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Design And Performance Analysis of Hexagonal-SPR Based Photonic Crystal Fiber Biosensor for Malaria Detection in Biomedical

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Surface Plasmon Resonance and Gold-Coated Photonic Crystal Fiber and Hexagonal Lattice Structure and Biomedical Optical Detection System and Malaria Detection System and Biosensor Device and Refractive Index Measurement System.

ABSTRACT

The inability of healthcare facilities in developing countries to detect malaria during its initial stages results in ongoing fatal outcomes for human beings. The proposed method for precise malaria identification uses a surface plasmon resonance biosensor that operates on hexagonal lattice photonic crystal fiber technology. The sensor detects different stages of malaria infection through changes in red blood cell refractive index. The gold-coated PCF structure with titanium dioxide adhesive layer achieves better sensing performance through its ability to enhance light-matter interaction while limiting electromagnetic field distribution. The proposed sensor system undergoes numerical evaluation through the application of the finite element method. The x-polarized mode shows three different wavelength sensitivities which include 14285.714 nm/RIU for the ring phase and 10263.157 nm/RIU for the trophozoite phase and 8620 nm/RIU for the schizont phase. Our measurements of the y-polarized sensitivities revealed three distinct values: 10,714.285 nm/RIU, 8,421.052 nm/RIU, and 7,413.793 nm/RIU. The study results demonstrate that x-polarization sensitivity has increased and the novel PCF-SPR biosensor device shows effectiveness for early malaria diagnosis without labeling. The PCF-SPR biosensor device which researchers demonstrated enables real-time point-of-care malaria diagnoses because it needs only minimal resources for functionality in healthcare settings

INTRODUCTION

The female Anopheles mosquito transmits malaria through its bites which occur when Plasmodium species enter the bloodstream of their human hosts. The disease maintains its status as a global health danger because it results in death through infant and pregnant women fatalities while infecting tropical and subtropical populations throughout the entire year. Medical staff encounter challenges with diagnosing malaria because its initial symptoms remain minimal or entirely absent which extends until the disease reaches its terminal phase. Scientists believe that rapid and precise methods for malaria detection should be developed because they will help decrease disease transmission while increasing patient survival rates.

Traditional methods for diagnosing malaria include clinical diagnosis and blood smear microscopy and rapid diagnostic tests and molecular techniques which use polymerase chain reaction testing. Microscopy serves as the gold standard method because it requires expert technicians who operate high-quality microscopes together with laboratory equipment [6] [7]. RDTs provide fast test results but their low parasite detection capacity results in frequent false negative outcomes [8] [9]. PCR-based techniques provide precise results but their high costs and lengthy processing times make them unsuitable for use in resource-deficient field settings [10] [11]. The existing limitations require the development of diagnostic methods which provide rapid testing results while maintaining high sensitivity and low testing costs and ease of use [12].

Optical biosensors show high potential for biomedical diagnostics because they can detect disease in real time without using any specific detection methods and their sensors identify even the smallest biological changes. Photonic crystal fiber (PCF) sensors show special appeal because their microstructured design enables them to achieve excellent light control and to create optimal conditions for light-matter interactions. Researchers can design PCFs for specific sensing functions by changing their air-hole diameter and pitch and lattice structure. PCF sensors have shown better performance than standard optical fiber sensors in three areas which include chemical sensing and biological detection and refractive index measurement.

The combination of photonic crystal fibers and surface plasmon resonance enables better detection capabilities through their ability to control light through surface plasmon waves that propagate along metal-dielectric interface boundaries. Gold-coated PCF-SPR sensors demonstrate optimal performance for biomedical applications because gold exhibits exceptional plasmonic properties while maintaining chemical stability and biocompatibility. The detection method achieves excellent sensitivity through identifiable resonance wavelength variations which occur when malaria-infected red blood cells exhibit different refractive index changes during their various disease stages. The PCF-based SPR biosensors enable early and accurate malaria testing because they can detect the disease without requiring identification procedures.

LITERATURE SURVEY

Scientists have studied photonic crystal fiber biosensors because these biosensors provide advanced optical properties and customizable design options. Research shows that improved light trapping capability is provided by hexagonal, triangular, and circular lattice PCFs which improves sensor performance for sensitive detection tasks [1]–[3]. Researchers can create PCF sensors that detect refractive index changes by changing air hole dimensions and spacing and lattice configurations [4], [5]. Numerous articles have proven the effective use of PCFs in chemical gas and biological sensing applications which demonstrate their ability to detect even the smallest refractive index changes. [6]–[8]

The optical sensing technique of surface plasmon resonance (SPR) improves detection sensitivity through its ability to use guided light which interacts with surface plasmons at metal-dielectric interfaces as its detection mechanism [9], [10]. The two main noble metals used for SPR excitation are silver and gold because gold provides chemical stability together with corrosion resistance and biocompatibility [11], [12].The SPR-based fiber sensors enable biological diagnostics because they can detect without labels and track results in real time while maintaining high detection accuracy [13], [14]. The research findings demonstrate that SPR integration provides substantial improvements to the detection capabilities of traditional fiber sensors. [15]

The limitations of existing diagnostic methods have created a surge of interest in studying optical biosensors for malaria detection. The experimental study found that malaria-infected red blood cells exhibit optical properties changes through their refractive index alterations [16] [17]. Malaria displays three distinct disease stages which scientists can identify through the different refractive index values that occur during the disease progression [18]. Scientists used this research concept to create PCF-based SPR biosensors which detect malaria-infected red blood cells at their minimal detection thresholds while maintaining high sensitivity to various wavelengths [19] [20]. The tests demonstrated that PCF-SPR sensors can precisely detect early stage malaria through their sensitivities which exceed 10,000 nm/RIU [21].

The hexagonal lattice PCF-SPR biosensors have been extensively studied because their symmetric design enables better modal control and proficient mode coupling between core-based and surface plasmon modes. According to comparative studies hexagonal PCFs demonstrate better sensitivity and polarization capabilities than square or circular lattice arrangements [24]. Researchers proposed D-shaped and dual-core and microchannel PCFs as advanced designs to enhance system performance [25] [26]. The designs require complex fabrication methods which create obstacles for their practical use according to research that shows the need for simple yet functional sensor systems [27].

Researchers have investigated ways to enhance sensor capabilities through their studies of material and structural optimization techniques. The researchers developed a technique that enhanced the stability of gold films and their capacity to generate plasmonic coupling using titanium dioxide (TiO_2) adhesion layers. The researchers tested hybrid plasmonic materials which included MXene and MoS_2 to achieve extreme sensitivity with better image resolution. The numerical simulations which used finite element techniques showed major improvements in wavelength sensitivity and figure of merit and detection accuracy. Researchers continue to develop PCF-SPR biosensors which will provide high sensitivity at low production costs while maintaining manufacturing simplicity despite current technological improvements.

PROPOSED METHODOLOGY

The proposed method develops a hexagonal lattice photonic crystal fiber (PCF) device that detects malaria using surface plasmon resonance (SPR) technology. The PCF structure uses a fused silica base with symmetrically spaced air holes of different diameters to achieve better light containment and control its modal characteristics. The exterior of the PCF system features a titanium dioxide (TiO_2) coating, which enhances material durability and adhesion while boosting plasmonic performance. Surface plasmon resonance is triggered by applying a gold layer to the metal–dielectric interface.

The sensing technique depends on detecting changes in the refractive index of red blood cells which occur during malaria infection. The RCBC samples create an analyte layer which surrounds the gold-coated PCF structure. The analyte region displays different refractive index values which represent the normal, ring, trophozoite, and schizont phases of the organism. The optical resonance wavelength shifts because the analyte refractive index changes cause the phase-matching condition between surface plasmon polariton mode and core-guided mode to be affected.

The suggested sensor is subjected to numerical analysis using the finite element method in conjunction with COMSOL Multiphysics software. The outer boundary of the system uses a perfectly matched layer (PML) to prevent reflection while absorbing all emitted electromagnetic radiation. The study uses wavelength scanning in the near-infrared area to quantify confinement loss and effective refractive index. The work evaluates resonance behavior and plasmonic effects close to the metal-analyte contact point using an improved mesh system.

The performance evaluation process requires five essential criteria which include confinement loss and resonance wavelength shift and wavelength sensitivity and resolution and figure of merit. The sensor detection capability needs performance testing across all three malaria disease stages. The PCF-SPR biosensor system demonstrates its efficiency through its ability to detect minor changes in resonance patterns. The method achieves highly precise results through its non-labeling approach which enables early malaria detection while meeting the requirements for biological detection.

A. System Architecture

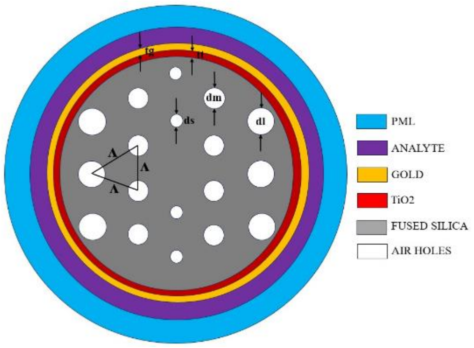

Fig 1 The PCF biosensor's prescribed cross-sectional view is displayed

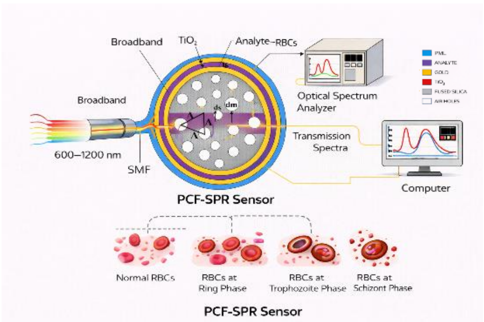

Fig 2 measuring setup for a PCF-based SPR malaria detection sensor

TABLE 1 OPTIMAL PARAMETER FOR THE PROPOSED PCF BIOSENSOR

Name	Expression
A	2.5[um]
ds	0.8[um]
dm	1.1[um]
dl	1.3[um]
tt	10[nm]
tg	36[nm]
ta	1.2[um]
Pml	1.5[um]
opw	800[nm]

B. Methodology

Data Collection and Sensor-Based Optical Sensing

The proposed device uses a photonic crystal fiber surface plasmon resonance biosensor for optical sensing data collection. The gold-coated PCF structure contains an analyte layer which includes red blood cell samples from healthy people and malaria-infected patients. The researchers used different refractive index values to model malaria progression through the ring and trophozoite and schizont stages of the disease. The fiber produces resonance wavelength shifts when directed light interacts with the analyte after near-infrared spectrum broadband light enters the system. The changes in data provide essential sensory information which enables researchers to identify and categorize different malaria infection stages.

The optical sensing data comes from two main sources which are confinement loss and changes in the effective refractive index of guided modes. The loss spectrum shows a major resonance peak which occurs when the surface plasmon polariton mode matches the core-guided mode phase-matching condition. Infected red blood cells show different refractive index measurements during different stages of malaria which cause their resonance wavelengths to change. The researchers measure the wavelength shift that occurs at the resonance point for both x-polarized and y-polarized modes. The wavelength-based sensing method detects blood samples with extreme sensitivity while maintaining label-free detection which enables the identification of healthy and contaminated samples.

The complete numerical simulation process depends on finite element analysis which functions as the primary method used to gather sensor data. The simulation environment includes complete modeling of all components which make up the sensor system from its material properties to its boundary conditions and its optical interaction components. The system uses a special coating system which absorbs all electromagnetic waves that exit the system while it prevents any false reflections from occurring. The optical measurements include three methods which scientists use to measure resonance wavelength and confinement loss and effective refractive index. The system analyzes three parameters which include sensitivity and resolution and figure of merit to evaluate sensor performance. The suggested biosensing system verification procedure uses this research approach to collect performance evaluation data.

Table 2 The mean RI of healthy and infected RBC samples at various malaria parasite stages

RBCs status	Average RI
Normal RBCs	1.402
Infected RBCs at ring phase	1.395
Infected RBCs at trophozoite phase	1.383
Infected RBCs at Schizont	1.373

Embedded Optical Control and System Architecture

The proposed malaria detection system architecture consists of two main components which are an optical sensor and its dedicated analysis pipeline. The system uses a single-mode fiber link which connects to a photonic crystal fiber that receives light from a broadband light source. The PCF-SPR sensor functions as the main detection device because it can detect optical changes that occur when it contacts malaria-infected red blood cells. The system uses an optical spectrum analyzer to collect the transmitted light that reaches its output. The system enables continuous observation of wavelength changes which occur because of variations in the analyte layer's refractive index.

The sensing process is controlled through software-based modeling and signal interpretation methods which do not require actual integrated hardware. The simulation platform establishes numerical control parameters which include the wavelength range and mesh resolution and material dispersion models and boundary conditions. The three factors determine how resonance behavior and plasmonic coupling and light propagation will occur. Logical control is used to change refractive index values which correspond to different stages of malaria. The controlled variation system enables researchers to evaluate sensor response across different biological scenarios.

The optical spectrum analyzer output data needs computational methods for processing the data to extract essential sensing information. The research identifies loss peaks together with resonance wavelength locations and examines their differences across multiple analyte testing conditions. The system architecture enables researchers to study how different polarizations affect their findings through separate assessment of x and y modes. The systematic control and analysis framework establishes a complete system which ensures all sensing data maintains its robust and precise and repeatable characteristics. The design integrates data interpretation and numerical control and optical sensing into one complete system for malaria detection.

Automated Detection Strategy and Diagnostic Decision Process

The automated detection method relies on detecting resonance frequency shifts caused by red blood cells infected with malaria. The PCF-SPR sensor needs specific refractive index ranges which correspond to different infection stages to match its phase-matching condition. The disease progression causes resonant wavelength changes because the refractive index of the material decreases. The system uses loss spectrum data to detect shifts which are then matched against established reference points. This method enables stage-based classification of malaria infections because it does not require any manual work or chemical identification process.

The diagnostic decision-making process uses resonance shift data to calculate wavelength sensitivity. The sensitivity computation uses a ratio that measures the relationship between wavelength shifts and changes in refractive index. The detection accuracy of a sensor increases when its sensitivity values increase. The system uses figure of merit evaluation together with sensitivity and resolution testing to confirm detection reliability. The technology uses threshold-based reasoning to distinguish between contaminated samples and normal red blood cells. The automatic decision-making system produces accurate diagnostic results under various testing settings while removing human error.

The system uses polarization-dependent analysis and comparison validation methods to achieve higher reliability standards. The system uses x-polarized and y-polarized tests to verify resonance behavior while eliminating false detection results. The automated system establishes valid detection results through its ability to track consistent resonance changes across different polarization states. The safety system enhances diagnostic accuracy through its reliable detection capabilities and fortified performance. The complete process enables early malaria diagnosis through accurate stage determination and potential use in point-of-care biomedical testing which operates with minimal operational complexity.

Electric Fields of Core and SPP Modes

The x-polarized core-guided mode's electric field distribution demonstrates that optical confinement peaks in the photonic crystal fiber's silica core region. The system demonstrates effective guidance because its center region produces high field intensity while losing minimal energy to the adjacent air-hole cladding. The system needs high confinement because it requires maximum interaction with the plasmonic layer when operating in resonance to achieve accurate sensing results.

The y-polarized core-guided mode's electric field distribution shows multiple confinement patterns which match the current distribution. The hexagonal lattice structure creates symmetrical field distribution which enables effective steering of both polarizations. Anisotropic interactions in the microstructured cladding create slight changes to intensity. The study demonstrates that the proposed PCF structure enables polarization-dependent operation while maintaining high sensing efficiency.

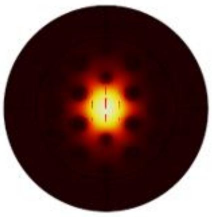

Fig 3 The distribution of the y-axis polarized core mode's electric field

The x-polarized surface plasmon polariton mode shows high field concentration at the boundary between gold and analyzing materials. The system achieves successful surface plasmon amplification through its phase-matching conditions. The sensor can detect extremely small refractive index changes because the metal surface produces strong evanescent fields that enhance detection of nearby analytes.

The y-polarized surface plasmon polariton mode at the plasmonic boundary demonstrates two distinct characteristics. The guided mode demonstrates its capacity to transfer energy to the plasmonic mode through an increase in electromagnetic field strength. The proposed PCF-SPR biosensor uses polarization-based plasmonic activity for malaria detection to demonstrate its operational efficiency while improving detection capability through refractive index variations.

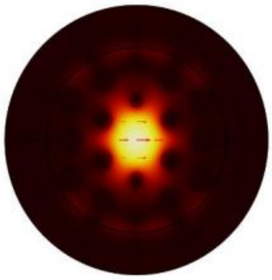

Fig 4 The x-polarized core mode's electric field distribution

The x-polarized surface plasmon polariton SPP mode at the gold-analyte interface creates its maximum electromagnetic field intensity throughout its operational range. The system achieved surface plasmon excitation through its phase-matching core mode and SPP mode coupling system. The metal layer enables the technology to detect changes in refractive index for malaria-infected red blood cells because it creates stronger field intensity effects.

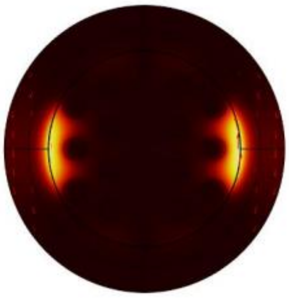

Fig 5 Distribution of the x-polarized SPP mode's electric field

The y-polarized SPP mode demonstrates two distinct properties which include strong field confinement and a special polarization distribution at the plasmonic boundary. The system achieves plasmonic coupling to the analyte layer through strong evanescent fields which successfully contact the analyte layer. The PCF-SPR biosensor achieves high sensitivity which enables effective mode coupling to detect malaria infection stages through refractive index changes.

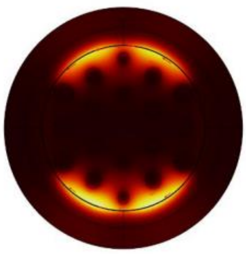

Fig 6 Electric field distribution of y-polarized SPP mode

The 100 nanometer wavelength shift together with the 0.007 refractive index change caused red blood cells to change from their normal state to the ring phase, which showed a wavelength sensitivity of 14,285.714 nanometers per refractive index unit. The transition from normal to trophozoite phase red blood cells showed a wavelength sensitivity of 10,263.157 nanometers per refractive index unit because of a 195 nanometer wavelength shift together with a 0.019 refractive index difference.

$$\text{Loss (dB/cm)} = 8.686 \times \frac{2\pi}{\lambda} \times \text{Im}(n_{\text{eff}}) \times 10^4$$

The transition from normal RBCs to schizont phase RBCs shows a wavelength sensitivity of approximately 8,620 nm/RIU because the calculation considers a 250 nm wavelength shift and a 0.029 RI differential.

$$S_\lambda \text{ (nm/RIU)} = \frac{\Delta\lambda_{\text{res}}}{\Delta n}$$

The x-polarized mode wavelength sensitivities of the three phases are 14,285.714 nm/RIU for Phase-1, 10,263.157 nm/RIU for Phase-2, and 8,620 nm/RIU for Phase-3. The three phases show x-polarized mode sensitivities which have values of 10,714.285 nm/RIU for Phase-1, 8,421.052 nm/RIU for Phase-2, and 7,413.793 nm/RIU for Phase-3.

Table 3 The sensitivity of one earlier-published Malaysian analysis method is set against a proposed PCF biosensor

Title	Ring Phase RBC (Phase-1) Wavelength Sensitivity (nm/RIU)	Trophozoite Phase RBC (Phase-2) Wavelength Sensitivity (nm/RIU)	Schizont Phase RBC (Phase-3) Wavelength Sensitivity (nm/RIU)	REFERENCES
Gold-Immobilized Photonic Crystal Fiber-Based SPR Biosensor for Detection of Malaria Disease in Human Body	14,285.71	10,000	8,206.90	16
Design and Analysis of a Single Elliptical Channel Photonic Crystal Fiber Sensor for Potential Malaria Detection	11,428.57	9,473.68	9,655.17	21
Simultaneous Detection of Ague Stages by Using a Multi-Inner Channel Photonic Crystal Fiber Based Surface Plasmon Resonance Sensor	6,250	5,300	4,750	23
Dual Self-Referenced Refractive Index Sensor Utilizing Tamm Plasmons in Photonic Quasicrystal for Multistage Malaria Parasite Detection	425	405	383	22
Design And Performance Analysis Of Hexagonal-Spr Based Photonic Crystal Fiber Biosensor For Malaria Detection In Biomedical	14,285.714	10,263.157	8,620	THIS WORK

RESULTS

The proposed hexagonal photonic crystal fiber biosensor detects malaria through its ability to create plasmonic coupling together with its strong optical confinement system. The microstructured fiber shows effective light propagation because its guided mode remains strongly confined to the silica core. The symmetric hexagonal lattice design of the sensor system reduces leakage losses while it delivers consistent modal distribution throughout its operation. The results demonstrate that the proposed PCF design functions effectively for biosensing purposes which depend on changes in refractive index.

The system shows strong field confinement for its core-guided modes which polarize in the x and y directions according to results from polarization analysis. The system maintains its ability to detect different types of light because both light polarizations show identical capabilities to restrict their respective confining areas. The sensor maintains consistent performance across different optical testing conditions because its dual-polarization system increases its reliability.

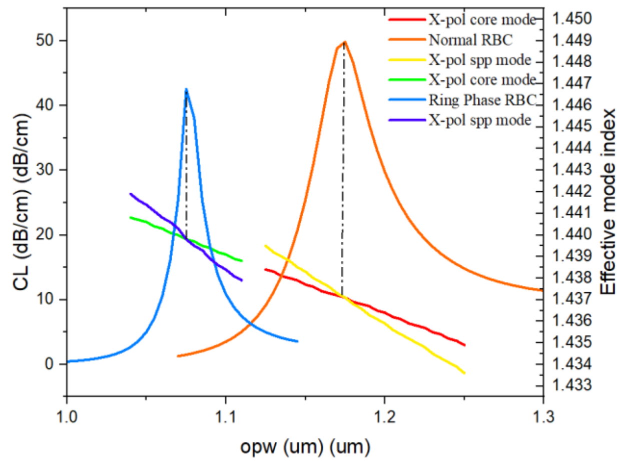

Fig 7 Confinement Loss and Effective Refractive Index Properties for Ring Phase and Normal RBCs (X-Polarized Mode)

The research investigates how x-polarized stimulation affects the effective refractive index and confinement loss measurements of malaria-infected red blood cells. The graph shows two separate resonance peaks which display the phase matching between surface plasmon polariton mode and core-guided mode. The typical red blood cells show a strong resonance peak which occurs at a more advanced operating wavelength because their analyte refractive index exceeds normal levels. The research demonstrates that plasmon excitation continues to operate effectively while successful coupling takes place under normal blood conditions.

The resonance characteristics of both normal and ring phase malaria-infected red blood cells show different responses to y-polarized excitation which affects their effective refractive index and their confinement loss measurement. The normal red blood cells show a distinct peak in their confinement loss at a particular wavelength, which matches their higher refractive index value. The ring phase infected red blood cells show a resonance peak shift which moves to a shorter operating wavelength because their refractive index is lower.

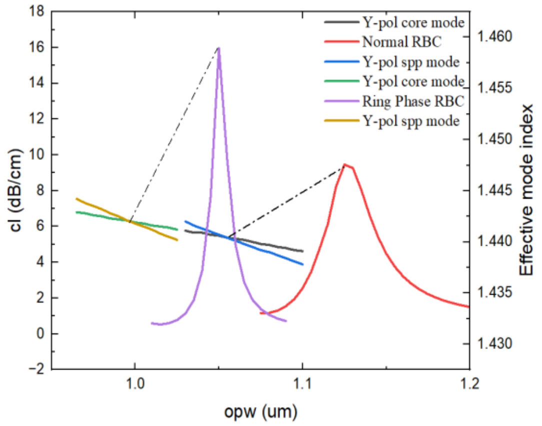

Fig 8 Effective index option for Y-polarized principle allows to know reflectivity and confinement loss along with abundant contrast in the respective losses.

The phase-matching condition that generates surface plasmon resonance is confirmed by the intersection of the effective refractive index curves of the core-guided mode and surface plasmon polariton mode. The sensor achieves its early-stage malaria diagnostic sensitivity through polarization-dependent wavelength shift analysis which produces distinct resonance peak separation.

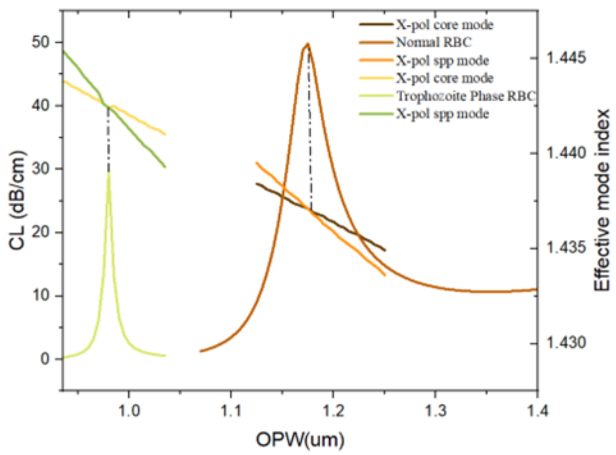

Fig 9 Confinement Loss and Effective Refractive Index Response for Trophozoite and Normal Phase RBCs (X-Polarized Mode)

The proposed PCF-SPR biosensor can identify standard and trophozoite stage malaria-infected red blood cells through the measurement of confinement loss and effective refractive index response to x-polarized light. The normal red blood cells show a specific resonance peak at their high operating wavelength which matches their increased refractive index. The refractive index of trophozoite-infected red blood cells decreases more than during the ring phase which causes their resonance peak to shift toward lower operating wavelengths.

The testing of normal red blood cells together with malaria-infected red blood cells in their trophozoite phase showed that both groups produced different resonance patterns when exposed to y-polarized light. Typical red blood cells produce a distinct resonance peak at a longer wavelength because their refractive index values are higher than normal. Trophozoite red blood cells show a new resonance peak which operates at shorter wavelengths because their refractive index decreases during this particular infection stage. The point where the effective refractive index curves of the core-guided mode and surface plasmon polariton mode converge indicates the phase-matching need for surface plasmon resonance.

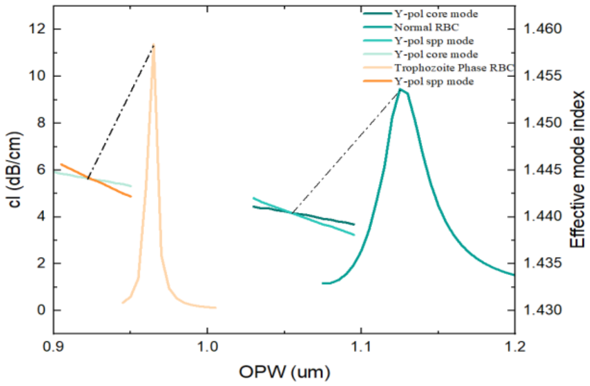

Fig 10 Confinement Loss and Effective Refractive Index Response for Normal and Trophozoite Phase Red Blood Cells (Y-Polarized Mode)

The application of X-polarized stimulation on malaria-infected red blood cells leads to their demonstration of peak resonance activity which shows their typical behavior during both normal and schizont phases. The normal red blood cells show their maximum optical performance at higher operating wavelengths because their refractive index exceeds that of other blood cell types. Schizont-phase infected red blood cells show a decrease in refractive index which causes their resonance peak to move toward lower operating wavelengths as the infection advances. Surface plasmon resonance occurs when the effective refractive index curves of surface plasmon polariton mode and core-guided mode intersect at their phase-matching point.

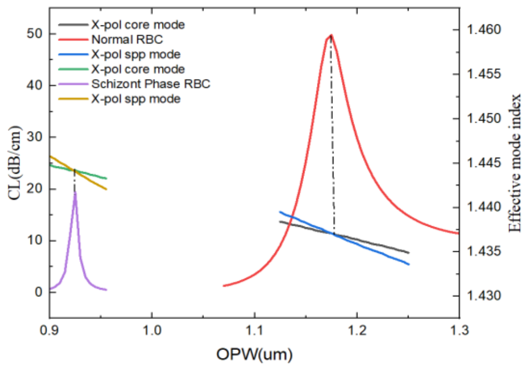

Fig 11 Confinement Loss and Effective Refractive Index Response of Normal and Shizont Phase Red Blood Cells (X-Polarized Mode)

The malaria-infected red blood cells show strong resonance activity through both their normal and schizont stages when researchers apply x-polarized stimulation. Red blood cells reach their maximum peak at higher working wavelengths because their refractive index exceeds the refractive index of other blood cell types. Schizont phase infected red blood cells display a resonance peak that moves to lower operating wavelengths because their advanced infection stage has decreased their refractive index. Surface plasmon resonance occurs when the effective refractive index curves of the surface plasmon polariton mode and the core-guided mode cross at their phase-matching point.

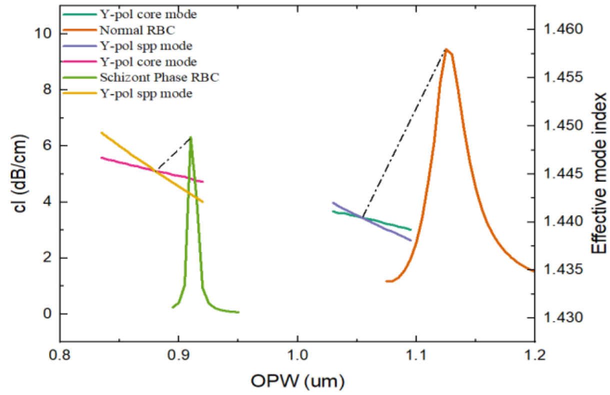

Fig 12 Resistance against confinement loss and effective refractive index response for stages of Schizont phase and normal RBCs (Y-polarized mode)

Malaria-infected red blood cells during their normal state and their schizont state display different loss of confinement and effective refractive index changes when researchers expose them to y-polarized light. Normal red blood cells create a resonance peak which operates at a higher wavelength because their refractive index exceeds that of other materials. The infected cells at this advanced stage of infection experience a significant fall in refractive index which results in a major resonance peak shift that moves to lower operating wavelengths during the schizont phase of red blood cell infection. Surface plasmon resonance occurs when the effective refractive index curves of the surface plasmon polariton mode and the core-guided mode reach their junction point through phase-matching conditions.

CONCLUSION

The research study presents a design for a biosensor which uses hexagonal photonic crystal fiber-based surface plasmon resonance technology to detect malaria. The proposed sensor can detect malaria infection by changes in red blood cell refractive index that occur during the ring, trophozoite, and schizont stages of the disease. The biosensing capability of the sensor construction is demonstrated by strong optical confinement in the fiber core and efficient plasmonic coupling at the gold-analyte border. The sensor detects both x- and y-polarized signals accurately because the polarization-dependent testing shows uniform performance across different tests.

The sensor demonstrates its ability to differentiate between healthy blood samples and malaria-infected samples through numerical studies which show distinct resonance wavelength patterns between healthy red blood cells and those infected with malaria. The infection progression leads to a reduced refractive index which causes the system to operate at lower working wavelengths. The system demonstrates strong light-matter interaction together with its high sensitivity during the schizont development stage because it produces significant wavelength changes. The results demonstrate that the PCF-SPR biosensor system successfully detects malaria through different disease stages with accurate results.

The suggested biosensor provides a compact yet highly sensitive diagnostic system which does not require any labels for malaria detection. The system enables both advanced infection monitoring and early-stage detection because its simple design powers its reliable performance and its strong plasmonic response. The PCF-SPR biosensor presents high potential for practical biomedical applications and point-of-care diagnostic use because it needs further testing and development to achieve operational status which will enable quick malaria detection and better health outcomes.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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[13] The researchers T. Das A. Roy and P. K. Paul developed numerical models for PCF-SPR sensors which they used to perform biomedical analysis in their study at J. Lightwave Technol. The study appeared in volume 41 issue 2 between pages 321 and 329 in the year 2023.

[14] The study presents a refractive index sensor that operates through surface plasmon resonance in a dual-core photonic crystal fiber system. The research conducted by A. K. Singh and P. Chauhan appeared in Photonics Nanostructures Fundam. The study covers volume 43 of their work with article number 100495-2023.

[15] F. Liu and Y. Zhao published "Graphene-enhanced PCF-SPR sensor for chemical and biomedical sensing" in IEEE Photonics Technol. Lett. which appears in volume 35 and issue 12 on pages 789 to 792 for the year 2023.

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[17] The study "Investigation of surface plasmon resonance based PCF sensor for multi-parameter sensing" appears in J. Opt. vol 26 no 6 under article number 065501 for the year 2024 with H. S. Lee and D. H. Kim as authors.

[18] The research "Optimization of photonic crystal fiber SPR sensors for low RI detection using FEM" appears in Opt. Fiber Technol. volume 78 under article number 103273 for the year 2024 with R. D. Kumar and P. K. Sharma as authors.

[19] The document presents an analysis of PCF-SPR sensor performance. The research uses hybrid plasmonic materials to detect biochemical substances. The publication appears in Opt. Mater. under article number 113373 in volume 138. The article shows the research work of V. R. Patel together with J. S. Bhatt.

[20] The document presents a PCF-SPR refractive index sensor which uses multiple functional coatings to improve its biomedical detection capabilities. The research appears in IEEE Access volume 12 between pages 65432 and 65445. N. Chatterjee and A. Basu conducted the research study.

[21] The authors A. Shafkat A. N. Z. Rashed H. M. El-Hageen and A. M. Alatwi published their work "Design and analysis of a single elliptical channel photonic crystal fiber sensor for potential malaria detection" in the Journal of Sol-Gel Science and Technology volume 98. The article can be found in the publication through page 202 to page 211. The publication date of the article is February 2021.

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