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Ultra-Senstive Plasmonic Biosensor using Photonic Crystal Fiber for Early Detection of Breast (Type1), Blood and Cervical Cancer

Vinod G V[1], Gayathri Karripeti[2], Navyasri Pulletikurthi[2], Ayyappa Vepakayala[2], Palguna Sri Ram Tadi[2]

Department of ECE, Godavari Global University, Rajamahendravaram, INDIA.
Department of ECE, Godavari Institute of Engineering & Technology (A), Rajamahendravaram, INDIA

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KEYWORDS

Perfectly Matched Layer, Photonic crystal fiber, Surface plasmon resonance, Resolution, Confinement loss.

ABSTRACT

This project presents the design and simulation of an ultra-sensitive plasmonic biosensor based on photonic crystal fiber (PCF) for advanced biomedical applications. The sensor is engineered to detect minute refractive index changes caused by specific biomolecules in body fluids, enabling real-time, label-free diagnosis of breast type 1(BCT1) cancer, blood cancer (BLC), and cervical cancer. The refractive index variations considered from 1.376 to 1.399. By enhancing surface plasmon resonance (SPR) through optimized PCF structures, the proposed design achieves high sensitivity and compactness suitable for portable, point-of- care diagnostics. Unlike conventional bulky and less sensitive optical sensors, this work employs a solid-core PCF design with gold nanowires to overcome issues like metal film degradation and fabrication complexity. Finite element method (FEM)-based simulations using COMSOL Multiphysics are used to analyze confinement loss, field distribution, and wavelength shifts under varying analyte indices.

INTRODUCTION

Cancer is a group of diseases in which there is abnormal and uncontrolled growth of cells, resulting in the invasion of neighboring tissues and metastasis in distant areas of the body through the bloodstream or the lymphatic system. The traditional approaches used for the determination of the presence and nature of cancer include biopsy, whereby samples are studied microscopically, and imaging techniques in medical sciences, including X-ray imaging, computed tomography scanning, magnetic resonance imaging, and ultrasonography, whereby cancerous tissues are visualized. Furthermore, blood tests and analysis of tumor markers are commonly used to determine

abnormal bioactivities caused by the presence of cancer. Cancer is mainly caused by mutations in the genetic makeup of organisms, characterized by irregular regulation of the cell cycle and leading to abnormal growth and multiplication of cancerous cells. The mutations in the genetic makeup of organisms may result from exposure to carcinogens, including smoke from tobacco, ionizing radiations, toxic chemicals, infections, genetic makeup, unhealthy lifestyles, weak immune capability, and other environmental factors. The onset of cancer due to the cumulative effects of these factors causes normal cells to become cancerous, thereby supporting the need for early intervention in the treatment of cancer. Recently, the use of photonic crystal fiber surface plasmon resonance biosensors (PCF-SPR) has gained considerable popularity owing to their high sensitivity to the minute refractive indices of biomedical samples. The strong subwavelength light confinement offered by photonic crystal fibers and the metal/dielectric interface-induced plasmonic resonances in PCF SPR biosensors make them promising tools for the early diagnosis of various diseases, including cancer.

Efforts to improve the efficiency of resonance coupling and biosensing precision have led to the proposal of various PCF- SPR biosensor designs. Gold twin-core PCF SPR biosensors have shown improved plasmonic resonance coupling efficiency for accurate identification of malignant cells based on variations in their refractive indices [1]. Other advancements are bidirectional surface optimized dual-core PCF-SPR biosensors that exhibit high efficiency in resonance coupling as well as the ability to identify multiple variants of cancerous cells accurately and have excellent potential for diagnosing early-stage cancers [2]. Numerical simulation has become an important area for improving the efficiency of SPR biosensors, and simulation research has indicated large resonance wavelength variations for refractive index differences of cancerous cells [3] Apart from cancer detection, PCF-based SPR biosensors have been studied extensively in infectious disease diagnosis as well.

Highly sensitive PCF-based plasmonic sensors optimized in terms of structural and material approaches have been effectively used in the diagnosis of malaria infection, showing the high biomedical applicability of PCF-based SPR sensors [4]. Sensitivity improvement and confinement loss features continue to play a vital role in accurately detecting cancer cells. Highly optimized PCF-based SPR biosensors with enhanced sensitivity and different confinement loss spectrum features have enabled the effective discrimination between healthy and cancer cells [5].

Numerical analysis has been performed extensively to confirm the efficiency of PCF-based SPR biosensors in cancer cell detection using resonance wavelength differences caused due to refractive index differences [6]. Structural modification methods like side polishing have also received significance for plasmonic interaction improvement. Dual- side-polished PCF-SPR biosensors provide strong field confinement and high accuracy of measurements for various types of cancer cells [7].

Dual-core PCF has also demonstrated substantial potential because of its optimal mode coupling properties, producing high sensitivity and stable measurements of cancer cells through refractive-index modulation [8]. Light-matter interaction can also be increased by polishing techniques. The bottom side-polished PCF-SPR biosensor greatly improves the light matter interaction, thus enabling the early and accurate detection of cancerous cells [9]. New geometries in PCFs have been recently proposed, aiming to improve sensing properties. Spiral PCF-SPR biosensors show improved sensitivity and effective light-matter interaction, thus enabling accurate early-stage cancer diagnosis [10]. Material engineering has proved to become an effective technique for the enhancement of sensor capabilities. Au-TiO2 coated PCF-SPR refractive index sensors have shown better sensing capabilities and detectability because of the enhanced light-matter interaction at the plasmonic boundary layer interface [11].

In the similar context, the advanced configuration of the enhanced PCF-SPR sensors has been shown to have better plasmonic intensity and sensing capabilities [12]. There have been critical review articles that acted as key effective tools for the recognition of the gaps within the study of PCF biosensors for the diagnosis of cancer on the platforms regarding the basic operation and design aspects due to biosensor limitations [13]. The D-shaped PCF-SPR biosensors have also undergone enhanced analyte interaction, which resulted in a high refractive index for cancer diagnosis [14]. The early works on PCF-based biosensors for SPR biosensing paved the way for modern developments, achieving high sensitivity for

cancer cell sensing [15]. The use of advanced hybrid materials also further enhanced limits on its capabilities. Hybrid biosensors for PCF-SPR, with layers of gold, graphene, and layers of $Ti_3C_2T_x$ MXene, displayed ultra-high sensitivity for its detections due to strong plasmonic properties [16].

The optimized PCF-SPR biosensors are still showing immense potential in diagnosing cancer. Highly sensitive PCF-SPR biosensors with high resolution ability have successfully identified cancer cells with high accuracy [17]. Dual-core refractive index PCF biosensors have also shown efficient mode conversion ability, allowing for early diagnosis of blood cancer with precise refractive index measurements [18]. Moving beyond the optical domain, a Terahertz-based PCF biosensor has been designed for identifying breast cancer cells based on electromagnetic effect ability, further progressing the use of PCF biosensor technology in healthcare applications [19].

In addition, the exposed-core PCF-SPR biosensor has increased the accessibility of the analyte, remarkably improving the detection accuracy of cancer cells [20].

MODEL BASED STRUCTURAL ANALYSIS

The structure of the proposed photonic crystal fibre for early detection of BCT1, BLC and cervical cancer is designed with multiple layers like PML Layer, Analyte and Gold. It is a multiple layer cylindrical structure. Fig1(a) shows that the diagram of sensor to detect the early stage of some type of cancers. Here it has four layers. The outer layer is perfectly matched layer (PML) and its thickness is 1.3[um], it mainly absorbs outing waves. The second layer is Analyte the thickness of it is 1.7[um]. It is filled with RBCs. The third layer is Gold (Au), it is used for SPR. The thickness of gold layer is 60[nm]. Here we use a single core PCF. The horizontal distance between each hole (horizontal pitch(a1)) is 2 [um]. and the vertical pitch 1(a2) is 1.414[um] and vertical pitch 2(a3) is 1.5[um]. The diameter of each hole in the core is 0.4[um]. Fig1(b) tells the mesh analysis of the proposed biosensor. For the proposed biosensor, mesh analysis was performed using a normal element size, resulting in 78 vertex elements, 640 boundary elements, and a total of 12,582 elements.

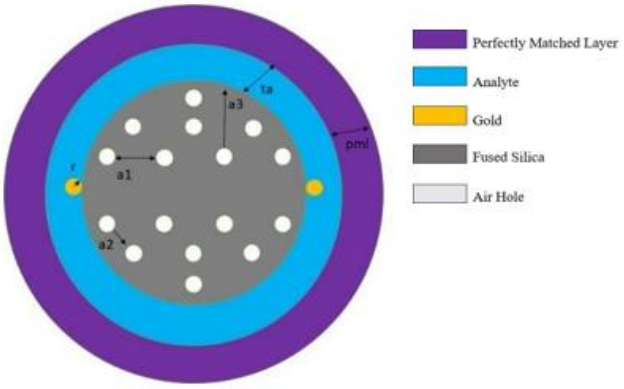
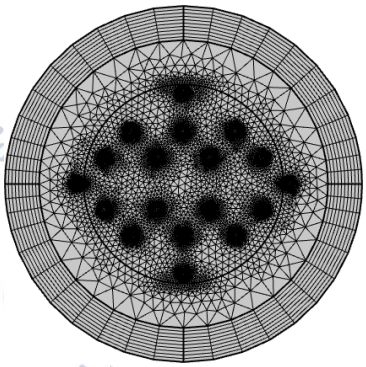


Fig1.ProposedPCF
Cross-sectional geometry of proposed PCF



Physically controlled Mesh

EXPERIMENT SETUP

The test setup of the proposed PCF-based plasmonic biosensor is sketched in Fig. 2. Initially, abroad bandlight source is coupled to an SMOF for stable and low-loss transmission of the input signals

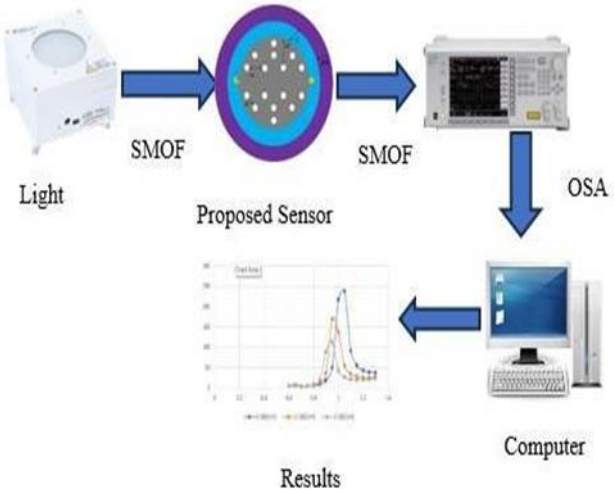


Fig2: Experimental Setup of the proposed method

Then, the guided light is launched into the designed PCF sensor region, in which the evanescent field interacts with the gold-coated analyte channel and excites SPR. Any change in the refractive index of the analyte representing healthy or cancer-affected samples will provide a measurable shift in resonance wavelength and confinement-loss characteristics

The signal fromthe PCF sensor is collected byanother SMOF and routed towards an Optical Spectrum Analyzer (OSA). This OSA records the transmitted spectrum and identifies the resonance dips corresponding to refractive- index changes in BCT1,BLC,and cervicalcancer samples.A computer processes the spectral data,studying wavelength shift and lossvariations ,plotting ,and making comparisons.This setup provides are liable platform for the evaluation of sensor sensitivity and demonstrate sits capability for early and accurate cancer detection based on subtle refractive-index variations.

MATHEMATICAL CALCULATIONS

In the proposed plasmonic sensor, quartz glass is selected as the material for boththe overlay and the PML. Its refractive index (RI) is determined using the Sellmeier dispersion relation shown in equation (1):

Here, *n*silica represents the Ri of quartz glass, and λ denotes the operating wavelength measured in micrometers (μm).

To enable effective coupling betweenthe guided core mode and the surface plasmon mode, a thin gold (Au) layer is employed. The optical response ofAu is evaluated using the Drude– Lorentz model, expressed in equation (2):

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

In this equation, ε_{Au}denotes the permittivity of gold, and the parameters ε_{∞}, ω_D, γ_D, , $\Delta\varepsilon$ correspond to the high-frequency constant, plasma frequency, damping frequency, oscillator strength, oscillator bandwidth, and weighting factor, respectively.

Wavelength sensitivity(WS), indicating the system's ability to detect RI variations, is calculated using equation (3):

$$S_w(\lambda) = \frac{\Delta\lambda_{peak}}{\Delta n_a}\,[nm/RIU]$$

Where $\Delta\lambda_{peak}$ is the peak resonance shift between healthy and cancerous samples,and Δn_a represents their RI difference.

Sensor resolution, which determines the smallest detectable RI change,is evaluate dusing equation (4):

$$\text{Res}(\lambda) = \Delta n_a \times \frac{\Delta\lambda_{min}}{\Delta\lambda_{peak}}\,[\text{RIU}]$$

A minimum detectable wavelength shift of 0.1 nm is considered for $\Delta\lambda$min.

The sensing performance is further assessedusing the Figure of Merit(FoM),defined by equation (5):

$$\text{Figure of Merit} = \frac{S\lambda}{FWHM}\,[\,\text{RIU}^{-1}]$$

Where FWHM denotes the full width at half maximum of the resonance curve.

The equation represents amplitude sensitivity(AS), which quantifies how strongly the optical attenuation (loss) changes with a small variation in the analyte refractive index.

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

ANALYSIS OF SIMULATED DATA

This interaction facilitates the excitation of surface Plasmon oscillations,a phenomenon constituting the operational principle behind surface plasmonic resonance based sensing.Due to its strong sensitivity to minute changes in the refractive index of the surrounding medium,this interaction represents a mechanism especially applicable to biomedical detection, where even minor biochemical or structural alterations carry important information.

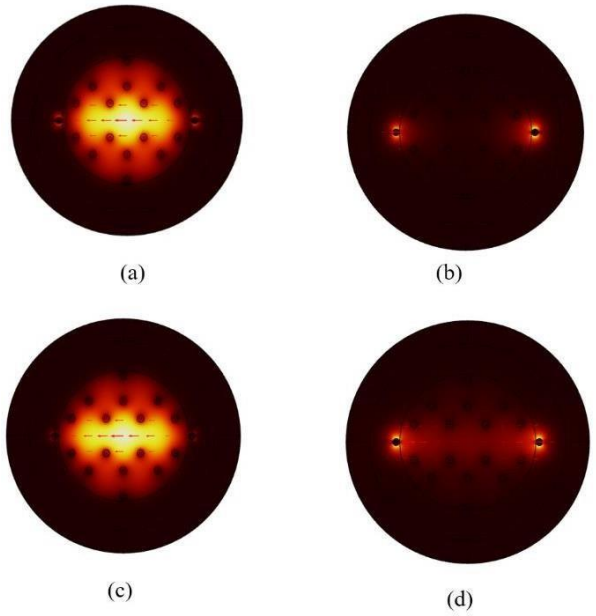


Fig3:X-polarizedElectric Field Distribution for BCT1 a)core(Normal) b)SPP(Normal)c) core (Infected) d) SPP(Infected)

The present structure gives an x-polarized mode with significantly higher confinement loss compared with the y-polarized mode.The higher confinement losss hows that the guided light is more coupled with the sensing interface, providing better light-matter interaction and ultimately better sensing performance. Figure (3a) depicts the x-polarized mode distribution for the normal (uninfected) sample, while Figure (3b) shows the corresponding x-polarized SPP mode. Figure (3c) depicts the x-polarized mode for the infected cell structure.

Figure (3d) presents the associated x-polarized SPP mode for the infected cell. These figures show the difference in the field behaviour between the healthy and infected states and thus justify the efficiency of the proposed structure in refractive index-based biomedical sensing.

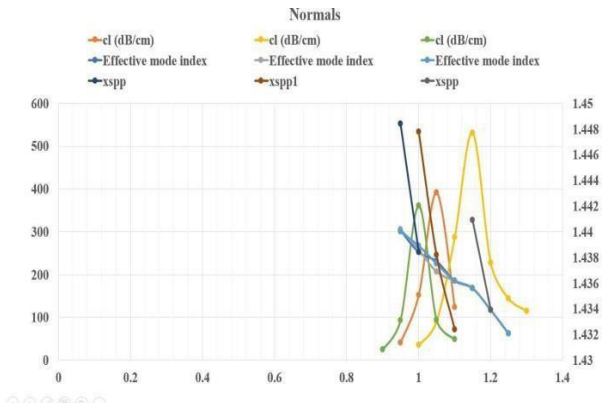


Fig4(a):Normals of all three cancers

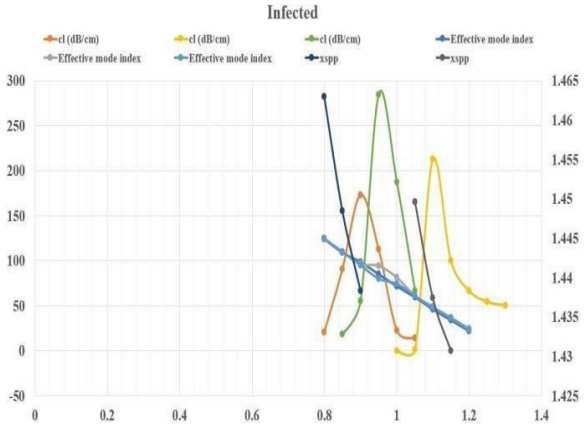


Fig4(b):Infected of all three cancers

Fig(4a):operating wavelength vs confinement loss in normal cells of BCT1,BLC and Cervical cells and Fig(4b) are operating wavelength vs confinement loss in infected cells of BCT1,BLC, Cervical cells.

BREAST(TYPE1)CANCER

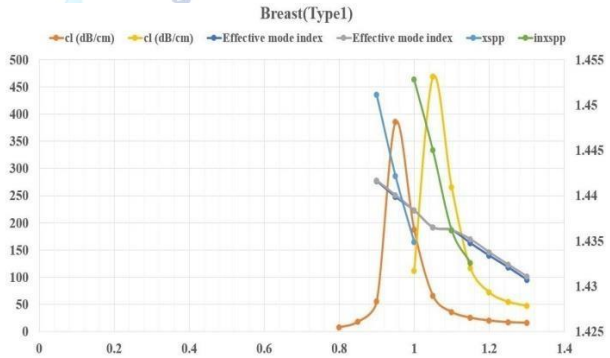


Fig5(a):Phase matching of BCT1

In this high-loss region, strong interaction between the guided mode and the altered dielectric properties ofthe cancerous tissue is suggested. The effective mode index decreases gradually with increasing wavelength, while the SPP curve shifts toward the resonance point.All these features confirm that BCT1 shows a unique optical signature and hence its reliable identification is possible using the proposed PCF–SPR sensing structure.

CERVICALCANCER:

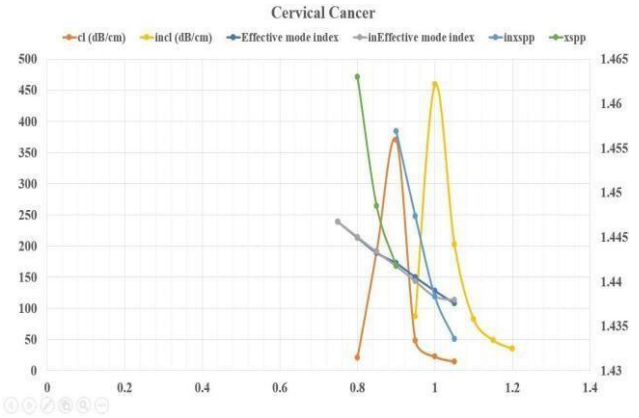


Fig5(b):Phase matching of CervicalCancer

The set graphs illustrate the plasmonic and optical behaviour of cervical cancer under PCF- SPR sensing. It can be seen from the confinement-loss curve that there is a sharp resonance peak near the operating wavelength due to the strong coupling between the guided mode and the cancerous medium. Such a peak truly reflects the changed refractive index profile of cervical cancer tissue. The effective mode index decreases gradually with wavelength, while the SPP curve shifts toward the resonance region, which confirms that the plasmonic interaction is stable. Both of these trend's evidence that cervical cancer will induce a distinct and well- defined optical signature, which in turn allows for accurate detection and differentiation using the proposed sensing structure.

BLOODCANCER

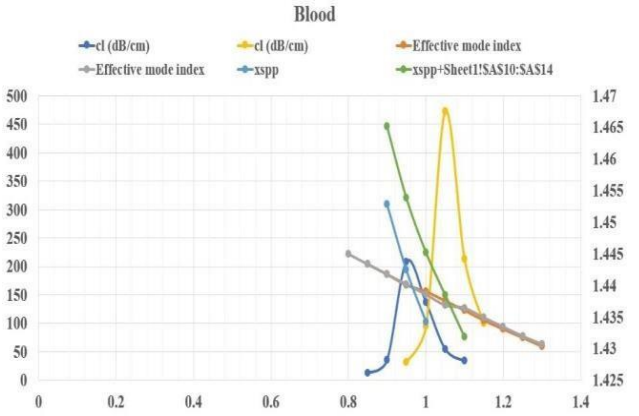


Fig5(c):Phase matching of BLC

The two graphs represent the plasmonic and optical characteristics of BLC with in the proposed PCF–SPR sensing structure.The confinement-loss curve shows a sharp and narrow resonance peak, indicating highly sensitive light–tissue interaction influenced by the altered refractive- index profile of blood cancer cells. Indeed, the effective mode index gradually decreases with wavelength and the SPP position shifts toward the resonance point, confirming strong plasmonic coupling near the peak region. Blood cancer has a more pronounced and steeper resonance response compared to other types of cancer, offering a distinct signature in its optical representation, enabling proper detection and discrimination by the designed sensor.

CONCLUSION

The proposed single-core photonic crystal fiber-based plasmonic biosensor shows extensive potential in the early detection of BCT1, BLC, and cervical cancer cells. Each type of cancer shows a different optical signature, as evidenced bywell-separated resonance peaks,significant changes in confinement loss, and consistent shifts in the effective mode index. The sensor is highly sensitive to changes in refractive index.The WS value varies from 7142.857nmRIU^{-1} to 10714.28 nmRIU^{-1} for different samples of cancer. More importantly, the refractive-index resolution varies from1.4×10^{-5}to9.33×10^{-5}RIU.The maximum FoM for detecting cervical cancer is achieved. This clearly implies that the proposed biosensor has high capabilities for correct, sensitive, non-invasive detection of cancer, hence holding immense promise for biomedical diagnosis toward early-stage screening applications.

Conflict of interest statement

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

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