of both big and small air holes, we can observe a significant hike in both Gold only and MXene-Gold PCF. The wavelength sensitivity of gold only PCF for HIV cell and Sickle cell anaemia enhanced from 9714.28nm/RIU and 3000nm/RIU to 10571.4285nm/RIU and 3500nm/RIU respectively, on using the optimized structural parameters. Similar surge is observed in MXene-gold PCF also, wherein the sensitivity increased from 13071.42nm/RIU and 3500nm/RIU to 14142.85nm/RIU and 4000nm/RIU.

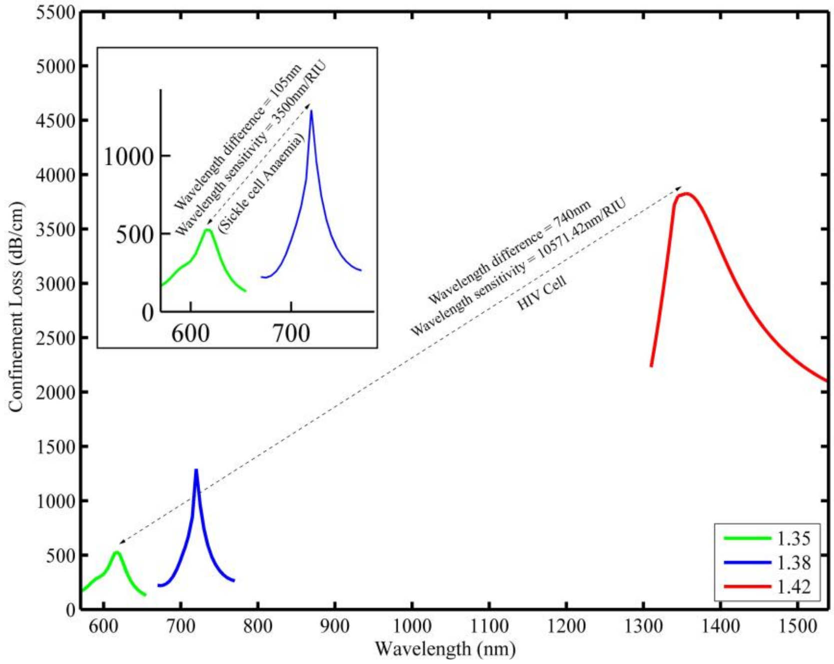

Figure 15: Loss spectrum and sensitivity of gold only PCF with optimized

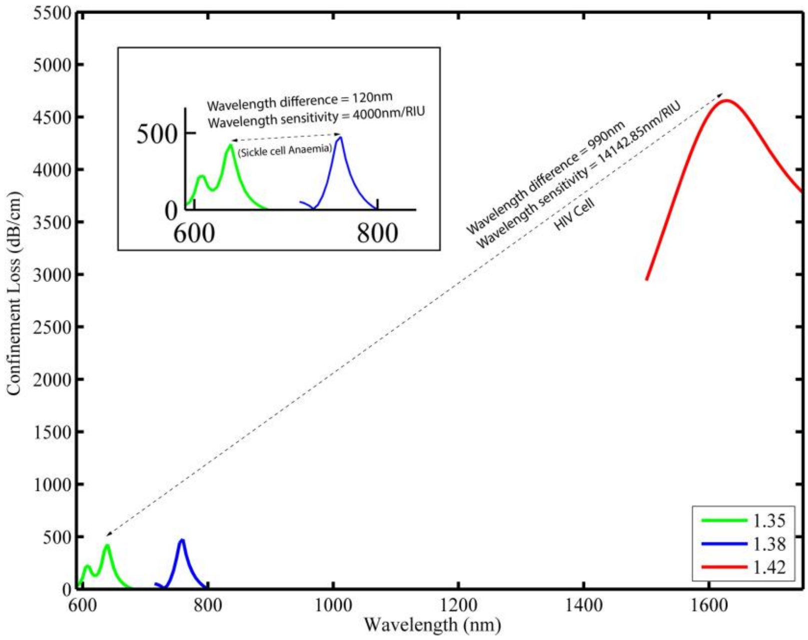

Figure 16: Loss spectrum and sensitivity of MXene-gold PCF with optimized parameters

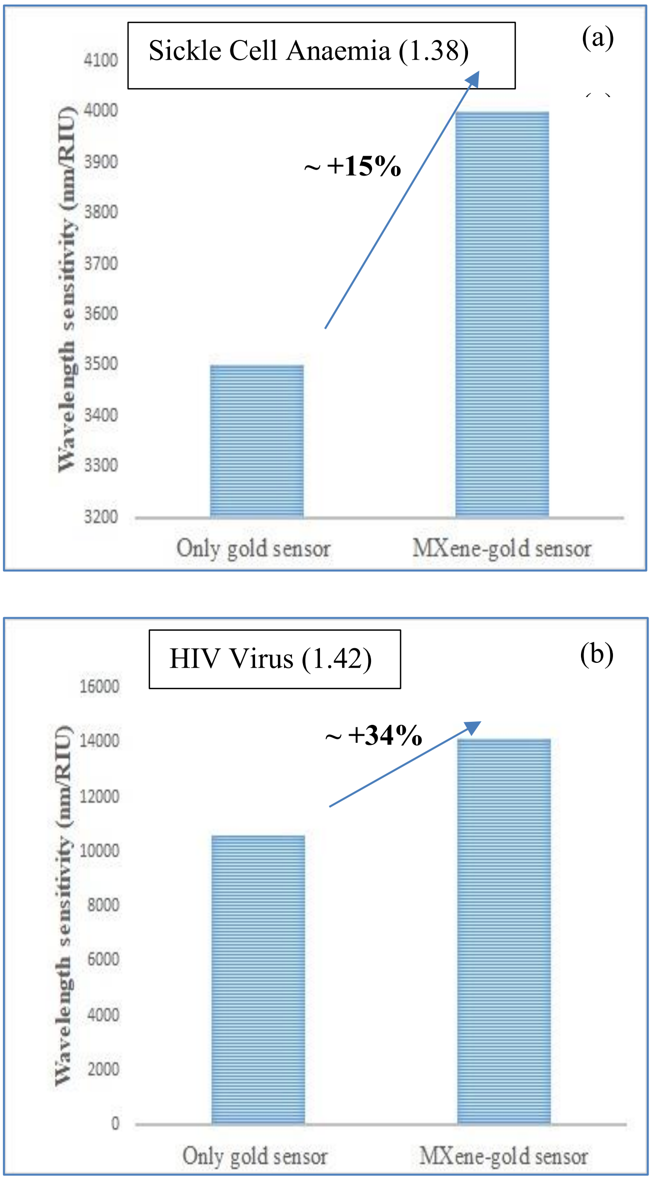

Figure 17: Performance analysis of both the sensors

5.7. Tolerance study of the structural parameters

To study the tolerance of the structural parameters, the dimensions are adjusted at a range of±5% to analyze the significant variations in the optimized results. The first tolerance study covers the variation of gold thickness by±5%, shows no variation in the sensitivity with a change in confinement loss by~±10% from the optimized results. After discussing the thickness of gold, the small air holes are varied by±5%, observing negligible variation with the optimized sensitivity. The respective loss at 1.38 RI (Sickle cell) have suffered alterations of~±8%. At final step of tolerance study, big air holes are altered by±5%, again showing minor changes in the sensitivity magnitude with loss variations of±6%. The whole tolerance study concludes that the sensitivity is not affected by±5% variations of the parameters, which creates our proposed sensor highly feasible to experimental fabrication, and can tolerate minor dimensional instabilities.

Table 2: Comparative study between only gold PCF and MXene-gold PCF using optimized parameters

Biosensing Application.	Gold only sensor		MXene-Gold sensor	
	Wavelength Sensitivity (nm/RIU)	Confinement Loss (dB/cm)	Wavelength Sensitivity (nm/RIU)	Confinement Loss (dB/cm)
HIV cell detection	10571.42	3825.1	14142.85	4655.3
Sickle cell anaemia detection	3500	1293.2	4000	475.37

The highlight of the design is the appropriate use of the bio-compatible, 2D plasmonic enhancer MXene along with a layer of gold for maximizing the wavelength sensitivity. A noticeable rise of sensitivity from 9714.28nm/RIU and 3000nm/RIU to 13071.42nm/RIU and 3500nm/RIU was observed for HIV cell and sickle cell anaemia respectively. Furthermore, an even higher sensitivity surge from 10571.42nm/RIU and 3500nm/RIU (Gold only PCF) to 14142.85nm/RIU and 4000 nm/RIU (MXene-Gold PCF) can be achieved on optimization of the structural parameters. Therefore, in view of the desired sensor performance based on wavelength and confinement loss spectra for the suggested sensor, it is appropriate for the detection of HIV infected cell and Sickle cell anaemia.

CHAPTER 6

CONCLUSION AND FUTURE WORK

The work is based on HIV caused AIDS and Sickle cell anaemia, which are two of the most threatening diseases in the present scenario. Although there exist many treatment approaches, none is useful in the case of delayed detection. The aim of this work is to fabricate a biosensor reliant on the RI of the bio-analytes of HIV infected cell and Sickle cell anaemia, facilitating a much earlier detection. The proposed design put forth a PCF sensor based on SPR for the concurrent detection of HIV infected cell and Sickle cell anaemia. The two sets of semi-concentric arrangement of air holes offers an eye-shaped core, with a MXene-Gold hybrid layered coating on the microchannels on either side. The concave shaped microchannels produce a much-pronounced wavelength sensitivity as it provides optimized light guidance and enhanced surface area, resulting in increased coupling of evanescent field. The highlight of the design is the appropriate use of the bio-compatible, 2D plasmonic enhancer MXene along with a layer of gold for maximizing the wavelength sensitivity. A noticeable rise of sensitivity from 10,571.42 nm/RIU and 3500 nm/RIU (Gold only PCF) to 14,142.85 nm/ RIU (+34%) and 4000 nm/RIU (+15%) (MXene-Gold PCF) can be achieved on optimization of the structural parameters. Therefore, in view of the desired sensor performance based on wavelength sensitivity and confinement loss spectra for the suggested sensor, it is appropriate for the detection of HIV infected cell and Sickle cell anaemia.

The future work aims at exploring more potential applications in the SPR Based PCF RI sensor. Other than bio-medical applications, this sensor can be used for various other purposes like temperature sensing, which can be explored further. Moreover, the plasmonic enhancer materials are not limited to just the 2D class of materials, which we explored in this work. There are a class of materials called Phase Changing Materials (PCM), Phase-change materials (PCMs) are substances that can reversibly switch between different physical states (typically amorphous and crystalline) when exposed to external stimuli like heat, light, or electric fields. These transitions are very quick (sub-nanosecond time scale and repeated billions of times). This phase transition results in a change in properties, such as Refractive Index, Electrical Conductivity, Optical Absorption, Thermal Conductivity etc. Examples include $Ge_2Sb_2Te_5$ (GST), GeSbTe

(GST-based alloys), Sb_2Se_3, Sb_2Te_3 (Antimony-based PCMs).

The main reason to incorporate PCMs in SPR PCF Sensors is that the sensors attain a Reconfigurable Nature as it provides refractive index Control by switching between aGST (low RI) and cGST (high RI) allowing dynamic sensitivity tuning for different applications; Enhanced Field Confinement as cGST enables stronger field confinement at NIR wavelengths, improving SPR sensor sensitivity; Spectral Shift where the phase transition shifts resonance wavelength, allowing operation at different ranges without structural changes; Dynamic & Reversible Sensing like thermal, optical, or electrical switching that enables real-time sensor reconfiguration for adaptive applications

REFERNCES

[1] G Singh, S Sharma, A Kumar, "Design and simulation of solid-core octagonal photonic crystal fber for terahertz wave propagation", Microw Opt Technol Lett vol. 66, no. 6, p. 34173, 2024.
[2] N. Singh, A. Khamaru, and A. Kumar, "Design and analysis of a rectangular core refractive index-based PCF sensor for bio-sensing application" Optical and Quantum Electronics, vol. 56, no. 7, p.1133, 2024.
[3] S Das, VK Singh, "Highly sensitive PCF based plasmonic biosensor for hemoglobin concentration detection", Photonics Nanostructures Fundamentals Appl, vol. 51, p. 101040, 2022.
[4] S Jain, K Choudhary, S Kumar, "Photonic crystal fiber based SPR sensor for broad range of refractive index sensing applications", Opt Fiber Technol vol. 53, p. 103030, 2022.
[5] D.K BS, A. Khamaru, & A. Kumar, "Design and Analysis of Twin-Core Side-Polished SPR PCF Sensor for Preliminary Malaria Detection", Plasmonics, pp. 1-12, 2025.
[6] A. Bhuyan, A. Khamaru, A. & Kumar, "Black Phosphorus-Based Slotted D-Shaped PCF SPR Sensor for Cancer Detection", Plasmonics, pp. 1-13, 2024.
[7] ME Dávila, L Xian, S Cahangirov, A Rubio, G Le Lay, "Germanene: a novel two-dimensional germanium allotrope akin to graphene and silicene", New J Phys vol. 16 no.6, p. 095002, 2014.
[8] K Tong et al, "Study on increasing measurement range and enhancing sensitivity of PCF surface-plasmon-resonance biosensor using black phosphorus", J Russ Laser Res vol. 42 pp. 283–291, 2021.
[9] S. Singh, Y. K. Prajapati, "TiO2/gold-graphene hybrid solid core SPR based PCF RI sensor for sensitivity enhancement". Optik, 224, 165525, 2020.
[10] J. Singh, A. Khamaru, and A. Kumar, "Spiral shaped highly sensitive rectangular PCF-based cancer cells detector in terahertz regime", Physica Scripta, vol. 99, no. 11, p.115546, 2024.
[11] N. Singh, A. Khamaru, and A. Kumar, "Design and analysis of a rectangular core refractive index-based PCF sensor for bio-sensing application" Optical and Quantum Electronics, vol. 56, no. 7, p.1133, 2024.
[12] W. Li, Y. Chen, J. Xu, M. Jiang, & H. Zou, "A D-shaped SPR-based PCF sensor

with an extremely high-amplitude sensitivity for measuring the refractive index”, Micromachines, vol. 14, no.7, p. 1295, 2023.
[13] M. R. Islam, A. N. M. Iftekher, K. R. Hasan, M. J. Nayen, S. B. Islam, A. Hossain, & T. Tahsin, “Design and numerical analysis of a gold-coated photonic crystal fiber based refractive index sensor”, Optical and Quantum Electronics, vol. 53, pp. 1-18, 2022.
[14] A. D. Dillon, M. J. Ghidiu, A. L. Krick, J. Griggs, S. J. May, Y. Gogotsi, ... & A. T. Fafarman, “Highly conductive optical quality solution- processed films of 2D titanium carbide”, Advanced Functional Materials, vol. 26, no. 23, pp. 4162-4168, 2016.
[12] J. Divya, S. Selvendran, S. Itapu, & V. Borra, “A Novel Dual-Channel SPR-based PCF Biosensor for Simultaneous Tuberculosis and Urinary Tract Infection Diagnosis towards SDG3”, IEEE Access, 2024.
[13] A Gupta, T. Singh, R. K. Singh & A. Tiwari, “Numerical Analysis of Coronavirus Detection Using Photonic Crystal Fibre–Based SPR Sensor”, Plasmonics, vol. 18 , no. 2, pp. 577-585, 2023.
[14] V. S. Chaudhary, D. Kumar & S. Kumar, “Au-TiO 2 coated photonic crystal fiber based SPR refractometric sensor for detection of cancerous cells”, IEEE transactions on nanobioscience, vol. 22 no. 3, pp. 562-569, 2022.
[15] Poli, Federica, Annamaria Cucinotta, and Stefano Selleri. Photonic crystal fibers: properties and applications. Vol. 102. Springer Science & Business Media, 2007.
[16] Knight, C Jonathan, “Photonic crystal fibres." nature vol. 424, no. 6950 pp. 847-851, 2003.
[17] Bjarklev, Anders, and Chinlon Lin, “Applications of photonic crystal fibers in optical communications-what is in the future?”, In 2005 IEEE LEOS Annual Meeting Conference Proceedings, pp. 812-813. IEEE, 2005.
[18] P. Hansen, Theis , Jes Broeng, Stig EB Libori, Erik Knudsen, Anders Bjarklev, Jacob Riis Jensen, and Harald Simonsen. "Highly birefringent index-guiding photonic crystal fibers." IEEE Photonics Technology Letters 13, no. 6 (2001): 588-590.
[19] J.C Knight, T. A. Birks, P. St J. Russell, and J. P. De Sandro. "Properties of photonic crystal fiber and the effective index model." JOSA A 15, no. 3, pp. 748-752, 1998.
[20] J.M. Senior, “Optical Fiber Communications Principles and Practice Third Edition Optical Fiber Communications Optical Fiber Communications Principles and Practice”, 2009.
[21] F. Benabid and P. J. Roberts. "Linear and nonlinear optical properties of hollow core photonic crystal fiber." Journal of Modern Optics 58, no. 2, pp. 87-124, 2011.

[22] Gérôme, Frédéric, Raphaël Jamier, Jean-Louis Auguste, Georges Humbert, and JeanMarc Blondy. "Simplified hollow-core photonic crystal fiber." Optics letters vol. 35, no. 8, pp. 1157-1159, 2005.
[23] Dragic, D Peter, M. Cavillon, and J. J. A. P. R. Ballato. "Materials for optical fiber lasers: A review." Applied Physics Reviews vol. 5, no. 4, 2018.
[24] Nizar, S. Mohamed, S. Rafi Ahamed, E. Priyanka, R. Jayasri, and B. Kesavaraman. "Comparison of different photonic crystal fiber structure: a review." In Journal of Physics: Conference Series, vol. 1717, no. 1, p. 012048. IOP Publishing, 2021.
[25] Roth, M. Martin, Hans-Gerd Löhmannsröben, Andreas Kelz, and Michael Kumke. "innoFSPEC: fiber optical spectroscopy and sensing." In Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation, vol. 7018, pp. 1643- 1650. SPIE, 2008.
[26]. Naghizade, Saleh, and Hamed Saghaei. "A novel design of all-optical 4 to 2 encoder with multiple defects in silica-based photonic crystal fiber." Optik 222 pp.165419, 2022.
[27] V. S. Chaudhary, D. Kumar & S. Kumar, "Au-TiO 2 coated photonic crystal fiber based SPR refractometric sensor for detection of cancerous cells", IEEE transactions on nanobioscience, vol. 22 no. 3, pp. 562-569, 2022.
[28] X. Yu, D. Yong, Y. Zhang, "Photonic Crystal Fiber-Based Biosensors. In: Ho, AP., Kim, D., Somekh, M. (eds) Handbook of Photonics for Biomedical Engineering. Springer, Dordrecht, 2022.
[29] W. Hou, & S.B. Cronin, "A review of surface plasmon resonance-enhanced photocatalysis. Advanced Functional Materials, vol. 23 no.13, pp. 1612-1619, 2013.
[30] R. B. Schasfoort, (Ed.), "Handbook of surface plasmon resonance", Royal Society of Chemistry, 2017.
[31] H. R. Gwon, & S.H. Lee, "Spectral and angular responses of surface plasmon resonance based on the Kretschmann prism configuration", Materials transactions, vol. 51 no.6, pp.1150-1155, 2010.
[32] J. Homola, I. Koudela & S.S Yee, "Surface plasmon resonance sensors based on diffraction gratings and prism couplers: sensitivity comparison. Sensors and Actuators B: Chemical, vol. 54 no. 1-2, pp. 16-24, 1999.
[33] T. Haque, H.K. Rouf, "A performance improved Kretschmann configuration based surface plasmon resonance (SPR) sensor", In 2019 1st International Conference on Advances in Science, Engineering and Robotics Technology (ICASERT) (pp. 1-4). IEEE, 2019.

[34] R. Araguillin, A. Méndez, J. González & C. Costa-Vera, "Comparative evaluation of wavelength-scanning Otto and Kretschmann configurations of SPR biosensors for low analyte concentration measurement", In Journal of Physics: Conference Series vol. 2796, no. 1, p. 012009). IOP Publishing, 2024.
[35] L. Li, Y. Liang, J. Guang, W. Cui, X. Zhang, J.F. Masson, & W. Peng, "Dual Kretschmann and Otto configuration fiber surface plasmon resonance biosensor", Optics express, vol. 25 no. 22, pp. 26950-26957, 2017.
[36] D.M. Hernández, J.S. Velazquez-Gonzalez, D. Luna-Moreno, M. Torres-Cisneros, & I. Hernandez-Romano, Prism-based surface plasmon resonance for dual-parameter sensing. IEEE Sensors Journal, vol. 18 no. 10, pp. 4030-4037, 2018.
[37] P. Singh, 2, "SPR biosensors: historical perspectives and current challenges", Sensors and actuators B: Chemical, vol. 229, pp. 110-130, 2016.
[38] C. Caucheteur, T. Guo, & J. Albert, "Review of plasmonic fiber optic biochemical sensors: improving the limit of detection", Analytical and bioanalytical chemistry, vol. 407, pp. 3883-3897, 2015.
[39] Z. Zhang, Z.Yin & S. Li, "A SPR sensor with wide RI measuring range and narrow FWHM based on PCF-silver film structure" , Journal of Lightwave Technology, 2024.
[40] G. Luo, X. Zhang X.S. Zhu & Y.W.Shi, "Experimental study of the coppercoated hollow fiber surface plasmon resonance sensor", Optics Communications, vol. 520, p. 128481, 2022.
[41] Z. Zhang, T. Shen, H. Wu, Y. Feng & X. Wang, "A temperature sensor based on D-shape photonic crystal fiber coated with Au–TiO2 and Ag– TiO2", Optical and Quantum Electronics, vol. 53, pp. 1-11, 2021.
[42] Y. Zhang, J. Xue, W. Liu, Y. Zhang, S. Li, Z. Liu ... & L. Yuan, "Cascaded Dual-Channel Fiber SPR Sensor Based on Ge2Sb2Te5", IEEE Sensors Journal, vol. 22, no. 5, pp. 4083-4089, 2022.
[43] V. Kumar, S. K. Raghuwanshi & S. Kumar, "Highly sensitive Ag/BaTiO3/MoS2 nano composite layer based SPR sensor for detection of blood and cervical cancer", Results in Optics, vol. 14, pp. 100597, 2024.
[44] Y. Singh, M. K. Paswan & S. K. Raghuwanshi ,"Sensitivity enhancement of SPR sensor with the black phosphorus and graphene with bi-layer of gold for chemical sensing", Plasmonics, vol. 16, pp. 1781-1790, 2021.
[45] M. S. Bhargava Reddy, S. Kailasa, B. C. Marupalli, K.K Sadasivuni & S. Aich, "A family of 2D-MXenes: synthesis, properties, and gas sensing applications", ACS sensors,

vol. 7, no. 8, pp. 2132-2163, 2022.
[46] E. C. Britto, B. Krishnamoorthi, R. Rajasekar & S. M. Nizar, "Photonic Crystal–Based Nanoscale Multipurpose Biosensor for Detection of Brain Tumours, HIV, and Anaemia with High Sensitivity", Plasmonics, pp. 1-17, 2024.
[47] D. V. Parums, "Forty Years of Waiting for Prevention and Cure of HIV Infection–Ongoing Challenges and Hopes for Vaccine Development and Overcoming Antiretroviral Drug Resistance", Medical Science Monitor: International Medical Journal of Experimental and Clinical Research, vol. 30, e944600-1, 2024.
[48] R. T. Gandhi, R. Bedimo, J. F. Hoy, R. J. Landovitz, D. M. Smith, E. F. Eaton, & M. S. Saag, "Antiretroviral drugs for treatment and prevention of HIV infection in adults: 2022 recommendations of the International Antiviral Society",USA panel. Jama, vol. 329 no. 1, pp. 63-84, 2023.
[49] A. Tavakoli, M. H. Karbalaie Niya, M. Keshavarz, H. Ghaffari, A. Asoodeh, S. H. Monavari, & H. Keyvani, "Current diagnostic methods for HIV", Future Virology, vol. 12, no. 3, pp. 141-155, 2017.
[50] B. H. Kumar, A. M. Vaibhav, & P. C. Srikanth, "Si/SiO2 based nano-cavity biosensor for detection of anemia, HIV and cholesterol using refractive index of blood sample", Indian J Sci Technol, vol. 15, no. 18, pp. 899- 907, 2022.
[51] J. F. Tisdale, S. L. Thein, & W. A. Eaton, "Treating sickle cell anemia", Science, vol. 367, no. 6483, pp. 1198-1199, 2020.

APPENDIX I

PLAGIARISM REPORT

PREETHI

PK Thesis final.pdf

Delhi Technological University

Document Details

Submission ID
trn:oid:::27535:99439765

Submission Date
Jun 5, 2025, 10:57 AM GMT+5:30

Download Date
Jun 5, 2025, 10:59 AM GMT+5:30

File Name
PK Thesis final.pdf

File Size
1.9 MB

52 Pages

11,319 Words

63,181 Characters

turnitin Page 1 of 56 - Cover Page Submission ID trn:oid:::27535:99439765

5% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

Filtered from the Report

- Bibliography
- Quoted Text
- Cited Text
- Small Matches (less than 12 words)

Exclusions

- 1 Excluded Source

Match Groups

- **26** Not Cited or Quoted 5%
  Matches with neither in-text citation nor quotation marks
- **0** Missing Quotations 0%
  Matches that are still very similar to source material
- **0** Missing Citation 0%
  Matches that have quotation marks, but no in-text citation
- **0** Cited and Quoted 0%
  Matches with in-text citation present, but no quotation marks

Top Sources

4%	Internet sources
2%	Publications
3%	Submitted works (Student Papers)

APPENDIX II

RESEARCH PUBLICATION

Optical and Quantum Electronics (2025) 57:270
https://doi.org/10.1007/s11082-025-08123-1

MXene coated concave shaped microchannel PCF SPR biosensor for the detection of HIV and sickle cell anaemia

Preethi Krishnan[1] · Akash Khamaru[1] · Ajeet Kumar[1]

Received: 11 December 2024 / Accepted: 19 February 2025

Abstract
The paper presents the analysis and discussions on a Surface Plasmon resonance (SPR) based Photonic Crystal Fiber (PCF) Refractive index (RI) Biosensor, designed specifically to detect two of the most widespread diseases—HIV-caused AIDS and Sickle cell anaemia. The detection is purely dependent on the RI of the affected cells (1.42 for HIV and 1.38 for Sickle cell anaemia), compared to 1.35 for normal cells. The proposed RI biosensor has concave-shaped microchannels on either side of the PCF acting as a channel, where the plasmonic material interacts with the bio-analytes of HIV-infected and sickle cells. Additionally, a layer of MXene, an emerging 2D plasmonic enhancer is coated on the microchannels, to enhance the sensor performance in terms of sensitivity and confinement loss. Moreover, the optimized structure achieved wavelength sensitivities of 10,571.43 nm/RIU and 3500 nm/RIU for the Gold PCF sensor, and 14,142.86 nm/RIU and 4000 nm/RIU for MXene-Gold PCF sensor for HIV-infected cell and Sickle cell anaemia, respectively. Hence, the proposed SPR biosensor using MXene has the potential for the early detection of HIV and Sickle cell anaemia.

Keywords MXene-coated · Sickle Cell Anaemia · HIV · Concave-Shaped Microchannel · Surface Plasmon Resonance · Confinement Loss

1 Introduction

Surface plasmon resonance (SPR) is an extensively preferred optical technique employed in photonic crystal fibers (PCF) which is an evolved form of optical fiber consisting of periodic arrangement of micro structured air holes for enhanced light confinement (Elabdein et al. 2024). SPR technique entails the collective excitation of surface plasmons which

✉ Ajeet Kumar
ajeetdph@dtu.ac.in

Preethi Krishnan
preethikrishnan_23mscphy68@dtu.ac.in

Akash Khamaru
akashkhamaru_23phdap02@dtu.ac.in

[1] Advanced Photonics Simulation Research Laboratory, Department of Applied Physics, Delhi Technological University, Bawana Road, Delhi 110042, India

Published online: 20 April 2025 Springer

APPENDIX III

CONFERENCE CERTIFICATE


PHOTONICS-2024
12 - 15 December
16th International Conference on
FIBER OPTICS AND PHOTONICS

Certificate of Participation

This is to certify that Prof./ Dr./ Mr./ Miss Ms. Preethi Krishnan
from Delhi Technological University
attended/ presented Paper in the
16th International Conference on Fiber Optics and Photonics
December 12 - 15, 2024, Kalidas Auditorium, IIT Kharagpur, India
Organized by
INDIAN INSTITUTE OF TECHNOLOGY KHARAGPUR

Organizing Secretary | Co-Convenor and TPC Chair | Convener

APPENDIX IV

PROOF OF SCIE INDEXING

Clarivate   Products

Master Journal List   Search Journals   Match Manuscript   Downloads   Help C

The power of the Web of Science™ on your mobile device, wherever inspiration strikes.   Dismiss   Learn More

Already have a manuscript?

Use our Manuscript Matcher to find the best relevant journals!

Find a Match

Filters   Clear All

Web of Science Coverage

Open Access

Category

Country / Region

Language

Frequency

Journal Citation Reports

Refine Your Search Results

optical and quantum electronics   Search

Sort By: Relevancy

Search Results

Found 940 results (Page 1)   Share These Results

Exact Match Found

OPTICAL AND QUANTUM ELECTRONICS

Publisher: **SPRINGER , VAN GODEWIJCKSTRAAT 30, DORDRECHT, NETHERLANDS, 3311 GZ**

ISSN / eISSN: **0306-8919 / 1572-817X**

Web of Science Core Collection: **Science Citation Index Expanded**

Additional *Web of Science* Indexes: **Current Contents Electronics & Telecommunications Collection | Current Contents Engineering, Computing & Technology | Essential Science Indicators**

Share This Journal   View profile page

Other Possible Matches

https://mjl.clarivate.com/search-results   1/5