

Numerical Optimization of a Single-Mode Fiber-Based SPR Sensor for Air Contaminant Detection Applications

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Keywords

Single Mode Fiber
SPR Sensor
COMSOL
Air Contaminants

Abstract

This paper presents a numerical study of a single-mode fiber (SMF) based surface plasmon resonance (SPR) sensor, intended for air contaminant detection. Utilizing the finite element method (FEM) in COMSOL, the sensor's optical performance is evaluated by varying the gold coating thickness. Results demonstrate that thinner coatings yield stronger field enhancement, which is beneficial for sensitive detection applications. The findings offer insights into sensor design optimization prior to experimental implementation.

Article History

Received: 19 June 2025

Accepted: 7 July 2025

Published: 30 November 2025

1. Introduction

Air pollution poses a significant threat to global health, contributing to millions of deaths annually. Sensitive and reliable detection of air contaminants is crucial for effective monitoring and mitigation strategies. Fiber optic sensors, particularly those based on surface plasmon resonance, offer promising solutions due to their high sensitivity, remote sensing capabilities, and resilience to harsh environments [1]. While existing fiber optic sensor solutions such as photonic crystal fiber SPR sensors are available, they have limitations of cost and complexity.

SMF-SPR sensors utilize the principle of exciting surface plasmons by removing a portion of the fiber cladding and depositing a thin metal film. The resonance condition is highly sensitive to changes in the refractive index of the surrounding medium, enabling the detection of air contaminants. The performance of such sensors is influenced by several factors, including the choice of metal coating material, coating thickness, and the wavelength of the incident light. This paper builds upon the foundation established in previous work by exploring the optimal combination of these parameters for enhanced detection of air contaminants.

2. Simulation Settings

The sensor structure consists of an unclad SMF coated with a thin layer of gold. The surrounding medium acts as the analyte, representing the air contaminant to be detected. A cross-sectional schematic of the sensor is shown in Figure 1. The core diameter of the SMF is 8.2 μm . The coating thickness is varied from 30 nm to 50 nm in increments of 10 nm. These parameters have been chosen to be similar to those investigated in literature on SPR sensors for comparison, and to provide an optimal balance between manufacturing feasibility and sensing performance.

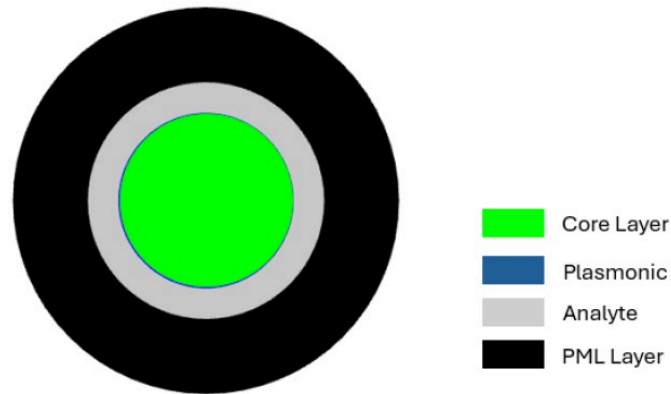


Figure 1: Cross-sectional schematic of the SMF-SPR sensor

The numerical modelling is performed using the finite element method (FEM) in COMSOL Multiphysics. The simulation domain includes the SMF core, metal coating, analyte, and a perfectly matched layer (PML) to absorb outgoing radiation. The material properties of the SMF core are modelled using the Sellmeier equation, while the refractive index of the analyte is varied to simulate different concentrations of air contaminants, focusing on acetone as a representative contaminant.

The selected gold coating thicknesses of 30 nm, 40 nm, and 50 nm were chosen based on prior literature which demonstrated that SPR sensors with metal thicknesses within this range achieve an optimal balance between strong surface plasmon excitation and practical manufacturability [2], [3]. Thicknesses below 30 nm often result in incomplete film coverage and weak plasmon coupling due to fabrication limitations, while those above 50 nm can introduce significant optical losses and reduce sensitivity due to over-damping of the evanescent wave.

By limiting the thickness range to 30-50 nm, we focused on the most relevant and commonly used region for performance optimization. The criteria for identifying optimal field enhancement and confinement were based on two key indicators obtained from FEM simulations: (1) the magnitude of the normalized electric field intensity at the core-coating-analyte interface, and (2) the spatial distribution of the electric field. A higher peak field intensity signifies stronger coupling between the guided mode and surface plasmons, which is essential for achieving high surface sensitivity. Tighter confinement, on the other hand, ensures that more of the field remains localized near the sensing surface.

3. Results and Discussion

Simulations were performed for gold coating thicknesses ranging between 30 nm to 50 nm to determine the optimal configuration. The electric field intensity distribution within the sensor structure provides valuable insights into the plasmon excitation and mode confinement. Figure 2 shows the electric field distributions at 30 nm and 50 nm thicknesses. In all cases, the electric field distribution is concentrated in the fiber core, indicating that the fiber is operating in single mode as expected. While no major changes were observed in the overall shape of the mode with varying coating thickness, there are subtle differences in the intensity and distribution near the core-coating boundary, which are primarily due to the complex interaction between the guided mode and surface plasmons.

SPR is highly dependent on the interaction between the evanescent field (the portion of the light that extends beyond the fiber core) and the free electrons in the metal coating. The presence of the metal coating introduces a new boundary condition at the core-coating interface. As the coating thickness changes, the way the electromagnetic field behaves at this boundary is altered. Different coating thicknesses can also change the efficiency and spatial distribution of the transfer of energy

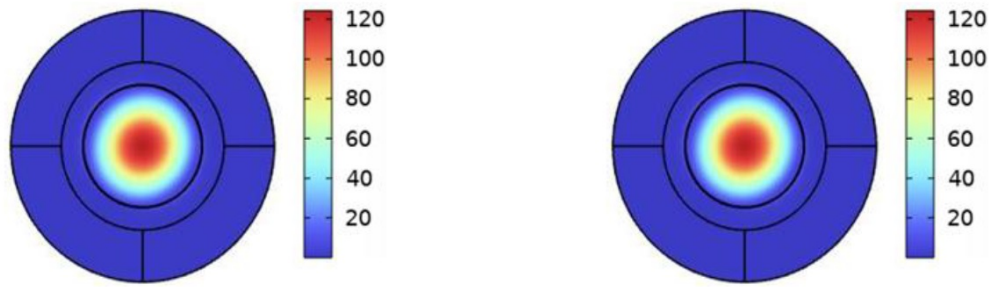


Figure 2: Electric field intensity distribution of the SMF sensor for (a) 30 nm and (b) 50 nm gold thicknesses

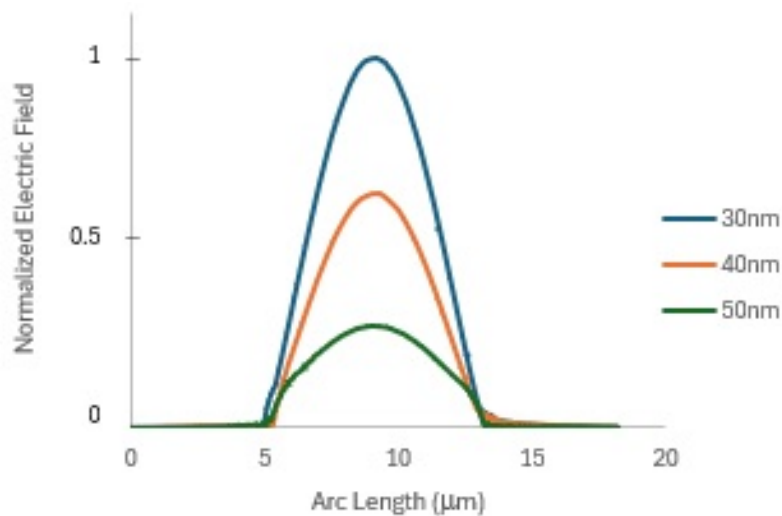


Figure 3: Normalized electric field of the SMF sensor

from the guided mode in the fiber core to surface plasmons in the metal, leading to variations in the electric field [2].

Figure 3 shows the normalized electric field of the SMF sensor. It is observed that the 30 nm coating exhibits a relatively high peak normalized electric field. The gold layer facilitates transfer of energy from the guided mode in the fiber core to surface plasmons at the metal surface. As the thickness increases, more energy is transferred from the core to surface plasmons, causing the light to interact more strongly with the metal layer. This interaction reduces the amount of light confined within the fiber core and can cause the mode to spread out slightly. In contrast, thinner gold coatings result in less interaction between the core-guided mode and the surface plasmons. Consequently, more light remains confined within the fiber core, leading to tighter mode confinement.

Although this study is simulation-based, the relevance of the sensor to air contaminant detection lies in the surface plasmon resonance mechanism, which is inherently sensitive to changes in the refractive index of the surrounding medium. In practical applications, air contaminants such as volatile organic compounds (VOCs) or particulates can alter the refractive index near the sensing region. This shift affects the resonance condition and can be detected as a change in resonance wavelength or signal intensity.

For this study, acetone was used as a representative contaminant due to its well-documented optical properties and relevance as a VOC pollutant. The presence of acetone molecules near the metal surface perturbs the local refractive index, influencing the evanescent field and modifying the electric field distribution observed in the simulation. Thus, the simulation results provide insight

into how different coating thicknesses affect the sensor's ability to interact with the surrounding analyte field and, by extension, its sensitivity to contaminant-induced refractive index variations.

4. Conclusion

This research provides a framework for optimizing SMF-SPR sensor design for sensitive and reliable detection of air contaminants. The sensor shows excellent mode confinement due to improved mode characteristics, with plasmon excitation on the outer surface of the material and minimal optical attenuation. 30 nm gold provides the strongest field enhancement, which is beneficial for sensing applications requiring high surface sensitivity. 50 nm gold offers more field confinement but at the expense of sensitivity due to reduced field amplitude at the interface.

References

- [1] M. A. Butt, G. S. Voronkov, E. P. Grakhova, R. V. Kutluyarov, N. L. Kazanskiy, and S. N. Khonina, "Environmental Monitoring: A Comprehensive Review on Optical Waveguide and Fiber-Based Sensors," *Biosensors*, vol. 12, no. 11, p. 1038, Nov. 2022, doi: 10.3390/bios12111038.
- [2] S. K. Al-Hayali, A. M. Salman, and A. H. Al-Janabi, "High sensitivity balloon-like interferometric optical fiber humidity sensor based on tuning gold nanoparticles coating thickness," *Measurement*, vol. 170, p. 108703, Jan. 2021, doi: 10.1016/j.measurement.2020.108703.
- [3] M. A. Fakhri et al., "A gold nanoparticles coated unclad single mode fiber-optic sensor based on localized surface plasmon resonance," *Scientific Reports*, vol. 13, no. 1, Apr. 2023, doi: 10.1038/s41598-023-32852-6.