

Surface Plasmon Resonance Polymer Optical Fiber Sensor for Enhanced Oxygen Detection with PdTFPP-Based

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Abstract

This study presents an enhanced oxygen detection method combining fluorescence sensing with surface plasmon resonance (SPR) using a multimode polymer optical fiber (POF). The POF is coated with a silver layer for SPR and the palladium-based dye PdTFPP, known for its high oxygen sensitivity. PdTFPP alone showed an emission peak at 668.62 nm, with intensity decreasing as oxygen concentration increased. The SPR-enhanced sensor showed a sensitivity of 0.1045 compared to 0.0944 for PdTFPP alone, demonstrating improved performance.

1. Introduction

Oxygen (O₂) shortages in physiological and environmental systems can lead to severe consequences, including cell dysfunction, organ failure, and ecosystem imbalances. Continuous oxygen monitoring is essential for early hazard detection and ensuring safe conditions. While electrochemical sensors are bulky, expensive, slow, and prone to calibration issues and gas interference, optical sensors provide better sensitivity and non-invasive detection, though challenges like photobleaching over time remain [1], [2]. To address this, SPR-based optical sensors provide improved stability and performance. This study enhances oxygen sensing by combining SPR with a fluorescence-based polymer optical fiber (POF) sensor, coated with silver (Ag) and the oxygen-sensitive dye 5,10,15,20-tetrakis(pentafluorophenyl)-21H,23H-porphine palladium (II) (PdTFPP). POF was selected for flexibility, low cost, and ease of fabrication. PdTFPP was chosen due to excellent photostability, strong oxygen sensitivity, and compatibility for fluorescence-based quenching [3]. The implementation of SPR aimed to improve signal amplification, and sensor performance was evaluated in terms of sensitivity, linearity, error reduction, and stability.

2. Methodology

A multi-mode POF with a 1000 µm core diameter was prepared by decladding the tip for the sensing region using a chemical etching process [4]. Ag was deposited by dissolving 0.5 g of AgNO₃ in 5 mL deionized water, adding 10 mL of NaOH, followed by 4 mL of 30% NH₃. After stirring, 2 g of commercial sugar in 15 mL deionized water was added, and the optical fiber tip was immersed in the Ag mixture at 65 °C for 10 minutes. The Ag-coated fiber was then dried at 50 °C for 5 minutes. PdTFPP dye solution was synthesized via sol-gel technique. First, 4 mL of TEOS was dissolved in 1.25 mL of EtOH, followed by 400 µL of 0.1 M HCl, 40 µL of Octyl-triEOS, and 40 µL of Triton X-100. The resulting colloidal solution was stirred for 1 hour. Meanwhile, 2 mg of PdTFPP was dissolved in 2.5 mL of THF and stirred for 1 hour. The dye solution was then combined

with the colloidal solution and stirred for another 2 hours and aged overnight. The dye solution was applied to the Ag-coated fiber using dip-coating at a withdrawal rate of 120 mm/min. The sensors were tested in a chamber with O₂ concentrations varying from 0% to 70%, controlled by adjusting the oxygen-to-nitrogen gas ratio, as depicted in the setup shown in Figure 1.

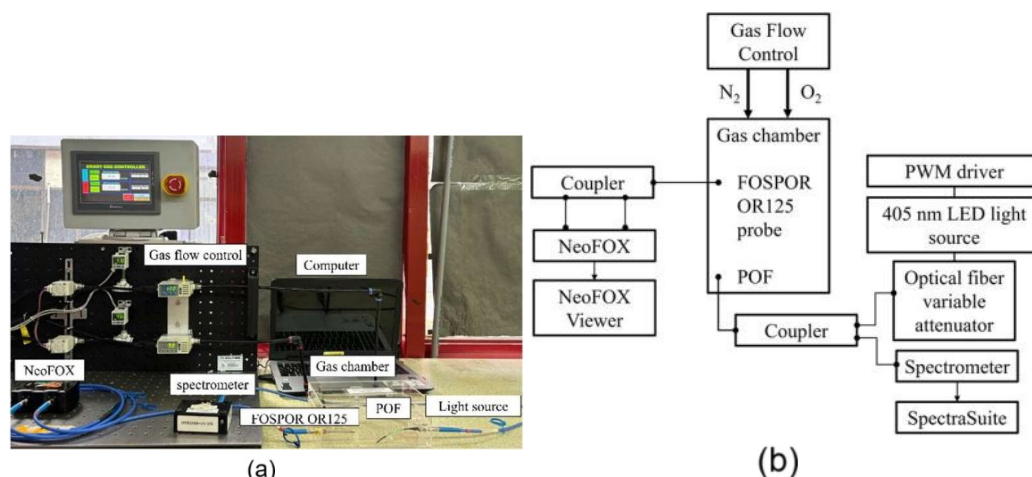


Figure 1. The (a) schematic diagram and (b) experimental setup for the sensor performance analysis outlining the components and connections involved in the sensor testing process.

3. Results and Discussion

The absorption spectrum of PdTFPP, measured using a UV-VIS spectrometer, showed an excitation peak at 405 nm, with an emission peak at 668.62 nm, which shifted slightly to 668.29 nm after SPR integration. Figure 2(a) illustrates the decrease in emission intensity as O₂ concentration increases, caused by fluorescence quenching, where energy transfer occurs between the dye and O₂ molecules, reducing fluorescence intensity [5]. Figure 2(b) shows that the emission intensity further decreased, and the wavelength shifted from 668.29 nm at 0% O₂ to 661.69 nm at 70% O₂. The wavelength shift indicates SPR activity, where changes in the refractive index around the sensor surface, caused by O₂ molecules, alter the optical properties and fluorescence emission, confirming the SPR principle [6]. As shown in Figure 2(c), the fluorescence-based PdTFPP sensor exhibited a linear calibration curve with a slope of 0.0944, which reflects its sensitivity and an R² value of 0.94. However, large error bars at higher oxygen concentrations indicate low stability and consistency. With the incorporation of SPR, the slope increased to 0.1045, reflecting enhanced sensitivity, while the R² value improved to 0.9749. The error bars were significantly reduced, which indicates more stable measures. These results demonstrate that the integration of SPR effectively enhances the sensor's overall performance in terms of sensitivity and stability.

4. Conclusion

In conclusion, the fluorescence-based PdTFPP sensor showed a slope of 0.0944 and R² of 0.94 but suffered from large error bars and low stability at higher oxygen levels. With SPR integration, the slope increased to 0.1045 and R² improved to 0.9749, while error bars were reduced. These findings demonstrate that SPR-enhanced sensors offer improved performance over standard fluorescence-based systems, with high sensitivity, strong linearity, and low variability, making them suitable for real-time monitoring and scalable in various advanced sensing applications.

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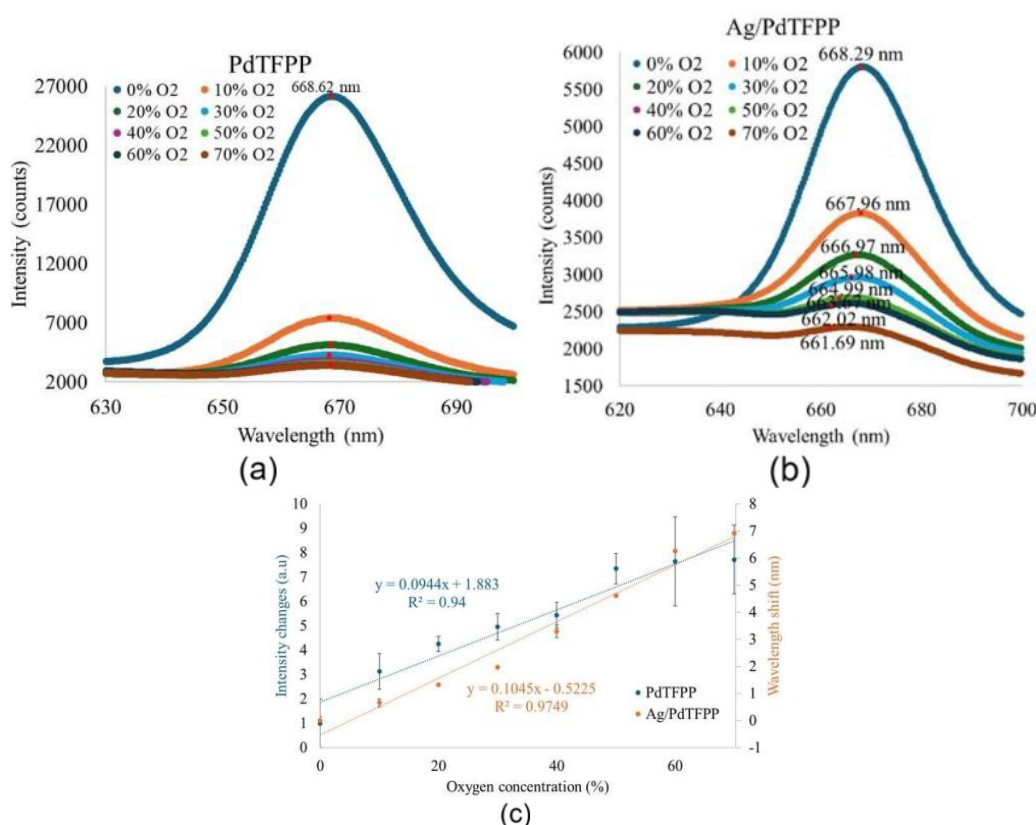


Figure 2. The emission spectra of (a) PdTFPP, (b) Ag/PdTFPP, and (c) the calibration curve for PdTFPP and Ag/PdTFPP, showing that Ag/PdTFPP exhibits better performance.

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