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Sensitivity Analysis of AuNP-Functionalized D-Shaped Optical Fiber SPR Sensor Using Agricultural Media

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Abstract

Agricultural water quality monitoring requires a robust and sensitive sensing platform capable of detecting changes in environmental media. However, conventional analytical techniques are not suitable for real-time and on-site agricultural monitoring due to complex instrumentation and high operational costs. This study presents the fabrication and characterization of a D-shaped optical fiber surface plasmon resonance (SPR) sensor functionalized with gold nanoparticles (AuNPs). The sensor performance was evaluated using carrot extract solutions with varying concentrations (20%–100%) as a model agricultural medium to induce refractive index variations at the sensing interface. Experimental results show a systematic red shift in the SPR resonance wavelength from 1546.944 nm to 1546.979 nm as the extract concentration increases, corresponding to a maximum wavelength shift of 107 nm. The observed response confirms the high sensitivity of the AuNP-enhanced D-shaped optical fiber to refractive index changes in liquid agricultural samples. This discovery establishes a reliable refractive index sensing platform that can serve as a basic structure for future functionalization towards the detection of selected heavy metals, such as lead (Pb^{2+}), in agricultural applications.

1. Introduction

The quality of agricultural water and liquid media plays a critical role in crop productivity, food security, and environmental sustainability. Variations in the chemical composition of agricultural water, including dissolved organic matter and environmental contaminants, can significantly affect plant growth and soil conditions [1], [2]. As a result, there is an increasing demand for reliable sensing technologies that are capable of monitoring changes in agricultural media in a rapid, sensitive, and cost-effective manner.

Conventional analytical techniques used for agricultural and environmental analysis, such as atomic absorption spectroscopy (AAS), inductively coupled plasma mass spectrometry (ICP-MS), and X-ray fluorescence (XRF), provide high sensitivity and accuracy for chemical analysis [3]. However, these techniques typically require complex sample preparation, bulky instrumentation, and laboratory-based operations, which limits their suitability for real-time and on-site monitoring. This has driven increasing interest in compact and portable sensing platforms for environmental applications [8]. Recent advances in optical fiber–based surface plasmon resonance (SPR) sensors have demonstrated strong potential for environmental and agricultural monitoring, offering high refractive index sensitivity and suitability for real-time liquid sensing [10].

Among optical sensing approaches, surface plasmon resonance (SPR) sensors are widely recognized for their high sensitivity to changes in the refractive index of the surrounding medium [4]. SPR occurs when incident light couples to the collective oscillations of free electrons at a metal-dielectric interface, resulting in a resonant state that is highly dependent on the optical properties of the adjacent medium. Small refractive index variations at the sensing interface can induce a measurable shift in the resonance wavelength, making SPR an effective technique for refractometric sensing of liquid samples.

Optical fiber-based SPR sensors offer several advantages, including compactness, flexibility, immunity to electromagnetic interference, and suitability for remote sensing applications [8]. In particular, D-shaped optical fibers have attracted considerable attention due to their side-polished geometry, which allows direct access to the evanescent field propagating near the fiber core [5]. This geometry enhances light-matter interactions and increases sensing sensitivity compared to conventional cylindrical optical fibers [6]. Recent reviews have reported that D-shaped optical fiber SPR sensors consistently exhibit enhanced sensitivity due to increased evanescent field exposure and improved plasmonic coupling at the sensing interface [11].

The sensing performance of optical fiber SPR sensors can be further enhanced by surface modification using noble metal nanostructures. Gold nanoparticles (AuNPs) are of great interest due to their strong plasmonic properties, chemical stability, and ability to support localized surface plasmon resonance (LSPR) [7]. The interaction between surface plasmon polaritons (SPPs) propagating on the gold film and localized plasmons generated by AuNPs leads to an enhanced electromagnetic field at the sensing interface, enhancing the sensitivity of the sensor to refractive index changes [6], [9].

In this study, a D-shaped optical fiber SPR sensor functionalized as AuNPs was fabricated and experimentally characterized for refractive index sensing in agricultural liquid media. Carrot extract with varying concentrations was used as a model agricultural sample to induce controlled refractive index variations at the sensing interface. The main objective of this work was to evaluate the wavelength shift response, sensitivity, and repeatability of the proposed sensor under concentration-dependent refractive index changes. By demonstrating reliable refractometric performance using agricultural media, this study establishes a basic sensing platform that can be further optimized and functionalized in future work for selected chemical or heavy metal detection applications.

2. Material and Methods

2.1 Materials

Single-mode optical fibers were used as the base sensing platform due to their compatibility with surface plasmon resonance (SPR) configurations and optical interrogation systems. A D-shaped geometry was selected to allow direct interaction between the evanescent field propagating near the fiber core and the surrounding sensing medium, thereby enhancing sensitivity [5], [6]. Gold nanoparticles (AuNPs) were employed for surface functionalization because of their strong plasmonic properties, chemical stability, and ability to support localized surface plasmon resonance (LSPR) [7]. The incorporation of AuNPs on the sensing surface enhances the local electromagnetic field and improves the refractive index sensitivity of SPR-based optical fiber sensors [6]. Carrot extract was used as a model agricultural liquid medium to evaluate the refractive index sensing performance of the fabricated sensor. The extract was prepared at different concentrations using deionized water to induce controlled refractive index variations arising from changes in dissolved organic and sugar content. No heavy metal ion solutions were evaluated in this study, as the experimental focus was limited to refractometric characterization of the sensor platform.

2.2 D-Shaped Optical Fiber Fabrication

The D-shaped optical fiber shown in Figure 1 was fabricated by mechanically polishing one side of the optical fiber cladding to produce a flat surface near the fiber core. The polishing length was approximately 10 mm. This polishing process allows the evanescent field to extend beyond the cladding area and interact with the surrounding sensing medium. Care was taken to ensure uniform polishing depth and surface smoothness to maintain consistent optical propagation characteristics.

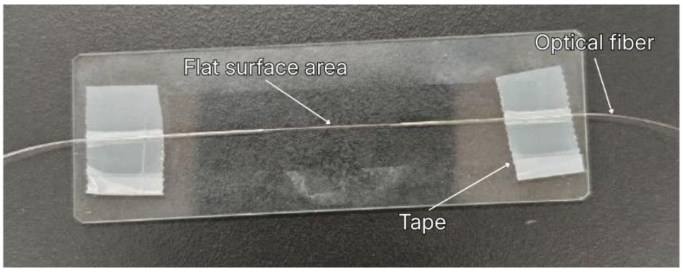

Fig. 1 D-shaped optical fiber

2.3 Gold Nanoparticle Functionalization

A thin layer of gold was sputtered onto the surface of the polished D-shaped optical fiber to support SPR excitation. The gold layer thickness was approximately 40 nm. Next, gold nanoparticles were immobilized on the gold-coated surface to enhance the localized plasmonic effect. The functionalization time was controlled to ensure uniform AuNP distribution without excessive aggregation, thereby increasing the effective sensing area and enhancing sensitivity.

2.4 Preparation of Agricultural Sensing Medium

Carrot extract was used in this study as a model agricultural liquid medium to investigate the refractive index sensitivity of the AuNP-functionalized D-shaped optical fiber SPR sensor. The extract was prepared from fresh carrot samples and diluted to obtain concentrations of 20%, 40%, 60%, 80%, and 100%. These varying concentrations produced systematic changes in refractive index due to differences in dissolved organic and sugar content. The carrot extract served solely as the analyte for refractive index sensing.

2.5 Experimental Setup

The experimental setup consisted of a broadband light source, a custom-designed SPR sensor probe, and an optical spectrum analyzer (OSA) [4], [6]. The light from the source was coupled into an optical fiber, and the emitted spectrum was recorded using the OSA as shown in Figure 2. The change in the SPR resonance wavelength was monitored when the sensor was exposed to carrot extract solutions of different concentrations. No heavy metal ions were introduced in this experiment, as the study focused on refractive index sensing characterization

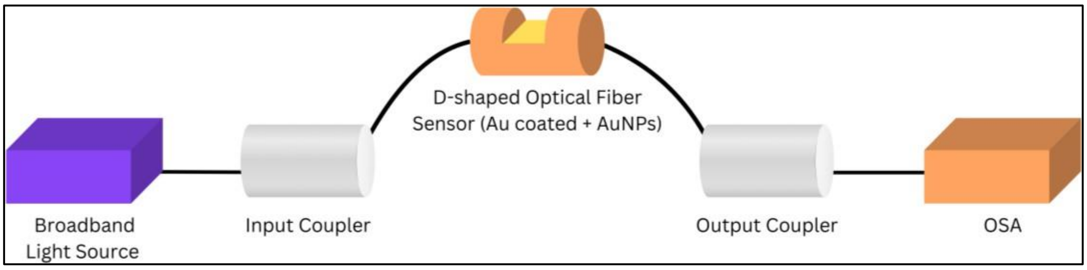

Fig. 2 Experimental setup D-shaped Optical Fiber Sensor with OSA

3. Results and Discussion

3.1 Surface Morphology of AuNP-Functionalized D-Shaped Optical Fiber

The surface morphology of the fabricated D-shaped optical fiber sensor was examined using Field Emission Scanning Electron Microscopy (FESEM), as shown in Figure 3. The FESEM images confirm the successful formation of a flat sensing area on the optical fiber, resulting from the side polishing and chemical etching processes. This flat geometry is important for surface plasmon resonance (SPR) excitation, as it allows the evanescent field from the fiber core to interact efficiently with the surrounding medium.

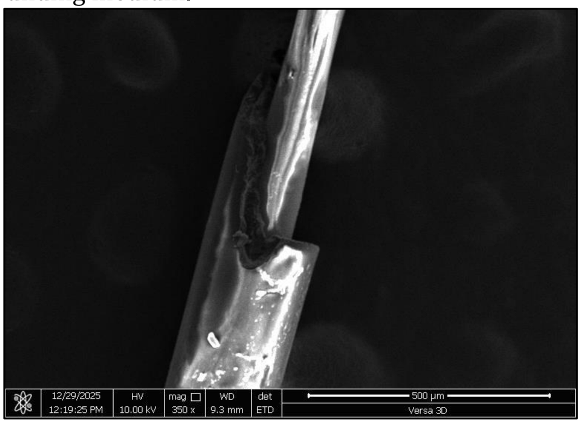

Fig. 3 D-shaped optical fiber sensor under Field Emission Scanning Electron Microscope (FESEM)

A relatively uniform coating of gold nanoparticles (AuNPs) can be observed along the D-shaped region. The continuous metal surface indicates effective sputter deposition, which is essential for stable plasmonic coupling. Non-uniform coating or surface defects can cause scattering loss and broaden the SPR decay. However, the observed morphology indicates good surface quality, supporting reliable resonance behavior. The presence of AuNPs on the sensing surface is expected to enhance the localized surface plasmon resonance (LSPR), thereby strengthening the electromagnetic field at the metal-dielectric interface and increasing the sensor sensitivity.

3.2 SPR Wavelength Shift Response to Carrot Extract Concentration

The refractive index sensing performance of the AuNP-functionalized D-shaped optical fiber SPR sensor was evaluated by monitoring the resonance wavelength shift in response to carrot extract solutions with increasing concentrations. The baseline resonance wavelength measured using deionized water was 1546.873 nm. When the sensor was exposed to carrot extract at concentrations ranging from 20% to 100%, a clear and systematic red shift in the SPR resonance wavelength was observed, indicating changes in the dielectric environment at the sensing interface.

Fig. 4 shows the relationship between the wavelength shift (Δλ) and carrot extract concentration, presented as an XY scatter plot with a linear regression fit. The wavelength shift increased monotonically from 71 nm at 20% concentration to a maximum of 107 nm at 100% concentration. This consistent increase confirms that the sensor response is governed by concentration-dependent refractive index variations arising from differences in the dissolved organic content of the extract.

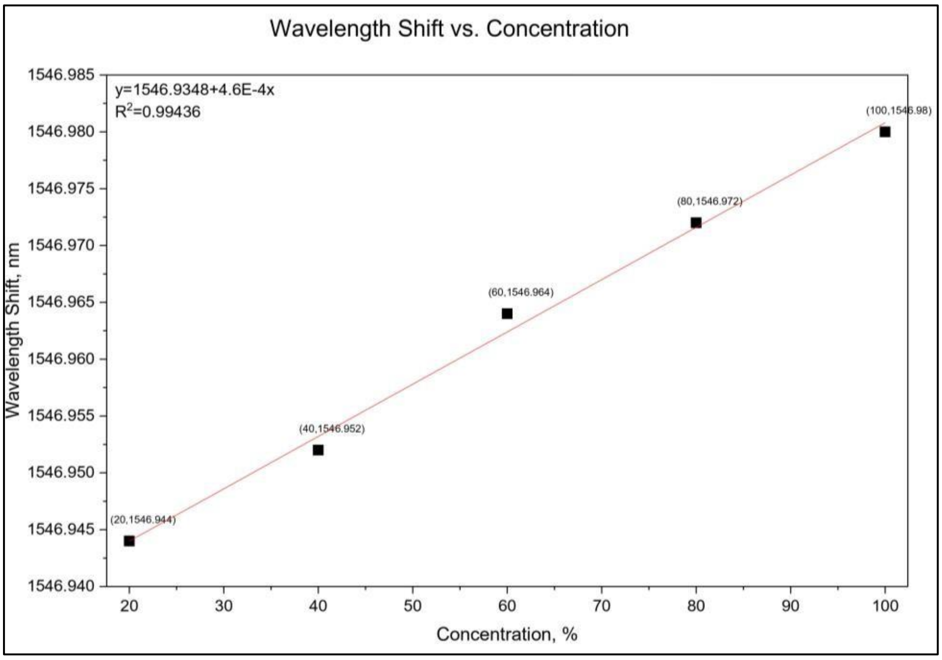

Fig. 4 Graph Wavelength Shift vs. Concentration

The linear regression analysis demonstrates a strong linear relationship between carrot extract concentration and resonance wavelength shift, indicating good linearity of the sensor response over the investigated range. The slope of the fitted line represents the refractive index sensitivity of the SPR sensor expressed in nm/% concentration, providing a quantitative measure of the sensor's performance. The observed linear behavior is characteristic of surface plasmon resonance–based refractometric sensing and confirms effective plasmonic coupling at the AuNP-functionalized sensing surface [4].

The clear and repeatable red shift behavior observed across the concentration range demonstrates the stability and reliability of the D-shaped optical fiber SPR sensor for refractive index sensing in agricultural liquid media. These results validate the suitability of the proposed sensor platform for concentration-dependent optical sensing and establish a solid foundation for further functionalization toward selective chemical detection in future studies.

3.3 Discussion of Sensing Mechanism and Performance

The observed surface plasmon resonance (SPR) behavior of the proposed sensor can be attributed to the combined effects of the D-shaped optical fiber geometry and gold nanoparticle (AuNP) functionalization. Partial removal of the fiber cladding creates a flat sensing surface that allows the evanescent field from the fiber core to extend into the surrounding medium, thereby enhancing light–matter interaction compared to conventional cylindrical optical fibers [5], [6]. This configuration significantly improves the sensor's sensitivity to refractive index changes occurring at the sensing interface. The observed linear and repeatable wavelength shift behavior is consistent with recent reports on D-shaped optical fiber SPR sensors used for refractive index and environmental sensing, confirming the reliability of the proposed sensor platform [10], [11].

The deposition of AuNPs on the gold-coated D-shaped region introduces localized surface plasmon resonance (LSPR), which enhances the local electromagnetic field intensity at the metal–dielectric boundary [7]. The coupling between propagating surface plasmon polaritons (SPPs) supported by the gold film and localized plasmons generated by the AuNPs results in amplified plasmonic interactions, leading to improved refractive index sensitivity and measurable wavelength shifts [4], [6].

As the concentration of carrot extract increased, the refractive index of the surrounding medium also increased due to a higher content of dissolved organic constituents. This modification of the dielectric environment altered the SPR coupling condition, producing a systematic red shift in the resonance wavelength, which is a characteristic response of SPR-based refractometric sensors [4]. The monotonic and repeatable wavelength shift observed in this study confirms the stability and reliability of the sensor response.

Although carrot extract was employed as a model agricultural medium in this study, the observed SPR response is fundamentally governed by refractive index variations at the AuNP-functionalized sensing interface. Therefore, the current results validate the refractometric performance of the sensor platform. With appropriate surface functionalization and specific binding layers, this platform can be extended in future work toward selective detection of heavy metal ions such as Pb^{2+}.

In addition to wavelength shift behavior, the linearity of the sensor response indicates stable plasmonic coupling across the investigated concentration range. The absence of abrupt resonance broadening suggests minimal optical loss and good surface uniformity of the AuNP coating. Furthermore, the magnitude of the wavelength shift compares favorably with previously reported D-shaped optical fiber SPR sensors, confirming the effectiveness of AuNP enhancement in improving refractive index sensitivity [6], [8].

These observations provide strong experimental evidence that the proposed sensor design is not only sensitive but also stable, which is critical for practical agricultural sensing applications.

4. Conclusion

This study successfully demonstrated the performance of a D-shaped optical fiber surface plasmon resonance (SPR) sensor functionalized with gold nanoparticles for concentration-dependent agricultural sensing. FESEM analysis confirmed the successful fabrication of a flat D-shaped sensing area with uniform AuNP coating, which is essential for stable and enhanced plasmonic excitation. Optical characterization showed a systematic and monotonic red shift in the SPR resonance wavelength as the concentration of carrot extract increased from 20% to 100%, with a maximum wavelength shift of 107 nm. The linear relationship between resonance wavelength shifts and extract concentration indicates consistent sensor response to refractive index variations in the surrounding medium. This behavior confirms effective evanescent field interaction and stable plasmonic coupling at the AuNP-functionalized D-shaped sensing interface.

The repeatable wavelength shifts trend and agreement with reported refractometric SPR sensing behavior demonstrate that the proposed sensor platform provides reliable refractive index sensitivity under controlled agricultural liquid conditions. While the present study is limited to refractometric characterization, the experimental results provide sufficient analytical evidence to support the feasibility of the sensor design. With further surface functionalization and analyte-specific studies, the platform may be extended toward selective detection of heavy metal ions in agricultural applications.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Muhammad Zelmy Hatim Mazlan, Noor Azura Awang; **data collection:** Muhammad Zelmy Hatim Mazlan; **analysis and interpretation of results:** Muhammad Zelmy Hatim Mazlan; **draft manuscript preparation:** Muhammad Zelmy Hatim Mazlan, Noor Azura Awang. All authors reviewed the results and approved the final version of the manuscript.*

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