



FDTD-Based CU/GO D-Shaped Fiber SPR Sensor for Detecting Refractive Index Changes in NaCl Solutions

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Abstract

Background: Surface Plasmon Resonance (SPR) is an optical sensing method with high sensitivity to refractive index changes near a metal surface. Integrating SPR with D-shaped optical fibers provides compact dimensions, flexibility, resistance to electromagnetic interference, and real-time sensing capabilities. Sensor performance is affected by the plasmonic material, metal thickness, and incorporation of two-dimensional materials such as graphene oxide (GO).

Objective: This study analyzes the characteristics of a D-shaped fiber-optic SPR sensor with a double-layer Cu/GO structure for detecting refractive index changes in NaCl solutions using the Finite-Difference Time-Domain (FDTD) method in Ansys Lumerical.

Methods: The study compared Ag and Cu as plasmonic materials, evaluated the effect of GO addition, optimized the Cu thickness from 30–60 nm with a fixed GO thickness of 5 nm, and optimized the GO thickness from 0.5–30 nm. Sensor performance was evaluated based on the resonance wavelength, sensitivity, full width at half maximum (FWHM), and figure of merit (FOM).

Results: Cu produced better resonance characteristics than Ag in the investigated configuration. Addition of GO induced a redshift in the resonance wavelength and enhanced the sensor response to refractive index changes. Variations in Cu and GO thickness demonstrated that sensor performance depends on their combined configuration. Optimization identified a configuration of 45 nm Cu and 5 nm GO provided a favorable balance among sensitivity, resonance sharpness, FWHM, and FOM.

Conclusion: Optimized Cu/GO configuration shows potential as a basic structure for D-shaped fiber-optic SPR sensors with improved sensitivity for refractive index detection and future biosensing applications.

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INTRODUCTION

Advances in optical sensor technology have accelerated substantially in response to the growing demand for highly sensitive detection systems capable of rapid, precise, and real-time measurements. Such resonant states demonstrate exceptional sensitivity to variations in the refractive index of the surrounding medium, whereby infinitesimal changes induce measurable shifts in the resonance wavelength.

Consequently, fiber-optic SPR sensors represent an attractive alternative, offering compact form factors, mechanical flexibility, lightweight construction, electromagnetic immunity, and the capability for *in-situ* real-time measurements. Such an architectural arrangement enhances the coupling efficiency between evanescent modes and surface plasmon polariton

waves, resulting in improved resonance sensitivity to variations in the refractive index.

Beyond geometric considerations, the selection of plasmonic materials critically influences sensor performance. Gold (Au) has traditionally dominated due to its excellent chemical stability and reliable generation of surface plasmon resonances. The deposition of a GO layer on plasmonic substrates enhances analyte adsorption while amplifying the electromagnetic field distribution throughout the sensing region.

Various studies have reported that the use of Cu and GO materials can improve the performance of fiber-optic SPR sensors. Liu et al. (2022) reported that the selection of plasmonic materials and the use of two-dimensional materials significantly influence the sensitivity and stability of fiber-optic SPR sensors. Navarrete et al. (2023) showed that the addition of a GO layer to an SPR sensor can increase the sensor's response to changes in the refractive index by strengthening the interaction between the evanescent field and the analytical medium. In addition, Zhang et al. (2022) stated that optimizing the fiber-optic structure and coating materials is one of the main factors in improving the performance of fiber-optic SPR sensors. Zhang et al. (2022) also reported that the selection of an appropriate material configuration affects both the sensitivity and resonance quality of SPR sensors.

NaCl solution serves as the analytical medium due to its precisely quantified refractive index and established use as a standard reference for SPR sensor evaluation (Liu et al., 2022).

While Cu and GO materials have gained considerable attention for enhancing SPR performance, comprehensive investigations specifically addressing dual-layer Cu/GO structures in D-shaped fibers using FDTD remain scarce. The existing literature predominantly addresses isolated layer optimization rather than the systematic evaluation of synergistic interactions between the layers and their effects on resonance characteristics.

Based on this background, this study aims to analyze the characteristics of D-shaped optical-fiber-based SPR sensors with a Cu/GO double-layer structure using the Finite-Difference Time-Domain (FDTD) method in Ansys Lumerical FDTD software. The analysis was conducted by comparing Ag and Cu materials, evaluating the effect of adding GO layers, optimizing variations in Cu layer thickness, and optimizing variations in GO layer thickness using NaCl solutions with refractive indices ranging from 1.335 to 1.340. Sensor performance was evaluated based on the resonance wavelength (λ_{res}), sensitivity, full width at half maximum (FWHM), and figure of merit (FOM). The results of this study are expected to serve as a reference for the development of fiber-optic-based SPR sensors using the plasmonic materials Cu and graphene oxide (Liu et al., 2022).

METHOD

SPR Sensor Design

Simulations were designed to assess how variations in plasmonic material composition, metallic layer thickness, and graphene oxide (GO) layer dimensions influenced the sensor's resonance properties for detecting changes in the refractive index of the medium.

The sensor architecture comprised a D-shaped optical-fiber geometry, in which partial polishing of the cladding layer brought the evanescent field into direct contact with the plasmonic layers and analytical medium during light propagation.

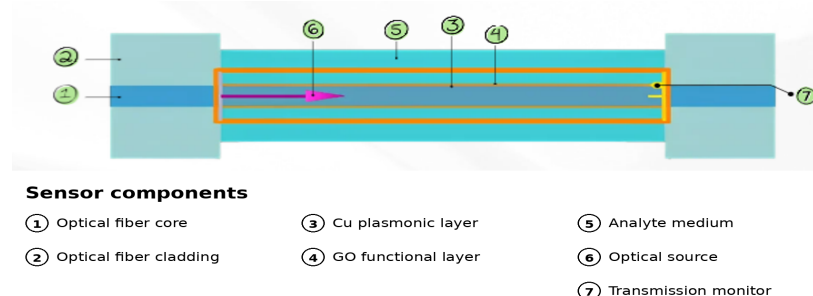


Figure 1. The structure scheme of the SPR sensor is based on D-shaped fiber optic which consists of optical fiber core, optical fiber cladding, Cu layer, graphene oxide (GO) layer, analytical medium, optical source, and transmission monitor.

Figure 1 shows the structure of the D-shaped optical-fiber Surface Plasmon Resonance (SPR) sensor used in this study. The sensor consisted of an optical fiber core that functioned as a light-propagation medium, as well as a cladding layer surrounding the fiber core. A portion of the cladding layer was polished to form a D-shaped structure, allowing the evanescent field generated during light propagation to interact directly with the plasmonic layer and analytical medium. This interaction enabled the occurrence of Surface Plasmon Resonance, which is highly sensitive to changes in the refractive index around the sensor surface.

The Cu coating was used as the main plasmonic material because it has good optical characteristics and a relatively lower cost than other noble metals. Furthermore, a graphene oxide (GO) layer was added on top of the Cu layer as a functional material to enhance the interaction between the evanescent field and the analyte medium and improve the sensor's sensitivity. The analyte medium was placed on top of the GO layer so that changes in the refractive index affected the resonance condition and caused a shift in the resonant wavelength. Light was emitted from the optical source toward the sensor structure, while changes in transmission intensity were recorded by the transmission monitor as the basis for analyzing the characteristics of the SPR sensor.

Simulation Setup

The simulation domain incorporated a plane-wave source, transmission/penetration monitors, mesh regions, and boundary conditions that enabled numerical analysis of the electromagnetic field distribution.

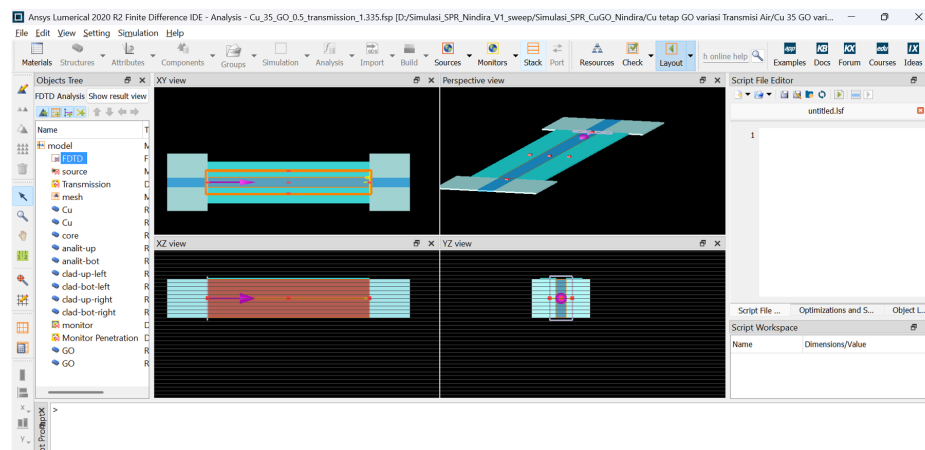


Figure 2. Implementation of sensor structures on Ansys Lumerical FDTD Solutions software

Figure 2 shows the implementation of the sensor structure in Ansys Lumerical FDTD Solutions software used during the simulation process. In the simulation domain, a plane-wave source functioned as the light source to produce electromagnetic waves that propagated along the optical-fiber axis. The light waves then formed an evanescent field in the sensing region, allowing it to interact with the Cu, graphene oxide (GO), and analytical medium.

Table 1

FDTD Simulation Parameters

Parameters	Value
Software	Ansys Lumerical FDTD Solutions
Solver	Finite Difference Time Domain (FDTD)
Simulation Dimension	2D
Simulation Time	1500 fs
Source Type	Mode Source
Injection Axis	X-axis
Spread Direction	Forward
Selected Mode	Mode 2
Simulation Wavelength	400–1200 nm

Parameters	Value
Boundary Condition	PML
Mesh Accuracy	2
Mesh Override	dy = 0.001 μm
Transmission Monitor	Frequency Domain Power Monitor (Linear Y)

The simulations were conducted across wavelengths of 400–1200 nm using a 2D FDTD solver. Calculation accuracy was enhanced through mesh refinement (0.001 μm in the y-direction) and Perfectly Matched Layer (PML) boundary conditions to suppress edge reflections.

Penetration monitors were used to observe the electromagnetic field distribution in the plasmonic layers, facilitating investigation of the resonance formation process.

Two refractive index values were used to model the analytical medium: $n = 1.335$ (reference) and $n = 1.340$ (NaCl solution).

Although the simulations covered the 400–1200 nm wavelength range, the results were presented within the 500–800 nm range to highlight the resonance region and clarify the wavelength shifts.

Simulation Parameter Variations

This research was carried out through several stages of systematic simulation to obtain a sensor configuration that provided optimal performance. Parameter variations were applied to the plasmonic materials, Cu layer thickness, and graphene oxide (GO) layer thickness. All simulation stages carried out in this study are presented in Table 2.

Table 2

Stages of simulation parameter variation

Stages	Parameter Variation	Purpose
1	Comparison of Ag 60 nm and Cu 60 nm	Determining plasmonic materials that have better resonance characteristics
2	Comparison of Cu 60 nm and Cu 60 nm/GO 5 nm	Analyze the effect of adding a GO layer
3	Cu thickness variations (30, 35, 40, 45, 50, 55, and 60 nm) at 5 nm GO	Determining the optimal Cu thickness
4	GO thickness variation (0.5; 5; 10; 15; 20; 25; and 30 nm) at Cu 45 nm	Determining the optimal GO thickness at 45 nm Cu
5	GO thickness variations (0.5; 5; 10; 15; 20; 25; and 30 nm) at Cu 35 nm	Evaluating the influence of GO on different Cu configurations

Based on Table 2, the research was carried out through five continuous simulation stages. The first stage aimed to compare the characteristics of the Ag and Cu plasmonic materials at the same thickness to determine which material provided the better resonance response. Once the optimum material was identified, a graphene oxide (GO) layer was added to evaluate its effect on the resonance characteristics of the sensor.

Furthermore, optimization was carried out by varying the thickness of the Cu layer while maintaining a fixed GO thickness of 5 nm. The Cu configuration that provided the best performance was then used as the basis for evaluating the effect of GO thickness variations. In addition, GO thickness variations were also applied to the Cu 35 nm configuration as a comparison, allowing the effects of the combination of Cu and GO thicknesses on the sensitivity, Full Width at Half Maximum (FWHM), and Figure of Merit (FOM) of the SPR sensor to be analyzed.

The entire sensor configuration was evaluated under two medium refractive index conditions, namely, $n = 1.335$ and $n = 1.340$. The comparison of the two conditions was used to calculate the resonance wavelength shift, sensitivity, FWHM, and FOM so that the sensor configuration with optimal performance could be quantitatively determined.

Evaluation Parameters

The characteristics of the Surface Plasmon Resonance (SPR) sensor in this study were evaluated based on four main parameters, namely, resonance wavelength shift ($\Delta\lambda_{res}$), sensitivity (S), Full Width at Half Maximum (FWHM), and Figure of Merit (FOM). These four parameters were used to determine the sensor configuration with the best performance in detecting changes in the refractive index of the medium. A summary of the evaluation parameters used in this study is presented in Table 3.

Table 3

Parameters of evaluation of SPR sensor characteristics

Parameters	Equations	Units	Remarks
$\Delta\lambda_{res}$	$\lambda_2 - \lambda_1$	NM	Resonant wavelength shift due to change in refractive index
Sensitivity(s)	$\Delta\lambda_{res}/\Delta n$	nm/RIU	Sensor ability to detect changes in refractive index
FWHM	Right - Left Hand	NM	The width of the resonance curve at half the depth of the curve
FOM	S/FWHM	RIU^{-1}	Comparison of sensitivity to resonance curve sharpness

Based on Table 3, sensor performance was evaluated using four main parameters. A shift in the resonant wavelength ($\Delta\lambda_{res}$) indicated a change in the position of the resonant wavelength due to a change in the refractive index of the medium. A greater $\Delta\lambda_{res}$ value indicated a greater sensor response to changes in the refractive index.

Sensitivity (S) expresses the sensor's ability to detect changes in the refractive index, expressed as the change in resonance wavelength per unit change in refractive index (RIU). In addition to sensitivity, the quality of the resonance curve was also evaluated using the Full Width at Half Maximum (FWHM) parameter. Smaller FWHM values indicate a sharper resonance curve, thereby improving the sensor's ability to distinguish very small changes in refractive index. Furthermore, the Figure of Merit (FOM) is used to evaluate the overall performance of the sensor by considering both sensitivity and resonance-curve sharpness. Sensors with larger FOM values exhibit better sensing performance.

Resonant Wavelength Shift ($\delta\lambda_{res}$)

Resonance wavelength shift ($\Delta\lambda_{res}$) is one of the main parameters used to evaluate the characteristics of Surface Plasmon Resonance (SPR) sensors. This parameter indicates a change in the position of the resonant wavelength due to a change in the refractive index of the analyte medium on the sensor surface. As the refractive index of the medium increases, the resonance conditions between the evanescent waves and the free electrons in the metal layer change, causing the resonant wavelength to shift toward a larger (redshift) or smaller (blueshift) value, depending on the structural characteristics of the sensor. The magnitude of the resonant wavelength shift is calculated using Equation (1).

$$\Delta\lambda_{res} = \lambda_{n=1.340} - \lambda_{n=1.335}$$

Equation (1)

with:

1. $\Delta\lambda_{res}$ = resonant wavelength shift (nm)
2. $\lambda_{n=1.340}$ = resonant wavelength at refractive index 1.340 (nm)
3. $\lambda_{n=1.335}$ = resonant wavelength at refractive index 1.335 (nm)

The $\Delta\lambda_{res}$ value was used to determine the extent to which the resonance response changed due to changes in the refractive index of the medium. A greater $\Delta\lambda_{res}$ value indicated a stronger sensor response to changes in the refractive index, resulting in better detection capabilities.

Sensor Sensitivity(*s*)

Sensitivity is a parameter that indicates the sensor's ability to detect changes in the refractive index of the medium through changes in the resonance wavelength. Sensitivity is expressed as the ratio of the shift in the resonant wavelength to the change in refractive index (RIU). A high sensitivity value indicates that the sensor can produce large changes in the resonant wavelength despite small changes in the refractive index. Sensitivity is calculated using Equation (2).

$$S = \frac{\Delta\lambda_{res}}{\Delta n}$$

Equation (2)

with:

1. *S* = sensor sensitivity (nm/RIU)
2. $\Delta\lambda_{res}$ = resonant wavelength shift (nm)
3. Δn = change in refractive index (RIU)

In this study, the changes in the bias index used are:

$$\Delta n = 1.340 - 1.335 = 0.005$$

A greater sensitivity value indicates a better ability of the sensor to detect changes in the refractive index of the medium.

Full Width at Half Maximum (FWHM)

In addition to sensitivity, the quality of the resonance response was also evaluated using the Full Width at Half Maximum (FWHM) parameter. This parameter indicates the width of the resonance curve at half of the minimum transmission-curve depth. The FWHM value is used to describe the sharpness of the resonance curve produced by the sensor. A narrower resonance curve results in better resolution for distinguishing very small changes in the refractive index. The FWHM value is calculated using Equation (3).

Table 4

Example of sensor parameter calculation results in Cu 55 nm/GO 5 nm configuration

Parameters	Value	Units
λ_{res} ($n = 1.335$)	653,552	NM
λ_{res} ($n = 1.340$)	660,773	NM
$\Delta\lambda_{res}$	7,221	NM
Sensitivity	1444,2	nm/RIU
FWHM	28,943	NM
FOM	49,899	RIU ⁻¹

Based on Table 4, the Cu 55 nm/GO 5 nm configuration resulted in a resonant wavelength shift of 7.221 nm when the refractive index increased from 1.335 to 1.340. With a change in refractive index of 0.005 RIU, a sensor sensitivity of 1444.2 nm/RIU was obtained, indicating the sensor's ability to detect changes in the refractive index. Furthermore, the FWHM and FOM values were calculated from the simulated transmission curve to evaluate the resonance sharpness and overall performance of the sensor.

RESULTS AND DISCUSSION

Results

Ag and Cu Comparison

Comparative simulations were performed using silver and copper materials, each with a thickness of 60 nm, under analytical conditions with a refractive index of $n = 1.335$ to identify the more suitable plasmonic material.

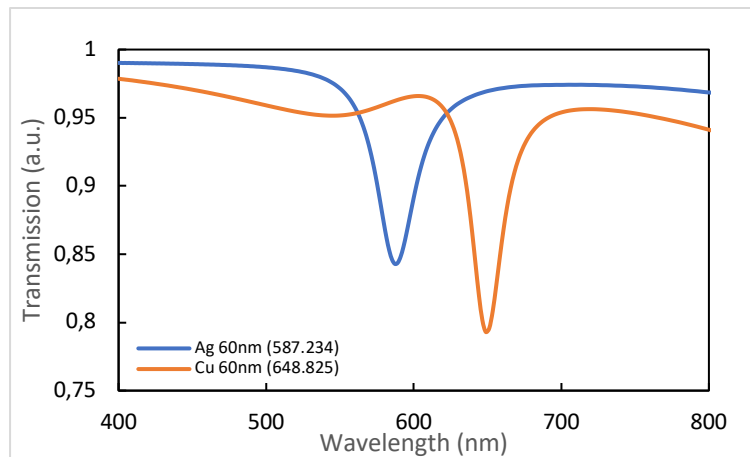


Figure 3. The transmission spectrum of the SPR sensor uses Ag and Cu materials at an analytical refractive index $n = 1.335$

Based on Figure 3, the Ag and Cu materials produce different transmission-spectrum characteristics. These differences can be observed in the resonant wavelength position, resonance depth, and shape of the transmission curve produced by each material. These differences suggest that each material exhibits a distinct optical response to the interaction between the evanescent field and the free electrons on the metal surface.

To quantitatively determine the sensor characteristic parameters, calculations were performed for the resonant wavelength (λ_{res}), resonant wavelength shift ($\Delta\lambda_{res}$), sensitivity, FWHM, and Figure of Merit (FOM). The calculation results are presented in Table 5.

Table 5

Transmission spectrum characteristics at analyte refractive index $n = 1.335$

Material	λ_{res} (nm)	Minimum transmission	FWHM (nm)
Ag 60 nm	587.234	0.842882	32.429
Cu 60 nm	648.825	0.793001	24.362

According to Table 5, copper exhibits a resonant wavelength of 648.825 nm and an FWHM of 24.362 nm, whereas silver exhibits a resonant wavelength of 587.234 nm and an FWHM of 32.429 nm. Under the analytical condition of $n = 1.335$, copper produces a narrower resonance profile than silver.

Effect of adding Graphene Oxide (GO) Layer

After determining the plasmonic material used in this study, a graphene oxide (GO) layer was added to investigate its effect on the resonance characteristics of the SPR sensor. Simulations were performed using Cu 60 nm and Cu 60 nm/GO 5 nm configurations at an analytical refractive index of $n = 1.335$. The resulting transmission spectra are shown in Figure 4.

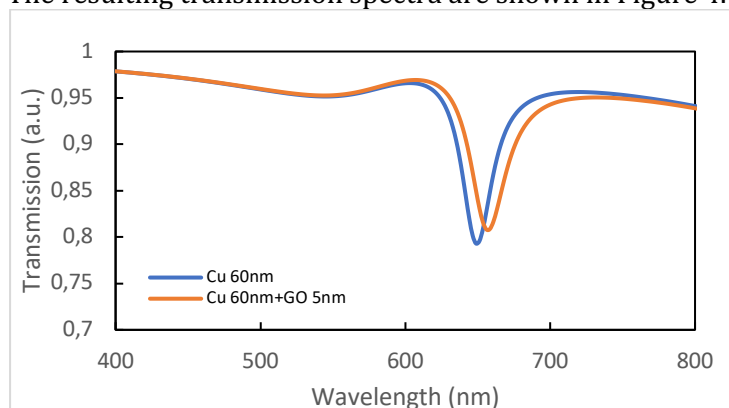


Figure 4. The transmission spectrum of the SPR sensor at Cu 60 nm and Cu 60 nm/GO 5 nm configurations with an analytical refractive index $n = 1.335$

Figure 4 demonstrates that the addition of a GO layer modifies the transmission-spectrum characteristics of the SPR sensor. The resonance wavelength shifted from 648.825 nm for the 60 nm Cu configuration to 655.941 nm for the 60 nm Cu/5 nm GO configuration.

Table 6

Transmission spectrum characteristics of SPR sensors in Cu 60 nm and Cu 60 nm/GO configurations 5 nm with an analyte refractive index $n = 1.335$

Configuration	λ_{res} (nm)	Minimum transmission	FWHM (nm)
Cu 60 nm	648,825	0,793001	24,362
Cu 60 nm/GB 5 nm	655,941	0,803547	22,318

Based on Table 6, the addition of a graphene oxide (GO) layer causes the resonance wavelength to shift from 648.825 nm to 655.941 nm. In addition, the FWHM value decreases from 24.362 nm to 22.318 nm, indicating that the resonance curve in the 60 nm Cu/5 nm GO configuration is narrower than that of the configuration without GO. This change demonstrates that the addition of the GO layer affects the resonance characteristics of the SPR sensor at an analyte refractive index of $n = 1.335$.

Effect of Cu Layer Thickness Variation on 5 nm Fixed GO Thickness

Figure 5 presents the transmission spectra obtained from the simulation results.

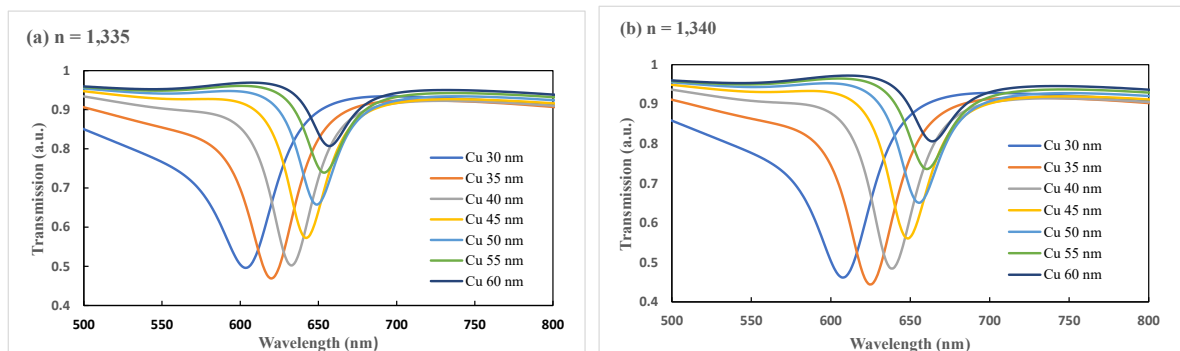


Figure 5. The transmission spectrum of the SPR sensor with a variation in Cu layer thickness (30–60 nm) at a GO thickness of 5 nm with an analyte refractive index of (a) $n = 1.335$ and (b) $n = 1.340$.

Figure 5 demonstrates that variations in copper thickness alter the resonant wavelength positions and transmission-curve profiles.

Table 7

Characteristics of SPR sensors with Cu thickness variation (GO = 5 nm)

Cu Thickness (nm)	λ_{res} ($n = 1.335$) (nm)	λ_{res} ($n = 1.340$) (nm)	$\Delta\lambda_{\text{res}}$ (nm)	Sensitivity (nm/RIU)	FWHM (nm)	FOM (RIU ⁻¹)
30	603,025	607,107	4,082	816,4	50,878	16,05
35	619,689	624,000	4,311	862,2	36,255	23,78
40	632,804	639,572	6,768	1353,6	32,741	41,34
45	641,860	648,825	6,965	1393,0	30,759	45,29
50	648,825	655,941	7,116	1423,2	29,510	48,23
55	653,552	660,773	7,221	1444,2	28,558	50,57
60	655,941	663,216	7,275	1455,0	27,602	52,71

Table 7 demonstrates that increasing the copper thickness induces a redshift of the resonant wavelength while decreasing the FWHM values, thereby narrowing the resonance profile.

Linear regression analysis was performed on the λ_{res} values across the Cu thickness variations to establish the relationship between Cu thickness and resonant wavelength.

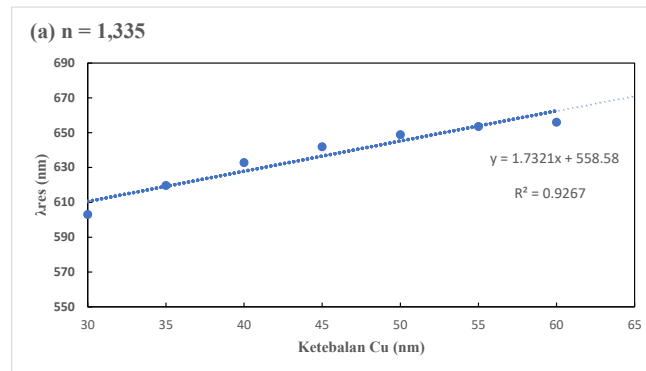


Figure 7. The relationship between the thickness of the Cu layer to the resonant wavelength (λ_{res}) at the analyte refractive index (a) $n = 1.335$ and (b) $n = 1.340$

Figure 7 shows that increasing the copper thickness produces a wavelength redshift under both analytical conditions.

Effect of GO Layer Thickness Variation on Cu 45 nm

After varying the Cu layer thickness, the thickness of the graphene oxide (GO) layer was varied in the Cu 45 nm configuration to determine its effect on the resonance characteristics of the SPR sensor. GO thicknesses of 0.5, 5, 10, 15, 20, 25, and 30 nm were evaluated, while the Cu layer thickness was maintained at 45 nm. The simulations were performed at analyte refractive indices of $n = 1.335$ and $n = 1.340$. The resulting transmission spectra are shown in Figure 8.

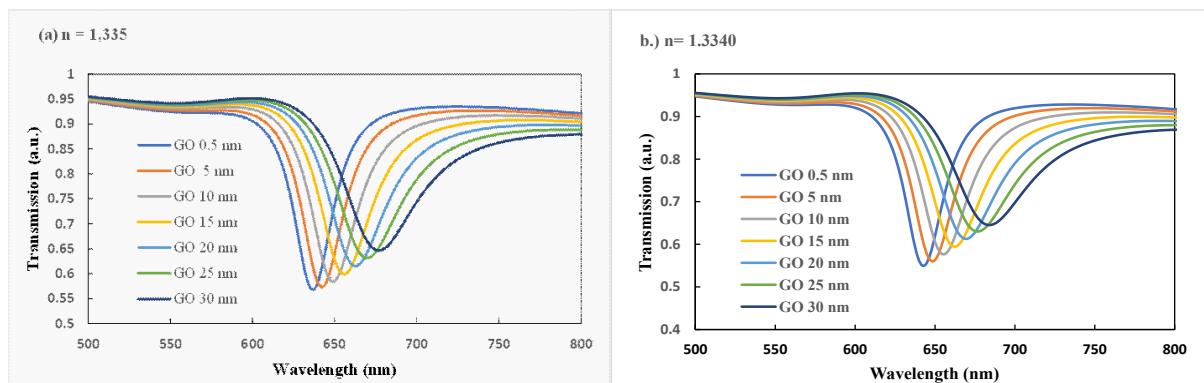


Figure 8. The transmission spectrum of the SPR sensor with the variation in the thickness of the GO layer at the Cu configuration was 45 nm for the analyte refractive index (a) $n = 1.335$ and (b) $n = 1.340$.

Based on Figure 8, variations in GO layer thickness result in changes in the resonant wavelength position as well as the shape of the transmission curve for each configuration. Under both analyte refractive index conditions, increasing the GO thickness causes the resonance curve to shift toward longer wavelengths (redshift). The values of the resonant wavelength, sensitivity, Full Width at Half Maximum (FWHM), and Figure of Merit (FOM) for each GO thickness variation are presented in Table 8.

Table 8

SPR sensor characteristics for GO thickness variation at Cu 45 nm

GO (nm)	Squirrels (1,335)	Squirrels (1,340)	$\Delta\lambda_{res}$ (nm)	Sensitivity (nm/RIU)	FWHM (nm)	FOM (RIU ⁻¹)
0,5	637,300	641,860	4,560	912,0	28,330	32,19

GO (nm)	Squirrels (1,335)	Squirrels (1,340)	$\Delta\lambda_{res}$ (nm)	Sensitivity (nm/RIU)	FWHM (nm)	FOM (RIU ⁻¹)
5	641,860	648,825	6,965	1393,0	30,759	45,29
10	648,825	655,941	7,116	1423,2	34,561	41,18
15	655,941	663,216	7,275	1455,0	39,356	36,97
20	663,216	668,156	4,940	988,0	45,196	21,86
25	670,654	675,706	5,052	1010,4	52,241	19,34
30	675,706	683,429	7,723	1544,6	60,533	25,52

Across both conditions, λ_{res} increases with GO thickness.

Effect of GO Layer Thickness Variation on Cu 35 nm

After analyzing the effect of GO layer thickness in the Cu 45 nm configuration, the GO layer thickness was varied in the Cu 35 nm configuration to determine its effect on the resonance characteristics of the SPR sensor. GO thicknesses of 0.5, 5, 10, 15, 20, 25, and 30 nm were evaluated, while the Cu layer thickness was maintained at 35 nm. Simulations were performed at analyte refractive indices of $n = 1.335$ and $n = 1.340$. The resulting transmission spectra are shown in Figure 10.

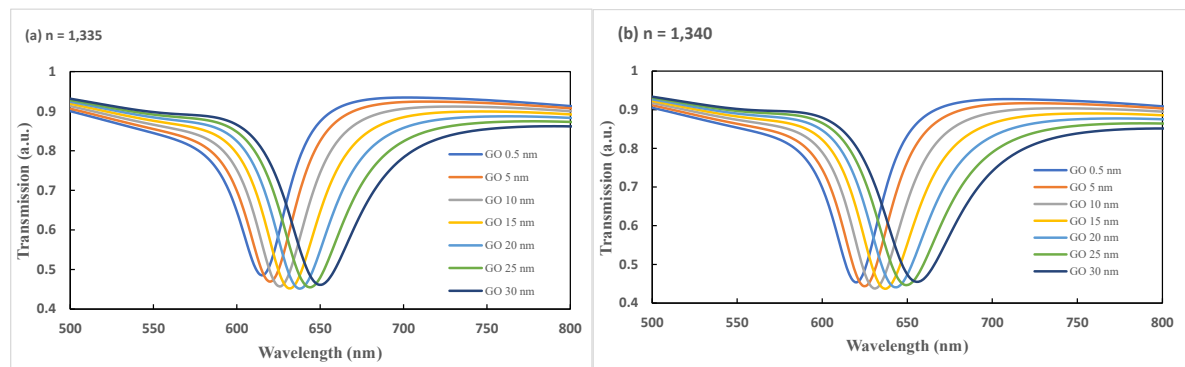


Figure 10. The transmission spectrum of the SPR sensor with the variation in the thickness of the GO layer at the Cu configuration of 35 nm for the analyte refractive index (a) $n = 1.335$ and (b) $n = 1.340$

Based on Figure 10, variations in GO layer thickness in the Cu 35 nm configuration result in changes in the resonant wavelength position as well as the shape of the transmission curve for each GO thickness. Under both analyte refractive index conditions, increasing the GO thickness causes the resonance curve to shift toward longer wavelengths (redshift). The values of the resonant wavelength (λ_{res}), resonant wavelength shift ($\Delta\lambda_{res}$), sensitivity, Full Width at Half Maximum (FWHM), and Figure of Merit (FOM) are presented in Table 9.

Table 9

Characteristics of SPR sensors on GO thickness variations with Cu 35 nm

GO (nm)	λ_{res} (1,335) (nm)	λ_{res} (1,340) (nm)	$\Delta\lambda_{res}$ (nm)	Sensitivity (nm/RIU)	FWHM (nm)	FOM (RIU ⁻¹)
0,5	619,689	624,095	4,406	881,2	38,236	23,05
5	626,178	632,915	6,737	1347,4	37,640	35,80
10	632,804	639,578	6,774	1354,8	38,116	35,55
15	639,578	646,241	6,663	1332,6	41,049	32,46
20	646,241	651,180	4,939	987,8	44,698	22,10
25	651,180	655,941	4,761	952,2	49,325	19,30

Across both conditions, λ_{res} increases with GO thickness.

Linear regression analysis was performed to examine the relationship between GO thickness and resonant wavelength for the Cu 35 nm configuration using the simulated λ_{res} values.

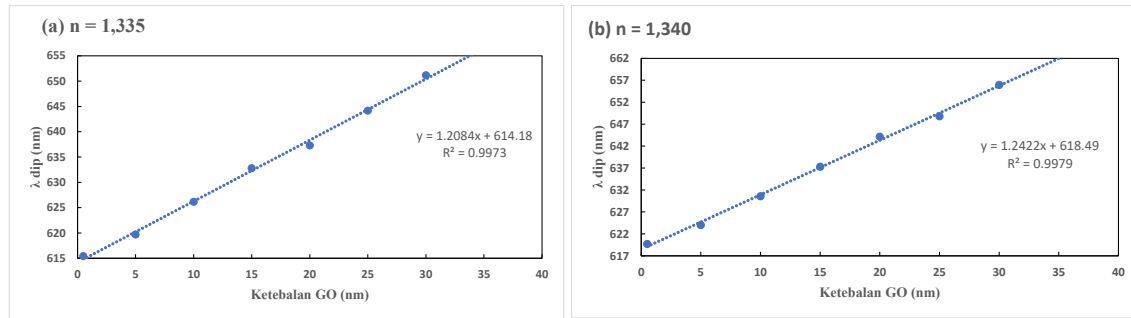


Figure 11. The relationship between the thickness of the GO layer to the resonant wavelength (λ_{res}) at the Cu 35 nm configuration with the analyte bias index (a) $n = 1.335$ and (b) $n = 1.340$

Figure 11 demonstrates that increasing GO thickness induces a wavelength redshift in the Cu 35 nm configuration under both conditions.

Discussion

Effect of Ag and Cu Materials on SPR Sensor Characteristics

Based on the simulation results presented in the Results section, the Ag and Cu materials exhibit different resonance characteristics when used as plasmonic layers on D-shaped fiber-optic Surface Plasmon Resonance (SPR) sensors. This difference can be observed in the resonant wavelength (λ_{res}), the depth of the transmission curve, and the Full Width at Half Maximum (FWHM) value. In the configurations used in this study, the Ag material produces a resonant wavelength of 587.234 nm with an FWHM of 32.429 nm, whereas the Cu material produces a resonant wavelength of 648.825 nm with an FWHM of 24.362 nm. The smaller FWHM value for Cu indicates that the resulting resonance curve is narrower than that of Ag, allowing the resonant position to be determined with greater precision. This result indicates that Cu exhibits more favorable resonance characteristics than Ag for the sensor structure investigated in this study.

The difference in resonance characteristics between Ag and Cu is influenced by the optical properties of each material, specifically their complex permittivity values, which determine the conditions for surface plasmon polariton (SPP) generation at the metal–dielectric interface (Liu et al., 2022). SPR resonance occurs when the momentum of the incident wave matches the momentum of the surface plasmon wave, allowing energy to be transferred from the light field to the free electrons at the metal surface (Zhang et al., 2022). The efficiency of this coupling process is strongly influenced by the optical characteristics of the plasmonic material. Materials with appropriate dielectric properties can produce a stronger evanescent field in the sensing region, thereby enhancing interaction with the analyte medium (Bai et al., 2022; Gao et al., 2023; Sharma et al., 2023). This phenomenon has been widely reported in studies of fiber-optic SPR sensors, which indicate that the selection of plasmonic material is one of the main factors determining sensor performance.

In addition to influencing the resonance position, the selection of plasmonic material also affects the shape of the resulting transmission curve. Based on the simulation results, the Cu material produces a sharper resonance curve than Ag. A sharp resonance curve indicates stronger localization of electromagnetic energy around the resonant region, so changes in the refractive index of the medium can produce more readily observable shifts in the resonant wavelength (Liu et al., 2022). In contrast, a broader resonance curve makes the resonance position less well defined, thereby reducing the accuracy of the sensor in detecting very small changes in refractive index (Zhang et al., 2022). Therefore, FWHM is an important parameter for evaluating the resonance quality of SPR sensors because it is directly related to sensor resolution (Liu et al., 2022).

The simulation results also show that the Cu material produces a lower minimum transmission value than Ag. The decrease in transmission intensity indicates that energy transfer from the incident wave to the surface plasmon wave occurs more effectively. The greater the energy coupled to the surface plasmon mode, the more pronounced the resonance dip in the transmission spectrum. This condition makes the resonant wavelength easier to identify, thereby improving the quality of the measurement process. This phenomenon suggests that the optical

characteristics of the material affect not only the resonant position but also the depth and sharpness of the resulting resonance curve (Gao et al., 2023; Li et al., 2023).

The differences in characteristics between silver and copper stem from their respective abilities to support conduction-electron oscillations at metal surfaces (Liu et al., 2022).

These findings are consistent with Navarrete et al. (2023), who demonstrated that the incorporation of functional materials can strengthen interactions between the evanescent field and the analyte, resulting in enhanced wavelength shifts.

The simulation results, supported by previous investigations, confirm that incorporation of a GO layer influences the characteristics of D-shaped fiber-optic SPR sensors.

Effect of Adding Graphene Oxide (GO) Layer on SPR Sensor Characteristics

After identifying Cu as the plasmonic material that provides more favorable resonance characteristics than Ag, the next stage was to analyze the effect of adding a graphene oxide (GO) layer on the characteristics of the D-shaped fiber-optic Surface Plasmon Resonance (SPR) sensor. The GO layer was added to enhance the interaction between the evanescent field formed at the sensor surface and the analyte medium. The simulation results showed that the presence of the GO layer produced noticeable changes in the resonance characteristics, including the resonant wavelength position, transmission-curve shape, and resulting Full Width at Half Maximum (FWHM). These changes suggest that GO acts as a functional layer that influences the surface plasmon resonance process (Wu et al., 2023). Similar findings were reported by Navarrete et al. (2023), who showed that the addition of a GO layer can enhance the interaction between the evanescent field and the analyte medium.

Based on the simulation results in Figure 4 and Table 6, the addition of the GO layer caused the resonance wavelength to shift from 648.825 nm in the 60 nm Cu configuration to 655.941 nm in the 60 nm Cu/5 nm GO configuration. This shift indicates a redshift, defined as a shift in the resonant position toward a longer wavelength following the addition of the GO layer (Wu et al., 2023). In addition, the FWHM value decreased from 24.362 nm to 22.318 nm, indicating that the resonance curve became narrower than that of the structure without GO. These results indicate that the addition of GO not only shifts the resonance position but also increases the sharpness of the resonance curve, thereby improving the sensor response characteristics (Muhamad Fauzi et al., 2022).

The redshift observed after the addition of GO is caused by changes in the optical conditions within the sensing region. The presence of the GO layer modifies the optical conditions at the metal–dielectric interface, thereby increasing the interaction between the evanescent field and the surface plasmon polariton (SPP) and affecting the SPR resonance conditions (Navarrete et al., 2023). These changes cause the resonance condition to shift toward longer wavelengths. In addition, the presence of GO can increase the distribution of the evanescent field around the sensor surface, strengthening the interaction between the electromagnetic field and the analyte medium (Lestari et al., 2026). As a result, changes in the refractive index of the analyte medium produce resonance-position changes that are more readily observable than those in structures without GO.

In addition to causing a redshift, the GO layer can enhance molecular adsorption on the sensor surface. GO contains hydroxyl, epoxy, and carboxyl functional groups that provide a large active surface area compared with metal layers alone (Wu et al., 2023). These characteristics increase the likelihood of interactions between the analyte medium and the sensor surface, allowing changes in the refractive index near the surface to affect the resonance conditions more effectively (Navarrete et al., 2023). Therefore, GO has been widely investigated as a functional layer in SPR sensors, particularly for enhancing sensitivity and expanding potential sensor applications in chemistry and biosensing (Lestari et al., 2026).

The simulation results also show that the addition of GO produces a sharper resonance curve than the structure without GO. Smaller FWHM values indicate that the resonance position can be determined with greater precision (Wu et al., 2023). A narrow resonance curve is an important characteristic of SPR sensors because it is directly related to the sensor's resolution in distinguishing very small changes in refractive index (Navarrete et al., 2023). Thus, even though the GO thickness was only 5 nm, the resulting changes in resonance characteristics already

indicate an improvement compared with the structure without GO.

These findings are consistent with Navarrete et al. (2023), who demonstrated that incorporation of functional materials strengthens interactions between the evanescent field and the analyte, resulting in enhanced wavelength shifts.

GO incorporation induces a wavelength redshift, strengthens evanescent-field-analyte coupling, and sharpens the resonance profile (Wu et al., 2023).

Effect of Cu Layer Thickness Variation on SPR Sensor Characteristics

The Cu thickness was varied from 30 to 60 nm while maintaining the GO layer thickness at 5 nm.

Based on Figure 5 and Table 7, increasing the thickness of the Cu layer causes the resonance wavelength to shift toward longer wavelengths (redshift) under both analytical refractive index conditions, namely $n = 1.335$ and $n = 1.340$. At a refractive index of $n = 1.335$, λ_{res} increases from 603.025 nm at a Cu thickness of 30 nm to 655.941 nm at a thickness of 60 nm. The same trend is observed at $n = 1.340$, where λ_{res} increases from 607.107 nm to 663.216 nm. These changes indicate that increasing the Cu layer thickness alters the SPR resonance conditions, causing the resonant wavelength to shift toward longer wavelengths (redshift). The linear regression analysis also showed a strong relationship between Cu thickness and resonant wavelength, with R^2 values of 0.9267 at $n = 1.335$ and 0.9208 at $n = 1.340$. Thus, the increase in Cu thickness exhibits an approximately linear relationship with the change in resonance position. These results are consistent with the theory that metal-layer thickness affects SPR resonance conditions through changes in the optical characteristics of the material and the coupling efficiency between the evanescent field and the surface plasmon mode (Gao et al., 2023; Liu et al., 2022).

The redshift occurs because increasing the Cu layer thickness changes the distribution of the electromagnetic field in the sensing region. When light propagates through the core of the optical fiber, some of its energy forms an evanescent field that penetrates the metal layer and interacts with free electrons at the Cu surface (Liu et al., 2022). Increasing the metal-layer thickness changes the propagation constant of the surface plasmon polariton (SPP), causing the resonance condition to shift toward longer wavelengths (Gao et al., 2023). A similar phenomenon was reported by Liu et al. (2022), who stated that changes in metal-layer thickness affect the resonance position by altering the coupling efficiency between the evanescent field and the surface plasmon mode.

Beyond resonance positioning, variations in copper thickness influence sensor sensitivity. Table 7 shows a gradual increase in sensitivity from 816.4 nm/RIU for 30 nm Cu to 1455.0 nm/RIU for 60 nm Cu.

Changes in Cu thickness also affect the FWHM, which describes the sharpness of the resonance curve. Based on the simulation results, the FWHM decreases from 50.878 nm at a Cu thickness of 30 nm to 27.602 nm at a Cu thickness of 60 nm. The decrease in FWHM indicates that the resonance curve becomes narrower, allowing the resonant position to be determined with greater precision (Maurya et al., 2023). A sharp resonance curve is important in an SPR sensor because it allows very small changes in refractive index to be distinguished more clearly. In contrast, a broad resonance curve makes the resonance position less well defined, thereby reducing sensor resolution (Liu et al., 2022).

The simulation findings reveal that different Cu thicknesses produce different performance characteristics across the evaluation metrics. While certain configurations maximize sensitivity, others produce sharper resonance profiles, demonstrating that no single thickness simultaneously optimizes all parameters.

Based on the FOM calculations, increasing Cu thickness tends to produce a higher FOM because of the combined increase in sensitivity and decrease in FWHM. This relationship was also reported by Gao et al. (2023), who showed that optimization of metal-layer thickness affects the sensitivity and sharpness of the resonance curve of SPR sensors. Similar findings were reported by Liu et al. (2022). Although the 60 nm Cu configuration provides the highest FOM value, this study does not directly establish this configuration as the basis for GO thickness optimization. The 45 nm Cu configuration was selected by considering the balance of resonance characteristics, the

feasibility of subsequent optimization processes, and the objective of evaluating the effect of GO thickness variations on representative configurations.

This selection reflects the fact that the purpose of the study is not solely to identify the configuration with the highest Figure of Merit (FOM) but also to evaluate the effect of GO thickness variations on representative Cu configurations. Therefore, Cu 45 nm was selected as the baseline configuration for the GO optimization stage. This selection allows GO thickness variations to be analyzed consistently using a Cu thickness within the middle of the investigated range while also considering the research objectives and potential implementation in the fabrication process. Thus, the 45 nm Cu configuration was used as the basis for the next stage of optimization, while the 35 nm Cu configuration was used as a comparator to evaluate the effect of GO thickness on a different metal thickness.

The results of this study are consistent with those of Gao et al. (2023), who reported that optimization of metal-layer thickness is one of the main factors in improving the performance of fiber-optic SPR sensors. Maurya et al. (2023) also showed that changes in metal-layer thickness affect the coupling process between the evanescent field and surface plasmon polaritons (SPPs), causing shifts in the resonance wavelength as well as changes in sensor resonance characteristics. Similar findings were reported by Ying et al. (2024), who showed that variations in metal-layer thickness affect sensitivity and resonance-curve sharpness. The results obtained in this study show the same tendency, namely that variations in Cu thickness affect the resonance characteristics across all evaluated parameters.

Overall, variations in Cu layer thickness have been shown to influence the resonance characteristics of D-shaped fiber-optic SPR sensors. These effects can be observed in changes in resonant wavelength (λ_{res}), sensitivity, Full Width at Half Maximum (FWHM), and Figure of Merit (FOM), as also reported in previous studies on plasmonic-layer optimization (Gao et al., 2023; Liu et al., 2022). Based on the evaluation of all parameters, the 45 nm Cu configuration was selected as the baseline configuration for the GO thickness optimization stage, while the 35 nm Cu configuration was used as the comparator configuration to evaluate the effect of GO variations at a different metal thickness. The selection of these configurations was based on the balance of resonance characteristics and the requirements of the subsequent optimization stage (Gangwar et al., 2023; Maurya et al., 2023; Ying et al., 2024).

Effect of GO Layer Thickness Variation on SPR Sensor Characteristics

After establishing the 45 nm Cu baseline configuration, the next stage was to analyze the effect of graphene oxide (GO) thickness variations on the characteristics of D-shaped fiber-optic Surface Plasmon Resonance (SPR) sensors. GO thicknesses of 0.5, 5, 10, 15, 20, 25, and 30 nm were evaluated, while the Cu layer thickness was maintained at 45 nm. Evaluation was performed based on the resonant wavelength (λ_{res}), resonant wavelength shift ($\Delta\lambda_{\text{res}}$), sensitivity, Full Width at Half Maximum (FWHM), and Figure of Merit (FOM). The GO thickness variation was investigated to determine the influence of the two-dimensional material on sensor performance and to identify a thickness that provides a balance between sensitivity and resonance-curve sharpness (Navarrete et al., 2023; Urade et al., 2023; Wu et al., 2023).

Based on the simulation results in Figure 8 and Table 8, increasing the GO thickness causes the resonance wavelength to shift toward longer wavelengths (redshift) under both analyte refractive index conditions. At $n = 1.335$, λ_{res} increases from 637.300 nm at a GO thickness of 0.5 nm to 675.706 nm at a GO thickness of 30 nm. Meanwhile, at $n = 1.340$, λ_{res} increases from 641.860 nm to 683.429 nm. This shift suggests that increasing GO thickness enhances the interaction between the evanescent field and the analyte medium, causing the resonance condition to shift toward longer wavelengths (Wu et al., 2023). A similar phenomenon was reported by Navarrete et al. (2023), who showed that a GO layer increases the distribution of the electromagnetic field around the metal–dielectric interface, resulting in a shift in the resonance position.

The redshift is caused by changes in the optical characteristics of the sensing region following the addition of the GO layer. The presence of the GO layer modifies the optical conditions at the metal–dielectric interface, thereby increasing the interaction between the evanescent field and the surface plasmon polariton (SPP) (Wu et al., 2023). As a result, the resonance condition

shifts toward longer wavelengths. The results of this study are consistent with Navarrete et al. (2023), who showed that graphene oxide can increase the distribution of electromagnetic fields around the sensor surface, resulting in larger changes in the resonance position than those observed in structures without two-dimensional materials.

In addition to affecting the resonance position, variations in GO thickness also affect sensor sensitivity. Based on Table 8, the sensitivity increases from 912.0 nm/RIU at a GO thickness of 0.5 nm to 1544.6 nm/RIU at a GO thickness of 30 nm. The increased sensitivity suggests that the GO layer can strengthen the interaction between the evanescent field and the analyte medium, so that changes in refractive index result in larger resonance-wavelength shifts (Wu et al., 2023). However, increased sensitivity does not necessarily indicate that a configuration provides the best overall sensor performance because performance is also affected by the shape of the resulting resonance curve (Alfi et al., 2022; Lestari et al., 2026; Thongsomboon et al., 2023).

This can be observed from the change in FWHM at each GO thickness. The FWHM increases from 28.330 nm at a GO thickness of 0.5 nm to 60.533 nm at a GO thickness of 30 nm. The increase in FWHM indicates that the resonance curve becomes broader as the GO thickness increases. A broader resonance curve makes the resonance position less sharply defined, reducing the sensor's ability to distinguish very small changes in refractive index (Navarrete et al., 2023). Thus, although greater GO thickness can increase sensitivity, the broadening of the resonance curve must also be considered during the sensor optimization process (Hallad et al., 2025; Lestari et al., 2026).

Overall sensor performance was evaluated using the Figure of Merit (FOM), which is the ratio of sensitivity to FWHM. Based on the simulation results, the highest FOM value was obtained at a GO thickness of 5 nm, with a value of 45.29 RIU⁻¹. When the GO thickness exceeds 5 nm, sensitivity continues to increase for some configurations, but this increase is accompanied by a larger increase in FWHM, causing the FOM value to decrease. For example, at a GO thickness of 30 nm, the sensitivity reaches 1544.6 nm/RIU, but the FWHM increases to 60.533 nm, resulting in an FOM of 25.52 RIU⁻¹. These results show that increased sensitivity does not necessarily result in improved overall sensor performance if it is not accompanied by a sufficiently sharp resonance curve (Liu et al., 2022; Navarrete et al., 2023).

Physically, this phenomenon may occur because an excessively thick GO layer increases optical loss in the sensing region. Some of the evanescent-field energy may no longer contribute effectively to the generation of surface plasmon polaritons (SPPs) and may instead be attenuated within the GO layer. As a result, the resonance curve becomes broader and the resonance quality decreases (Wu et al., 2023). Conversely, when the GO layer is too thin, the interaction between the evanescent field and the analyte medium may not be sufficiently strong, limiting the increase in sensitivity (Lestari et al., 2026; Sitorus et al., 2025). Therefore, an appropriate GO thickness is required to balance enhanced sensitivity and resonance-curve sharpness.

The results of this study are supported by Navarrete et al. (2023), who showed that functional materials used in SPR sensors can improve resonance characteristics by strengthening optical interactions at the sensor surface. In addition, Wu et al. (2023) explained that optimization of two-dimensional material thickness should consider both electromagnetic-field distribution and optical losses in the sensing region. The findings are also consistent with Liu et al. (2022), who stated that optimization of functional-layer thickness is an important factor in improving the sensitivity and Figure of Merit of fiber-optic SPR sensors.

Based on all evaluated parameters, a GO thickness of 5 nm was selected for the Cu 45 nm configuration. This selection was based on its highest Figure of Merit (FOM), indicating a balance between sensitivity and resonance-curve sharpness. Thus, the Cu 45 nm/GO 5 nm configuration exhibited the most favorable combination of resonance characteristics among the GO thickness variations investigated in this study and was selected as the optimized sensor structure. These findings are consistent with Liu et al. (2022), Navarrete et al. (2023), and Lestari et al. (2026), who showed that optimizing the thickness of the functional layer plays an important role in obtaining favorable SPR sensor performance.

Analysis of Sensor Configuration Optimization Results

Based on all the simulation stages conducted, the characteristics of D-shaped fiber-optic Surface Plasmon Resonance (SPR) sensors are influenced by the type of plasmonic material, the

addition of graphene oxide (GO) layers, and variations in the thicknesses of the Cu and GO layers. Each optimization stage produces changes in the resonant wavelength (λ_{res}), resonant wavelength shift ($\Delta\lambda_{\text{res}}$), sensitivity, Full Width at Half Maximum (FWHM), and Figure of Merit (FOM). These results show that sensor performance is not determined by a single parameter but results from the interaction among the optical properties of the materials, layer thicknesses, and electromagnetic-field distribution in the sensing region (Gao et al., 2023; Liu et al., 2022; Wu et al., 2023).

The first stage of the study showed that Cu produces more favorable resonance characteristics than Ag. Cu produces a narrower resonance curve with a smaller FWHM, allowing the resonance position to be determined with greater precision (Liu et al., 2022). In addition, the resonant wavelengths produced by Cu are in a longer-wavelength region than those produced by Ag. These characteristics indicate that Cu provides favorable coupling between the evanescent field and free electrons at the metal surface and was therefore selected as the plasmonic material for the subsequent optimization stages (Gao et al., 2023). These results are also supported by Maurya et al. (2023), who reported that Cu and optimization of metal-layer thickness play important roles in producing favorable resonance characteristics in fiber-optic SPR sensors. The variation in Cu thickness indicates that each configuration produces different resonance characteristics across the evaluated parameters. Therefore, a Cu thickness of 45 nm was selected as the baseline configuration for the GO layer optimization process so that the influence of GO thickness variations could be analyzed consistently within a defined sensor structure.

After the Cu material was selected, a graphene oxide (GO) layer was added as a functional material. The simulation results showed that the addition of GO caused a redshift in the resonant wavelength and produced a sharper resonance curve than the structure without GO (Wu et al., 2023). These changes indicate that GO can enhance the interaction between the evanescent field and the analyte medium, so that changes in refractive index produce a greater resonance response. In addition, the presence of GO can enhance the interaction between the evanescent field and the analyte medium, thereby improving the resonance response (Navarrete et al., 2023). This phenomenon is consistent with Lestari et al. (2026), who reported that two-dimensional materials used as functional layers can increase electromagnetic-field distribution at the sensor surface, thereby improving SPR sensor performance.

Optimization of the Cu layer thickness showed that increasing Cu thickness caused the resonant wavelength to redshift, increased sensitivity, and decreased the FWHM, resulting in a sharper resonance curve (Gao et al., 2023). The Figure of Merit (FOM) also showed an increasing trend with increasing Cu thickness (Liu et al., 2022). However, this study did not consider only a single parameter when determining the baseline configuration; the overall research process was also considered. Therefore, the 45 nm Cu configuration was selected as the baseline configuration for the GO thickness optimization process, allowing the influence of GO variations to be analyzed systematically and consistently.

Furthermore, GO thickness optimization showed that increasing GO thickness does not necessarily result in an overall improvement in sensor performance. Although greater GO thickness can increase sensitivity in some configurations, the increase is accompanied by an increase in FWHM, resulting in a broader resonance curve (Navarrete et al., 2023). Consequently, the Figure of Merit (FOM) does not necessarily increase. Based on the evaluation of all parameters, the 5 nm GO configuration produced the highest FOM value in the 45 nm Cu configuration, providing a balance between sensitivity and resonance-curve sharpness. Thus, the Cu 45 nm/GO 5 nm configuration was selected as the optimized sensor structure in this study (Lestari et al., 2026).

Physically, the optimization results indicate that an appropriate thickness exists for each layer comprising the SPR sensor. A Cu layer that is too thin may result in insufficient coupling between the evanescent field and free electrons, whereas a layer that is too thick can increase optical losses, causing some of the light energy to no longer contribute effectively to the generation of surface plasmon polaritons (SPPs) (Wu et al., 2023). Similar conditions can occur in the GO layer. A GO layer that is too thin may not maximize interaction with the analyte medium, whereas a layer that is too thick can broaden the resonance curve because of increased optical losses (Liu et al., 2022). Therefore, optimization of the thicknesses of both layers is an important

factor in obtaining favorable sensor performance.

The results of this study are consistent with previous studies showing that SPR sensor performance is influenced by the combination of plasmonic and two-dimensional materials. Liu et al. (2022) explained that optimization of metal-layer thickness is one of the main factors in increasing the sensitivity of fiber-optic SPR sensors. In addition, Wu et al. (2023) stated that graphene oxide can increase electromagnetic-field distribution and strengthen the interaction between the evanescent field and the analyte medium when used at an appropriate thickness. The findings are also supported by Navarrete et al. (2023), who reported that excessive GO thickness can decrease resonance quality because of increased optical losses. The results of this study further demonstrate these relationships through numerical analysis using the Finite Difference Time Domain (FDTD) method for a double-layer Cu/GO structure based on D-shaped fiber optics.

Overall, this study shows that optimization of the Cu/GO structure can improve the characteristics of D-shaped optical-fiber Surface Plasmon Resonance (SPR) sensors. The combination of Cu as a plasmonic layer and GO as a functional layer results in more favorable resonance characteristics than structures without GO (Gao et al., 2023; Wang et al., 2024). Based on the evaluation of λ_{res} , sensitivity, FWHM, and Figure of Merit (FOM), the Cu 45 nm/GO 5 nm configuration was selected as the optimized structure because it provides a balance between sensitivity and resonance-curve sharpness. This configuration can serve as a basis for the further development of fiber-optic SPR sensors for various refractive-index sensing applications (Liu et al., 2022; Navarrete et al., 2023).

CONCLUSION

Based on numerical simulations using the Finite Difference Time Domain (FDTD) method, the characteristics of the D-shaped fiber-optic Surface Plasmon Resonance (SPR) sensor are influenced by the type of plasmonic material, the addition of a graphene oxide (GO) layer, and variations in the thicknesses of the Cu and GO layers. Cu produced more favorable resonance characteristics than Ag, as indicated by a sharper resonance curve and a smaller Full Width at Half Maximum (FWHM), thereby providing better measurement resolution. Increasing the Cu layer thickness shifted the resonance wavelength toward longer wavelengths and increased sensor sensitivity. However, sensitivity alone was insufficient to determine the optimal configuration because sensor performance was also affected by FWHM and Figure of Merit (FOM). Therefore, the 45 nm Cu configuration was selected as the baseline for optimizing the GO layer thickness.

Variations in GO layer thickness showed that increasing the GO thickness could improve sensor sensitivity but could also broaden the resonance curve, as indicated by increased FWHM values. Based on the combined evaluation of resonance wavelength (λ_{res}), sensitivity, FWHM, and FOM, the Cu 45 nm/GO 5 nm configuration was selected as the optimized configuration because it provided the best balance among sensitivity, resonance-curve sharpness, and FOM within the configurations investigated. These findings indicate that optimization of the Cu/GO double-layer structure can improve the characteristics of D-shaped fiber-optic SPR sensors and support their further development for refractive-index sensing applications. Future research may focus on experimental validation and the use of other two-dimensional materials to further improve sensor sensitivity and stability.

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AUTHOR CONTRIBUTION STATEMENT

Nindira Amelia Keysa, Wiwis Sasmitaninghidayah, and Wildan Panji Tresna jointly contributed to the research conception, methodology, numerical simulation, data interpretation, manuscript preparation, and final approval of the published version. All authors are accountable for the integrity of the work.

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