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High-Sensitivity Plasmonic Refractive Index Sensor Based on a Split Disc–Ring Resonator

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Abstract

A highly sensitive plasmonic refractive index (RI) sensor based on a split disc–ring resonator (SDRR) is presented and numerically analyzed. The sensor comprises a split disc surrounded by a split ring, both fabricated on a SiO₂ substrate. This structure supports coupled plasmonic modes, specifically ‘bright’ and ‘dark’ modes, which lead to strong near-field interactions and Fano-type interference. These phenomena enable significant localized electric field enhancement at the metal–analyte interface, rendering the sensor extremely responsive to subtle changes in the analyte’s RI. Systematic optimization of structural parameters, including gap widths, disc and ring radius, and metallic composition, revealed that a silver disc–gold ring configuration provides an optimal trade-off between sensitivity and spectral stability. Numerical simulations performed using the Finite-Difference Time-Domain (FDTD) method validate the sensor’s capability to detect refractive index variations, demonstrating its high responsiveness to subtle biological changes. The simulations yield a maximum sensitivity (S) of 1670 nm/RIU, a figure of merit (FOM) of 3.6 RIU⁻¹, a quality factor of 7.4, and a full width at half maximum (FWHM) of 452.8 nm across a refractive index range of 1.33 to 1.53, exhibiting excellent linearity ($R^2 = 0.99983$). Owing to its simple geometry, strong field confinement, and tunable metal composition, the SDRR offers a versatile platform for practical biomedical and environmental sensing—such as biomolecule, cancer cell, virus, and bacterial detection. These findings highlight the potential of SDRR-based plasmonic sensors as highly reliable and high-performance devices for next-generation biosensing and environmental monitoring systems.

keywords: Plasmonic sensor, Split disc–ring resonator, Refractive index, Fano resonance, Biosensing.

1 Introduction

Surface plasmon resonance (SPR) occurs at the metal–dielectric interface when incident light couples with free electrons on the metal surface, producing collective oscillations known as surface plasmon polaritons (SPPs). Because the resonance condition depends strongly on the surrounding refractive index (RI), even slight variations caused by molecular binding or environmental changes lead to observable shifts in resonance wavelength or angle (Lv et al., 2022). This principle underlies the operation of many advanced optical sensors. Recent progress in nanotechnology has revolutionized the design and optimization of plasmonic sensors, enabling significantly enhanced sensitivity and compact structures (Islam, 2018, Miao et al., 2023). Optical sensors have found extensive use in biomedical, environmental, and chemical applications due to their capability for rapid, label-free molecular detection (Hurayya et al., 2025). In such systems, the electromagnetic field becomes highly confined at the metal–analyte interface, allowing precise monitoring of minute refractive-index changes (Butt, 2022, Harhouz and Hocini, 2021, Patel and Parmar, 2021, Yakes and et al., 2013). These sensors have been successfully employed for detecting various cancer cell types, viruses, bacteriophages (Elwasif et al., 2024), and bacteria (Hart et al., 2004) demonstrating their great potential for high-performance biosensing.

Recently, plasmonic nanostructures, including nano-rings and nano-disks, have significantly advanced the field of high-sensitivity optical sensors (Darweesh et al., 2022, Esfahani et al., 2025, He et al., 2023). Among

these, plasmonic split-ring nanostructures have attracted substantial interest for their application in RI sensing (Li et al., 2024, Rafiee and Negahdari, 2023). Advancements including metal–insulator–metal (MIM) layering have further boosted sensor performance. For instance, Ali et al. (2023) reported near-perfect absorption (99.94%) in the near-infrared range and achieved sensitivities of $S = 326 \text{ nm/RIU}$ (visible) and $S = 504 \text{ nm/RIU}$ (near-infrared) by optimizing geometric parameters within a specific RI range (Ali et al., 2023). These structures demonstrate the potential for enhanced sensitivity and accuracy in high-precision applications like biosensing. Further research has explored split-ring resonators for precise liquid RI measurements. In 2024, Hen et al. introduced a gold split-ring resonator achieving a sensitivity of 200 GHz/RIU , demonstrating effectiveness in detecting RI changes for biosensing applications, including disease identification (Han and Ruan, 2024). Khodai et al. (2024) utilized SRRs for detecting hemoglobin with a sensitivity of 361 nm/RIU and a quality factor (Qu et al.) of 97.5 RIU^{-1} , highlighting their utility for biosensing (Khodaie and Heidarzadeh, 2024b). Additionally, multilayer concentric ring or square resonators maximize light confinement, thereby enhancing light-analyte interaction and sensor performance, with one study achieving a sensitivity of 570.4 nm/RIU and a figure of merit (FOM) exceeding 14.1 (Khodaie and Heidarzadeh, 2024a). Patel et al. (2024) designed a two-concentric-ring sensor capable of detecting leukemia with an impressive sensitivity of $S = 3571 \text{ nm/RIU}$, an FOM of 714 1/RIU , and a Q of 322 (Patel and Alsalman, 2024). While these prior works showcase significant progress in achieving high sensitivities, they often focus on specific geometric optimizations or multi-layer configurations, and many struggle with maintaining a linear response across the critical RI range of 1.33 to 1.53, which is essential for accurate quantification in diverse biomedical applications.

This paper introduces and numerically analyzes a novel plasmonic sensor based on a split disc–ring resonator (SDRR) nanostructure uniquely designed for broadband biosensing. The primary innovation of this work lies in the synergistic integration of a split-disc with a split-ring, a configuration not extensively explored previously for broad-range biosensing. This structural design allows for enhanced control over electromagnetic field confinement and resonance tuning, enabling not only high sensitivity comparable to or exceeding existing state-of-the-art sensors but, crucially, a highly linear response across the medically relevant RI range of 1.33 to 1.53. This linearity overcomes a major challenge in previous plasmonic sensors operating in this range, making it exceptionally suitable for precise quantification in applications like blood analysis, cancer cell detection, and monitoring of biomolecular concentrations in physiological fluids. Numerical analysis based on the Finite-Difference Time-Domain (FDTD) approach confirms that resonance wavelengths are easily tunable via adjustments to material, radius, and gap width. Overall, the proposed SDRR architecture successfully merges sensitivity, linearity, and tunability—marking a significant step forward toward practical high-performance plasmonic biosensors for medical diagnostics.

2 Structure and Method

This section details the design of the proposed plasmonic sensor, which is based on a SDRR configuration, and describes the simulation method employed to solve the governing equations. The overall structure is depicted in Figure 1. Figure 1(a) illustrates the sensor's overall configuration, comprising alternating SDRR. A single unit cell of the structure is shown in top and side views in Figures 1(b) and 1(c), respectively. As illustrated in Figure 1(b), the split disc, fabricated from a metallic material (gold (Au), silver (Ag), or aluminum (Al)), possesses a radius r and an air-gap width w . This disc is surrounded by a ring with an inner radius R_{in} and an outer radius R_{out} , featuring a transverse air-gap with the width of a . The thickness of both the disc and the ring is denoted by h_r . As shown in Figure 1(c), the entire structure is situated on a SiO_2 substrate with a thickness of h_s . Noble metals such as Au, Ag, and Al are utilized for both the split disc and ring to enhance surface plasmon resonance. The analyte, characterized by a thickness h_a and RI (n_a), is deposited over the disc and ring to facilitate sensing with a thickness of h_a .

To elucidate how variations in the analyte's RI (n_a) lead to detectable spectral shifts, the electromagnetic energy flow is analyzed using the Poynting vector ($\vec{S}$). The instantaneous Poynting vector is defined as $\vec{S} = \vec{E} \times \vec{H}$, where $\vec{E}$ and $\vec{H}$ represent the electric and magnetic field vectors, respectively. The time-averaged Poynting vector ($\langle \vec{S} \rangle$) quantifies the directional energy flux density. Within the SDRR sensor, Poynting vector analysis is crucial for identifying regions of intense electromagnetic field localization and efficient energy transfer to the analyte layer. The primary motivation for integrating a split disc within a split ring resonator structure is to engineer strong near-field coupling and controlled modal interference. In this configuration, the split disc functions as a highly radiative “bright mode” (Radiative Mode), efficiently coupling to the incident electromagnetic wave. Conversely, the split ring supports a less radiative “dark mode” (Field-Confining Mode) with significant field confinement within its gap regions. The close proximity and geometric design of these components enable efficient near-field interaction between these modes, leading to Fano-type interference. This phenomenon arises from the interference between the localized discrete modes of the split disc and ring cavities and the broadband continuum modes supported by the surrounding plasmonic environment. The resulting constructive and destructive interference shapes sharp and asymmetric resonance lines, exhibiting high sensitivity to perturbations in the dielectric environment. Plasmonic resonance, occurring in the SDRR structure due to strong coupling between the radiative and field-confining modes, significantly enhances the local electric field intensity at the metal–analyte interface. This field enhancement, directly linked to the geometric design and material selection, forms the basis of the sensor's high sensitivity. Regions of high Poynting flux correspond to enhanced local field intensity, leading to stronger power absorption at the metal–analyte interface according to:

$$P_{abs} = \frac{1}{2} \omega \text{Im}(\epsilon(w)) |\vec{E}(\vec{r})|^2 \quad (1)$$

Where, w is the angular frequency and ϵ is the electrical permittivity.

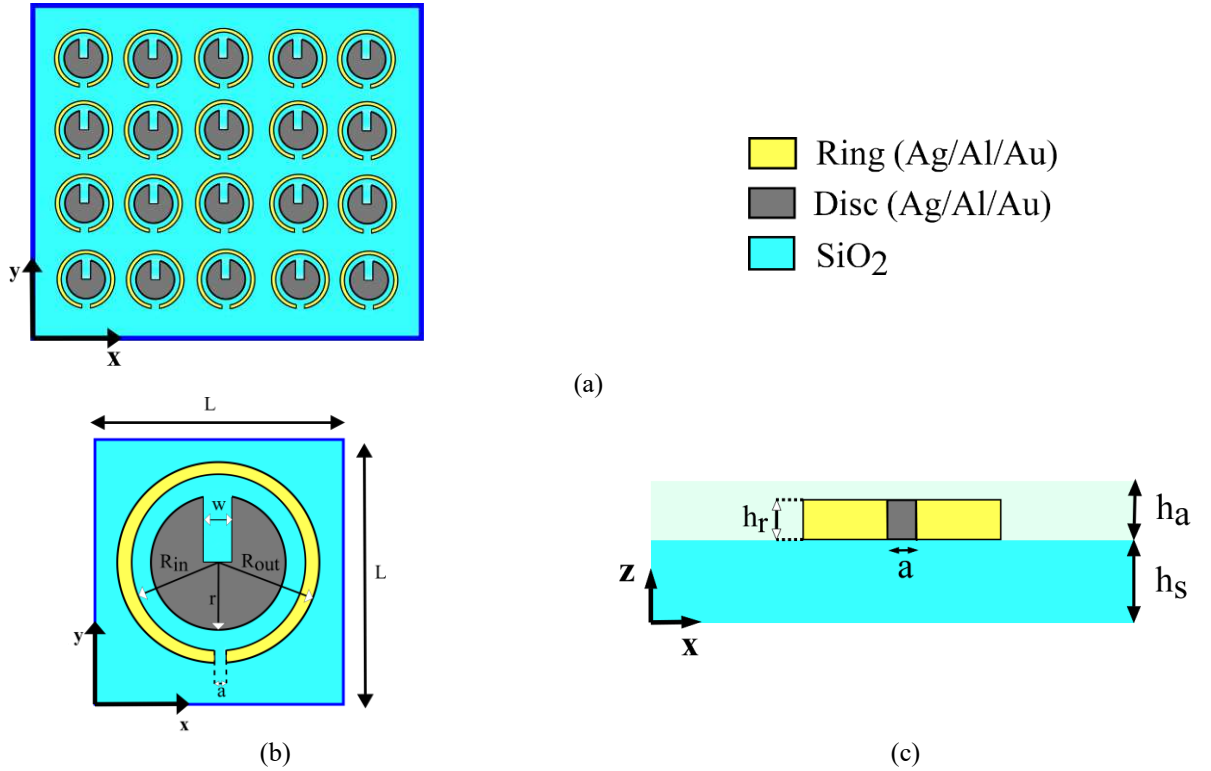


Figure 1. Schematic of the proposed SDRR sensor: (a) top view, (b) unit cell, and (c) side view.

By simulating the electromagnetic response using the FDTD method, we can accurately map the spatial distribution of the Poynting vector and electric field intensity, quantifying field confinement and energy localization directly correlated with sensor sensitivity. The RI range of the analyte medium is selected between 1.33 and 1.53 to cover a wide spectrum of detectable samples and analytes. For instance, RI ranges of 1.33–1.40 have been employed in monitoring hemoglobin concentration and other blood biomarkers for clinical diagnostics, while differences between 1.36–1.42 have been exploited to discriminate between normal and cancerous cells (Hurayya et al., 2025). These examples highlight that the selected range aligns with the optical properties of relevant biological samples and supports the sensor's applicability in disease detection and medical diagnostics.

The RI of the SiO₂ substrate is described by the Sellmeier equation (Islam, 2018):

$$n^2(\lambda) = 1 + \frac{0.6961663\lambda^2}{\lambda^2 - 0.0684043^2} + \frac{0.4079426\lambda^2}{\lambda^2 - 0.1162414^2} + \frac{0.9074794\lambda^2}{\lambda^2 - 9.896161^2} \quad (2)$$

The complex dielectric constants of metals such as Au, Ag, and Al are calculated using the Drude–Lorentz model (Vial et al., 2005):

$$\varepsilon_m = \varepsilon_\infty - \frac{\omega_D^2}{\omega(\omega + j\gamma_D)} - \frac{\Delta\varepsilon.\Omega_L^2}{(\omega^2 - \Omega_L^2) - j\Gamma_L\omega} \quad (3)$$

In this equation, ε_∞ represents the high-frequency dielectric constant, ω_D is the plasma frequency, and γ_D denotes the damping coefficient. Additionally, Ω_L and Γ_L correspond to the oscillator strength and spectral width of the Lorentz oscillators, respectively, while $\Delta\varepsilon$ acts as a weighting factor. The numerical parameters of the Drude–Lorentz model for Au, Ag, and Al are summarized in Table 1. The resonance wavelength of the SDRR structure is governed by the hybrid plasmonic modes formed through electromagnetic coupling between the split metallic disc, the split ring resonator, and the dielectric substrate. Variations in the complex permittivity of the employed metals, as described by the Drude–Lorentz model, directly affect the effective plasmonic mode index and field confinement.

Table 1. Numerical parameters of the Drude–Lorentz model for gold, silver, and aluminum (Rakic et al., 1998)

metal	ε_∞	$\omega_D/2\pi$ (THz)	$\gamma_D/2\pi$ (THz)	$\Omega_L/2\pi$ (THz)	$\Gamma_L/2\pi$ (THz)	$\Delta\varepsilon$
Au	5.9673	2113.6	15.92	650.07	104.86	1.09
Ag	3.70	2178.61	5.077	197.31	939.63	0.845
Al	1.00	3622.15	11.364	373.34	279.28	0.523

Simultaneously, the RI of the SiO₂ substrate and the analyte layer modifies the local dielectric environment, leading to a measurable shift in the resonance wavelength. Owing to the Fano-type nature of the resonance, even minute changes in the surrounding RI result in pronounced spectral shifts, forming the physical basis of the sensing mechanism.

Table 2 presents the initial dimensional parameters of the proposed SDRR sensor, which will be further examined to evaluate and optimize its performance. In this simulation, a Transverse Electric (TE) plane-wave light source with wavelengths ranging from 1700 nm to 4500 nm (corresponding to the near-infrared region) is incident normally on the structure along the Z-axis. Periodic boundary conditions are applied in the x and y directions to accurately model the optical behavior, treating the structure as an infinitely repeating array. Moreover, perfectly matched layer (PML) boundary conditions are applied along the z-axis to absorb reflected waves, preventing distortion of the simulation results and creating a quasi-open environment. By varying the RI of the analyte (Δn), a corresponding shift in the resonance wavelength

$(\Delta\lambda_0)$ appears in the reflection spectrum. The sensitivity parameter (S) of the sensor is calculated using the following equation:

$$S = \frac{\Delta\lambda_0}{\Delta n} \quad (4)$$

In this equation, the unit of sensitivity is nm/RIU.

Table 2. Initial dimensional parameters of the proposed SDRR sensor.

Parameter	Symbol	Value (nm)
Unit cell side length	L	520
Length of the disc air-gap	W	40
Length of the ring air-gap	a	40
Radius of the disc	r	110
Inner radius of the ring	R_{in}	150
Outer radius of the ring	R_{out}	180
Disc and ring height	h_r	50
Height of the Sio2 substrate	h_s	150
Height of the analyte	h_a	100

The FOM is another important parameter used to evaluate the resolution of RI optical sensors. The FOM is obtained by normalizing the S with respect to the full width at half maximum (FWHM) of the resonance mode. The FOM is calculated as follows (Yang and Lin, 2021):

$$FOM = \frac{S}{FWHM} (RIU^{-1}) \quad (5)$$

As the sensitivity increases and the FWHM bandwidth decreases, the FOM correspondingly increases. Additionally, the FOM is proportional to the Q , which is defined as follows (Fallahi et al., 2024):

$$Q = \frac{\lambda_0}{FWHM} \quad (6)$$

In this relation, λ_0 denotes the resonance wavelength. Therefore, to achieve an efficient RI optical sensor, it is essential to attain both large S and a large FOM.

The linearity of the sensor response was quantified using the coefficient of determination (R^2), calculated via linear regression between the resonance wavelength and the analyte RI. R^2 represents the proportion of variance in the resonance wavelength explained by changes in the RI, providing a quantitative measure of the sensor's reliability and predictability.

3 Results and Discussion

Optimizing the structural parameters of the proposed SDRR sensor (w , a , r , R_{in} and R_{out}) is crucial for enhancing its performance in accurately detecting the RI of the target material. Initially, the effect of the air-gap dimensions of the nano-disc (w) and nano-ring (a) on the sensor's performance is investigated.

Figure 2(a) demonstrates how varying w influences the resonance behavior. The resonance wavelength shifts linearly with both w and n_a , indicating a direct optical response to RI changes. The slope of this relationship characterizes the sensitivity, while Figure 2(b) shows corresponding variations in sensitivity and FOM. The optimum configuration is achieved at $w = 45 \text{ nm}$, where sensitivity and FOM reach 785 nm/RIU and 7.60 RIU⁻¹, respectively. This enhancement arises from stronger mode overlap between the split disc and ring, producing pronounced Fano-type interference and improved field confinement. Beyond this optimum, the weaker near-field coupling reduces the sensor's spectral response.

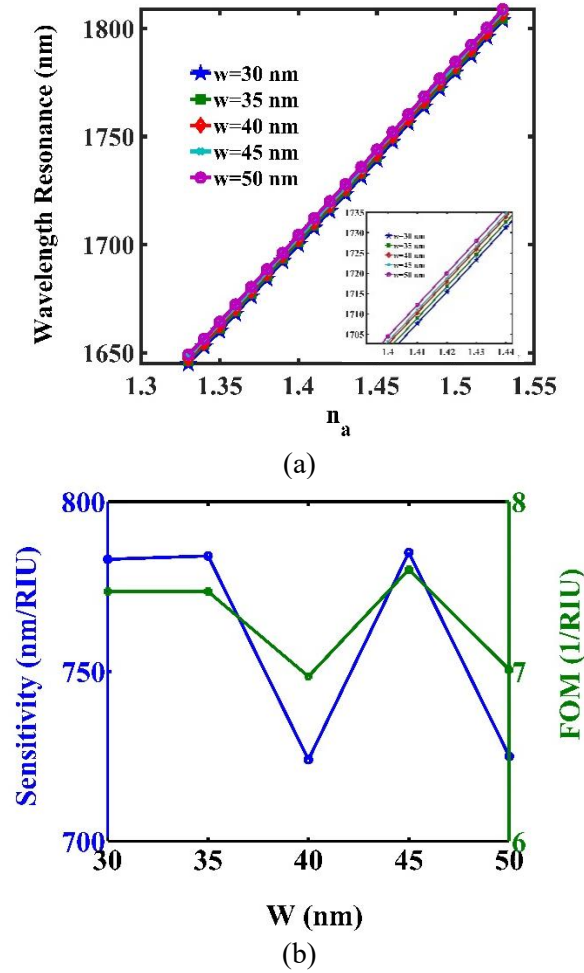


Figure 2. Influence of w on (a) the resonance wavelength and (b) the sensor's sensitivity and FOM. A magnified inset in the lower-right corner of (a) is included to clearly highlight the wavelength shifts between the resonance curves for different analyte RIs.

After establishing the common redshift behavior of the resonance wavelength for all geometrical parameters, the subsequent analysis (Figure 3) emphasizes how the structural dimensions influence the sensor performance in terms of sensitivity and FOM. As shown in Figure 3(a), the nano-ring air-gap width is a dominant factor in field confinement and spectral sharpness. Reducing a enhances the near-field coupling between the split disc and ring, leading to a stronger Fano resonance and improved performance; the optimum occurs at $a = 25$ nm, beyond which the broadened FWHM reduces the spectral resolution. In Figure 3(b), the effect of disc radius r in the range of 90–120 nm demonstrates a systematic reinforcement of hybridization between the localized plasmonic modes. A moderate radius yields higher coupling strength and sharper Fano interference, achieving a sensitivity of 868 nm/RIU and an FOM of 8.08 RIU⁻¹ at $r = 115$ nm. Larger radius slightly weakens confinement, confirming a geometric balance that governs the coupling regime. The influence of the inner ring radius, R_{in} , illustrated in Figure 3(c), reveals that its enlargement increases the resonance wavelength and the sensor's responsiveness to RI variations. Sensitivity peaks around 1043 nm/RIU at $R_{in} = 185$ nm, whereas further increases lead to spectral broadening. Finally, Figure 3(d) displays the effect of varying the outer ring radius, R_{out} , from 185 nm to 220 nm, where tighter confinement occurs when R_{out} exceeds R_{in} by only 5 nm. This narrow ring

arrangement maximizes field overlap and produces outstanding sensitivity 1670 nm/RIU with a high FOM of 5.62 RIU⁻¹.

The influence of material selection on sensor performance is systematically investigated using nine possible combinations of Au, Ag, Al for the disc and ring components, with geometric parameters optimized as $w = 45 \text{ nm}$, $a = 25 \text{ nm}$, $r = 115 \text{ nm}$, $R_{out} = 190 \text{ nm}$, and $R_{in} = 185 \text{ nm}$, values derived from earlier analyses. Figure 4 presents the average performance metrics across the analyte RI range. Figures 4(a)–4(d) illustrate the average sensitivity, FOM, FWHM, and Q-factor, respectively, with optimal configurations highlighted in green. The Ag disc–Au ring combination demonstrates the highest average sensitivity 1630 nm/RIU. The Al disc–Au ring and Au disc–Au ring configurations achieve the highest average FOM (3.66 RIU⁻¹) and average Q (7.6), respectively. The Ag disc–Ag ring structure exhibits the lowest average FWHM (423.7 nm). These results indicate that material choice critically affects the performance balance, with the Ag/Au configuration offering a favorable compromise for broad RI ranges.

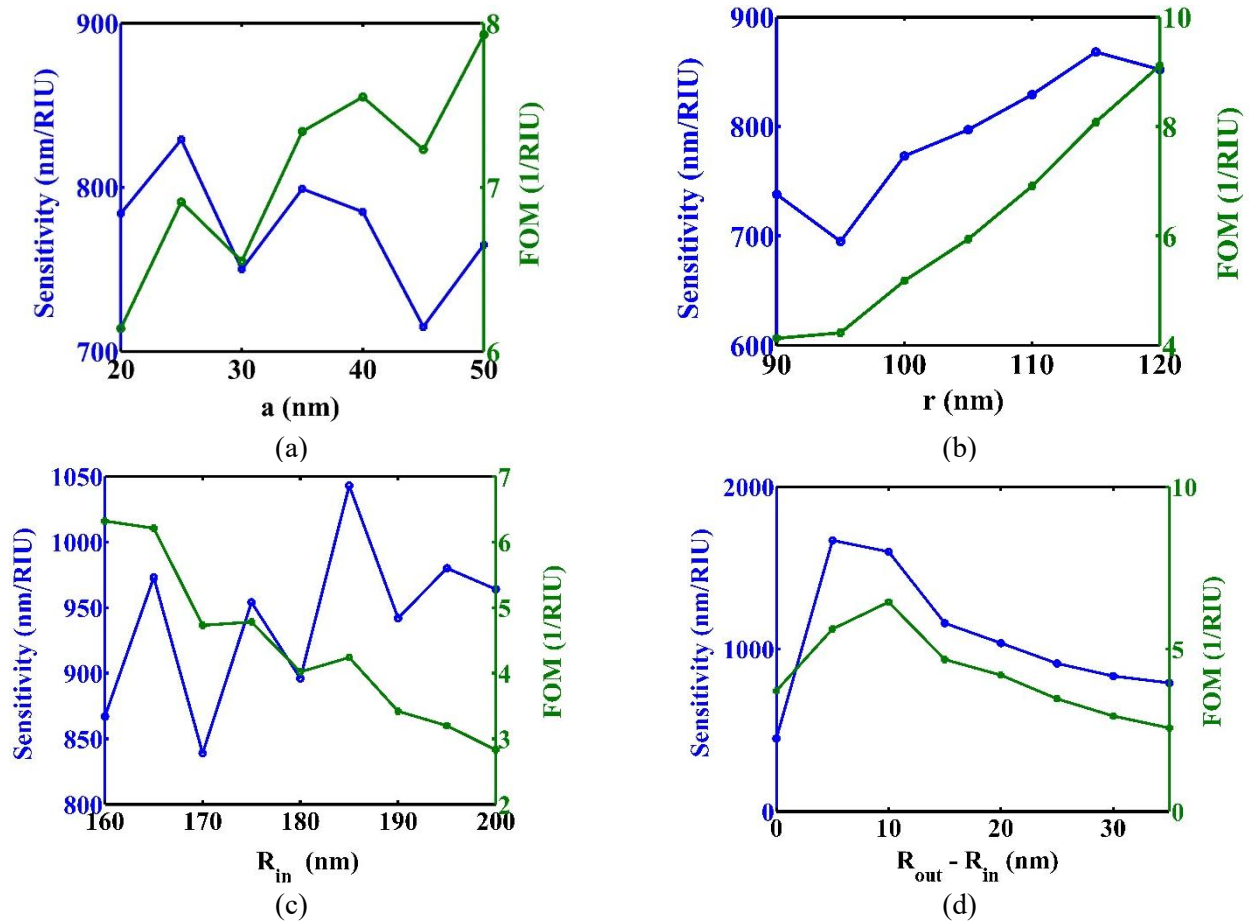


Figure 3. Comparative analysis of sensing performance (sensitivity and FOM) as a function of: (a) nano-ring air-gap width (a) (b) nano-disc radius (r), (c) inner ring radius (R_{in}) ($R_{out} - R_{in} = 20 \text{ nm}$) (d) outer ring radius (R_{out}).

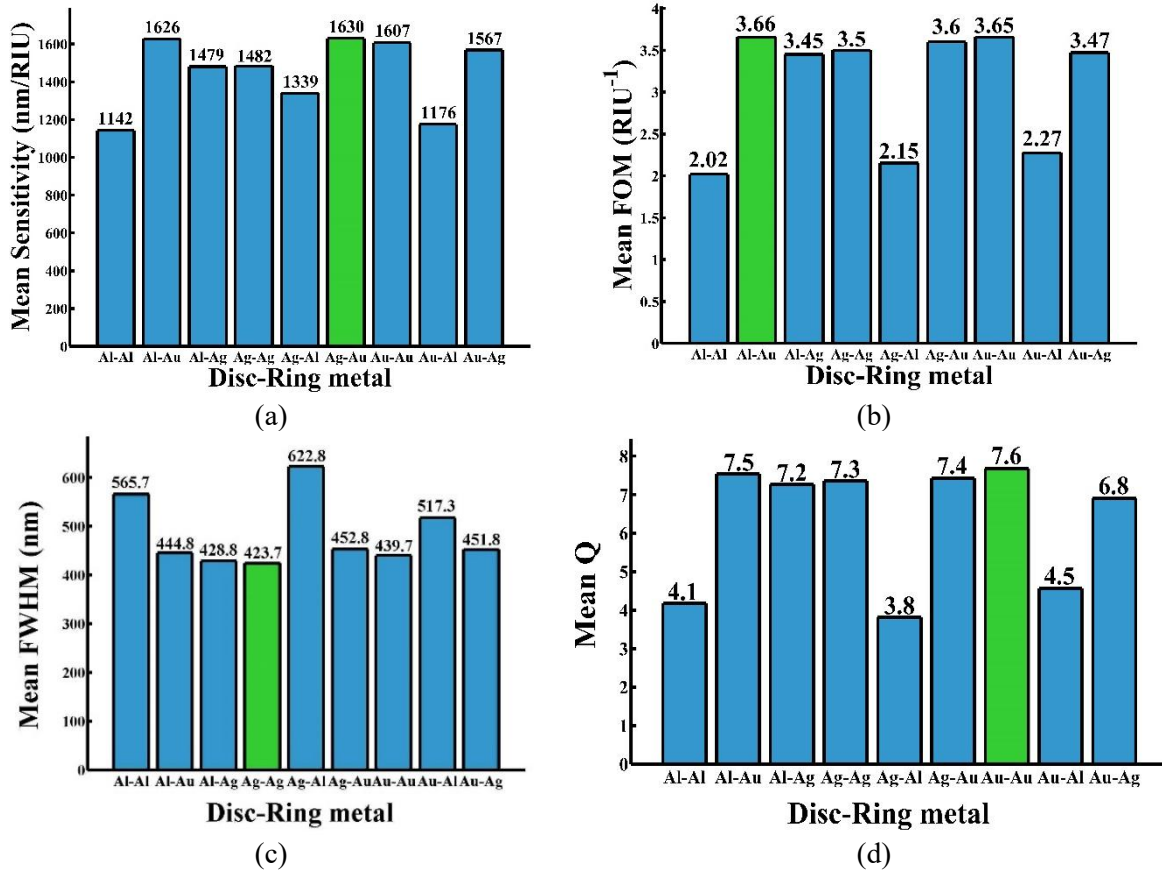


Figure 4. Average (a) sensitivity, (b) FOM, (c) FWHM, and (d) Q of the proposed sensor for different disc–ring metal combinations (Au, Ag, Al) over the analyte RI. The optimal configurations in each curve are highlighted in green.

Figure 5 summarizes the absolute peak performance values. The Al disc–Al ring combination achieves the highest individual sensitivity (2000 nm/RIU), while the Au disc–Au ring structure shows the maximum FOM (4.1 RIU⁻¹) and Q (7.6). The Ag disc–Ag ring combination yields the minimum FWHM (449.9 nm). While these combinations optimize specific metrics, they may compromise others. Consequently, achieving balanced performance requires careful material selection. The Ag/Au configuration consistently provides an optimal trade-off between high sensitivity, moderate FWHM, and robust FOM, making it the most suitable choice for practical biosensing applications.

To elucidate the physical mechanism behind the enhanced sensitivity, electric field intensity distributions were analyzed at three representative wavelengths for the optimized SDRR sensor ($n_a = 1.33$) and presented in Figure 6. At an off-resonance wavelength ($\lambda = 3\mu\text{m}$), the field shows weak confinement and broad distribution (Figure 6(a)), indicating limited near-field interaction due to off-resonant plasmonic modes. In stark contrast, at the Fano resonance wavelength ($\lambda = 3.1157\mu\text{m}$), a pronounced electric field localization occurs within the narrow disc–ring gaps (Figure 6(b)).

This intense field enhancement, often termed ‘hotspots’, results from the constructive interference between the split disc’s plasmonic mode and the split ring’s weakly radiative mode. Such confinement significantly increases light–matter interaction, directly correlating with the sensor’s high sensitivity. At a post-resonance wavelength ($\lambda = 3.20\mu\text{m}$), the field pattern shifts, reflecting the asymmetric spectral response characteristic of Fano interference (Figure 6(c)). These field distributions collectively confirm that the sensor’s high performance is governed by Fano-type plasmonic resonance driven by strong near-field coupling.

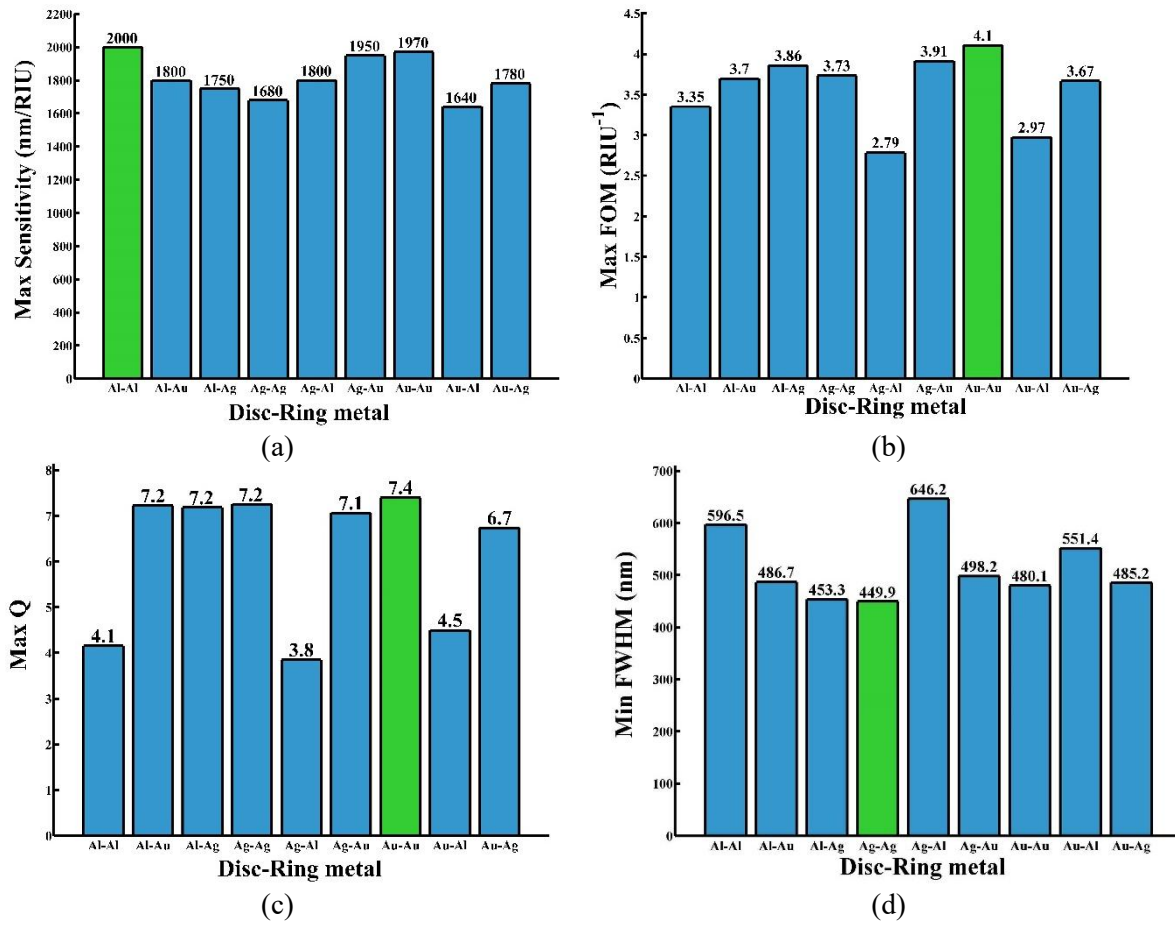


Figure 5. Maximum (a) sensitivity, (b) FOM, (c) Q, and (d) minimum FWHM of the proposed sensor for different disc-ring metal combinations (Au, Ag, and Al) over the analyte RI. The optimal configurations in each curve are highlighted in green.

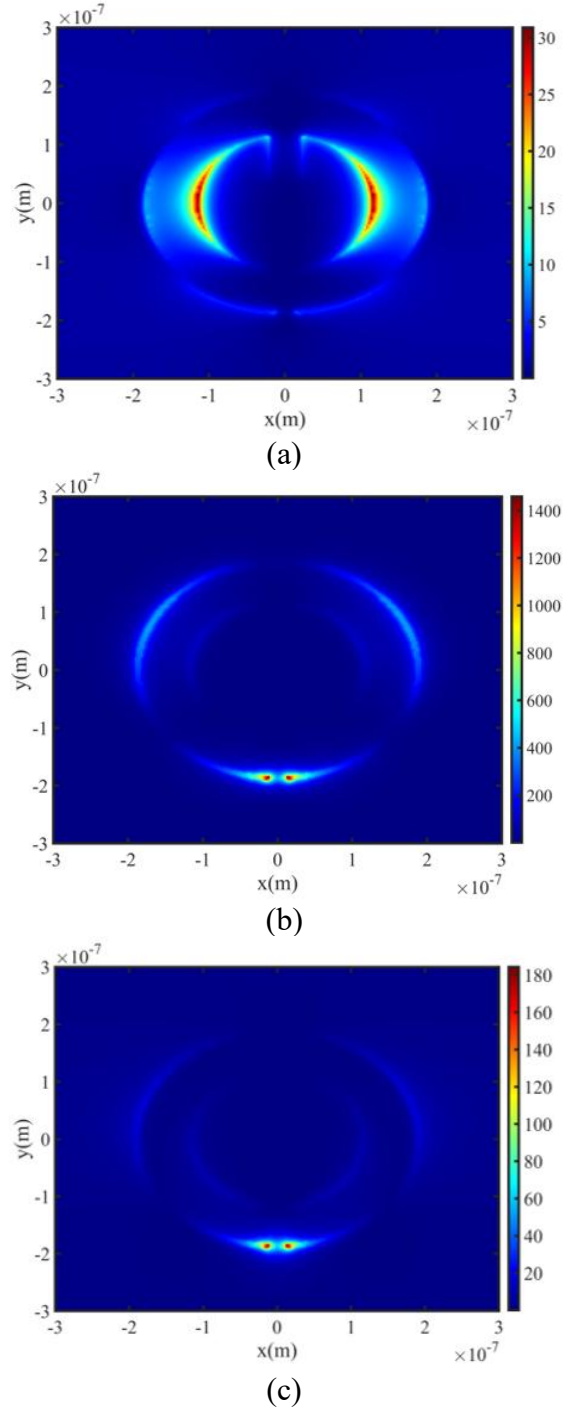


Figure 6. Electric field intensity distributions of the optimized SDRR sensor at RI $n_a = 1.33$ (a) $\lambda = 3 \mu\text{m}$ (off-resonance), (b) $\lambda = 3.1157 \mu\text{m}$ corresponding to the Fano resonance, and (c) $\lambda = 3.20 \mu\text{m}$ (post-resonance).

Figure 7 displays the reflection spectrum of the optimized silver disc–gold ring sensor across an analyte RI range from 1.33 to 1.53. A clear redshift in the resonance wavelength is observed as the RI increases, demonstrating a strong plasmonic response and validating the effectiveness of the optimized geometry in promoting near-field coupling.

To quantitatively assess the sensor's performance and linearity, Figure 8 plots the resonance wavelength against the analyte RI. The data exhibit an excellent linear relationship ($R^2 = 0.99983$),

confirming the sensor's high fidelity in detecting small RI variations, a crucial characteristic for reliable biosensing applications.

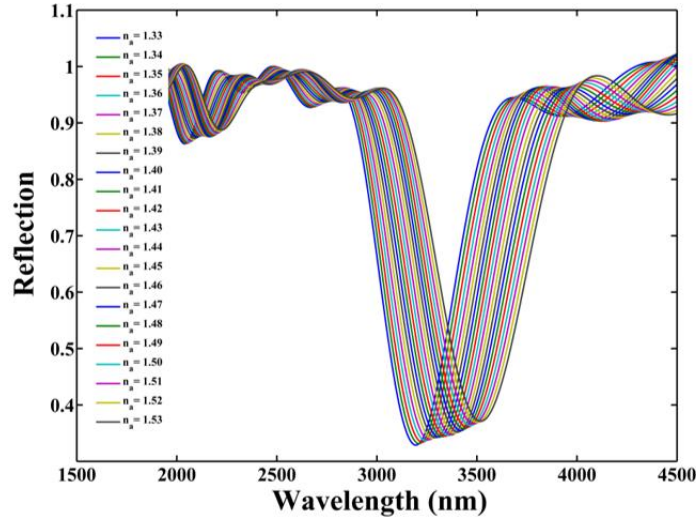


Figure 7. Reflection spectrum of the proposed sensor with a silver disc–gold ring configuration as a function of wavelength.

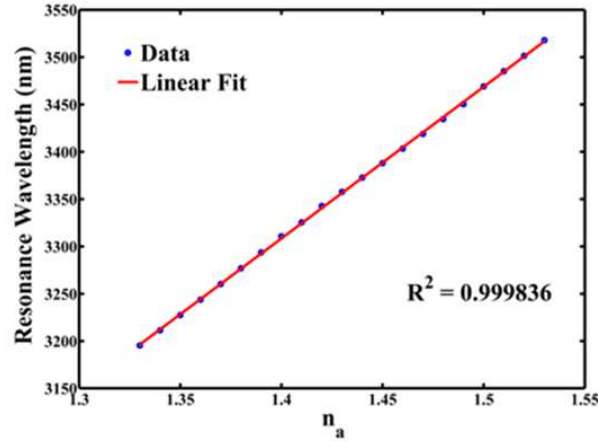


Figure 8. Resonance wavelength of the proposed sensor with a silver disc–gold ring as a function of the analyte RI.

A comprehensive comparison with previously reported studies, summarized in Table 3, unequivocally demonstrates the superiority of our design. Notably, the SDRR sensor achieves a sensitivity of 1670 nm/RIU, surpassing the highest previously reported value of 1097 nm/RIU (Faraji et al., 2025), by over 50%. This enhancement stems from superior electromagnetic field confinement in the disc–ring gap and optimized Fano-type plasmonic mode excitation. While some prior studies achieved high Q (e.g., $Q=27.5$ (Faraji et al., 2025)) or narrow linewidths (e.g., $\text{FWHM}=3.7$ nm (Khodaie and Heidarzadeh, 2024b)), these often came at the expense of drastically reduced sensitivity or a limited operational RI range. In contrast, our SDRR sensor delivers a high sensitivity while maintaining a substantial resonance bandwidth (FWHM : 452.8 nm) and, crucially, stable and linear performance across a wide RI range.

This broad dynamic range and reliable spectral response are essential for practical biosensing. Furthermore, the sensor demonstrates consistent stability with $Q=7.4$ across this wide RI range, unlike single-point

resonance enhancements seen in other designs. While the overall FOM is comparable to some existing sensors, the SDRR sensor achieves this by simultaneously optimizing all critical metrics – high sensitivity, broad operational range, and stability. This holistic performance confirms its suitability for advanced biosensing applications.

Table 3. Comparison of the sensing performance parameters of the proposed SDRR sensor.

Structure/parameter	S (nm/RIU)	FWHM (nm)	Q	FOM (RIU ⁻¹)	RI	Reference
Split ring nanostructures	504	---	---	---	1-2	(Ali et al., 2023)
Split ring resonator	361	3.7	---	97.5	1-1.5	(Khodaie and Heidarzadeh, 2024b)
Split ring resonator	570.4	139.22	15.28	4.1	1.35-1.401	(Khodaie and Heidarzadeh, 2024a)
Octa- square split ring	1097.1	---	27.5	15.64	1.36-1.401	(Faraji et al., 2025)
Split Disc–Ring Resonator	1670	452.8	7.4	3.6	1.33-1.53	This work

4 Conclusion

A plasmonic refractive index sensor based on a SDRR was designed and numerically optimized. By refining the disc and ring dimensions, gap widths, and metal combination, the sensor achieved high sensitivity (1670 nm/RIU), FOM = 3.6 RIU⁻¹, Q = 7.4, and FWHM= 452.8 nm across a broad RI range (1.33–1.53) with excellent spectral stability.

The sensor's superior response stems from strong near-field coupling and Fano-type resonance between the split nano-disc and the surrounding ring. This hybrid interaction sharply enhances the local electromagnetic field at the metal–analyte interface, amplifying the resonance shift for small RI variations. The optimized geometry increases mode overlap with the analyte region, while the Ag–Au material combination balances strong field confinement with spectral stability.

An excellent linearity ($R^2 = 0.99983$) confirms predictable spectral shifts and stable hybrid modes over the entire RI range. Compared with previously reported structures, the SDRR sensor delivers a balanced performance across all key metrics—high sensitivity, wide dynamic range, spectral stability, and structural simplicity. These features make it a robust and scalable candidate for biological and environmental sensing, including the detection of cells, viruses, and bacteria.

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