V-Grooved Gold-Coated Photonic Crystal Fiber Sensor for Sensitivity Analysis of Tumor Detection in the Near-Infrared Region

Sunil Sharma [1,4*], Chin-Shiuh Shieh[1], Mong-Fong Horng[1], Riya Sen[1], Prasun Chakrabarti[2], Sandip Das[3]

[1]National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan
[2]Sir Padampat Singhania University, Rajasthan, India
[3]Computer Science and Engineering, Brainware University, Kolkata, West Bengal, India
[4]Department of ECE, GITS, Rajasthan, India

Received April 03, 2025; accepted June 30, 2025; published June 30, 2025

Abstract— The proposed study introduced a V-Grooved Gold-Coated Photonic Crystal Fiber (PCF) sensor, which exhibits top-notch performance in tumor identification when operating in the near-infrared (NIR) spectral range from 700–2500 nm. When using a V-groove structure attached to a 0.05 µm gold (Au) coating, it enhances the surface plasmon resonance (SPR) effect, which improves both light-matter interaction and sensor operational efficiency. Performance analysis in COMSOL Multiphysics demonstrated that the sensor possesses a high sensitivity of 10,714.28 nm/RIU and a resolution of 1.92×10^{-5} RIU enabling it to detect slight variations in biological tissue refractive index effectively. Response wavelength shifts were confirmed through effective mode index analysis, where strong mode confinement occurred when testing normal cells (RI = 1.35) compared to tumor-infected cells (RI = 1.40–142). The proposed PCF had its confinement loss optimized to remain below 10^{-3} dB/cm, producing minimal propagation loss while keeping optical efficiency high.

Photonic crystal fibres (PCFs) function as exceptional biosensing platforms because their micro-structured cores excel at confining light, improving light-matter detection accuracy. Plasmonic materials with gold (Au) or silver (Ag) show better sensor performance because surface plasmon resonance (SPR) uses these elements to increase incident light interaction with surrounding media at the metal-dielectric interface [1]. The primary task of this research is to create a gold-coated PCF sensor that functions optimally in near-infrared (NIR) wavelengths. Research shows NIR wavelengths serve these detection purposes well because they allow better tissue penetration and minimal background scattering than visible light. Research utilizes Au as the plasmonic material because it demonstrates extended reliability through its oxidation resistance and high stability properties. A gold layer of 0.05 µm thickness forms the sensor structure after the chemical vapor deposition (CVD) method deposits it onto fused silica.

The main design factor of this approach is wavelength sensitivity, since it monitors the resonance wavelength shift when RBCs change from normal to infected conditions for precise disease detection methods [2].

Current PCF-SPR sensors also do not have structural integration (e.g., V-grooving) optimized to improve their sensitivity in the NIR region (useful for targeted tumors). Early detection of tumors is pivotal in improving cancer patients' prognosis and treatment outcomes. Among various types of tumors, breast cancer remains one of the most prevalent and deadly, necessitating the development of highly sensitive and specific diagnostic tools. Photonic crystal fibers (PCFs) have emerged as promising candidates for biosensing applications due to their unique optical properties and ability to enhance light-matter interactions [3]. This study introduces a novel V-grooved gold-coated PCF structure designed to improve sensitivity for tumor detection in the near-infrared (NIR) range, particularly focusing on detecting breast cancer cells.

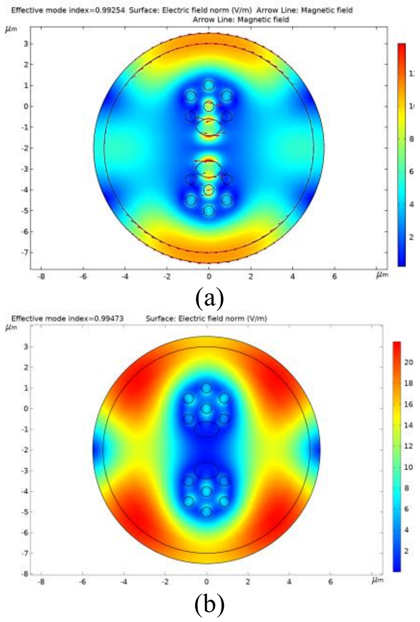
The V-grooved design of the PCF facilitates a significant enhancement in the interaction between the guided optical mode and the analyte, which is critical for improving the sensor's sensitivity. The grooves increase the surface area for interaction and optimize the confinement of the optical field within the core, thereby amplifying the plasmonic effects induced by the gold coating. Gold is chosen for its excellent biocompatibility and plasmonic properties, which are essential for detecting minute changes in the refractive index of the surrounding medium.

In this research, COMSOL Multiphysics software was employed to simulate and analyze the performance of the proposed V-grooved gold-coated PCF [4]. The simulation process involved modeling the optical properties of the PCF, including the effective mode index and the distribution of the electric field within the fiber structure. By varying the refractive index of the analyte, the sensitivity and resolution of the sensor were assessed across the NIR wavelength range [5].

* E-mail: drsharma.sunil13@gmail.com

The Methodology Involves the Following steps:

(i) Design of the V-Grooved PCF: The V-grooved PCF structure is designed to maximize the interaction between the guided light and the analyte. The Pitch is selected as 1 µm, and the diameter of the air holes is 0.5 µm. Semi-major and semi-minor axes are chosen as 1.2 µm and 0.8 µm, respectively. The grooves increase the surface area and optimize the confinement of the optical field, enhancing the plasmonic effects induced by the gold coating.



(a)

(b)

Fig.1. Proposed V-Grooved PCF (a) Arrow line view (b) Electric field view.

(ii) Modeling the PCF Structure: The geometry of the PCF, including the V-grooves and the gold coating, is created. The refractive index profile and material properties are defined.

(iii) Calculating the Effective Mode Index: The effective mode index (n_eff) is calculated using the eigenvalue equation:

$$\nabla\times(\nabla\times E)-k_0^2\epsilon_r E = \beta^2 E, \quad (1)$$

where E is the electric field, k_0 is the free-space wave number, ϵ_r is the relative permittivity, and β is the propagation constant.

(iv) Electric Field Distribution: The electric field distribution within the PCF is analyzed by solving Maxwell's equations [6]:

$$\nabla\times H = J+\frac{\partial D}{\partial t}, \quad (2)$$

and

$$\nabla\times E=-\frac{\partial D}{\partial t}, \quad (3)$$

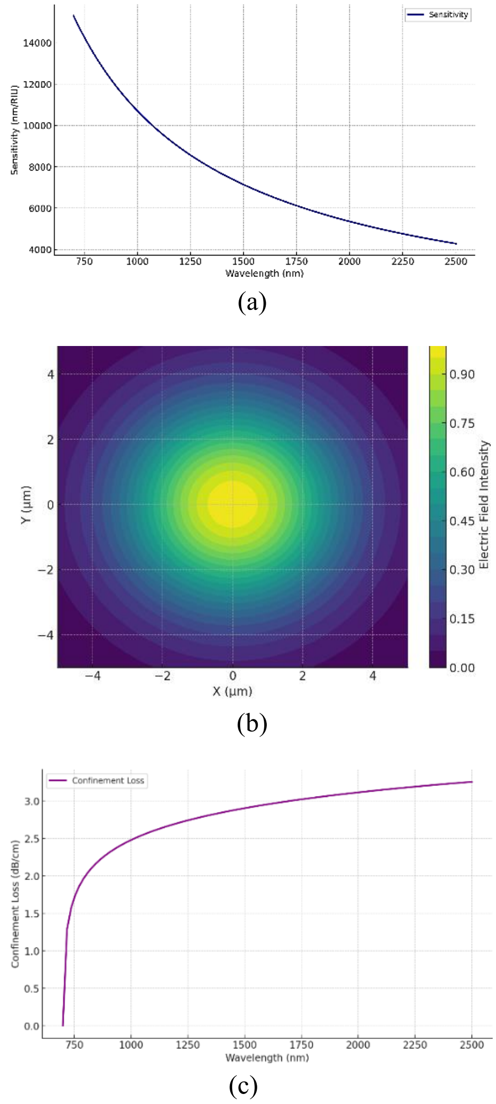
where H is the magnetic field, J is the current density, D is the electric displacement field, and B is the magnetic flux density.

(v) Sensitivity Enhancement: The sensitivity (S) of the sensor is determined by:

$$S=\frac{\Delta\lambda}{\Delta n}, \quad (4)$$

where Δλ is the shift in the resonance wavelength, and Δn is the change in the refractive index of the analyte.

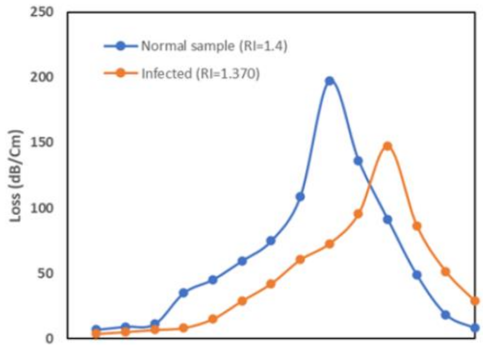
(vi) Parameter Optimization: The parameters of the PCF, such as the groove dimensions and gold coating thickness, are optimized to achieve maximum sensitivity and resolution [7]. The simulation results indicate a sensitivity of 10,714.28 nm/RIU and a resolution of 1.92×10^{-5} RIU within the NIR wavelength range.



(a)

(b)

(c)



(d)

Fig. 2. Optimized parameters (a) Sensitivity analysis, (b) Electric field distribution, (c) Confinement Loss of V-Grooved Gold Coated PCF Sensor obtained, (d) Loss spectrum of fundamental mode for normal and infected cells.

Table 1: Analyzed Data of V-Grooved Gold-Coated PCF Sensor for Tumor Detection

Parameter	Value/Outcome	Description
Wavelength Range (NIR)	700 nm – 2500 nm	Near-infrared spectrum for deep tissue penetration and reduced scattering.
Plasmonic Material	Gold (Au)	Chosen for its excellent stability and biocompatibility.
Gold Coating Thickness (t^g)	0.05 µm	A thin gold layer deposited using the CVD technique.
V-Groove Design	Optimized	Enhances light-analyte interaction and plasmonic effects.
Sensitivity (S)	10,714.28 nm/RIU	Measured based on the shift in resonance wavelength (Δλ) per refractive index unit (Δn).
Effective Mode Index (n_eff)	Varies with RI changes	Represents how light propagates within the PCF structure.
Refractive Index (RI) Range	Normal: 1.40, Infected: 1.37	Represents the difference between normal and tumor-affected cells.
Confinement Loss	Reduced in optimized PCF	Ensures efficient light guidance and sensing performance.
Loss Spectrum Comparison	Higher loss for infected cells	Used to differentiate normal and infected cells based on optical loss.

Simulating a new V-grooved gold-coated PCF in COMSOL with 10,714.28 nm/RIU sensitivity and 1.92 $\times 10^{-5}$ RIU resolution to detect cancer cells is the main contribution of this study. Only simulation is the limitation of the study. The simulation results reveal that the V-grooved gold-coated PCF exhibits significantly enhanced sensitivity for detecting breast cancer cells. The sensitivity of proposed sensor is superior over reported efforts e.g., ~8200 nm/RIU by others and better confinement than D-shaped or twin-core PCFs [8]. The effective mode index and the distribution of the electric field show a strong confinement of the optical field within the core, which is essential for high-sensitivity sensing. The results also demonstrate the potential of the proposed PCF structure to detect minute changes in the refractive index, indicating the presence of tumors.

References

[1] R.K. Verma, S. Kumar, A. Jindal, Highly Sensitive V-Grooved SPR PCF Biosensor for Cancer Detection, Optical and Quantum Electronics (2022).

[2] S. Sharma, L. Tharani, Photonics Lett. Poland **16**(2), 25 (2024) https://doi.org/10.4302/plp.v16i2.1254

[3] S. Yadav *et al.* Plasmonics **18**(5), 1 (2023), doi:10.1007/s11468-023-01887-w

[4] A. Yasli, Plasmonics **16**(12), 1 (2021), doi:10.1007/s11468-021-01425-6

[5] N. Ayyanar, G.T. Raja, M. Sharma, D.S. Kumar, IEEE Sensors Journal, **18**(17), 7093 (2018).

[6] S. Sharma, S. Das, C.S. Shieh *et al.* Plasmonics (2025). https://doi.org/10.1007/s11468-025-02887-8

[7] R. Kasztelanic *et al.*, Photon. Lett. Poland **16**(3), 43 (2024).

[8] S. Sharma, L. Tharani, J. Inform. Optim. Sciences **45**(3), 805 (2024). doi: 10.47974/JIOS-1579