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Photonic Crystal Fiber Surface Plasmon Resonance (PCF-SPR) Design for Low Concentration Biomolecule Detection

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Abstract- This study aims to design, model, and optimize a Photonic Crystal Fiber Surface Plasmon Resonance (PCF-SPR) sensor capable of detecting biomolecules at very low concentrations, particularly in the picomolar to femtomolar range, which are generally difficult to detect using conventional biosensing methods. Optimization efforts were carried out through a numerical simulation approach using a standard hexagonal PCF structure with an air hole diameter of 0.8–1.2 µm and a pitch of 1.8–2.2 µm. A gold layer with a thickness of 35–50 nm was deposited on the central capillary as the sensing core to produce strong coupling between the fundamental mode of the fiber and the surface plasmon polariton (SPP). TM mode was selected because it provides the most optimal evanescent field interaction with the plasmonic layer. The sensor performance evaluation process included measurements of resonance wavelength shift, confinement loss, full width at half maximum (FWHM), sensitivity, and figure of merit (FOM) against variations in the analyte refractive index. The simulation results show that a gold layer thickness of 40 nm produces the best performance, characterized by a sensitivity of 4500 nm/RIU, FWHM of 38 nm, confinement loss of 210.5 cm^{-1}, and the highest FOM of 118.4 RIU^{-1}. These values indicate an ideal balance between evanescent field penetration, optical attenuation, and plasmon coupling efficiency. This design has also been proven capable of detecting changes in refractive index down to 10^{-6} RIU, making it potentially useful for detecting protein, DNA, or antigen biomarkers at ultra-low concentrations. In conclusion, this PCF-SPR design offers highly sensitive, stable biosensing performance and is worth developing for early medical diagnostics, environmental monitoring, and food safety applications. Further development is recommended by integrating 2D materials, microfluidic systems, and D-shaped structure-based metal deposition techniques to improve long-term stability and ease of fabrication.

Keywords: *Optical Sensor, PCF-SPR, Biomolecular Biosensor, High Sensitivity, Biomedical*

1 Introduction

PCF can be used in designing biosensors based on Refractive Index variations. Various techniques for RI sensing have been developed to date, among which the SPR phenomenon is most often used for optical sensing applications, with a nanometer scale that is highly suitable for biomolecular detection. Several commercial SPR sensor products typically use prism-based configurations that are difficult to miniaturize (Ganesan, 2020). This technique is used in the fields of food quality monitoring, environmental monitoring, biomedical diagnostics, and so on. In this modern era, SPR biosensors have dominated the field of biomedical engineering. SPR biosensors have been widely used to detect unknown analytes in disease diagnosis, measure protein and fibrinogen density, detect coagulation, antigens, and antibodies, as well as identify toxins, environmental safety, and temperature sensors (Hossain, 2020). In 1962, Liedeberg and Nylander demonstrated the usefulness of SPR as an optical sensor, which has provided a boost in the fields of chemistry, physics, and biology. The use of SPR has been commercialized by many companies under different brand names. SPR can measure the movement and affinity of biomolecular bonds in real time and is label-based. SPR has distinct advantages over radioactive or fluorescent labeling methods because those labeling methods can damage bonds (Putra et al., 2021).

PCF has revolutionized photonic sensors because it can easily control light flow through structural parameter changes. PCF is equipped with unique features such as controlled birefringence, high

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nonlinearity, single-mode behavior, and other advances related to dispersion. Anisotropic biosensor designs use PCF. They have created spiral air hole arrays for their sensors. Au (gold) is used as a plasmonic material in the sensors they designed. Their sensors show WS (Wavelength Sensitivity) of 4600 nm/RIU and 4300 nm/RIU (Shakya et al., 2022). The factor that affects the sensing performance of the SPR sensor is the metal film. Strong resistance to chemicals and oxidation makes gold (Au) an attractive choice for SPR sensors characterized by high stability. However, high gold losses are attached, thus sacrificing sensing sensitivity and resolution due to the wide width of the spectrum. In contrast, silver (Ag) allows low losses to improve sensing sensitivity and resolution due to its small part of imaginary permittivity, but it is susceptible to oxidation and also easily forms silver sulfide (Zekriti, 2021). Gold is a popular choice due to its resistance to oxidation and high chemical stability, although it has the disadvantage of lower sensitivity than silver. On the other hand, silver has a higher sensitivity due to its superior optical properties, but it is susceptible to oxidation and degradation, which can limit its use in long-term applications (Mauludi et al., 2024).

SPR based on gold nanoparticles is mixed in solution and used as a substrate for surface plasmon formation. When biomolecules interact with gold particles, changes in local refractive indexes cause shifts in plasmon resonance, which can be measured with UV-VIS spectrometers. UV-VIS measurements are concerned with electronic transitions induced by the interaction between UV (200-380 nm) and VIS (380-780 nm) electromagnetic wave radiation (Wakary et al., 2020). Gold nanoparticles have a large surface area and can interact with a greater number of biomolecules, resulting in stronger signals (Karnwal et al., 2024). SPR imaging is a technique that allows visualization of the distribution distribution of biomolecular interactions on the sensor surface. Image detectors are used to capture changes in the intensity of light reflected across the sensor's surface, creating a spatial map of biomolecular interactions. This technique is particularly useful for studies that require local information about interactions, such as protein interaction mapping or multiple detection (Apsari et al., 2025). Several sensing methods have been developed in optical communication such as fiber Bragg grating, micro-ring resonator, multimode interference, etc. Recently, SPR has been widely explored in SPR sensing on polymer optical fibers (PCF). In the PCF SPR sensor, there are three types of fabrication methods, namely internal metal deposition (IMD), D-shaped PCF, and external metal deposition (EMD) technique. The IMD technique of the air pit is coated with plasmonic material. This deposition technique is challenging, and its practical fabrication is very complex (Ramola et al., 2021).

The ability to detect biomolecules (biomarker proteins, DNA, miRNAs, exosomes, or viral antigens) at very low concentrations (picomolar to femtomolar) is key in the early diagnosis of cancer, neurodegenerative diseases, viral infections, as well as real-time monitoring of drug therapies (Sowmya et al., 2024). For example, the concentration of carcinoembryonic antigen (CEA) in early-stage colorectal cancer patients is only about 5–20 pg/mL, while prostate-specific antigen (PSA) for early detection of clinically meaningful prostate cancer is below 100 fg/mL. Concentrations of such small amounts are almost impossible to detect reliably by conventional methods such as ELISA, PCR, or even last-generation prism-based surface plasmon resonance (Runkai et al., 2020). Different types of PCF-SPR sensors have been reported by coating plasmonic materials on the inner air vents or outer surfaces of the PCF. However, it is difficult to add plasmonic material to the inner walls of the air vent due to the very small scale of PCF, so coating plasmonic material on the surface of optical fibers is more technically feasible (Liu et al., 2020). Current SPR technology has limitations in terms of sensitivity, especially for low-concentration analyzers or single-molecule detection. Addressing these challenges requires the design and synthesis of new nanostructural materials that can improve the interaction between incoming light and the analyte. Among these innovations, the nanoplasmonic antenna has attracted significant attention. Advances in nanoantenna design over the past decade, including dipole, bowtie, and slit-based geometry, have shown better performance in biosensing and labelless detection of proteins, nucleic acids, and pathogens (Ahmad et al., 2025). This research aims to design and optimize the structure of an advanced fiber optic sensor (PCF) that utilizes the principle of surface plasmon resonance (SPR), with the specific purpose of detecting and measuring biological molecules (such as proteins or DNA) that are present in very small amounts, and cannot be accurately detected by most conventional sensors.

2 Research Methodology

The proposed PCF-SPR design uses a standard hexagonal structure with a pitch of 1.8–2.2 µm and an air hole diameter of 0.8–1.2 µm. A 35–50 nm thick gold layer is selectively coated on the central capillary wall (or large canal) as a place for liquid analyte flow. The TM (transverse magnetic) mode was chosen as

the sensing mode because it has an electric field component that is perpendicular to the metal-dielectric interface, resulting in the most powerful coupling with the surface plasmon polariton (SPP). The sensitivity of the sensor is evaluated through the shift in resonance wavelength (or loss peak) to the variation of the analyte bias index, which is the main indicator of sensor performance in detecting changes in biomolecular concentration at very low levels. Deposition of the Gold (Au) layer on the Gold Prism with a concentration of 99% is coated on the surface of the prism using a vacuum evaporator. The mass of gold deposed on the prism is 15 mg and the deposed gold mass is 0.8 mg for each prism (Satrio & Melatih, 2020).
Performance Parameters of PCF-SPR Sensors at Gold Coating Thickness Variations

Table 1: Assumption of Bias Index Value from Analyte (detected sample) is 1.33

No.	Gold Thickness (Nm)	Resonance Wavelength (nm)	Containment Loss (Lc) (cm)	Sensitivity (nm/RIU)	FWHM (nm)	Figure of Merit (FOM) (RIU $^{-1}$)
1.	35	1120	185,2	4200	45	93,3
2.	40	1105	210,5	4500	38	118,4
3.	45	1090	195,8	4350	42	103,6
4.	50	1150	165,3	4100	50	82,0

Table 1 explains that a gold layer thickness of 40 nm is the optimal design parameter for the PCF-SPR structure, as it results in the best overall sensor performance (highest FOM) which is very promising for low-concentration biomolecular detection applications. The thick metal layer causes greater attenuation of plasmon energy (*damping*), which widens the resonance peak (enlarged FWHM) and reduces sensitivity.

PCF-SPR Sensor Measurement Configuration System Scheme

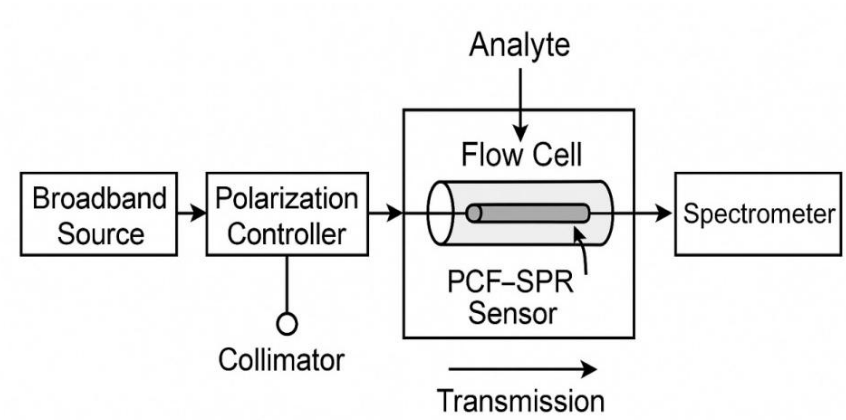

Figure 1: PCF-SPR (Real Time Measurement) Measurement System Flow Diagram

Figure 1 describes the broad-spectrum light sources (usually supercontinuum lasers, halogen lamps, or SLEDs) that produce light (most commonly used in the range of 500–1700 nm). This is necessary because plasmon resonance can occur at different wavelengths depending on the design of the PCF and the analyte index that makes the light parallel (collimated beam) in order to enter the optical fiber efficiently. The light that comes out of the PCF-SPR (transmission mode) end with resonance wavelengths, the intensity of the light will drop drastically as the energy absorbed by the plasmon forms a dip in the spectrum (Khodatars et al., 2025). The spectrometer will break down light into color components, using elements such as a diffraction lattice to separate the light into a complete spectrum. The more the wavelength shifts, the more biomolecules attach to it. SPR systems have a unique shape depending on their optical configuration, which includes prism-based and grating-based configurations as the most commonly used. The SPR system consists of key components such as a laser light source, an optical connector, a metal coating sensor chip, a sample delivery system, and a high-sensitivity detector (Yi et al., 2023). SPR sensors become simpler when diffraction grating replaces prisms in the system to generate surface plasmon waves, when light waves hit the grating surface at a specific wavelength and direction thanks to their regular design (Das et al., 2025).

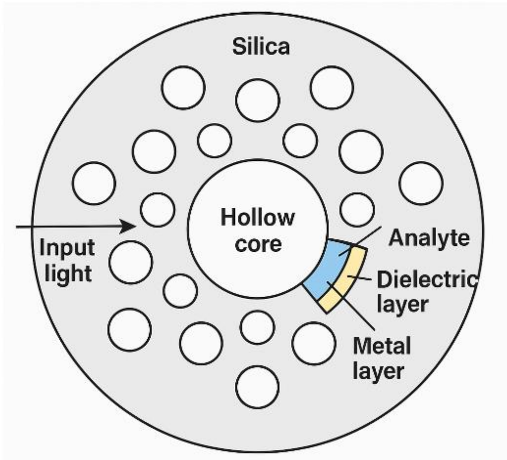

Figure 2: PCF-SPR Cross Sectional

Figure 2 illustrates that as light travels through the PCF, the electric field from the light (e.g., from visible to infrared light) that comes out will interact with the electrons in the metal layer. At certain wavelengths that meet resonance conditions, light energy is transferred to generate surface plasmons, causing light absorption (seen as peak loss in the spectrum). Changes in the concentration of biomolecules in the analyte will change the refractive index on the surface of the metal, which further shifts the wavelength of this resonance. Surface plasmon waves can only be efficiently excited by light with a specific polarization (usually transversal-magnetic or TM). This shift is measured as a sensor signal. A hollow core that serves to guide light with unique dispersion characteristics (Danlard & Akowuah, 2020). This structure is designed to optimize the overlap (*overlap*) between the light evanesen field and the metal layer, so that the excitation efficiency of SPR can be maximized. The central air vent is used to reduce the effective refractive index of the core region, so that phase matching between the plasmonic mode and the core directional mode can be achieved (Sardar & Faisal, 2024). A liquid sample containing the target biomolecule (e.g., protein, DNA) that flows over the surface of the metal layer. These biomolecular bonds will change the local refractive index on the surface of the metal.

3 Results and Discussion

The thickness of the gold layer significantly affects the interaction between the core mode and the plasmon resonance mode (SPR). At a thickness of 35 nm, the sensor achieves a sensitivity of 4,200 nm/RIU with a confinement loss of 185.2 cm^{-1}, but the FWHM is relatively wide (45 nm) so the FOM is only 93.3 RIU^{-1}. Increased thickness up to 40 nm results in optimal performance: sensitivity increases to 4,500 nm/RIU, confinement loss of 210.5 cm^{-1} (still within the low limit for efficient propagation), FWHM narrows to 38 nm, and highest FOM of 118.4 RIU^{-1}. This is due to the optimal balance between evanescent field penetration into the plasmonic layer and minimal damping, resulting in stronger phase coupling between mode cores, resulting in carefully controlled roses to ensure that the protective layer thins out without damaging the photonic crystal core (Singh et al., 2025).

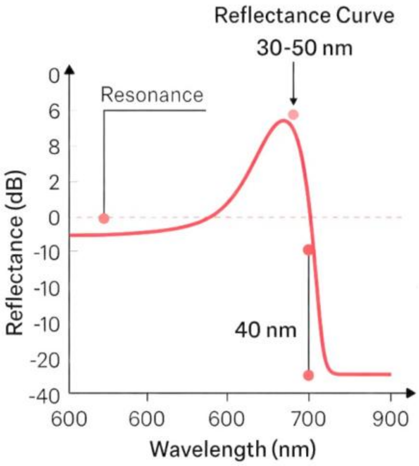

Figure 3: PCF-SPR sensor reflectance curve for 30-50 nm gold coating thickness variance

Figure 3 describes the fundamental characteristics in SPR sensors that represent optimal resonance conditions. The peak of resonance is that there is a sharp decrease in reflectance (valley) over a given wavelength range, indicating the maximum energy transfer from the incident light to the surface plasmon mode. In this condition, the light propagation constant is in line with the surface plasmon propagation constant (*phase-matching condition*). The thickness of the gold layer of 40 nm shows the most optimal resonance characteristics, characterized by the most significant depth of reflectance valley, relatively narrow curve width (*FWHM*), clear resonance position. The effect of 30 nm thickness variation with a layer that is too thin results in a less efficient coupling between the evanesen field and the plasmon mode and 50 nm indicates that the layer is too thick causing excessive optical *damping loss*, widening the resonance curve and reducing the depth of the valley (Pasquardini et al., 2023).

4 Conclusion

Analysis of a Photonic Crystal Fiber Surface Plasmon Resonance (PCF-SPR) sensor optimized for the detection of biomolecules at low concentrations with numerical simulations, it can be concluded that the PCF-SPR design with a hexagonal structure and a 40 nm thick gold coating shows the best performance by achieving a sensitivity of 4500 nm/RIU and a Figure of Merit (FOM) of 118.4 RIU^{-1}. This configuration results in an optimal coupling between the fiber fundamental mode and the surface plasmon mode, which is demonstrated by a sharp resonance peak with a narrow FWHM (38 nm) and a significant confinement loss (210.5 dB/cm). This superior performance makes the proposed sensor capable of detecting very small changes in the refractive index up to the level of 10^{-6} RIU, which is equivalent to the ability to detect biomolecules such as biomarker proteins at picomolar concentrations. Sensor system applications using transmission configurations with broadband light sources, polarization controllers, flow cells, and spectrometers have proven to be effective for real-time monitoring of biomolecular interactions. The PCF-SPR sensor design has broad application potential in the fields of early medical diagnostics, environmental monitoring, and food safety, particularly for the detection of analyte targets at ultra-low concentrations that conventional methods cannot reach. With further development, this PCF-SPR sensor has the potential to become a new generation of affordable, portable, and high-performance diagnostic tools to support personal medicine and public health globally.

5 Reference

Ahmad, W., Wang, Y., Du, G., Yang, Q., & Chen, F. (2025). Graphene-Based Plasmonic Antenna for Advancing Nano-Scale Sensors. *Nanomaterials*, *15*(12), 943.

Apsari, R., Zaidan, A. H., & Trilaksana, H. (2025). *BIOPHOTONICS AND LASER APPLICATIONS*. Airlangga University Press.

Danlard, I., & Akowuah, E. K. (2020). Assaying with PCF-based SPR refractive index biosensors: From recent configurations to outstanding detection limits. *Optical Fiber Technology*, *54*, 102083.

Das, A., Huraiya, M. A., Rahman, M. I., Chakrabarti, K., Tabata, H., Ramaraj, S. G., & Razzak, S. A. (2025). Advanced low loss PCF-based SPR sensor for enhanced sensor length configurations flexibility with exceptional superior sensing performance capability. *Applied Physics A*, *131*(6), 472.

Ganesan, S. (2020). Surface plasmon resonance based biosensor applied to phytosanitary domain.

Hossain, M. B., Hossain, M. S., Islam, S. R., Sakib, M. N., Islam, K. Z., Hossain, M. A., ... & Cho, G. H. (2020). Numerical development of high performance quasi D-shape PCF-SPR biosensor: An external sensing approach employing gold. *Results in Physics*, *18*, 103281.

Hu, R., Sou, K., & Takeoka, S. (2020). A rapid and highly sensitive biomarker detection platform based on a temperature-responsive liposome-linked immunosorbent assay. *Scientific reports*, *10*(1), 18086.

Karnwal, A., Kumar Sachan, R. S., Devgon, I., Devgon, J., Pant, G., Panchpuri, M., & Kumar, G. (2024). Gold nanoparticles in nanobiotechnology: from synthesis to biosensing applications. *ACS omega*, *9*(28), 29966-29982.

Khodatars Dashtmian, M. R., Fallahi, V., Seifouri, M., & Olyaee, S. (2025). Optimized SPR-PCF sensor for sucrose detection inspired by vertical pupil geometry. *Scientific Reports*, *15*(1), 29076.

Liu, Q., Sun, J., Sun, Y., Ren, Z., Liu, C., Lv, J., & Chu, P. K. (2020). Surface plasmon resonance sensor based on photonic crystal fiber with indium tin oxide film. *Optical Materials*, *102*, 109800.

Lv, Y., Ma, F. L., Wang, J. N., Zhang, Y., Jiang, Y., Ge, Q., & Yu, Y. J. (2023). A strategy for differentiating oak barrel aged and non-oak barrel aged wines by using UHPLC–HRMS combined with chemometrics. *Chemosensors*, *11*(3), 165.

Mauludi, L. D., Yantidewi, M., & Firdaus, R. A. (2024). Optimized surface plasmon resonance sensor (SPR) with gold and silver coating for heavy metal detection. *Collaborative Journal of Science*, *7*(7), 2328-2336.

Pasquardini, L., Cennamo, N., Arcadio, F., Perri, C., Chiodi, A., D'agostino, G., & Zeni, L. (2023). Immuno-SPR biosensor for the detection of Brucella abortus. *Scientific Reports*, *13*(1), 22832.

Putra, R. A., Fadlly, T. A., Yakob, M., Jalil, Z., & Rahwanto, A. (2021). *Surface Plasmon Resonance (SPR)-Based Biosensor*. Deepublish.

Ramola, A., Marwaha, A., & Singh, S. (2021). Design and investigation of a dedicated PCF SPR biosensor for CANCER exposure employing external sensing. *Applied Physics A*, *127*(9), 643.

Sardar, M. R., & Faisal, M. (2024). Dual-core dual-polished PCF-SPR sensor for cancer cell detection. *IEEE Sensors Journal*, *24*(7), 9843-9854.

Satrio, M. A., & Melatih, A. (2020, May). Surface Plasmon Resonance (SPR) phenomenon In a kretschmann configuration with a thin layer of gold (Au)/nanomagnetite (Fe3O4) for the detection of pig gelatin. In *Proceedings of the National Seminar on Physics Festival* (Vol. 1, pp. 5-10).

Shakya, A. K., Ramola, A., Singh, S., & Van, V. (2022). Design of an ultra-sensitive bimetallic anisotropic PCF SPR biosensor for liquid analytes sensing. *Optics Express*, *30*(6), 9233-9255.

Singh, S., Kumar, R., Chaudhary, B., Bhardwaj, P., Upaddhyay, V. K., Upadhyay, A., & Daher, M. G. (2025). Gold immobilized SPR-Enhanced PCF biosensor for detection of cancer cells: a numerical simulation. *Plasmonics*, *20*(6), 3535-3544.

Sv, S., Augustine, D., Hosmani, J., Pagnoni, F., Reda, R., Testarelli, L., & Patil, S. (2024). Nanoparticle-based biomolecules in cancer diagnosis, therapy, drug delivery and prognosis. *Frontiers in Dental Medicine*, *5*, 1482166.

Wakary, P., Taunaumang, H., & Lolowang, J. (2020). Analysis of the physical structure and optical properties of thin film Sudan III results of vacuum evaporation deposition. *Journal of FisTa: Physics and Its Applications*, *1*(2), 46-52.

Zekriti, M. (2021). Theoretical comparison between graphene-on-silver and gold-on-silver based surface plasmon resonance sensor. *Materials Today: Proceedings*, *45*, 7571-7575.