

Simulation of a Dual-Side Polished Photonic Crystal Fiber for Surface Plasmon Resonance Sensing

M. Othman^{1*}, M. I. S. Mohammad Hilmy¹, M. F. Mohd Fadhil¹, N. Mohd Faizun Saring Cisarua¹, J. Jamaludin¹, K. N. Z. Ariffin¹, and N. N. H. Saris²

¹Faculty of Engineering and Built Environment, Universiti Sains Islam Malaysia, Negeri Sembilan, Malaysia

²Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia

*Corresponding author: marinah@usim.edu.my

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Abstract

This paper presents a dual-side polished photonic crystal fiber (PCF) designed for surface plasmon resonance (SPR) sensing. The sensor leverages a gold layer deposited on the PCF surface to excite surface plasmons, enabling highly sensitive detection of changes in the surrounding refractive index. Numerical simulations using COMSOL Multiphysics were performed to analyze the sensor's performance as a function of pitch distance, ranging from 3.0 μm to 4.0 μm . The analysis focuses on the mode characteristics and electric field distribution within the sensor. The simulation results demonstrate the influence of the PCF pitch on the sensor's optical properties. Optimal performance is achieved at a pitch of 3.0 μm , where mode confinement and electric field localization at the gold interface are strongest, thereby enhancing surface plasmon resonance effects crucial for sensing applications.

1. Introduction

Surface plasmon resonance sensing is a cornerstone of modern optical sensing technologies, with applications spanning biomedical diagnostics, environmental monitoring, and chemical process control. Traditional fiber optic SPR sensors face challenges in balancing sensitivity, fabrication complexity, and robustness [1]. PCFs, with their tunable air-hole structures, offer a compelling solution by enabling precise control over light-matter interaction. Recent advancements in PCF sensors include side-polished designs to enhance evanescent field exposure and gold-coated structures for improved chemical stability. However, existing studies often prioritize confinement loss metrics over direct analysis of mode profiles and electric field distributions, limiting insights into plasmonic coupling efficiency [2].

This work addresses these gaps by proposing a dual-side polished PCF for SPR sensing applications. The design eliminates complex air-hole patterning, reducing production costs while maintaining high sensitivity [3], achieved by removing the need for intricate lattice asymmetry or specialized core shaping, which are common in conventional designs. By varying the pitch distance of the PCF, this study quantifies the effects on mode confinement and electric field enhancement. The selected pitch distance range between 3.0 μm and 4.0 μm reflects a balance between physical feasibility and optical performance. Pitches below 3.0 μm may result in excessive structural deformation during fabrication or collapse of the air holes, while values beyond 4.0 μm leads to poor confinement and reduced evanescent field interaction with the plasmonic surface. This range also aligns with prior research optimizing PCF-SPR sensors for effective sensitivity and manufacturability [4].

2. Sensor Design and Simulation Framework

The schematic cross-section of the dual-side polished PCF is shown in Figure 1. A thin layer of gold is deposited on the outer surface of the PCF to facilitate the excitation of surface plasmons when light propagates through the fiber core and interacts with the metal layer under phase-matching conditions. The analyte is assumed to surround the gold layer.

In this study, the focus is on the effect of varying the pitch distance, p , which is the center-to-center distance between adjacent air holes, on mode field confinement and electric field intensity, factors which influence

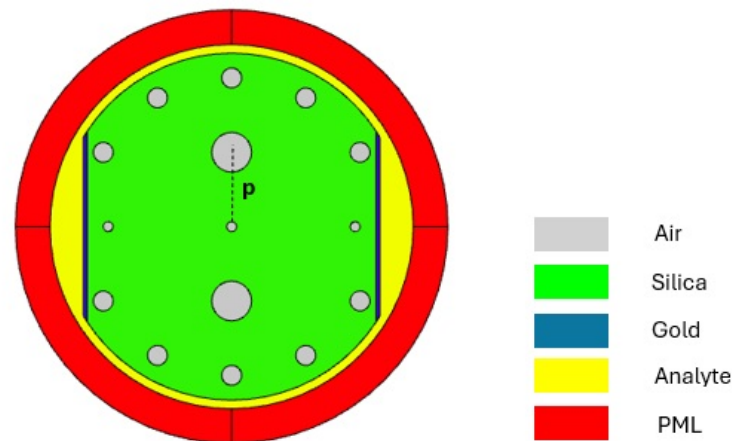


Figure 1. Cross section of the dual-side polished PCF

the sensitivity and performance of the PCF-SPR sensor. The simulations were performed for three different pitch values: $3.0\ \mu\text{m}$, $3.5\ \mu\text{m}$, and $4.0\ \mu\text{m}$, while the core diameter and gold layer thickness were set at $400\ \text{nm}$ and $40\ \text{nm}$, respectively. Numerical simulations were carried out using the finite element method (FEM) implemented in COMSOL Multiphysics software. A perfectly matched layer (PML) was used as the outer boundary condition to ensure minimal boundary reflection.

3. Results and Discussion

The electric field distribution ($|E|$) for each pitch configuration was obtained to assess how tightly the core mode is confined and how much energy leaks into the plasmonic region. Figure 2 shows the fundamental mode profiles for pitch distances of $3.0\ \mu\text{m}$, $3.5\ \mu\text{m}$, and $4.0\ \mu\text{m}$. The $3.0\ \mu\text{m}$ design exhibits tighter mode confinement, enhancing light-analyte interaction. As the pitch increases, a broader modal field is observed. At $4.0\ \mu\text{m}$, the mode becomes less confined to the core, with noticeable dispersion into the cladding and surrounding plasmonic layer. This demonstrates that tighter pitch arrangements facilitate stronger light-plasmon coupling, crucial for enhancing sensitivity in SPR sensing. The improved coupling arises from a more confined modal field, which enhances evanescent interaction with the metal-analyte interface.

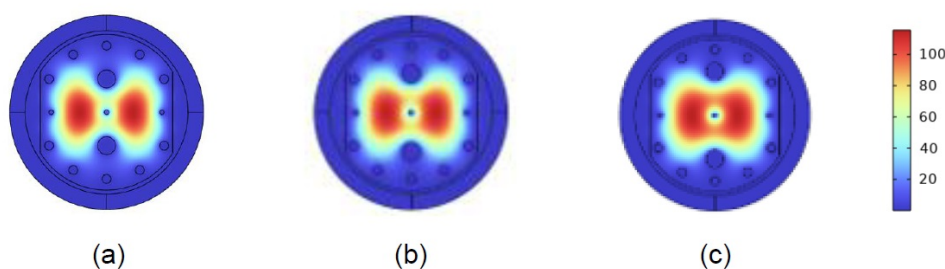


Figure 2. Mode field distributions for the fundamental mode at pitch distances of (a) $3.0\ \mu\text{m}$, (b) $3.5\ \mu\text{m}$, and (c) $4.0\ \mu\text{m}$

To quantify the confinement behaviour, the peak electric field intensity across the cross-section was extracted for each pitch distance, providing a direct measure of the field localization at the plasmonic interface. Figure 3 compares normalized $|E|$ fields for $3.0\ \mu\text{m}$, $3.5\ \mu\text{m}$, and $4.0\ \mu\text{m}$, respectively.

The peak intensity is highest for $3.0\ \mu\text{m}$, indicating optimal plasmonic excitation due to stronger field localization, aligning with prior SPR studies [1], where reduced pitch enhanced the overlap of the core mode with the plasmonic surface, improving field coupling and sensor response. As the pitch distance increases, the modal field becomes more dispersed into the cladding, reducing the overlap with the gold-analyte interface. This results in weaker SPR excitation and thus lower sensitivity. Conversely, reducing the pitch below $3.0\ \mu\text{m}$ does not substantially increase the peak field intensity due to saturation of the field localization and potential fabrication limitations.

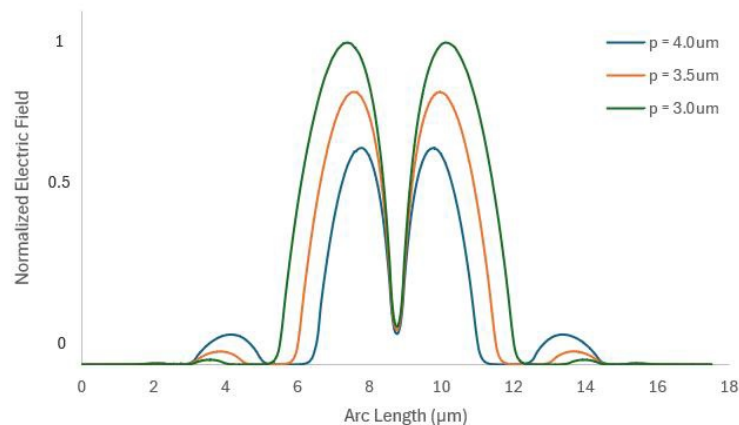


Figure 3. Normalized electric field intensity profiles for pitch distances of 3.0, 3.5, and 4.0 μm

4. Conclusion

This paper presents a dual-side polished PCF for SPR sensing, analyzed using electric field intensity and modal distribution metrics. Simulation results reveal that reducing the pitch distance enhances mode confinement and electric field localization near the plasmonic interface. However, this enhancement reaches a saturation point below which further pitch reduction offers marginal improvement and can lead to increased confinement loss or fabrication challenges. Conversely, larger pitches beyond the tested range result in poorer sensitivity due to weaker plasmonic coupling. The findings reinforce the importance of geometrical optimization in PCF-SPR sensor design and provide a basis for future fabrication and experimental validation efforts.

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