DESIGN AND SIMULATION OF SPR BASED PCF SENSORS FOR PRELIMINARY MALARIA DETECTON AND RI SENSING

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

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CANDIDATE DECLARATION

I, **Devi Kangan B S**, hereby certify that the work which is being presented in the thesis entitled "**Design and simulation of SPR based PCF sensors for preliminary malaria detection and RI sensing**" 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-index journal 'Plasmonics' and some part of the work is presented in International Conference "PHOTONICS 2024" as poster presentation with the following details:

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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 the students is correct.

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ABSTRACT

This research presents the design and numerical simulation of two ultra-sensitive surface plasmon resonance (SPR) sensors based on photonic crystal fiber (PCF) for early disease diagnosis and high-performance refractive index (RI) sensing. The first design suggests a double-side polished twin-core PCF SPR sensor optimized for the detection of malaria at early stages. By employing a gold-coated hourglass-shaped configuration, the sensor achieves significant core mode-surface plasmon mode coupling, resulting in high wavelength sensitivities of 26,428.57 nm/RIU, 16,052.6 nm/RIU, and 12,586.2 nm/RIU for ring, trophozoite, and schizont stages of infected red blood cells, respectively. High figures of merit (FOM) values also attest its application in biomedical diagnostics.

The second sensor design examines a side-polished PCF structure coated with a bilayer of 40 nm gold and 12 nm TiO_2, leveraging the plasmonic enhancement properties of the 2D material TiO_2. The structure boasts an impressive improvement in sensitivity, with peak wavelength sensitivity ranging from 4000 nm/RIU for the plain gold sensor to 27,000 nm/RIU for the TiO_2–gold coated structure. These two sensors together demonstrate the ability of SPR-PCF platforms to facilitate highly sensitive, miniaturized, and selective detection devices beneficial in applications for malaria diagnostics, RI sensing, and other biomedical and environmental monitoring aims.

LIST OF PUBLICATIONS

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LIST OF ABBREVIATIONS

PCF: Photonic Crystal Fiber

SPR: Surface Plasmon Resonance

SPP: Surface Plasmon Polaritons

FEM: Finite Element Method

TIR: Total Internal Reflection

QBC: Quantitative Buffy Coat

RDT: Rapid Diagnostic Test

PCR: Polymerase Chain Reaction

IFA: Indirect Fluorescent Antibody

LAMP: Loop-mediated Isothermal Amplification

FCM: Flow Cytometry

ACC: Automated blood Cell Counter

Chapter 1

INTRODUCTION

1.1. Background

Photonic crystal fiber (PCF) is constituted by number of air holes drilled in the cross-section which act as a cladding and offers some distinct features other than conventional fiber. Its unique and flexible structural design enables various applications in telecommunications, sensing, and nonlinear optics. The PCF based sensors have been extensively used for chemical and biosensing applications due to advancements in manufacturing and sensing technologies, particularly for detecting refractive index (RI) changes. Likewise, sensors utilizing surface plasmon resonance (SPR) have garnered increased attention owing to their remarkable capabilities, such as real-time monitoring, label-free detection, and enhanced sensitivity [1]. In SPR phenomenon, when the angle or wavelength of the incident light changes, it excites the surface electrons leading to the coherent oscillations of the electrons and generate surface plasmon polaritons (SPPs), which will resonate with the incident EM wave. The oscillation of electrons facilitates the energy transfer from EM wave to SPPs, which in turn generates surface plasmon waves (SPWs). A change in the surrounding medium affects the RI, which in turn influence the SPWs, giving maximized sensitivity to such variations. SPR has applications in various fields like medical diagnostics, environmental monitoring, food quality control and pharmaceutical development. Traditional SPR based sensors used prism-based designs, but it was extremely bulky and inappropriate for remote sensing applications. To miniaturize, provide design flexibility, and improve sensitivity, SPR has been integrated with PCFs. This integration takes advantage of both the technologies' strengths, broadening their applications. With this integration, it is possible to construct miniaturized, portable, and highly sensitive sensors for a variety of applications, such as those in harsh environments [2]. In Surface Plasmon Resonance (SPR)-based Photonic Crystal Fiber (PCF) sensors, gold and titanium dioxide (TiO_2) are used as complementary plasmonic materials to improve performance. Gold is universally adopted because of its superior plasmonic properties, chemical stability, and strong surface plasmon resonance, which qualify it for detecting minute refractive index changes in sensing purposes. TiO_2, which is a high-refractive index dielectric, completes gold by increasing the electromagnetic field confinement and sensitivity of the SPR response when utilized as a spacer or in multilayer structures. Gold combined with TiO_2 offers tunable plasmonic characteristics, enhanced sensing discrimination, and wider operating versatility, rendering it a promising strategy for advanced biosensing and chemical analysis [3]. SPR-based PCF sensors are novel devices for disease detection such as malaria through exploitation of their high sensitivity, compact construction, and real-time monitoring features. Malaria, a potentially life-threatening infection caused by Plasmodium parasites and spread by the bites of infected Anopheles mosquitoes, is still a major global health problem. Early and accurate detection of malaria is crucial for effective treatment and control, particularly in endemic regions [4]. The Refractive index is a critical parameter for detecting various diseases like malaria, as healthy and infected RBCs exhibit distinct RI's. Infected RBCs with malaria display a non-uniform RI, which varies across different stages of the infection - ring phase, trophozoite phase, and schizont phase having RI like 1.395, 1.383, 1.373 respectively. Normal RBC's have a RI of 1.402. When a sample of malaria-infected RBCs are introduced into the SPR PCF biosensor, a significant shift in resonance wavelength occurs due to the coupling between the SPP mode and the core mode. This shift enables the detection of various stages of malaria infection [5].

1.2. Aim of thesis

The main objective of this thesis is to design and analyze a high-performance PCF-based SPR sensor for biosensing purposes. The detailed objectives are:

- To design and simulate high-sensitivity SPR-based PCF sensors based on side-polished structures for biomedical refractive index detection.
- To optimize sensor performance by material engineering with plasmonic metals (Au) and nanomaterial coatings (TiO_2), and maximize structural parameters for peak sensitivity and figure of merit (FOM).

- To assess the viability of the suggested SPR PCF sensors for real-time, label-free, and early-stage malaria detection through refractive index difference between healthy and infected red blood cells.

Chapter 2

OPTICAL FIBER AND ITS TYPES

2.1. Introduction

In this era of information technology (IT), optical fiber plays an important role in communications, sensing and various other fields. An optical fiber is a cylindrical dielectric waveguide that facilitates the transmission of light over long distances, enabling the transfer of information through the principle of total internal reflection (TIR). In this mechanism, when light traveling within the core of the fiber reaches the interface between two dielectric media (typically the core and cladding), it is entirely reflected back into the core rather than being refracted into the cladding.

The following conditions must be satisfied for TIR:

- The light should be propagating from a medium of higher refractive index (lower optical wave speed) to a medium of lower refractive index (higher optical wave speed), such as from the fiber core to the cladding.
- The angle of incidence at the core-cladding boundary must exceed the critical angle (θ_c). This principle ensures that light remains confined within the core of the fiber, allowing for efficient and low-loss optical signal transmission.

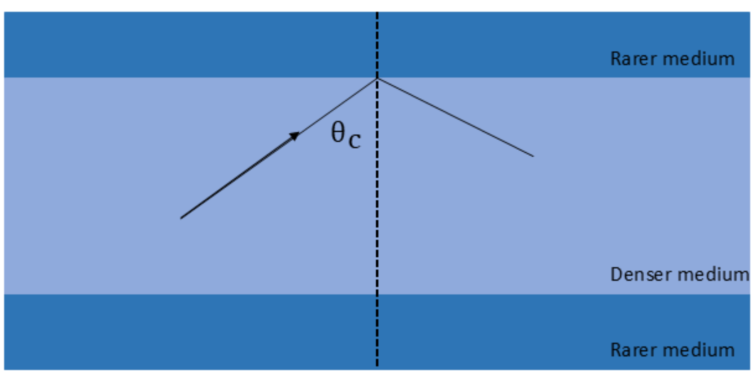


Fig. 2.1. Phenomena of TIR

2.2 Types of Optical fibers

On the basis of the structural design the optical fibers can be classified mainly as:

2.2.1 Single-mode fiber

They allow only the fundamental mode to propagate through them because the core diameter of such fiber is decreased to a certain limit. These fibers have the core diameter of few wavelengths as compared to the wavelength of light propagating into the fiber. These fibers do not exhibit modal dispersion hence are more compatible for long range communications.

2.2.2 Multi-mode fiber

They allow multiple modes of light to propagate through them, so called as multimode fibers. The diameter of core in multimode fibers is larger than wavelength of light propagating through them. The number of modes that can propagate through them is directly proportional to the diameter of core i.e. with the increase in diameter of core the number of propagating modes also increases and vice versa. The multi-mode fibers can be classified into two categories as follows

2.2.2.1 Step index fiber

The optical fibers in which the refractive index profile of core and cladding regions are constant are known as step index fibers. The refractive index of core region is higher than that of cladding region. Thus, at the interface of core and cladding regions, there is sharp and sudden decrease of refractive index. These fibers can be fabricated using Vapour phase deposition method [6].

Due to difficulties in dispersion engineering and large effective mode areas of step index fibers, they are not much used for supercontinuum generation. The schematic diagram of refractive index profile of step index fiber is shown in figure 2.2 (a)

2.2.2.2 Graded index fiber

The optical fibers in which the refractive index profile gradually decreases as we move from core region to cladding region are known as graded index fibers. The gradual decrease in the refractive index of graded index fibers helps in achieving low modal dispersion and hence graded index fibers are used in long haul communications. The refractive index profile for the graded index fibers is parabolic as shown in the fig 2.2 (b).

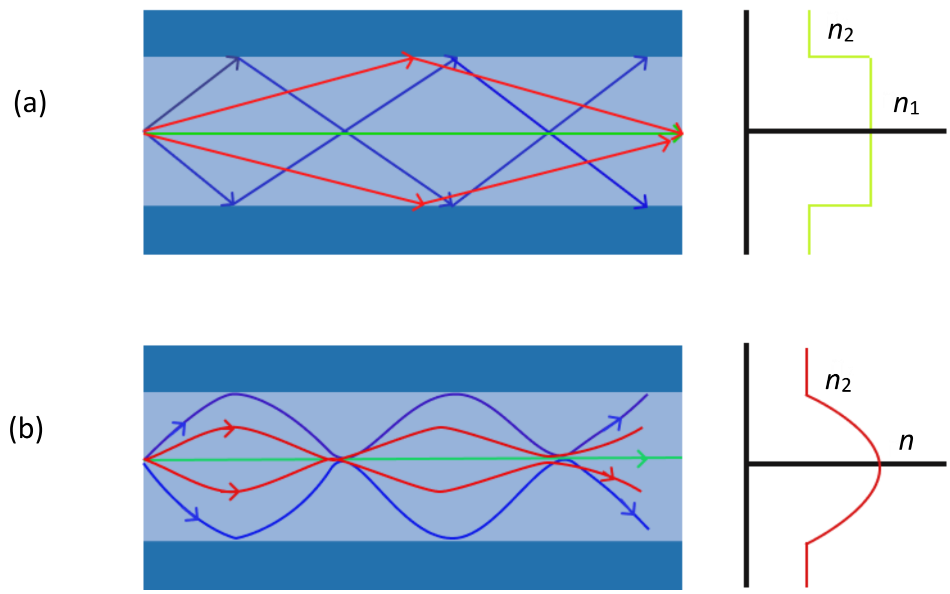


Fig. 2.2. Refractive index (RI) profile of (a) step index and (b) graded index fibers

2.3 Specialty fibers: Photonic crystal fibers

Photonic crystal fibers (PCF) are holey fibers which uses photonic crystals for the cladding and core. The core region is high index region and cladding consists of air holes arranged in a certain manner which reduces the refractive index of cladding region. Photonic crystal fibers are more efficient than conventional fibers as the refractive index of the core and cladding region can be changed easily either by changing the arrangement or shape of air holes in the cladding region or by altering size of air holes in the cladding region. Losses in photonic crystal fibers are also low as compared to conventional fibers. PCFs can be mainly classified in two categories.

a) Index guided PCF

In index guided PCF modes of light propagate core in the same way as in conventional fibers i.e. by the phenomena of total internal reflection. The core of the fiber is made up of high refractive index material and cladding consist of air holes with the same dielectric material as that of core. As the cladding region now has air holes in it, due to this the effective refractive index of the cladding region decreases, hence the leakage of light energy to the cladding region is minimized. The structure of index guiding PCF is shown in fig.2.3 (a)

b) Band gap guided PCF

In bandgap guided PCF, the core is made hollow through which the modes of light can propagate utilizing the photonic band gap effect. This effect arises from the periodic structure of air holes in the cladding region and is analogous to the formation of band gaps in solid state physics in the presence of periodic potential. The light in the core region is guided as cladding prevents the propagation of some wavelengths and effectively reflects those in the core region. The core of the fiber can be hollow i.e. air filled or can be filled with liquid or gases resulting in the increase in non-linearity which can help in various non-linear applications [7]. The fabrication of the index guided PCF is comparatively difficult but fiber can be realized by using stack and draw technique [8]. The structure of bandgap guided PCF is shown in fig.2.3(b).

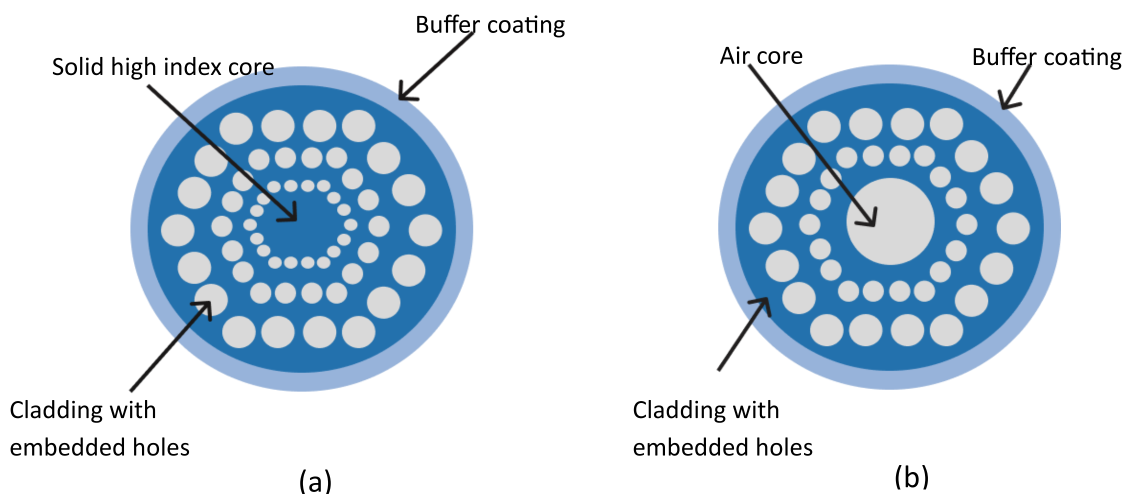


Fig. 2.3. Structure of an index guided PCF (a) and band gap guided PCF (b)

Chapter 3

SURFACE PLASMON RESONANCE

3.1. Introduction

Surface Plasmon Resonance (SPR) has emerged as one of the most powerful techniques for highly sensitive detection of chemical and biological species. Traditionally implemented using prism-based platforms, SPR enables the detection of changes in refractive index at a metal-dielectric interface [9]. However, the conventional configurations are often bulky and unsuitable for integration with compact or fiber-based sensing platforms [10]. This is widely used in the field of sensing application like biosensing [11], temperature sensing [12], humidity [13], atmospheric contents, and various other applications also. SPR has lot more advantages than other sensing systems, they have high sensitivity, label free detection, real time monitoring, low volume sample consumption, quantitative evaluation, and determination of kinetic rate constants. Furthermore, SPR is easy to perform and can be a cost-effective solution [14].

Conventional SPR based sensors utilized prism-based designs, but it was very bulky and not suitable for distant sensing purposes. To achieve miniaturization, design flexibility, and enhanced sensitivity, SPR has been coupled with PCFs. This combination leverages the strengths of both technologies, expanding their applications. This integration allows the development of compact, portable, and highly sensitive sensors suitable for various applications, including those in challenging environments [15].

3.2. Principle of SPR

SPR is a phenomenon that occurs when polarized light hits a metal film like gold or silver at the interface of media with different refractive indices, SPR techniques excite and detect collective oscillations of free electrons called plasmons via the Kretschmann configuration.

In SPR phenomenon, when the angle or wavelength of the incident light changes, it excites the surface electrons leading to the coherent oscillations of the electrons and generate surface plasmon polaritons (SPPs), which will resonate with the incident EM wave. The oscillation of electrons facilitates the energy transfer from EM wave to SPPs, which in turn generates surface plasmon waves (SPWs) resulting the maximum absorption of light at that angle this creates a dark line in the reflected beam. A change in the surrounding medium affects the RI, which in turn influence the SPWs, giving maximized sensitivity to such variations. The whole process shown in the figure 3.1.

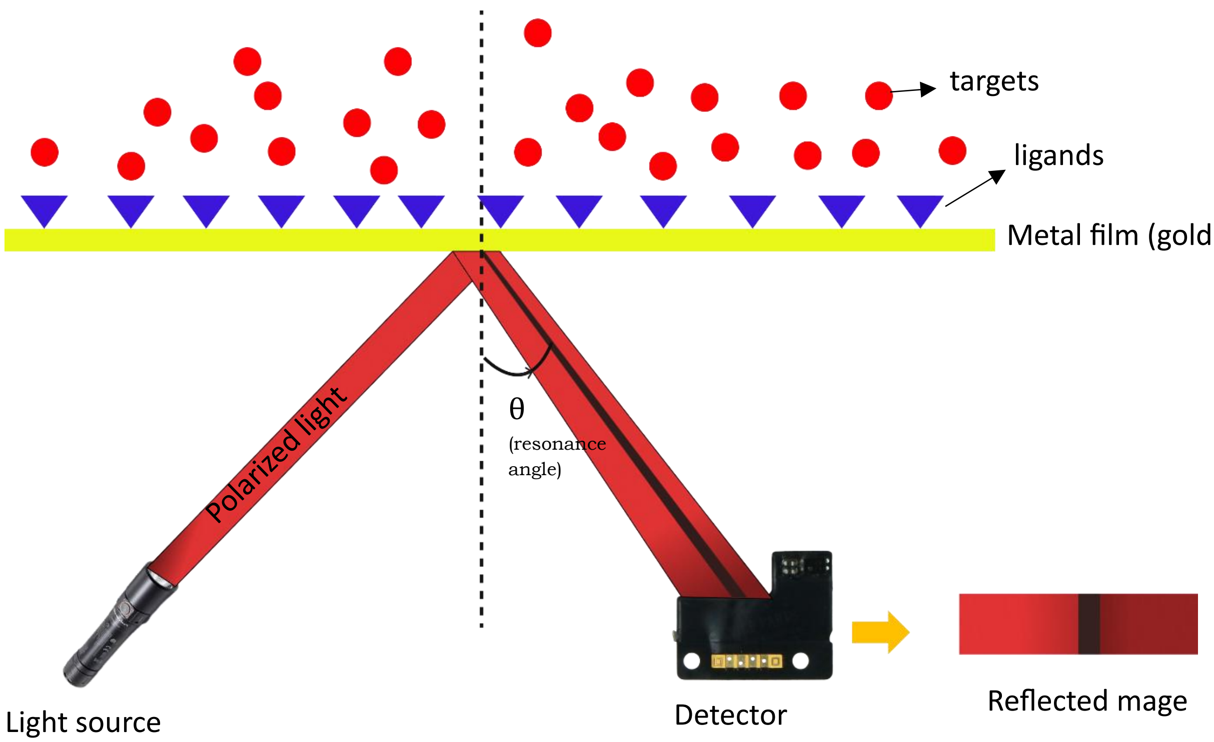


Fig. 3.1. surface plasmon resonance process

3.3. SPR-based PCF sensors

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. Its unique and flexible structural design enables various applications in telecommunications, sensing, and nonlinear optics. The PCF based sensors have been extensively used for chemical and biosensing applications due to advancements in manufacturing and sensing technologies, particularly for detecting refractive index (RI) changes. Likewise, sensors utilizing SPR have garnered increased attention owing to their remarkable capabilities, such as real-time monitoring, label-free detection, and enhanced sensitivity. The integration of SPR technology into the PCF sensors has maximized sensitivity by detecting even a small refractive index change in the surrounding analyte [16]. In SPR-PCF sensors, side-polishing, cladding removal, or hollow-core designs are used to bring the light close to the metal/analyte interface. This technique is mostly exploited in the biomedical field for the detection and early diagnosis of various diseases like Cancer, Malaria, Tuberculosis etc. The detection is purely reliant on the refractive index differences between the bio analytes of the normal and infected cells [17-20]

3.3.1. Principle of SPR-based PCF sensors

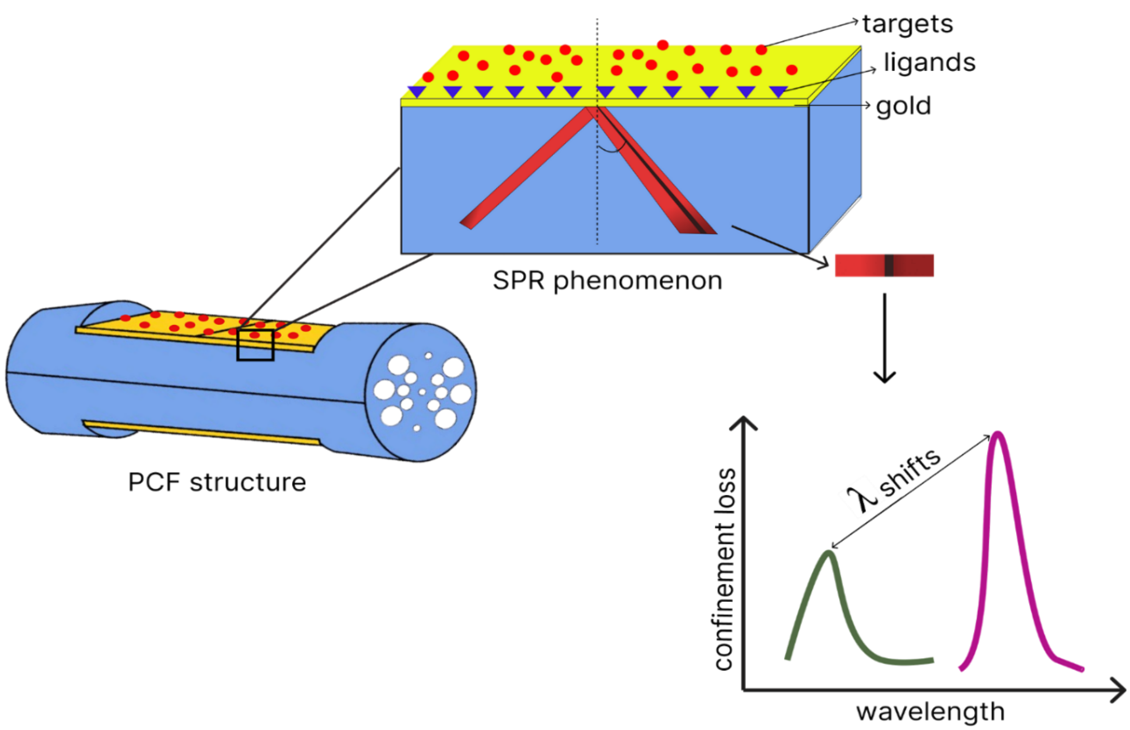


Fig. 3.2. Principle of SPR based PCF sensor

As shown in the figure 3.2, the plasmonic metal is coated on the polished or modified surface of PCF. Light is launched into the core of the PCF, and the guided light interacts with the plasmonic metal coated on the PCF surface. The resonance will occur due to the phase-matching condition of the core mode and the SPP mode. This causes a sharp confinement loss peak in transmitted light at a specific wavelength as shown in the figure. The resonance wavelength shifts when the refractive index of the surrounding medium (analyte) changes, which can be measured and correlated to detect chemical or biological substances.

Chapter 4

THEORY AND LITERATURE REVIEW

There are numerous deadly diseases in our society, posing significant challenges to public health and necessitating immediate detection for effective management and treatment. Early and accurate diagnosis is critical for controlling diseases like malaria, which continues to claim millions of lives globally, especially in resource-limited settings. Advanced sensing techniques play a vital role in providing rapid, reliable, and cost-effective diagnostic solutions [21]. The conventional method for diagnosing malaria typically involves clinical assessment based on patient symptoms. But this can cause misdiagnosis because these symptoms can be similar to other common diseases [22]. Another widely used method is the microscopic examination of stained peripheral blood smears using field's stains. However, this method can cause false positive detection due to the low parasite level and it needs skilled technicians and the process is time-consuming [23]. The quantitative buffy coat (QBC) method can detect low-concentrated parasites and detected through an epi-fluorescent microscope. Even though it is faster than conventional microscopes, it needs skilled technicians and specialized devices to operate [24]. Rapid diagnostic test (RDT) is a quick and convenient technique for disease detection, offering rapid results and easy handling. The method is especially useful in resource-limited settings, where timely diagnosis is pivotal for effective treatment and control of disease outbreaks. But RDTs do not differentiate between various Plasmodium species, which is crucial for making informed treatment decisions [25]. The serological method is another traditional method, which is straightforward and sensitive, though it requires significant time to obtain the results [26].

Recently, various efficient methods for malaria detection are emerging. The polymerase chain reaction (PCR)-based technique is a highly sensitive method capable of detecting low levels of parasites, including various Plasmodium species. The method is expensive as it requires specialized expertise and sophisticated equipment [27]. The indirect fluorescent antibody (IFA) test relies on the binding of fluorescently labeled antibodies to specific target antigens within a sample. However, this method requires specialized equipment and skilled technicians [28]. Loop-mediated isothermal amplification (LAMP) is a simple, quick, and cost-effective alternative to PCR for detecting malaria. The technique operates at a constant temperature, thus removing the necessity of thermal cycling and streamlining the overall procedure. However, the high sensitivity of LAMP can also increase the risk of contamination. The possibility of false detection is high without proper precautions [29]. Flow cytometry (FCM) can detect malaria parasites by analyzing labeled cells in a blood sample; however, it has a high initial installation cost and requires ongoing maintenance, with the potential to skip low-level parasites, which could lead to misdiagnosis [30]. The method automated blood cell counter (ACC) analyzes blood samples to provide complete blood counts and can indicate the presence of malaria by assessing red blood cell changes. The method requires regular calibration and maintenance [31]. Therefore, the present situation demands a faster and more efficient method for early-stage malaria detection. The latest and accurate optical techniques are key to produce high-advancing tools which can be available for diagnosis of blood diseases [32].

Photonic crystal fibers (PCF) based biosensor is one of these optical techniques, which plays an important role in biosensing. PCF is constituted by number of air holes drilled in the cross-section which act as a cladding and offers some distinct features other than conventional fiber. Its unique and flexible structural design enables various applications in telecommunications, sensing, and nonlinear optics. The PCF based sensors have been extensively used for chemical and biosensing applications due to advancements in manufacturing and sensing technologies, particularly for detecting refractive index (RI) changes [33]. Likewise, sensors utilizing surface plasmon resonance (SPR) have garnered increased attention owing to their remarkable capabilities, such as real-time monitoring, label-free detection, and enhanced sensitivity [34]. In SPR phenomenon, when the angle or wavelength of the incident light changes, it excites the surface electrons leading to the coherent oscillations of the electrons and generate surface plasmon polaritons (SPPs), which will resonate with the incident EM wave. The oscillation of electrons facilitates the energy transfer from EM wave to SPPs, which in turn generates surface plasmon waves (SPWs). A change in the surrounding medium affects the RI, which in turn influence the SPWs, giving maximized sensitivity to such variations. SPR has applications in various fields like medical diagnostics, environmental monitoring, food quality control and pharmaceutical development. Conventional SPR-based sensors utilized prism-based designs, but it was very bulky and not suitable for distant sensing purposes. To achieve miniaturization, design flexibility, and enhanced sensitivity, SPR has been coupled with PCFs. This combination leverages the strengths of both technologies, expanding their applications. This integration allows the development of compact, portable, and highly sensitive sensors suitable for various applications, including those in challenging environments [35,36].

One of the most commonly utilized materials for SPR-based sensors is gold owing to its superior plasmonic characteristics. It allows for the excitation of surface plasmons, or free electron oscillations at the dielectric-metal interface, to enable the accurate measurement of variations in the refractive index of the surrounding environment. Gold's resistance to oxidation and stability in its chemical state guarantee the long-lasting nature and dependability of the sensor, and its biocompatibility enables functionalization with biomolecules like antibodies or DNA for applications in biosensing. Moreover, the potential for tunable optical properties in gold by controlling the thickness or morphology of the thin film increases the sensitivity and selectivity of the sensor, positioning it as a central material for plasmonic sensing. Apart from gold, other plasmonic materials such as titanium dioxide (TiO_2) contribute to the improvement in the performance of SPR-based sensors. TiO_2, having a high refractive index, enhances the confinement of surface plasmon waves and hence sensitivity. It can also sustain localized surface plasmon resonance (LSPR) when alloyed with noble metals, enhancing the electromagnetic field around the sensing interface. In addition, TiO_2 is a dielectric material that optimizes light coupling and plasmonic resonance. Its photocatalytic properties and controlled optical property tuning are also contributory factors to its versatility, enabling it to enhance sensor stability and performance in various advanced sensing applications [3,5].

The RI is a critical parameter for detecting various diseases like malaria, as healthy and infected RBCs exhibit distinct RI's. Infected RBCs with malaria display a non-uniform RI, which varies across different stages of the infection — ring phase, trophozoite phase, and schizont phase having RIs like 1.395, 1.383, and 1.373 respectively. In contrast Normal healthy RBCs have an RI of 1.402. When a sample of malaria infected RBCs is introduced into the SPR PCF biosensor, a significant shift in resonance wavelength occurs due to the coupling between the SPP mode and the core mode. This shift enables the detection of various stages of malaria infection. And this shift is sensitive to the RI of analytes [4].

The past literatures shows that PCF SPR sensors are already been explored for various biosensing applications. Das et al. introduced SPR based PCF biosensor for malaria detection in which air holes arrangement resembles a barred spiral galaxy and has computed sensitivity for different stages like ring, schizont, and trophozoite phases of malaria-infected RBCs are 17,857.14 nm/RIU, 10,210.53 nm/RIU, 8758.62 nm/RIU respectively [4]. Chaudhary et al. introduced circular PCF based SPR sensor for malaria detection [5]. The design has two layers of air holes arranged in hexagonal lattice. The calculated wavelength sensitivity for ring, schizont and trophozoite phases of malaria infection are 13714.29 nm/RIU, 9789.47 nm/RIU, and 8068.97 nm/RIU, respectively in x polarized direction and 14285.71 nm/RIU, 10000 nm/RIU, and 8206.9 nm/RIU, respectively in y-polarized direction. In the year 2023, Kumar et al. has reported a circular PCF based SPR for malaria detection using the non-uniform RI characteristics of unhealthy RBCs. The authors used the machine learning approach for this study, and finally detected the wavelength sensitivity of ring phase, schizont phase and trophozoite phase like 12,142 nm/RIU, 9736 nm/RIU and 8241 nm/RIU respectively [6]. Shafkat et al. reported a simple PCF sensor for malaria detection. The air holes are arranged in double circular loops in PCF and RBC sample for detection is kept in the horizontal channel at the center of the fiber and the maximum spectral sensitivities observed were approximately 11,428.57 nm/RIU for the ring stage, 9473.68 nm/RIU for the trophozoite stage, and 9655.17 nm/RIU for the schizont stage of the parasite [7]. Apart from malaria sensing, various generalized RI sensors are also proposed. In the year of 2024, Khamaru et at. have reported a graded index SPR based D-shaped PCF RI sensor which has a teardrop shaped core which facilitates the coupling of core mode with metal layer and having highest wavelength sensitivity of 21,000 nm RIU^{-1} at wide analyte RI range [8]. Lv et al. have reported a dual core D shaped SPR based PCF sensor for RI detection in liquids, the resonance wavelength shift varies according to the RI of analyte and the authors have reported average wavelength sensitivity of 17,200 nm / RIU in the RI range between 1.40 and 1.44 [9].

However, achieving higher sensitivity and efficient light-SPP mode coupling remains a challenge in many SPR-based PCF designs. To address these challenges, this work presents two novel approaches: a dual side-polished, twin-core SPR-based PCF biosensor for malaria detection, and a side-polished SPR-based PCF sensor utilizing gold and TiO_2 as plasmonic materials. In the first design, the symmetrical dual-side-polished layout and triangular dual-core structure optimize plasmonic material placement and coupling efficiency, enhancing performance for early malaria detection. The second design incorporates TiO_2, a high-refractive-index material, over a gold layer to improve light plasmon coupling and achieve higher sensitivity. Both designs are compact, involve minimal air-hole configurations, and are rigorously investigated using finite element method-based simulations. These approaches demonstrate significant improvements in sensitivity and practicality, addressing the limitations of conventional designs and providing a robust platform for applications such as early malaria detection.

Chapter 5

MATHEMATICAL AND ANALYTICAL MODELING

5.1. COMSOL MULTIPHYSICS SOFTWARE

COMSOL Multiphysics is a multipurpose simulation software that allows users to calculate complicated engineering and physics issues by finite element analysis (FEA). It is a single environment that can simulate wide phenomena, such as structural mechanics, fluid flow, heat transfer, electromagnetics, acoustics, optics, and chemical reactions. Solving coupled sets of partial differential equations (PDEs), COMSOL supports multi-physics simulations where diverse physical effects couple together, providing high flexibility and accuracy. The software includes easy-to-use user interfaces for simple model setup as well as robust solvers to perform steady-state and transient analysis. COMSOL also allows users to customize using scripting and an Application Builder, enabling them to develop customized simulation tools that can be used for dedicated tasks. The tool is thus a must-have in aerospace, automotive, energy, electronics, as well as biomedical engineering industries, whereby designs are optimized and performance is enhanced across numerous engineering fields.

Fig. 5.1. COMSOL Multiphysics software

5.2. Mathematical modelling

Fused silica is the background material of the SPR PCF sensor, which has high transparency and low loss at NIR region. RI which is dependent upon wavelength is derived from Sellmeier's equations [10].

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

Where B_1=0.69616300, B_2 =0.407942600, B_3=0.897479400 C_1=4.6791482610^{-3}μm^2 C_2=1.35120631× 10^{-2}μm^2, C_3=97.934002μm^2

The Lorenz-Drude model gives the relative permittivity or dielectric constant of the plasmonic material gold, given in the Eq. (2)

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

The values of the parameters used in the above equation are ε_{∞}=5.9673, $\Delta\varepsilon$=1.09, Γ_L= 16.69, γ_d= 2.534, Ω_L=103.46, $\omega = {}^{2\pi c}/_{\lambda}$,where ε_{∞} is the permittivity at high frequency, Γ_L is the spectral width of Lorentz oscillator, $\Delta\varepsilon$ is weighted coefficient, ω is the optical angular frequency, γ_d is damping frequency and Ω_L represents oscillator strength.

To evaluate the performance of a PCF sensor the confinement loss of the core mode is a crucial parameter. The confinement loss, denoted as α_{loss}, can be calculated using the following equation: Eq. (3) [10].

$$\alpha_{Loss} = 8.686 \times \frac{2\pi}{\lambda} \times I_m\left(n_{eff}\right)\times 10^4\,\frac{dB}{cm} \qquad (3)$$

Where I_m (n_{eff}) is the imaginary part of the effective mode index.

In this work the wavelength sensitivity (WS) is explored, which represents the difference between two resonant wavelengths per unit change in refractive index (RI) difference. It can be determined by the following equation[10].

$$S_\lambda = \frac{\Delta\lambda_{peak}}{\Delta n_a} (nm/RIU) \quad (4)$$

Amplitude Sensitivity defines a different way of sensitivity investigation technique and the same is analysed by given equation 5 [10];

$$S_A(\lambda) = -\frac{1}{\alpha(\lambda, n_a)} \frac{\partial\alpha(\lambda, n_a)}{\partial n_a} \; [RIU^{-1}] \quad (5)$$

$\alpha(\lambda, n_a)$ denotes the confinement loss at working wavelength, $\partial\alpha(\lambda, n_a)$ is the measure of the loss gradient between two consecutive analytes at same working wavelength and ∂n_a defines the difference between the refractive indices of the analytes [10].

For accessing the detection capability of the bio-sensor we need figure-of-merit (FOM) which is calculated by FWHM (Full Width at Half Maximum) [10].

$$FOM = \frac{Wavelength\ sensitivity}{FWHM} \quad (6)$$

Chapter 6

EXPERIMENTAL SETUP

Figure 6.1 illustrates the proposed practical setup of the SPR PCF sensor. Using light source which is emitting spectrum of appropriate wavelength range optical light launched through single mode fiber SMF. The SPR PCF can be combined with this SMF using various splicing machine. The RBC sample are located in outside channel and they are pumped through the inlet to the analyte layer. Using a pump the inflow and outflow of the analyte is controlled. For analyzing new sample, the sensor probes should be rinsed with deionized water. When the RBC and the gold coated surface's ligand interacts the refractive index changes and this causes the resonance wavelength to shift. This shift can be monitored by Optical Spectrum Analyzer (OSA).

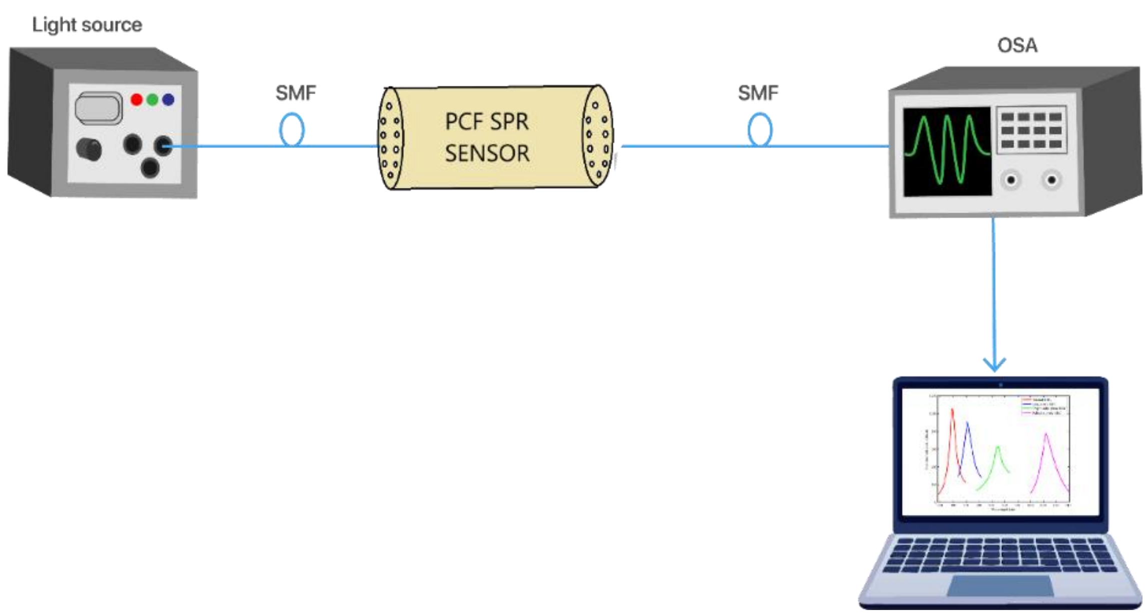


Fig.6.1. Proposed practical setup of the sensor

Chapter 7

DESIGN AND ANALYSIS OF TWIN CORE SIDE POLISHED SPR PCF SENSOR FOR PRILIMINARY MALARIA DETECTION[1]

This work presents a double-side polished twin-core photonic crystal fiber (PCF)-based surface plasmon resonance (SPR) sensor specifically designed for early-stage malaria detection. The innovative design features an "hourglass" air-hole arrangement and a gold-coated symmetrical surface to enhance light confinement and strong coupling with surface plasmon modes. By leveraging the distinct refractive indices of normal and malaria-infected red blood cells (RBCs) at various stages of infection, the sensor enables precise and sensitive detection. This work addresses the limitations of current diagnostic methods, offering a promising solution for early malaria diagnosis.

7.1. Structural and theoretical modelling

The three-dimensional (3D) and two-dimensional (2D) geometry of the dual-side polished, twin-core SPR PCF sensor shown in Fig.7.1 (a) and (b), (d) respectively. For the accurate simulation, physics-controlled mesh sequence is used, as displayed in Fig. 7.1 (c). Here, the analytical domain is subdivided into triangular mesh. The increased mesh density enhances the light transmission to the sensor, making mathematical calculations easier and more accurate. In the proposed sensor design, the air holes arrangement resembles the shape of an “hourglass”, consisting of three different diameters of air holes, in which two types of air holes are arranged in a circular ring structure and three air holes arranged longitudinally in center, having diameter d_1 (0.6μm).. The first and second ring of air holes have diameter d_2 (1μm) and d_3 (1.6μm) respectively. The spacing between adjacent air holes, referred to as the pitch of the structure, is consistently maintained as Λ (1.5μm). From both circular rings, two

[1] A part of the results presented in this chapter have been reported in a research publication
BS, D. K., Khamaru, A., & Kumar, A. (2025). Design and Analysis of Twin-Core Side-Polished SPR PCF Sensor for Preliminary Malaria Detection. *Plasmonics*, 1-12.

air holes are removed purposefully and two air holes of diameter similar to center one is placed symmetrically at 2Λ distance to create a passage for core light to interact with plasmonic material. The two symmetrical sides of the cladding is polished carefully to enhance the coupling. The two missing air holes from both the circular structure and the central air hole constitutes the dual core PCF structure. A nanolayer of gold which is an efficient plasmonic material having greater chemical stability, good corrosion resistance and good biocompatibility is coated above the polished surface with thickness t_g=40nm [35]. A layer of bio-analyte is deposited on the top of gold. Finally, a perfectly matched layer (PML) which act as a boundary which absorbs scattering light the sensor.

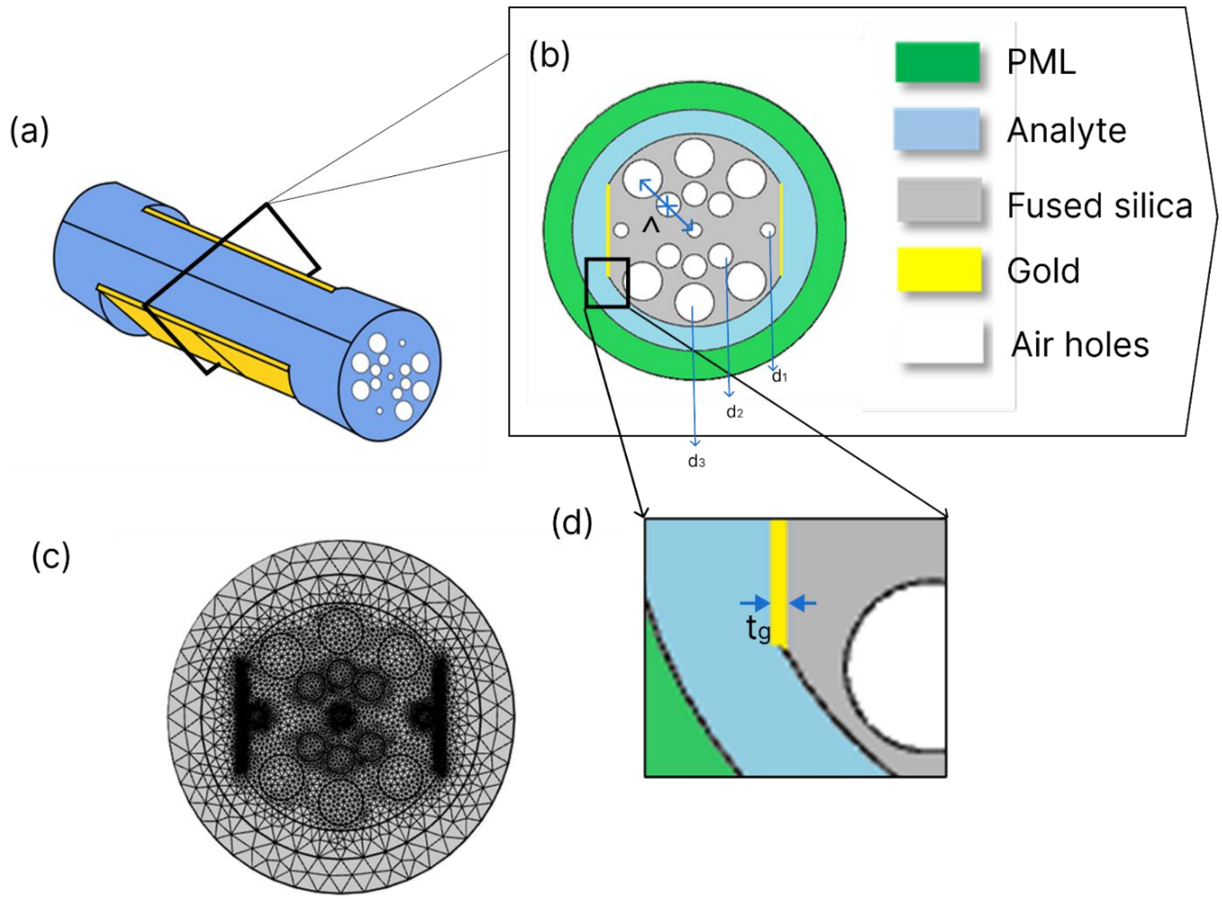


Fig.7.1. (a) 3D view of the sensor. **(b)** Cross-sectional view of the sensor. **(c)** Physics-controlled mesh view **(d)** zoomed view of PCF showing plasmonic material (gold)

RI which is dependent upon wavelength is derived from Sellmeier's equations which is mentioned in Equation 1. In this work gold is used as the plasmonic material. The Lorenz-Drude model gives the relative permittivity or dielectric constant of the plasmonic material gold, given in the Equation (2) To evaluate the performance of a PCF sensor the confinement loss of the core mode is a crucial parameter. The confinement loss, denoted as α_{loss}, can be calculated using the Equation (3). The wavelength sensitivity (WS), which represents the difference between two resonant wavelengths per unit change in refractive index (RI) difference. It can be determined by the Equation (4). Amplitude Sensitivity defines a different way of sensitivity investigation technique and the same is analysed by given Equation (5). For accessing the detection capability of the bio-sensor we need figure-of-merit (FOM) which is calculated by FWHM (Full Width at Half Maximum) given by the Equation (6).

For the detection of malaria, we introduce the infected RBC in the analyte layer by using selective filling method, The distinct RI of healthy and infected RBCs, as shown in the Table.7.1, which lead to a shift in the resonance wavelength. This shift is crucial for real-time and label-free detection of malaria.

Table.7. 1. Average refractive indices of normal and infected RBC at different stages of malaria parasites

RBC stages	Average RI	References
Normal RBCs	1.402	4,5
Ring phase RBCs	1.395	
Trophozoite phase RBCs	1.383	
Schizont phase RBCs	1.373	

7.2. Results and discussions

The effective mode index (n_{eff}) of the proposed PCF SPR is calculated by solving Maxwells equation by FEM. The effective mode index is a complex function which contains real part and imaginary part, real part signifies the guided modes and imaginary part describes the loss. Figure 7.2 depicts the dispersion characteristics of SPP and core mode combined with the loss curve of ring phase RBC. The green line indicates the n_{eff} of core mode, the red line indicates n_{eff} of the SPP mode, while the blue curve depicts the confinement loss. The n_{eff} of both SPP mode and the core mode decreases with increasing wavelength. They intersect at the resonance wavelength (λ_r = 875 nm), where the loss reaches its peak at 631.63 dB/cm. At this point, both the SPP mode and the core mode exhibit the same real component of the RI, indicating a coupling between them that facilitates maximum energy transfer from the core mode to the SPP mode. Fig.7.3 (a), (b), (c), represents the electric field distribution of this core mode, SPP mode and coupling (SPR) mode of the ring phase RBC respectively. In bio-analyte detection, the coupling mode is crucial because it allows the energy of the core mode to directly couple with SPP mode.

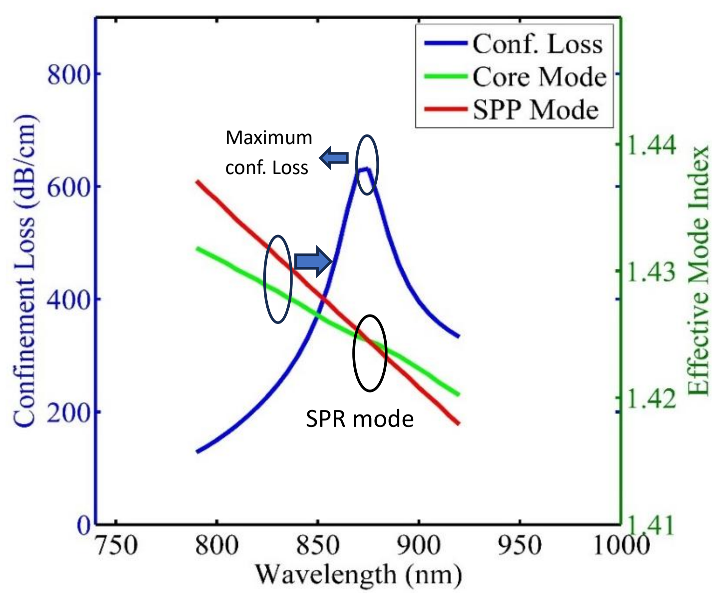


Fig.7.2. Dispersion characteristics of Ring phase RBC (RI: 1.395)

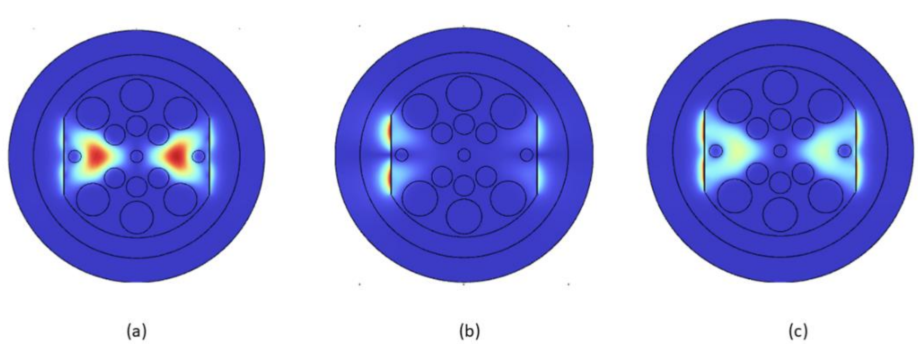
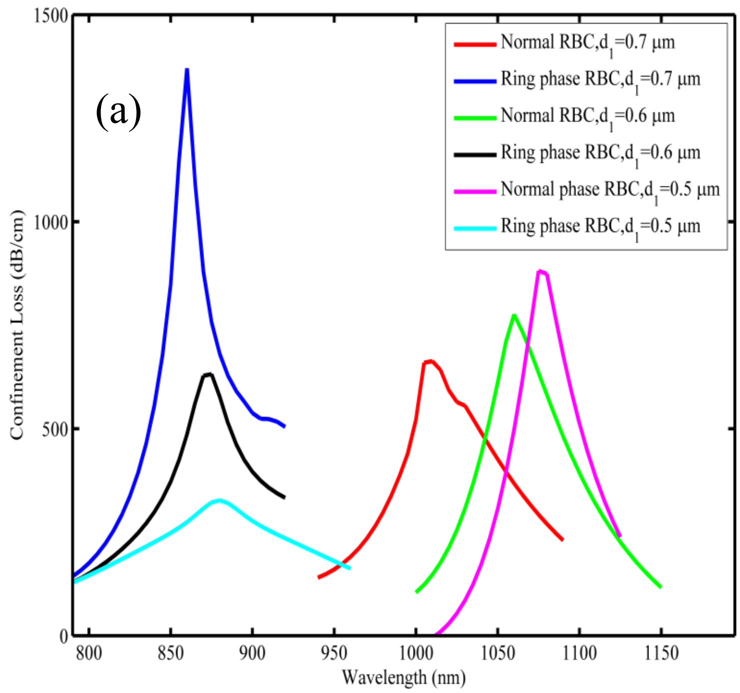
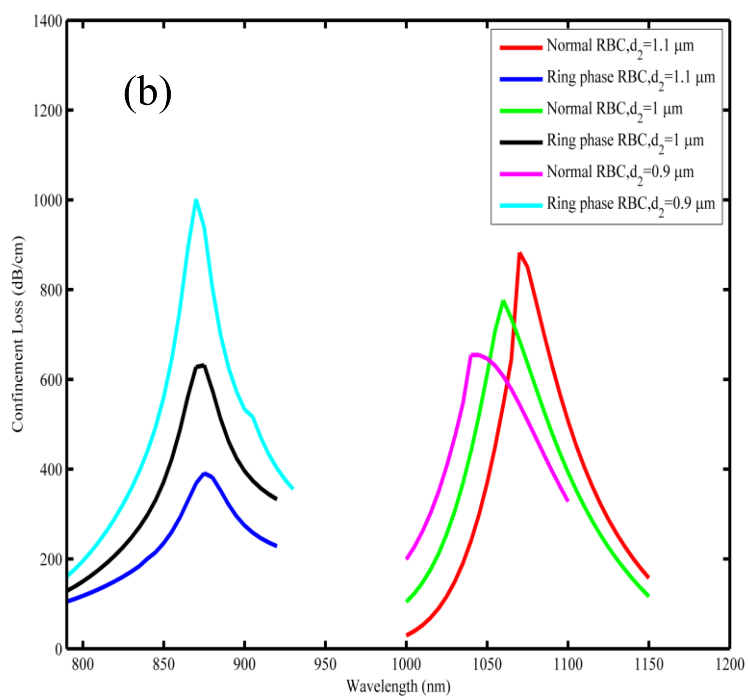


Fig.7.3. (a) Core mode (b) SPP mode (c) Coupling mode

The geometrical parameters influence the sensitivity of the sensors, so their optimization is necessary. The optimization is done for small circle(d_2), central circle(d_1), large circle(d_3) and the gold layer thickness(t_g). The loss characteristics obtained for the different optimization parameters is given below.





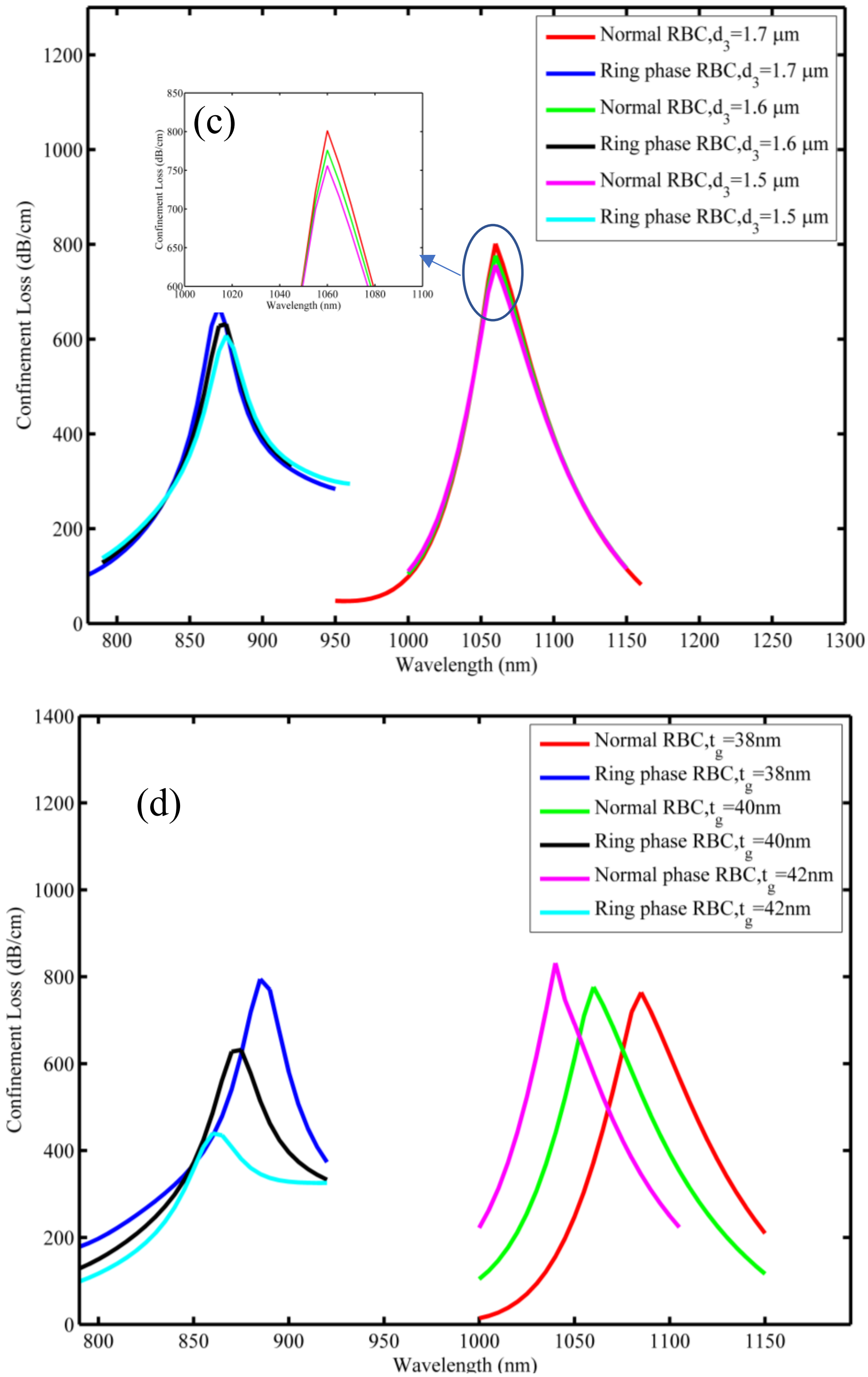


Fig.7.4. Confinement loss spectrum for varying (a). central air hole, (b) small air hole, (c)large air hole, (d) thickness of gold

Through the systematic investigation of the effects of structural parameters on the sensing performance and peak loss of the proposed sensor, the optimal parameters were identified. These carefully fine-tuned parameters, listed in Table 7.2, are associated with the proposed SPR PCF sensor for malaria detection. Table 3 summarizes the performance with these optimized parameters. Figure 7.5 represents the loss spectrum obtained by these optimized parameters for different RI of normal and infected RBCs. By examining the figure, it is clear that the normal RBCs peak loss is of 776.18 dB/cm at the resonance wavelength 1060nm. For the ring phase RBC, the resonance wavelength is 875nm and corresponding loss peak is 631.63 dB/cm, here the wavelength shift is about 185nm. For trophozoite phase the resonance wavelength is 755nm and correspond peak loss is 910.38 dB/cm, now the wavelength shift from the normal RBC is 305nm and for schizont phase the resonance wavelength and the peak loss is 690nm and 1052.5 dB/ cm respectively, corresponding wavelength shift with the ring phase is 365nm. The pronounced shift in the wavelength is the key parameter for the measurement of wavelength sensitivity. The wavelength sensitivity corresponding to ring phase, trophozoite phase and schizont phase are 26428.57 nm/RIU,16052.63 nm/RIU and 12586.21 nm/RIU respectively. Apart from wavelength sensitivity, our proposed sensor shows maximum amplitude sensitivity of -318.82 RIU^{-1} and the same is displayed in figure 7.6.

Table.7. 2. Optimized parameters of the sensor

Parameter	Optimized value
Larger diameter(d_3)	1.6μm
Smaller diameter(d_2)	1μm
Central diameter(d_1)	0.6μm
Gold thickness(t_g)	40nm

Table.7. 3. Performance Summary of the proposed sensor

Parameter	Peak loss (dB/cm)	Resonance wavelength (nm)	Wavelength sensitivity (nm/ RIU)	Amplitude Sensitivity (RIU^{-1})	Average Wavelength Sensitivity (nm/RIU)	Average Amplitude Sensitivity (RIU^{-1})	FOM (RIU^{-1})
Normal RBC	776.18	1060					
Ring phase RBC	631.63	875	26428.6	-318.82	18355.4	-172.96	334.53
Trophozoite RBC	910.38	755	16052.6	-122.52			321.05
Schizont RBC	1052.5	695	12586.2	-77.55			381.4

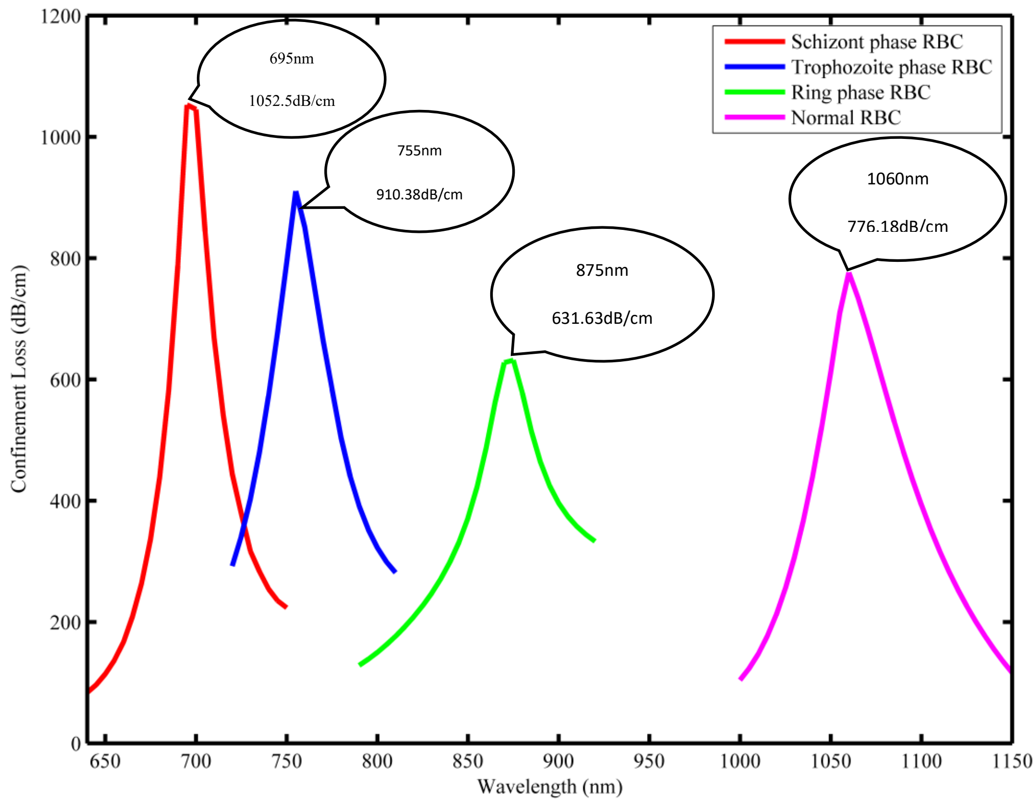


Fig.7.5. Wavelength Sensitivity for different RBCs with optimized parameters

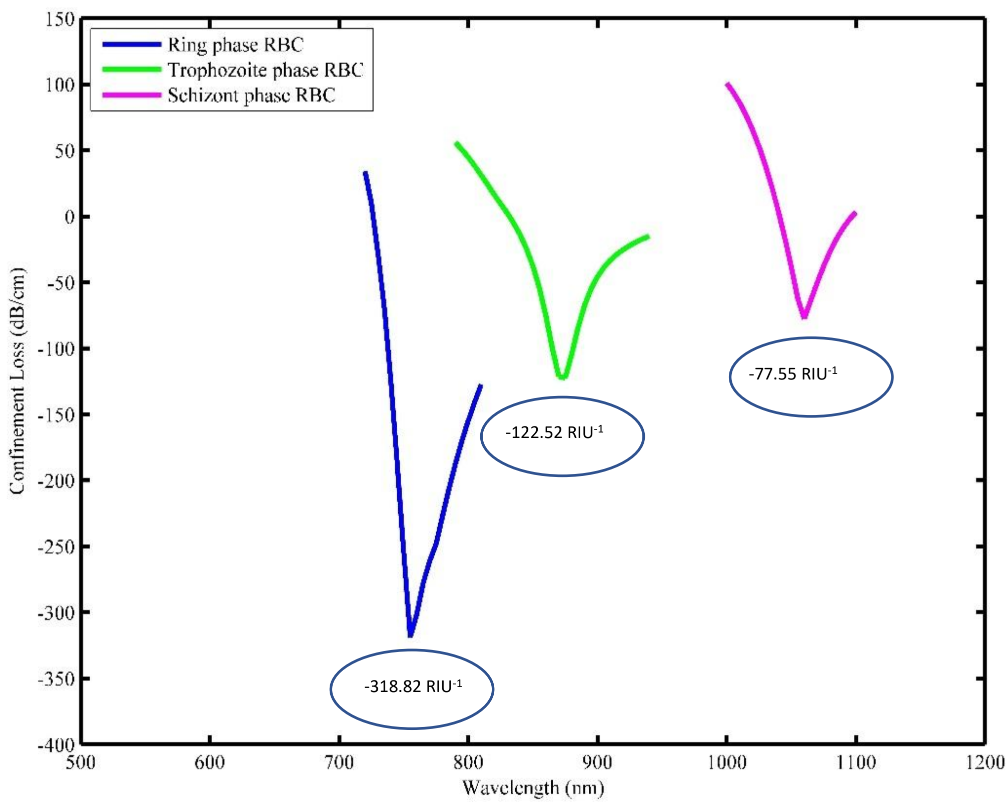


Fig.7.6. Amplitude Sensitivity for different RBCs with optimized parameters

Table 7.4 provides a performance comparison of the proposed sensor against other PCF SPR designed for malaria detection. The data clearly demonstrates that the proposed sensor outperforms both circular and elliptical structures. This enhanced performance is a viable alternative not only to existing circular-based PCF sensors for malaria detection but also to certain dual-side polished and dual-core SPR PCF RI biosensors. The findings suggest that the proposed sensor could significantly improve detection capabilities, potentially leading to more accurate and efficient diagnostic methods.

Table.7.4. Performance comparison with other malaria detection PCF sensor

Reference	PCF configuration	Materials used	λ_{range} in μm	Wavelength sensitivity(nm/RIU)
4	circular	Gold coated and TiO_2	0.7-1.1	17,857.14 (ring phase) 10,210.53(trophozoite phase) 8758.62 (schizont phase)
5	circular	gold	0.7–1.0	14,285.71 (ring phase) 10,000 (trophozoite phase) 8206.9 (schizont phase)
37	circular	Gold coated and Mxene	0.7-1.05	12,142 (ring phase) 9736 (trophozoite phase) 8241 (schizont phase)
38	Elliptical	silica	1.3-2	11,428.57 (ring phase) 9473.68 (trophozoite phase) 9655.15 (schizont phase)
17	Dual Square Groove	Gold and MoS_2	0.7-0.95	12,248 (ring phase) 9210 (trophozoite phase) 7758 (schizont phase)
39	Circular	Gold and Al_2O_3	0.6-1.0	5714.28 (ring phase) 5263.15 (trophozoite phase) 5931.03 (schizont phase)
This work	**Side polished**	**gold**	**0.65-1.15**	**26,428.57(ring phase)** **16,052.6(trophozoite phase)** **12,586.2(schizont phase)**

7.3. Fabrication viability of the proposed sensor

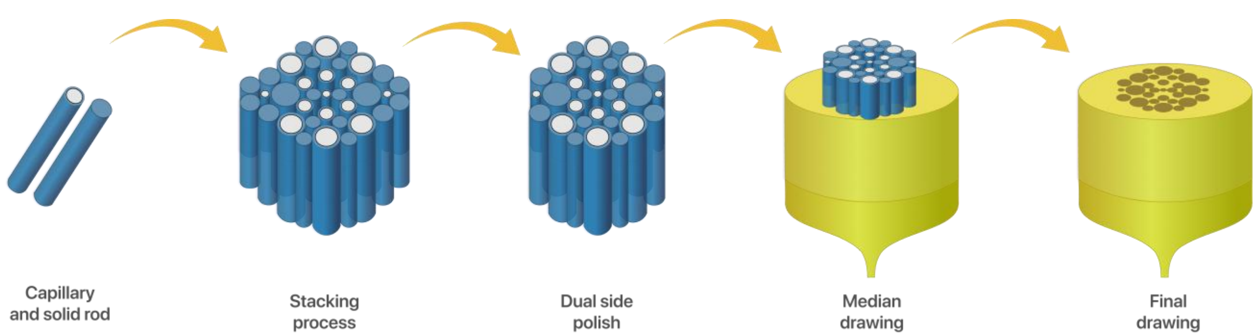


Fig.7. 7. Proposed sequential fabrication steps involved in the stack and draw

Nowadays fabrication of PCF sensors faces several limitations and challenges. The dual side-polishing technique makes fabrication easier than methods with complex internal coatings, making it better suited for large-scale production. The use of external sensing methods also reduces complications associated with analyte injection and extraction. There are many fabrication techniques such as stack and draw, sol-gel casting and injection molding. Due to lower cost and flexibility, stack and draw approach is chosen. The silica capillaries used for PCF fabrication offer a negligible transmission loss of 0.18 dB/km at 1.55 μm. Since we are working on below 1.55 μm wavelength range, the loss can be neglected. Figure 9 shows the sequential fabrication steps involved in the stack and draw method. The thin and thick capillaries and solid rods are stacked still the PCF is formed. Once the PCF is formed, two sides are polished symmetrically by different methods such as diamond polishing. A thin layer of gold is coated above these polished surfaces. Normal metal coating methods such as RF sputtering, thermal evaporation methods, electro plating, and wet-chemistry deposition create massive surface roughness in coating the circular surface. The Chemical vapor deposition technique (CVD) is the most suitable one, which provides uniform coating in the nanometer thickness range. The usage of a surfactant layer of oxidized copper or chromium on Au and Ag films can avoid percolation tendencies of gold. At final step, the RBC sample is introduced above this layer for the malaria detection [11].

7.4. Conclusion

The proposed sensor design achieves high wavelength sensitivities of 26,428.57 nm/RIU, 16,052.6 nm/RIU, and 12,586.2 nm/RIU for the ring, trophozoite, and schizont phases, respectively. Additionally, it demonstrates high Figure of Merit (FOM) values of 334.54 RIU^{-1}, 321.05 RIU^{-1}, and 381.40 RIU^{-1} for the respective phases.

Chapter 8

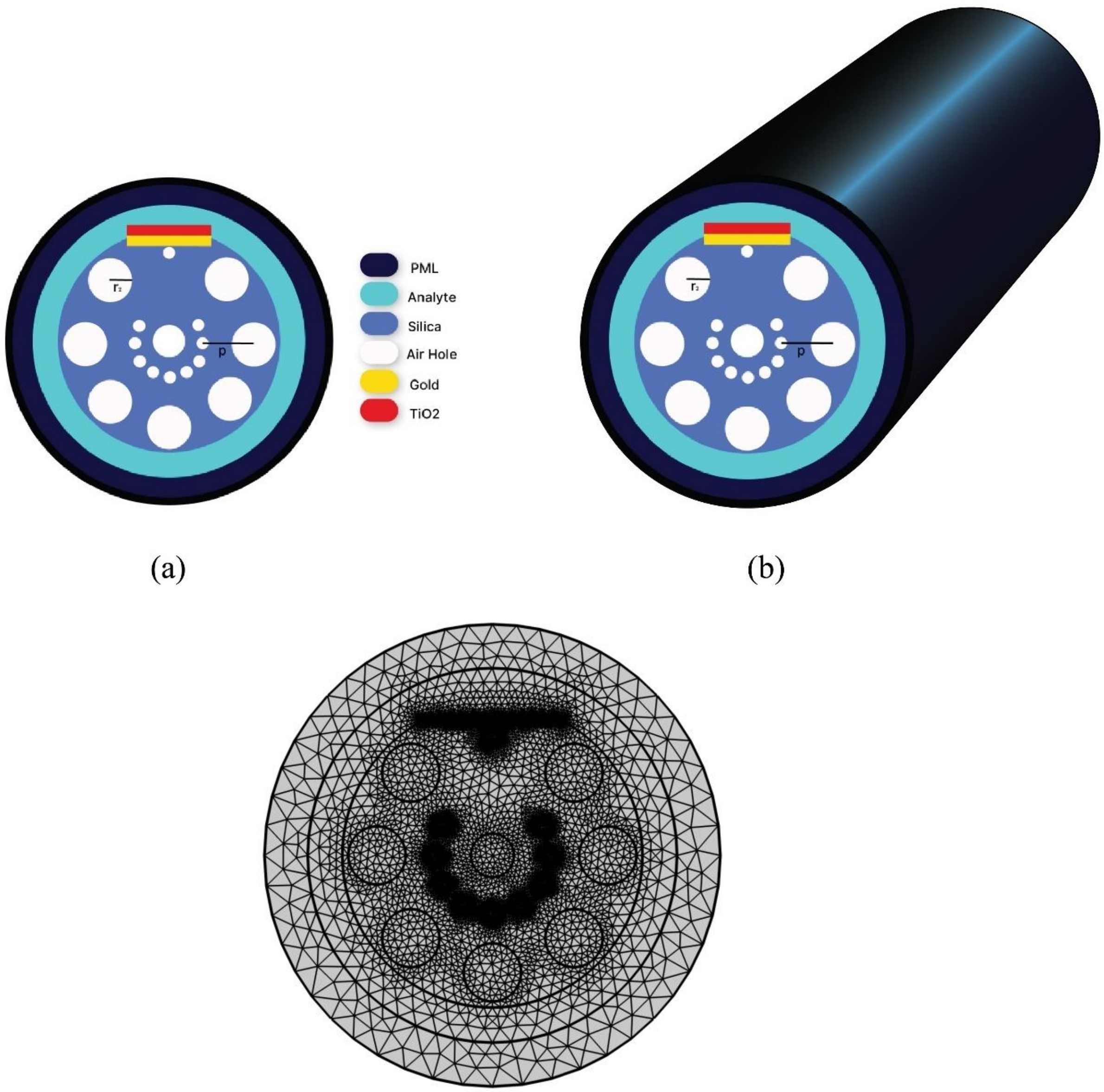
A SIDE POLISHED GOLD-TiO_2 COATED SURFACE PLASMON RESONANCE BASED PCF RI SENSOR

Plasmonic materials play a crucial role in enhancing the performance of photonic crystal fiber (PCF)-based surface plasmon resonance (SPR) sensors by enabling strong light-plasmon coupling and improving sensitivity. Among these materials, titanium dioxide (TiO_2) has emerged as a highly effective choice due to its high refractive index and superior optical properties.

This study explores the application of TiO_2 as a coating layer in a side-polished SPR-based PCF sensor, layered over a gold substrate. The inclusion of TiO_2 not only amplifies plasmonic resonance but also significantly boosts sensor sensitivity. Compared to a gold-only configuration, which achieved a sensitivity of 4000 nm/RIU for an analyte with a refractive index of 1.38, the addition of TiO_2 increased the sensitivity to 27,000 nm/RIU. These results highlight the transformative potential of TiO_2 in advancing SPR-based PCF sensor technology for applications in biomedical diagnostics and environmental monitoring.

8.1. Structural and theoretical modelling

Figure 8.1 (a) the 2D cross sectional view of the proposed sensor. The finite element method (FEM) based COMSOL Multiphysics is employed for the modelling and the performance investigation of the proposed sensor. Figure 8.1(c) depicts the Physics-controlled mesh view of the proposed sensor. It will make the mathematical calculations easier and accurate due to the increased mesh density. In this proposed PCF the pitch distance (p) of two adjacent air holes is set at a constant value of 2µm.This structure consist of three different sized air holes of diameters d_1=0.6µm, d_2=2µm and d_3=1.5µm. In this shape the air holes are arranged in two concentric circular rings. A few air holes are absent on both the rings in order to enhance the field contact with sensor layers. To enhance the coupling one side of the cladding is polished carefully. Plasmonic active metal (gold) is deposited on the flat surface with thickness of 40 nm and above that a layer of TiO_2 is also deposited with thickness of 12nm. The TiO_2 layer facilitates plasmon excitation at the gold-dielectric interface, enhancing the evanescent field, which in turn amplifies the interaction between the surface plasmon polariton and the surrounding medium (analyte).



(c)

Fig.8. 1.(a) Cross-sectional view of the sensor. **(b)** 3D structure **(c)** Physics-controlled mesh view

Silica is the main material of the fiber core and the effective RI of Silica can be calculated using the Sellmeier equation. Drude–Lorentz model is used for the calculation of dielectric constant of Au and following to find RI of gold by taking sqrt of ε_{Au}

The RI of TiO_2 is given by the following equation [3]

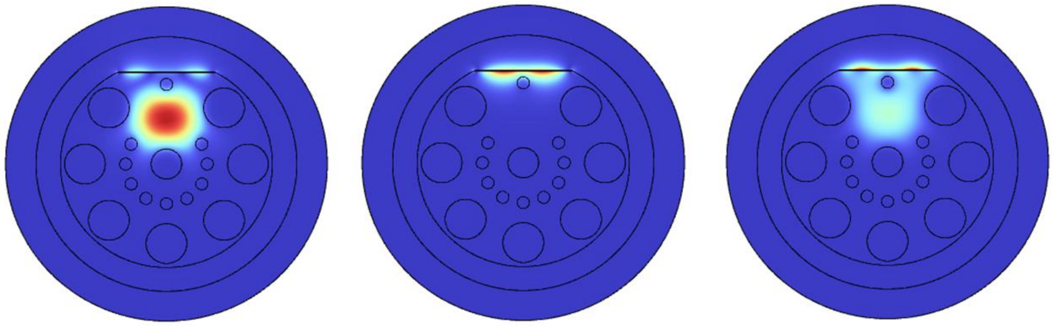
$$\mathbf{n_{ti}} = \sqrt{5.913 + \frac{\mathbf{2.441 \times 10^7}}{\boldsymbol{\lambda^2 - 0.803 \times 10^7}}} \qquad \mathbf{(7)}$$

Wavelength sensitivity, which represents the difference between two resonant wavelengths per unit refractive index (RI) difference, can be determined by the Equation no (4). From all these provided equations we found out the sensitivity of our proposed sensor.

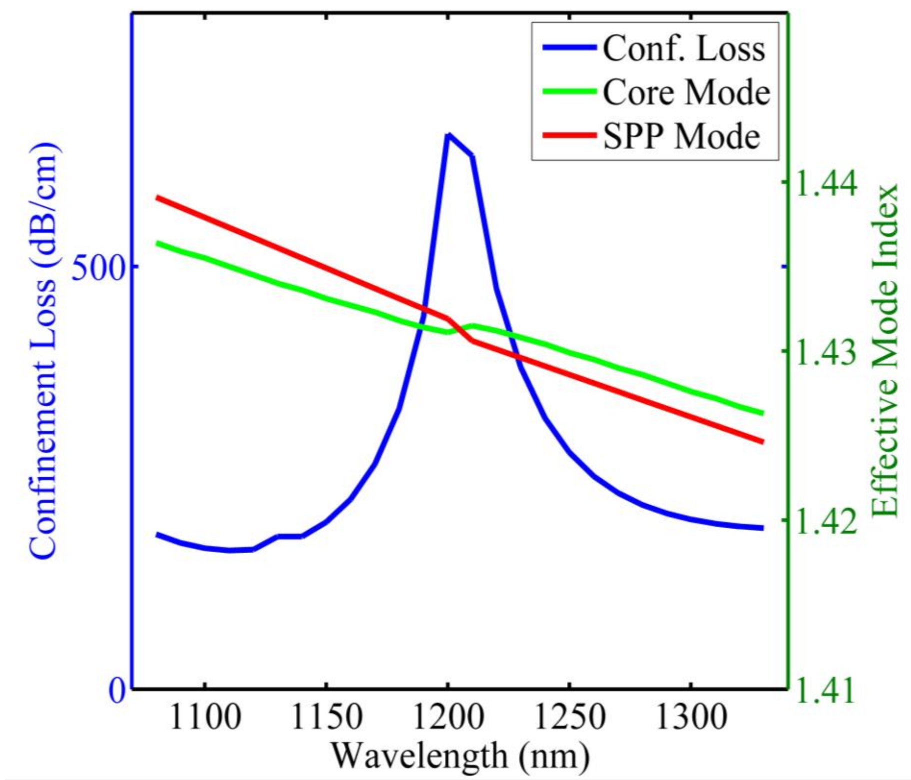
8.2. Simulation result and analysis

8.2.1 Dispersion relation

The electric field distribution of core mode, SPP mode and coupling mode is given in the Figure 8.2 (a), (b), (c) respectively. When the light passes through the PCF, it will interact with the plasmonic layer coated on the polished surface. This causes the production of surface plasmon polaritons (SPPs). When the frequency of this SPP mode matches with the frequency of the core mode causes the resonance condition called surface plasmon resonance. During this time maximum energy of the core mode is transferred to the SPP mode leading the confinement loss to reach its peak value. The resonance condition is dependent on the RI of the surrounding medium. Figure 8.2 (d) depicts the dispersion characteristics of the SPP and core mode combined with the confinement loss curve of RI 1.39 analyte. The green and red line indicates the core mode and SPP mode respectively and the blue curve indicates the confinement loss. The neff of both SPP mode and the core mode decreases with increasing wavelength and intersect at the resonance wavelength (λ_r = 1200 nm). At this point the SPP and core mode share same real component of RI which shows the coupling between them. Due to this maximum energy is transferred and confinement loss reaches its maximum value at 656.63dB/cm.



(a) (b) (c)



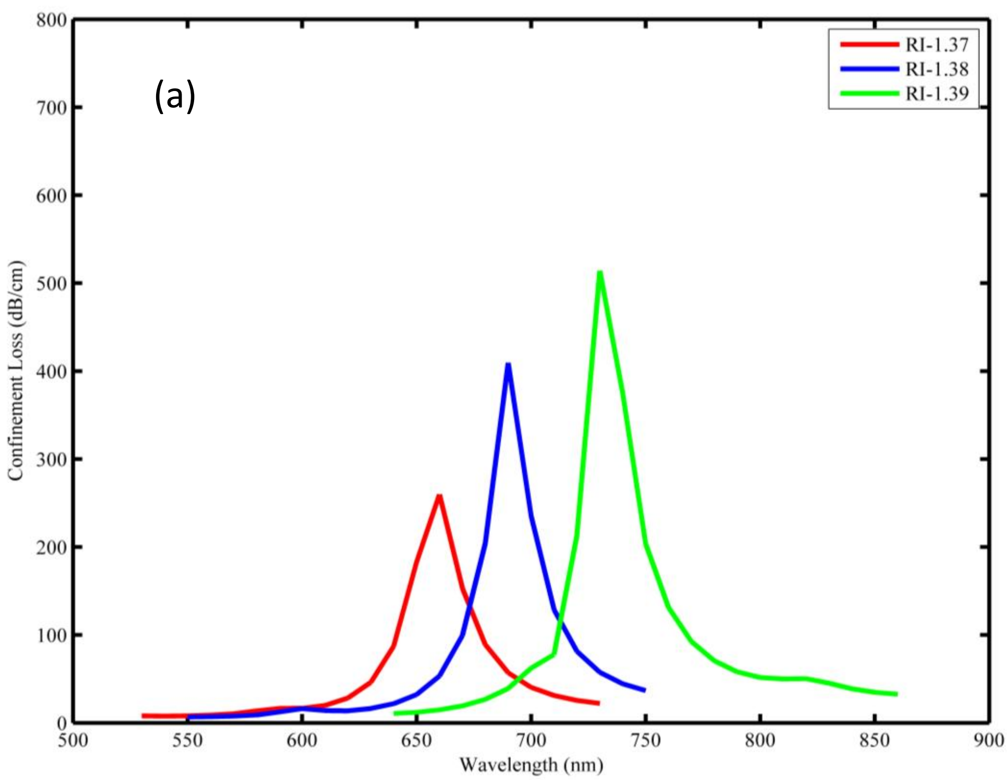
(d)

Fig.8. 2. (a) Core mode **(b)** SPP mode **(c)** Coupling mode **(d)** Dispersion characteristics of analyte of RI 1.39

8.2.2. Comparative analysis of gold only and TiO_2-gold SPR PCF sensor

Initially, the loss peak for Gold only PCF RI sensor (probe 1) is found out for three different analytes of refractive indices (1.37, 1.38, 1.39) shown in fig. 8.3(a). For 1.37 RI analyte, peak is observed at 660nm with a loss of 259.68 dB/cm. Similarly for 1.38 and 1.39 analytes, it is observed at 690nm and 730nm with loss magnitudes of 409.36 dB/cm and 514.09 dB/cm respectively. It is then compared to the PCF coated with TiO_2 (probe 2) and the loss peak is obtained as given in the Fig. 8.3(b). Here, loss peak corresponding to 1.37, 1.38 and 1.39 analytes are at 880nm, 930nm and 1200nm with loss values of 454.64 dB/cm, 430.51 dB/cm and 656.63 dB/cm respectively.

Wavelength sensitivity is then calculated for both the sensor probes and their comparison is given in the table 8.1.



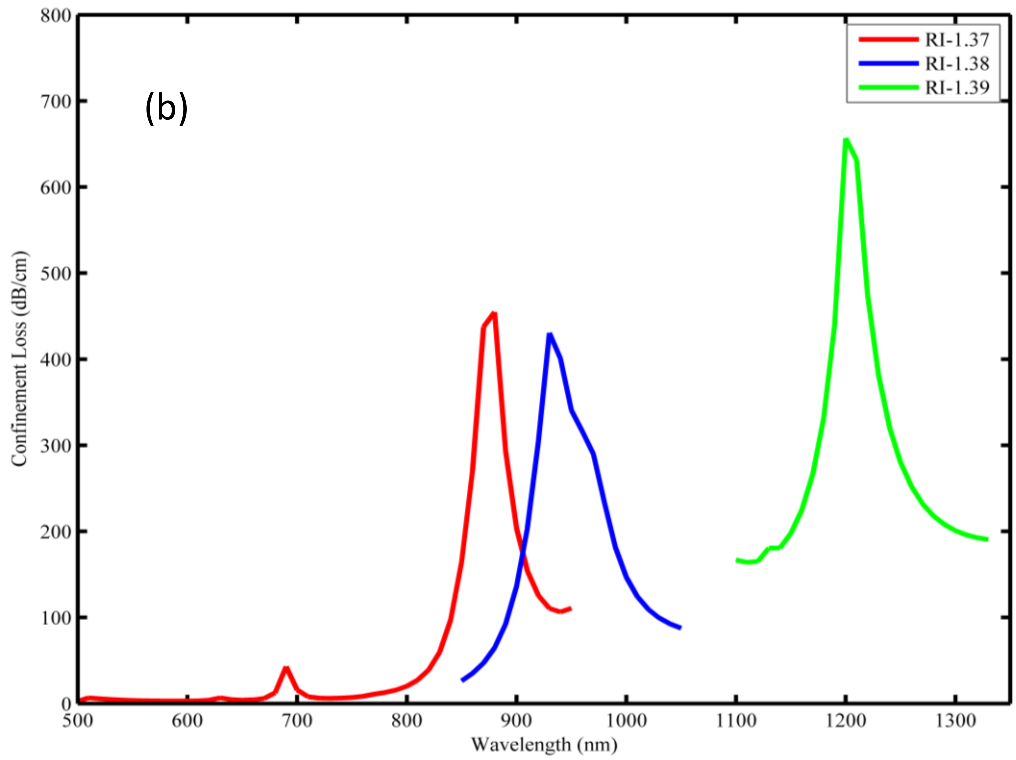


Fig.8. 3.(a). Loss profile of Sensor Probe 1 **(b)** Sensor Probe 2

Table 8. 1. Performance Assessment of proposed SPR

Analyte RI	**Proposed sensor probe 1 with Au**		**Proposed sensor probe 2 with Au and TiO_2**	
	Wavelength (λ) (nm)	*Sensitivity (nm/RIU)*	*Wavelength (λ) (nm)*	*Sensitivity (nm/RIU)*
1.37	660	3000	880	5000
1.38	690	4000	930	27000
1.39	730		1200	

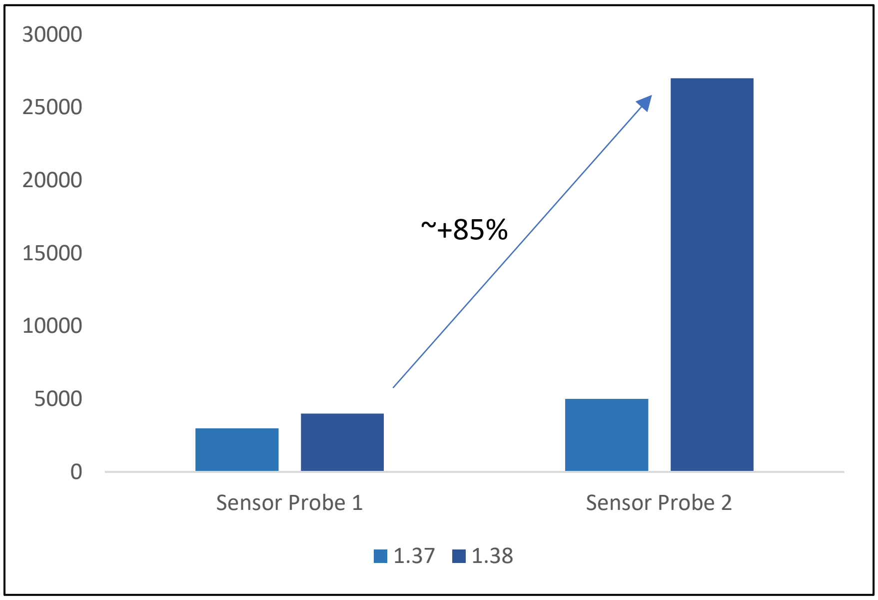


Fig.8. 4. Graphical depiction of wavelength sensitivity enhancement

The above figure represents the graphical summary of the wavelength sensitivity enhancement of the proposed sensor. Probe 1 is found to have a sensitivity of 3000 nm/RIU and 4000 m/RIU for the analyte of RI 1.37 and 1.38 respectively, which increased to a sensitivity of 5000 nm/RIU and 27000 nm/RIU for probe 2 for the same set of analytes. The hike is observed as a result of the additional TiO_2 coating over the gold layer, allowing for better light penetration into the evanescent field.

8.3. Conclusion

This work suggests a SPR PCF RI sensor probe with a one-side polished geometry in which the effect of TiO_2 is investigated and it is evident from table 1 that the sensor shows a significant increment in the wavelength sensitivity. Probe 1 is found to have a sensitivity of 3000 nm/RIU and 4000 m/RIU for the analyte of RI 1.37 and 1.38 respectively, which increased to a sensitivity of 5000 nm/RIU and 27000 nm/RIU for probe 2 for the same set of analytes. It is thereby observed that the proposed side polished TiO_2 coated SPR based PCF RI sensor showcases a remarkable performance in terms of wavelength sensitivity.

Chapter 9

CONCLUSION

This thesis puts forward and discusses two new SPR based PCF sensor designs for efficient malaria detection and refractive index sensing. One of them is a twin core double side polished SPR PCF sensor, which is optimized for malaria detection during its intraerythrocytic phase. It excels with high wavelength sensitivities and FOM values owing to greater mode coupling and an hourglass shaped air hole structure enhanced light confinement

The second model is a single side polished SPR PCF sensor that is TiO_2 coated which greatly improves plasmonic sensitivity. It has a notable enhancement of wavelength sensitivity from 3000 to 5000 nm-/RIU and 4000 nm-/RIU to 27000 nm/RIU for RI 1.37 and 1.38 analytes respectively.

Both the sensor structures have considerable ability for portable, affordable and highly sensitive biosensing applications. Especially considerable for a low concentrated analytes and it’s important to diagnose malaria preliminarily.

Chapter 10

FUTURE WORK

Future work will involve the development of SPR-PCF sensors by investigating new plasmonic materials including MoS_2, graphene, and other 2D materials with remarkable optical and plasmonic characteristics. These materials will be combined with nanostructures and tailored coatings to achieve improved sensitivity and expand the application range of the sensor.

These efforts will also be concentrated in the direction of broadening the application of SPR-PCF sensors to fields such as environmental monitoring, food safety, and disease diagnosis with the goal of achieving trace-level detection of the analyte and multiplex sensing ability. Development of more advanced techniques for fabrication, like polishing and coating, will also take precedence to make their scalability and real-world applicability more suitable.

Lastly, optimization of sensor design in terms of structural parameters and material configurations will further pursue maximizing performance figures such as sensitivity, figure of-merit, and reliability for applications.

Additionally, new research will investigate novel PCF geometries, with emphasizing on multi-channel structures to facilitate the simultaneous multi-analyte detection. Dual-channel PCF structures with the ability to detect two dissimilar diseases at the same time will receive special attention as a promising route towards compact multifunctional biosensors for next-generation medical diagnostics. The strategy is designed to enhance diagnostic efficacy without sacrificing high sensitivity and specificity.

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APPENDIX I

Plagiarism Report

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APPENDIX II
Research publication

Plasmonics
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RESEARCH

Design and Analysis of Twin-Core Side-Polished SPR PCF Sensor for Preliminary Malaria Detection

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Abstract
This paper proposes a double-side polished twin-core photonic crystal fiber (PCF)-based surface plasmon resonance (SPR) sensor for early-stage detection of malaria. The analysis and the assessment of the proposed sensor are done by finite element method using the COMSOL Multiphysics software. The dual-side polished structure reduces the distance between the metal layer and core mode, thereby enhancing the sensor performance due to the strong coupling between them. The air holes arrangement resembles the shape of an "hourglass" which helps to confine light energy within the twin cores. A layer of gold, a preferred plasmonic material, is coated on the symmetrically polished surface of the PCF to induce SPR. Due to distinction in the refractive indices, the resonance wavelength is different for infected and normal red blood cells (RBCs). The analysis is done for infected RBCs (ring phase, trophozoite phase, and schizont phase). The structural parameters are optimized precisely and a maximum wavelength sensitivity of 26,428.57 nm/RIU was achieved for the ring phase, 16,052.6 nm/RIU for the trophozoite phase, and 12,586.2 nm/RIU for the schizont phase. The numerical analysis also shows that the sensor possess high figure-of-merit (FOM) values of 334.54 RIU^{-1}, 321.05 RIU^{-1}, and 381.40 RIU^{-1} for the ring, trophozoite, and schizont phases, respectively. These results confirm the potential of the proposed sensor and also justify its betterment than the existing methods. Due to its promising sensing performance and appropriate FOM value, the proposed sensor is suitable for the early-stage malaria detection.

Keywords Trophozite phase · Schizont phase · Twin-Core · Wavelength sensitivity · Figure-of-merit (FOM)

Introduction

Malaria is a highly virulent and potentially fatal illness triggered by a parasite that inhabits certain mosquitoes which bite humans. In the global population, approximately 44% is susceptible to malaria. The disease is caused by five distinct parasite species belonging to the *Plasmodium* genus: *P. falciparum*, *P. vivax*, *P. malariae*, *P. ovale*, and *P. knowlesi*. Among these species, the most dangerous one is *Plasmodium falciparum*, which causes the infection [1, 2]. Thus, the cycle consists of three stages: the ring stage, trophozoite stage, and schizont stage. The key parameter for the diagnosis of malaria is the difference in optical properties of healthy and infected erythrocytes [3, 4]. In 2022, the World Health Organization (WHO) estimated that there were approximately 249 million malaria cases worldwide, with around 608,000 related deaths reported across 85 countries [5]. To prevent the spread of disease in the communities and to provide effective treatment for the infected persons, accurate and timely malaria diagnosis is crucial [6]. The conventional method for diagnosing malaria typically involves clinical assessment based on patient symptoms. But this can cause misdiagnosis because these symptoms can be similar to other common diseases [7]. Another widely used method is the microscopic examination of stained peripheral blood smears using field's stains. However, this method can cause false-positive detection due to the low parasite level, and it needs skilled technicians, and the process is time-consuming [8]. The quantitative buffy coat (QBC) method can detect low-concentrated parasites and detected through an

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APPENDIX III

Conference Certificate


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APPENDIX IV

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