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High-Performance Hexagonal Cavity-Based Plasmonic MIM Waveguide Biosensor for Sensitive and Label-Free Detection of Carcinoembryonic Antigen (CEA)

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Abstract

In this research, a plasmonic metal-insulator-metal (MIM) biosensor is proposed and numerically analyzed for label-free and highly sensitive refractive index detection. The design incorporates a hybrid configuration consisting of a hexagonal resonant cavity coupled with a narrow rectangular slit along its lower boundary. This particular arrangement, which has not been previously reported, enables the excitation of two distinct resonance modes that contribute to improved spectral resolution and sensing precision relative to conventional MIM structures. Finite-difference time-domain (FDTD) simulations were employed to investigate the optical response and optimize the geometrical parameters of the device. The optimized sensor demonstrates strong electromagnetic field confinement, achieving a sensitivity of 770.27 nm/RIU and a figure of merit (FoM) of 160.47, both of which surpass values reported in related studies. Owing to its compact geometry and compatibility with nanoimprint lithography, the proposed design can be fabricated with high practicality. These findings suggest that the device offers an efficient and scalable platform for real-time, label-free detection of carcinoembryonic antigen (CEA) and other biomarkers relevant to early-stage disease diagnostics.

Keywords: Surface plasmon polariton, Sensitivity, MIM Biosensor, Plasmonic Waveguide Biosensor

Introduction

Recent progress in optical and photonic technologies has led to the rapid emergence of advanced devices capable of controlling, guiding, and detecting light for a wide range of applications, including communication, computation, and sensing. Representative examples of such developments include optical

demultiplexers [1], interferometers [2], plasmonic sensors [3], optical logic gates [4], and nanoantennas [5], all of which collectively illustrate the versatility and expanding influence of modern photonic systems.

Collectively, these devices exemplify the breadth of modern photonic technology and emphasize the fundamental importance of light-matter interactions in advancing communication, computation, and sensing applications. Among them, plasmonic structures based on metal-insulator-metal (MIM) configurations have received significant attention due to their remarkable capability to confine electromagnetic fields beyond the diffraction limit. This feature provides an excellent foundation for realizing high-sensitivity biosensing platforms and developing compact, integrated nanophotonic systems [6].

Early cancer detection relies heavily on identifying molecular changes at extremely low concentrations, a task well suited to highly sensitive optical sensing technologies. The detection of cancer biomarkers in bodily fluids provides a rapid and minimally invasive diagnostic route, offering a practical alternative to conventional clinical methods. Such approaches not only facilitate timely diagnosis but also contribute to improved patient outcomes and reduced healthcare costs [6, 7].

Molecular biomarkers that signal the onset or progression of pathological conditions have emerged as invaluable indicators for the early detection of cancer [8]. Detection of these biological indicators in biofluids such as blood, urine, or saliva offers a practical and non-invasive route for monitoring physiological and pathological conditions. For instance, alpha-fetoprotein (AFP) and prostate-specific antigen (PSA) serve as well-recognized biomarkers for liver and prostate cancers, respectively, though fluctuations in their concentrations may also occur in some benign disorders [9, 10]. These biomarkers are frequently integrated with advanced optical sensing methodologies to improve diagnostic accuracy and ensure greater reliability in disease detection.

Among the numerous cancer-associated biomarkers, carcinoembryonic antigen (CEA) has received notable scientific attention. This glycoprotein, typically secreted in trace amounts by epithelial cells of the gastrointestinal tract, exhibits markedly elevated levels in several malignancies, including colorectal, gastric, pulmonary, and pancreatic cancers [11]. From a clinical standpoint, serum CEA concentrations below 2.5 ng/mL are generally regarded as normal, whereas levels exceeding 5 ng/mL are strongly indicative of malignant progression [12]. Due to its strong association with tumor activity, CEA is widely recognized as a pivotal biomarker for early-

stage cancer detection as well as for monitoring therapeutic response and disease progression.

Beyond plasmonic architectures, refractive index (RI)-based optical sensing has been widely explored in diverse scientific and technological domains, underscoring the versatility of RI modulation as a fundamental detection principle. For example, chemical sensors harness RI fluctuations to track molecular adsorption or concentration variations [13], biosensors leverage RI sensitivity for label-free identification of biomolecular interactions [14], and pressure sensors convert mechanical deformation into detectable RI shifts [15]. Collectively, these investigations emphasize the universality, reliability, and cross-disciplinary potential of RI-based sensing mechanisms.

Given this versatility—and especially the demand for detecting subtle biochemical variations in biological fluids—RI-based optical sensors have become exceptionally effective platforms for biosensing. Changes in the refractive index of the surrounding medium directly correspond to molecular binding and concentration variations at the sensor interface, thereby enabling real-time, label-free detection of biomarkers such as CEA with high precision and sensitivity [16, 17].

Expanding upon this principle, plasmonic sensors utilizing Surface Plasmon Resonance (SPR)—the resonant coupling between incident photons and collective electron oscillations at a metal-dielectric boundary—exhibit exceptional sensitivity and pronounced electromagnetic field confinement, making them particularly well-suited for high-precision biosensing applications [18, 19]. Incorporating SPR principles into MIM architectures further amplifies electromagnetic coupling and improves spectral resolution, thereby allowing precise identification of minute refractive index fluctuations within complex biological environments.

In this framework, MIM waveguides coupled with resonant cavities have gained prominence as highly effective SPR-based sensing architectures, owing to their exceptional field confinement, wide operational bandwidth, and comparatively low propagation losses that collectively enhance sensing precision and efficiency [20, 21].

Recent progress in MIM-based plasmonic biosensors has focused on improving these parameters through advanced resonator geometries. For instance, Rahad et al. proposed an E-shaped resonator coupled to a MIM waveguide that achieved a remarkable sensitivity of 2453.75 nm/RIU, demonstrating significant potential for biomedical and environmental sensing [22]. Other studies have introduced diverse resonant designs such as elliptical, split-ring, and hybrid T-shaped resonators to enhance FoM and sensitivity [23-25]. Bahadur et al. [26] developed a ring-hexagonal resonator

coupled with dual square-ring resonators, reporting FoM values of 118.25 and 120.21 for two resonance modes. Furthermore, an H-shaped plasmonic refractive index sensor combined with a bus waveguide achieved sensitivities of 1960 nm/RIU and 1420 nm/RIU for Modes 1 and 2, respectively [27]. These advancements collectively demonstrate continuous improvements in MIM plasmonic sensor performance.

In the present work, an optimized MIM waveguide biosensor incorporating a hexagonal resonant cavity coupled with a rectangular slit is proposed. Comprehensive Finite-Difference Time-Domain (FDTD) simulations demonstrate that the structure supports dual resonance modes with pronounced electromagnetic confinement, yielding high sensitivity and robust performance for label-free detection of carcinoembryonic antigen (CEA) and related biomarkers.

Numerical Modeling and Analysis Method

The numerical investigation of the proposed plasmonic biosensor was conducted using the Finite-Difference Time-Domain (FDTD) technique implemented in the Lumerical simulation environment. This method provides a robust framework for solving Maxwell's equations in nanoscale photonic systems, enabling precise analysis of plasmonic field interactions and waveguide mode propagation.

A transverse electric (TE)-polarized source operating within the 600–1600 nm spectral range was employed to excite guided plasmonic modes in the MIM waveguide, resulting in strong electromagnetic confinement and efficient resonance coupling. To eliminate spurious reflections and ensure the physical accuracy of field propagation, Perfectly Matched Layer (PML) boundary conditions were applied along all spatial directions (X, Y, and Z). These absorbing boundaries effectively suppress outgoing waves, preventing artificial interference in the simulation results.

A uniformly distributed mesh was adopted across the computational domain, with the mesh size optimized to achieve high spatial resolution while maintaining computational efficiency. This ensured accurate representation of nanoscale features and local field variations throughout the device.

In the design of MIM-based biosensors, understanding the dispersion relation and effective refractive index of surface plasmon polaritons (SPPs) is fundamental. SPPs are hybrid electromagnetic waves confined at the metal-dielectric interface, and their propagation characteristics are strongly influenced by both material permittivity and structural geometry. For TE polarization in an MIM configuration, these parameters directly determine

the sensor's optical response, confinement strength, and overall detection performance.

The mathematical relationship describing the dispersion for the fundamental transverse electric (TE) mode in a metal-insulator-metal waveguide can be represented as [28]:

$$b^2 = \frac{\omega^2 \epsilon_m \epsilon_d}{c^2 (\epsilon_m + \epsilon_d)} \quad (1)$$

Where β is the propagation constant of the SPPs, ϵ_m represents the permittivity of the metal layer, while ϵ_d corresponds to the permittivity of the dielectric (insulator) layer, ω is the angular frequency of the electromagnetic wave, and c is the speed of light in a vacuum.

This dispersion relation is derived under the assumption that the metal is ideal, and it is dependent on both the permittivity of the metal and the dielectric, as well as the device's operating frequency. From the above dispersion relation, the effective refractive index, n_{eff} , of the SPPs, which quantifies the phase velocity of the wave in the waveguide, can be obtained. The effective refractive index is mathematically connected to the propagation constant β through the following relationship [29]:

$$n_{\text{eff}} = \frac{\beta}{k_0} \quad (2)$$

where $k_0 = \frac{\omega}{c}$ is the wavenumber in free space.

Substituting β from the dispersion relation (1), the effective refractive index becomes [29]:

$$n_{\text{eff}} = \frac{\sqrt{\epsilon_m \epsilon_d}}{\sqrt{\epsilon_m + \epsilon_d}} \quad (3)$$

the dispersion relation for SPPs in MIM waveguides and the associated effective refractive index are critical for the operation of biosensors. The effective refractive index, denoted as n_{eff} , is essential in determining the phase velocity of surface plasmon polaritons, and by extension, the performance of devices utilizing these surface waves. The complex permittivity values of both the metallic and dielectric materials, along with the geometry of the waveguide, dictate the propagation characteristics of the SPPs, which directly influence the sensitivity and efficiency of MIM-based biosensors.

The electromagnetic field distribution of SPPs in a MIM waveguide depends on the geometry and material properties of the waveguide. In TE mode, the

electric field does not have any component along the direction in which the wave is propagating. The electric field can be expressed as [30, 31]:

$$E(x, y, z) = E_0 e^{i(\beta x - \omega t)} \times f(x, y) \quad (4)$$

$f(x, y)$ is a spatial function that represents the field distribution across the metal-dielectric interface, and β is the propagation constant. For a typical metal-insulator-metal waveguide, the electric field is strongly confined near the metal-dielectric interface and decreases exponentially as it moves away from the metal surface. This behavior can be described by:[30, 31]:

$$f(x, y) \sim e^{-\kappa x} \quad (5)$$

Where κ is the decay constant that describes how the field decays into the dielectric and metal layers. The decay constant is related to the effective refractive index, n_{eff} , by [30, 31]:

$$\kappa = \frac{W}{c} \sqrt{e_m} - \frac{W}{c} \sqrt{e_d} \quad (6)$$

The performance evaluation of the proposed biosensor is based on several key metrics, namely Sensitivity (S), Full Width at Half Maximum (FWHM), Figure of Merit (FoM), and Quality Factor (Q-factor). These parameters collectively determine the precision and reliability of the device in practical sensing applications. Among them, the most defining attribute of MIM-based plasmonic sensors is their responsiveness to variations in the refractive index of the surrounding medium—an effect that occurs when analyte molecules adsorb onto the sensor surface. Sensitivity (S) is defined as the shift in the resonance wavelength ($\Delta\lambda$) corresponding to a change in the refractive index of the analyte (Δn_d), and serves as a direct measure of the sensor's capability to detect minute biochemical variations [32].

$$S = \frac{\Delta\lambda_{\text{res}}}{\Delta n_d} \text{ (nm/RIU)} \quad (7)$$

Where $\Delta\lambda_{\text{res}}$ is the shift in the resonance wavelength, and Δn_d is the change in the refractive index of the surrounding medium. A high sensitivity indicates that even small variations in the refractive index result in a significant wavelength shift, making the sensor highly effective for biosensing applications. The optimized design maximizes the resonance wavelength shift, thereby improving the sensor's detection capability.

FWHM represents the spectral width of the resonance peak at half of its maximum intensity. It is given by [33]:

$$FWHM = I_{\text{high}} - I_{\text{low}} \quad (8)$$

Where λ_{high} and λ_{low} the wavelengths are at half the peak intensity. A lower FWHM indicates a sharper resonance, improving selectivity and measurement precision. This parameter is essential in defining the resolution of the sensor. The proposed biosensor is based on a MIM waveguide configuration, which consists of a silver substrate featuring a hexagonal cavity with a rectangular slit at its bottom edge, as shown in Figure 1. The FoM is a crucial metric that combines Sensitivity and FWHM to assess the overall sensor performance [33]:

$$FoM = \frac{S}{FWHM} \quad (\text{RIU}^{-1}) \quad (9)$$

A higher FoM suggests that the sensor has both high sensitivity and a sharp resonance peak, which are desirable for accurate detection. The proposed design aims to maximize FoM by optimizing the geometric parameters of the cavity and waveguide structure.

The Q-factor measures the resonance sharpness and is defined as [33]:

$$Q = \frac{\lambda_{res}}{FWHM} \quad (10)$$

Where λ_{res} is the resonance wavelength. A higher Q-factor signifies a well-confined and efficient plasmonic resonance. The sensor's Q-factor is optimized to ensure minimal energy dissipation and high-quality resonances, making it suitable for label-free biosensing applications.

Structure and simulation

The proposed plasmonic biosensor is constructed on a MIM waveguide platform, incorporating a silver (Ag) substrate patterned with a hexagonal resonant cavity that features a rectangular slit at its lower edge, as depicted in Figure 1. The overall substrate dimensions are 1000×1000 nm. The structural and geometric parameters of the device were systematically optimized to maximize sensing performance, with the final dimensions summarized in Table 1.

In the numerical model, a mode source was employed to excite the plasmonic modes within the MIM waveguide, enabling strong coupling and efficient energy transfer between the cavity and the waveguide. The symmetric arrangement of the hexagonal cavity relative to the waveguide promotes balanced field distribution and stable resonance characteristics. To ensure accurate field propagation and eliminate artificial reflections, perfectly matched layer (PML) boundary conditions were applied along all spatial axes (X, Y, and Z).

Silver (Ag) was chosen as the metallic component due to its exceptionally low intrinsic losses and high plasmonic performance in the visible and near-infrared spectral ranges. Compared with gold (Au), Ag exhibits reduced ohmic damping, resulting in stronger electromagnetic confinement and sharper resonance peaks with higher Q-factors. These advantages make silver a preferred material for MIM-based label-free biosensing systems. The optimized configuration demonstrates a pronounced resonance response and enhanced sensing capability across the operational wavelength range of 600–1600 nm.

In this design, the excitation of the structure is performed under Transverse Electric (TE) mode operation, which promotes a more uniform electromagnetic field distribution within the sensing region. Compared to the conventional Transverse Magnetic (TM) mode, TE excitation minimizes absorption losses in the metallic layer and enhances the resonance stability of the system. This improved field uniformity contributes to stronger light-matter interaction within the hexagonal cavity, resulting in superior spectral sharpness and enhanced overall sensing performance [34, 35].

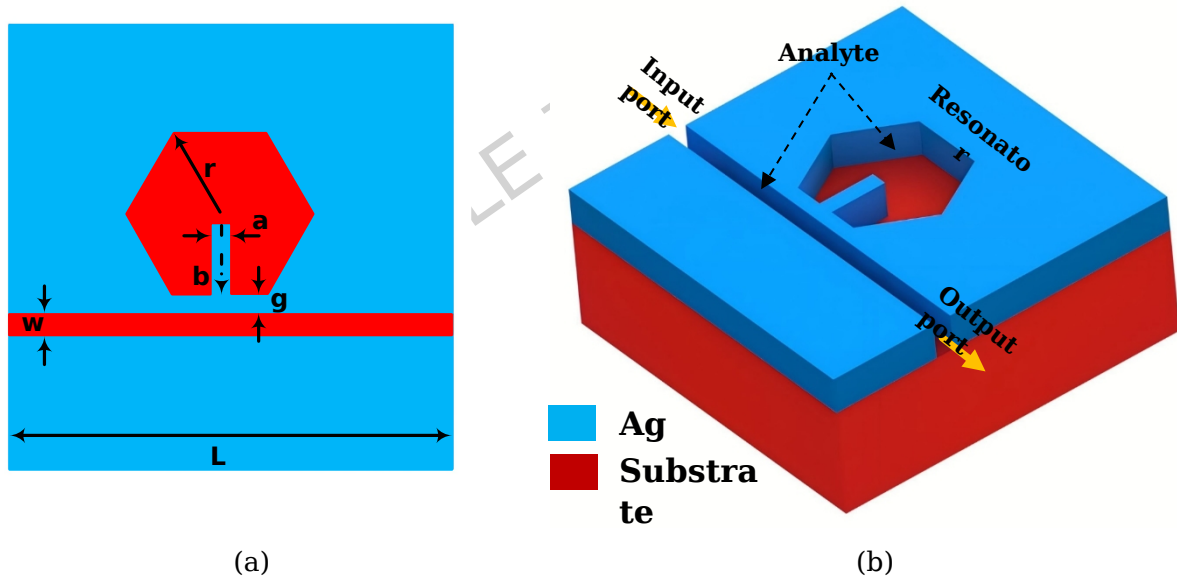


Figure 1: Metamaterial (MTM) sensor schematic design; (a) Two-dimensional view from the top of the structure with parameters; (b) Three-dimensional view of the structure.

Table 1: Optimal parameters of the simulation Model

Name of the parameter	symbol	Value(nm)
Structure periodicity length	L	1000
The hexagonal cavity radius	r	210
The slit width	a	45
The slit height	b	160
The gap between the waveguide and the cavity	g	42.5

The waveguide width	w	50
Structure thickness	h	100

Table 2: The refractive index of CEA with water ($n_0=1.33$) [36]

CEA concentration (ng/ml)	$n=n_0 + \Delta n$
1	1.3337
2	1.3374
3	1.3411
4	1.3448
5	1.3485

Fabrication process of the sensor

The proposed plasmonic biosensor can be realized using Nanoimprint Lithography (NIL), which is widely recognized for its simplicity, cost-effectiveness, and suitability for large-area nanostructure fabrication, as illustrated in Figure 2. In this process, a thermoplastic polymer layer such as PMMA (polymethylmethacrylate) is spin-coated onto a silicon substrate and patterned using a pre-fabricated mold that defines the designed hexagonal cavity and slit geometry [37].

After imprinting, the residual polymer layer is removed through a brief etching step to ensure structural precision. Subsequently, a thin silver layer is deposited on the patterned substrate, forming the MIM configuration of the sensor. Finally, the remaining polymer template is lifted off, revealing the desired plasmonic structure [38].

Although NIL provides high resolution and reproducibility, challenges such as alignment errors or minor residual layers may arise. These issues can be mitigated through optimized process control and cleanroom conditions [39]. It should be noted that the fabrication description here is provided only to illustrate the feasibility of the proposed structure, while the main focus of this study remains on numerical modeling and simulation analysis.

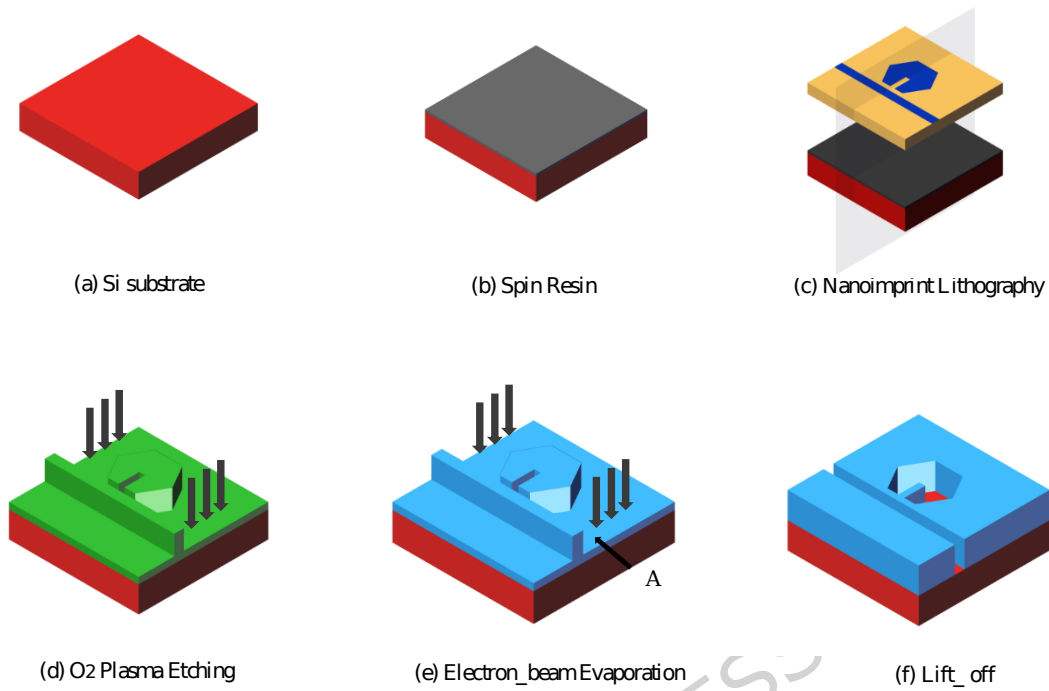


Figure 2: shows (a) the two-dimensional top view and (b) the three-dimensional schematic of the MIM waveguide with a hexagonal cavity featuring a rectangular slit at its bottom edge.

Results and Discussions

To excite surface plasmon polaritons (SPPs) within the proposed MIM waveguide, a mode source was introduced at the input port, serving as the excitation mechanism for guided plasmonic modes. A transmission monitor was positioned at the output port to record and analyze the resulting spectral response. Throughout the simulation domain, a uniform meshing grid of 2 nm was employed to ensure high spatial resolution and numerical accuracy, enabling precise representation of field variations across the structure.

As illustrated in Figure 1, the biosensor configuration consists of a hexagonal resonator integrated with a rectangular defect and side-coupled to a straight MIM waveguide. This geometric arrangement is designed to precisely modulate the interaction between the guided modes and the sensing region, thereby enhancing electromagnetic confinement and sensitivity. The optimized geometric parameters, summarized in Table 1, were obtained through an iterative trial-and-error process aimed at maximizing the optical response and resonance sharpness.

The excitation setup employed a mode source with 2325 discrete frequency sampling points to generate the transmittance and field spectra. Two distinct resonance modes were identified—Mode 2 at 853 nm and Mode 1 at 1101

nm—each corresponding to a unique coupling behavior between the resonator and the waveguide. The transmittance spectra also revealed the dip strength (ΔT), representing the intensity difference between the maximum and minimum transmittance values. These resonant features arise from the coupling between discrete cavity modes and the continuum of propagating modes in the waveguide, a characteristic phenomenon of Fano-like resonances. The magnetic field distributions associated with these modes, presented in Figure 4, further illustrate the physical origin of this coupling mechanism.

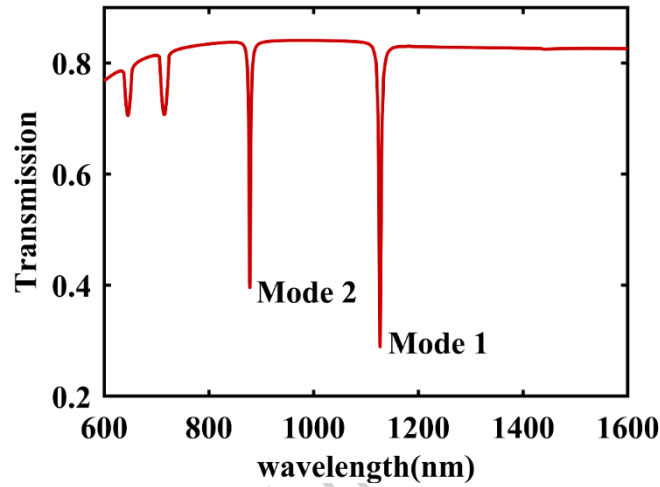


Figure 3: Transmittance characteristic of the proposed sensor with two resonant Modes

As illustrated in Figure 3, the transmission spectrum reveals two distinct resonance dips corresponding to Mode 1 at 1101 nm and Mode 2 at 853 nm. The magnetic-field intensity distributions ($|H|^2$) associated with these resonances, shown in Figure 4, confirm strong coupling between the guided plasmonic mode of the MIM waveguide and the localized surface plasmon modes within the hexagonal resonator.

The resonance at 1101 nm (Mode 1) exhibits a dipole-like field distribution characterized by two symmetric lobes separated by a central node, indicating a lower-order plasmonic oscillation with extended field confinement along the cavity boundaries. Conversely, the resonance observed at 853 nm (Mode 2) presents a quadrupole-like pattern with three distinct lobes and multiple nodal regions, corresponding to a higher-order mode with greater spatial field variation and a shorter effective wavelength. These modal characteristics highlight the capacity of the hybrid hexagonal-rectangular geometry to support multiple, well-defined resonance states, enabling dual-mode operation and improved spectral sensitivity for refractive index sensing applications.

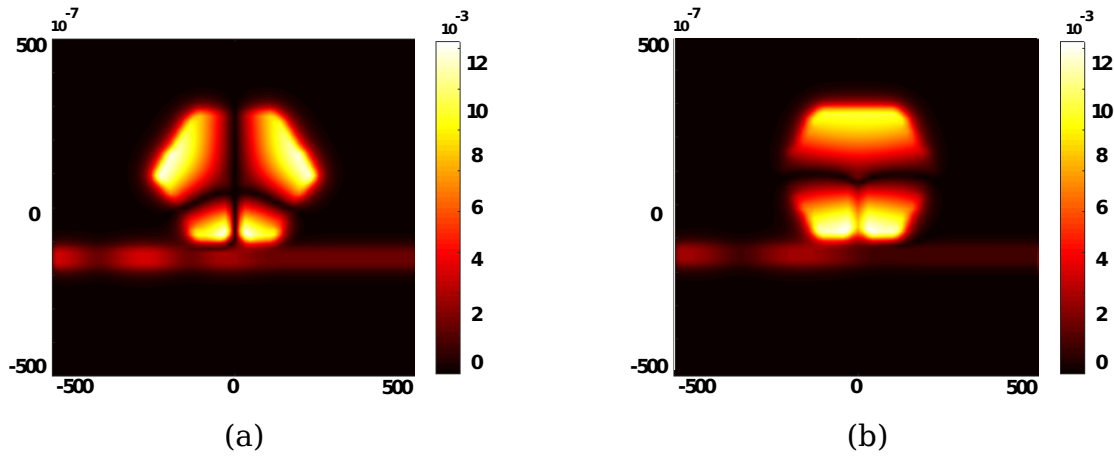


Figure 4: Magnetic field intensity profiles ($|H|^2$) of the biosensor at wavelengths (a) 853 nm and (b) 1101 nm. The field distribution is plotted in the central xz-plane, and the colormap represents the normalized field intensity on a logarithmic scale

The rectangular slit positioned at the base of the resonator serves as a controlled coupling channel that directs optical energy from the MIM waveguide into the cavity region. By intentionally breaking the structural symmetry, this aperture enables the simultaneous excitation of both dipole and quadrupole plasmonic modes within the resonator. The differing spatial overlap of each mode with the slit gives rise to variations in coupling strength and phase distribution, which manifest as distinct, spectrally separated resonances in the transmission spectrum, each characterized by its own quality factor (Q-factor).

These findings confirm that Mode 1 represents the fundamental dipole-like resonance, while Mode 2 corresponds to a higher-order quadrupole-like resonance. The coexistence of these two resonance states broadens the operational spectral range of the sensor, allowing for multi-mode detection. This hybrid modal interaction enhances the device's broadband sensitivity and overall detection capability, thereby improving its performance in label-free refractive index and biomolecular sensing applications.

Key structural parameters—most notably the coupling gap (g) and the hexagonal cavity radius (r)—play a decisive role in defining the optical behavior and overall sensing performance of the proposed plasmonic biosensor. Fine-tuning these parameters enables precise control over the resonance characteristics, electromagnetic confinement, and light-matter interaction strength, thereby significantly improving the device's sensitivity and figure of merit (FoM). Through systematic optimization, these

parameters can be adapted to support a wide range of biological sensing applications across various refractive index environments.

To evaluate the effect of the hexagonal cavity radius (r), its value was varied from 185 nm to 240 nm in 5 nm increments, and the corresponding optical responses—including FoM and transmission spectra—were analyzed, as shown in Figure 5. The results reveal that the FoM exhibits a strong dependence on r for both observed resonance modes. At smaller radii, the FoM values fluctuate due to incomplete field confinement and increased mode coupling losses. As r increases, both modes demonstrate a steady enhancement in FoM, indicating improved resonance stability and reduced radiative damping. However, beyond a certain threshold, further increases in r result in declining FoM values, attributed to weakened electromagnetic confinement and greater propagation losses within the cavity.

Specifically, the FoM reaches a maximum near $r = 215$ nm for Mode 1 and $r = 230$ nm for Mode 2, suggesting that each mode exhibits an optimal cavity size for efficient plasmonic coupling. The transmittance spectra confirm the presence of two distinct resonance dips whose positions shift slightly toward longer wavelengths with increasing r , reflecting the influence of the geometric expansion on the plasmonic dispersion characteristics. Based on the observed trends, selecting a radius in the range of $r = 215$ – 230 nm offers the most balanced trade-off between sensitivity and resonance sharpness. Therefore, $r = 210$ nm was chosen as the optimal configuration, ensuring high FoM, stable dual-mode operation, and enhanced sensing performance for practical biosensing applications.

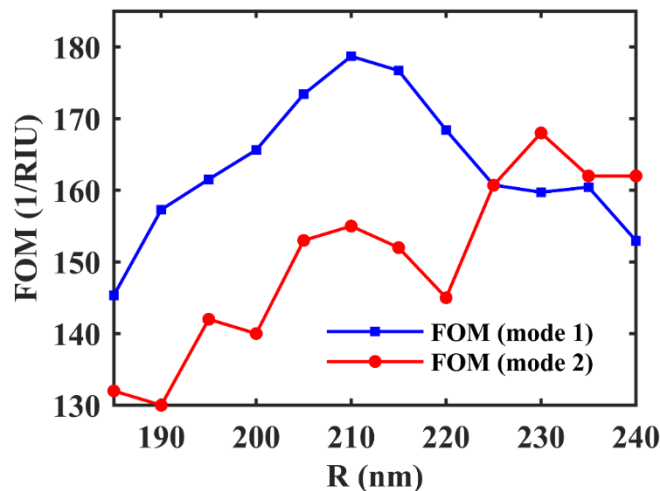


Figure 5: Graph of changes in FoM value as a function of hexagonal radius

In this work, the coupling gap (g) between the hexagonal resonator and the MIM waveguide was systematically optimized to achieve the best trade-off between sensitivity, figure of merit (FoM), and transmission amplitude. As shown in Figure 6, g was varied in 5 nm increments to examine its influence on the optical response of the two resonance modes. For smaller gap distances, the FoM of Mode 1 initially increases sharply, reaching a near-optimal point before gradually stabilizing, whereas Mode 2 displays a more irregular trend that transitions into a steady enhancement as g increases. This indicates that Mode 1 achieves efficient coupling at smaller separations, while Mode 2 benefits from a slightly larger gap where radiative losses are minimized and the field overlap remains strong.

A notable inverse correlation is observed between g and the amplitude of Mode 1—larger gaps lead to reduced transmission intensity due to weaker coupling between the waveguide and cavity. This behavior reflects the typical trade-off in plasmonic systems: increasing g enhances FoM by narrowing the resonance linewidth and improving mode selectivity but simultaneously reduces energy transfer efficiency. Therefore, instead of maximizing a single performance metric, an optimized gap value was selected to maintain both adequate sensitivity and acceptable transmission amplitude.

Based on the intersection of the FoM and transmission amplitude curves in Figure 6, an optimal gap distance of $g = 42.5$ nm was identified, representing a balanced configuration that ensures strong coupling for both resonant modes while minimizing undesired energy loss. These results demonstrate that fine-tuning the coupling gap provides a practical route for tailoring the sensor's optical response to specific detection requirements, highlighting the design's adaptability across various biosensing applications.

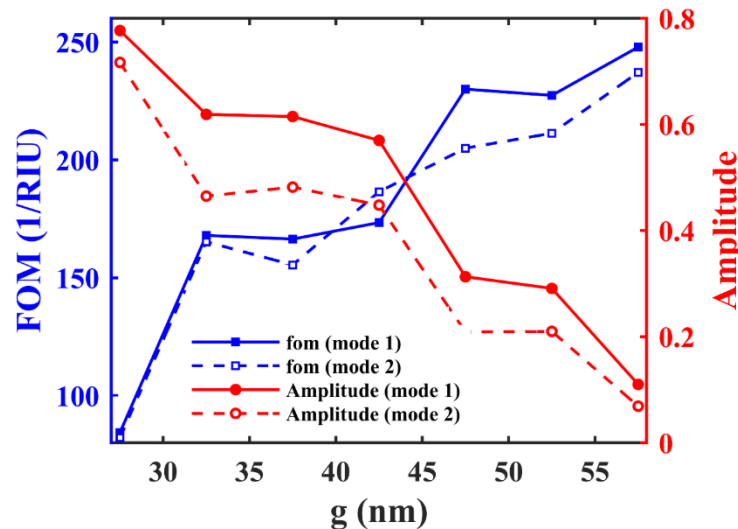


Figure 6: Graph of changes in FoM and amplitude value as a function of the gap of the hexagonal resonator and the waveguide

The influence of the internal rectangular defect length (b) on the sensor's Figure of Merit (FoM) for both resonance modes was systematically analyzed, as illustrated in Figure 7. The results reveal distinct behaviors for Mode 1 and Mode 2, highlighting the strong dependence of the sensor's performance on this structural parameter. For Mode 1, the FoM remains relatively steady at smaller b values but begins to increase noticeably near $b = 160$ nm, suggesting an improvement in resonance confinement and coupling efficiency. However, a sharp decline is observed between $b = 165$ nm and $b = 170$ nm, indicating a disruption in the resonance condition—likely due to destructive interference or excessive radiative losses within the cavity. Beyond this range, the FoM for Mode 1 recovers, peaking at higher b values before showing another fluctuation, confirming that Mode 1 is particularly sensitive to small geometric variations in the defect length.

In contrast, Mode 2 displays a smoother and more consistent response across the examined b range. A modest increase in FoM is observed near $b = 140$ nm, followed by a stable plateau region, with no sharp oscillations or abrupt drops. This stability suggests that Mode 2 is less affected by minor structural changes and maintains a robust optical response even under geometric perturbations.

Overall, the findings underscore the importance of precisely optimizing the defect length b to ensure both high sensitivity and spectral stability. While Mode 1 can achieve higher peak FoM values, its performance is more volatile, requiring precise control during fabrication. Mode 2, on the other hand, provides greater reliability with slightly lower but more stable FoM values. Based on the simulation results, an optimal b value of 160 nm was determined, at which both modes exhibit favorable and consistent performance, offering a balanced trade-off between peak sensitivity and operational stability for practical sensing applications.

The pronounced decline in the Figure of Merit (FoM) observed within the range of $b = 165$ – 170 nm arises from the onset of mode coupling between the cavity's fundamental plasmonic resonance and higher-order or radiative modes. At this critical configuration, the rectangular defect significantly modifies the local electromagnetic field distribution, resulting in destructive interference between these interacting modes. This destructive coupling increases radiative energy loss and broadens the resonance linewidth, thereby diminishing both the resonance sharpness and overall FoM. Physically, this behavior reflects a temporary weakening of field confinement

inside the cavity, as part of the guided optical energy escapes into radiation modes beyond the core structure. Such leakage reduces the effectiveness of light-matter interaction within the sensing region and momentarily degrades the device's spectral precision. However, as the defect length b increases beyond this coupling threshold, the interference effects subside, the cavity regains stable field confinement, and the FoM correspondingly recovers.

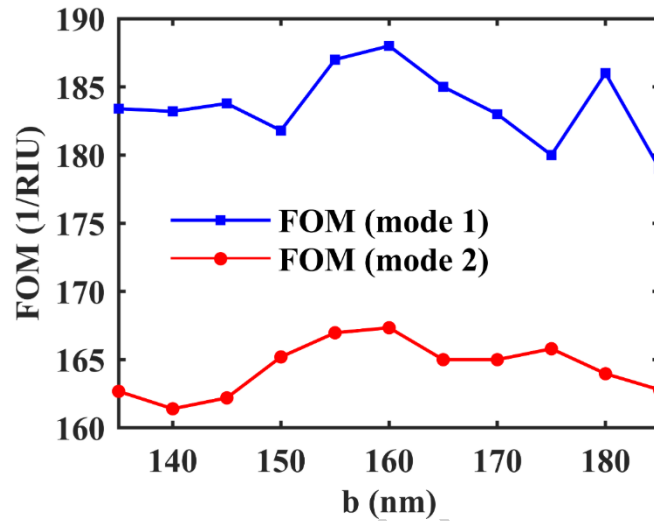


Figure 7: Graph of FoM changes in Modes 1 and 2 versus changes in the internal rectangle length

The optimized geometric parameters, along with their corresponding performance metrics—including sensitivity, FoM, and full width at half maximum (FWHM)—are summarized in Table 3, demonstrating that careful geometric tuning can mitigate radiative losses and yield high spectral selectivity for reliable biosensing applications.

After optimizing the simulation parameters, the sensitivity and performance of the system were thoroughly evaluated. The reference analyte, chosen with a refractive index of 1.33, played a crucial role in determining the sensitivity of the system. Sensitivity is defined as the system's ability to detect small changes in analyte concentration and is directly related to the refractive index change (Δn). As shown in Figure 8, there was a significant change in transmittance as the analyte concentration was varied. The system exhibited high sensitivity to concentration changes, particularly where the refractive index shifted from 1.3337 to 1.3485. These values are presented in Table 2. The system was able to detect these small changes, making it highly suitable for sensor technologies and biochemical analyses. To establish clinical

relevance, the proposed plasmonic biosensor was calibrated to detect refractive index (RI) variations corresponding to physiologically meaningful CEA concentrations. The RI range was varied from 1.33 (representing pure water) to 1.3485 (equivalent to approximately 5 ng/mL of CEA). Within this range, the sensor exhibited a total resonance wavelength shift of ≈ 14.25 nm, demonstrating strong responsiveness to subtle biochemical changes. Furthermore, an incremental CEA concentration increase from 2.5 ng/mL to 5 ng/mL produced a measurable wavelength shift of ≈ 7.1 nm, which is more than 350 times greater than the typical 0.02 nm spectral resolution achievable with advanced optical spectrum analyzers.

These results confirm that the optimized design—featuring a sensitivity of 770.27 nm/RIU—provides sufficient precision for clinically relevant CEA detection, even at very low concentrations. This level of spectral discrimination underscores the sensor's capability for early-stage biomarker identification and its potential integration into real-time, label-free diagnostic systems.

By accurately identifying the shifts in refractive index caused by CEA concentration variations, the system provides a reliable method for detecting the presence of this biomarker, which is crucial for the diagnosis and monitoring of cancerous conditions. Thus, the system's enhanced sensitivity, driven by refractive index changes, has significant potential for clinical applications in detecting diseases linked to CEA.

Table 3: the sensitivity, FoM, and FWHM for the optimized parameters ($r=210$ nm, $b=160$ nm, and $g=42.5$ nm)

Parameters	Mode 1	Mode 2
Sensitivity (nm/RIU)	770.27	655.94
FWHM (nm)	4.8	3.5
FoM (1/RIU)	16.47	187.4

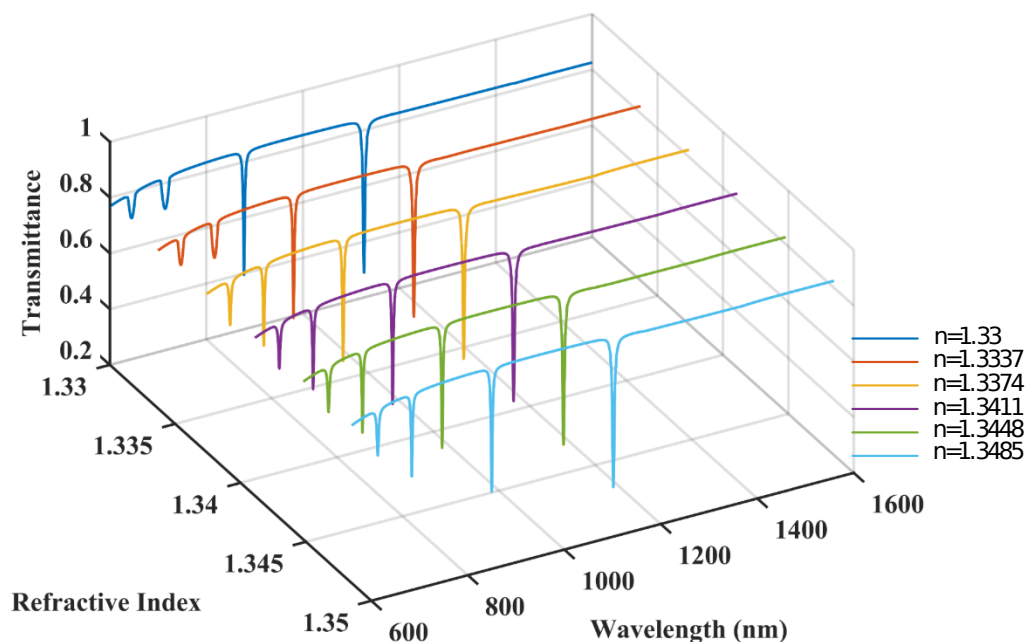


Figure 8: Three-dimensional transmittance spectra of the proposed sensor as a function of wavelength and surrounding refractive index ($n = 1.33$ to 1.3485). The results demonstrate a clear redshift in the resonance dip with increasing refractive index, indicating high sensitivity of the sensor.

To gain a clearer understanding of our system's performance, we conducted a comparison with several related studies, focusing on critical parameters such as sensitivity, FoM, and Full Width at FWHM. As shown in Table 3, our system demonstrates advantages in certain aspects over previous works.

In terms of sensitivity, our system outperforms some of the previous studies, showing a higher ability to detect small changes in analyte concentration, especially in the low-concentration range. This enhanced sensitivity is crucial for early detection applications, such as CEA-related disease diagnosis. However, when evaluating the FoM, our system performs similarly to other advanced systems, though it exhibits slight improvements in certain configurations. The higher FoM in these cases indicates that our system balances sensitivity, accuracy, and efficiency effectively.

In practical applications involving real serum samples, the sensor surface would be biofunctionalized with anti-CEA antibodies to enable selective capture of the target antigen. Upon exposure to serum, both specific CEA-antibody binding and non-specific adsorption of background proteins such as bovine serum albumin (BSA) can induce measurable resonance wavelength shifts. However, experimental evidence and prior studies indicate that non-

specific adsorption typically leads to only minor spectral deviations of about 1–3 nm, which are notably smaller than the specific CEA-induced shift of approximately 7 nm observed in this work.

The high Figure of Merit ($\text{FoM} = 160.47$) achieved by the proposed plasmonic biosensor—attributed to its sharp resonance and narrow full width at half maximum—enables precise distinction between genuine biomolecular interactions and spurious background effects. This spectral sharpness enhances signal-to-noise discrimination and allows reliable operation even in complex biological matrices. Consequently, the sensor demonstrates strong potential for accurate, label-free CEA quantification in clinically relevant samples, supporting its suitability for real-world diagnostic integration.

On the other hand, in terms of FWHM, our system excels in achieving narrower FWHM values compared to some of the earlier studies, which indicates better resolution and a more precise detection of refractive index shifts.

Overall, the comparison in Table 3 highlights that our system demonstrates superior sensitivity in certain scenarios, improved FoM in specific configurations, and a competitive FWHM performance. These results underscore the versatility and strength of our system in detecting CEA and other biomarkers, offering a well-rounded solution for clinical diagnostics.

In this study, the proposed biosensor demonstrates a sensitivity (S) of 770.27 nm/RIU and a full width at half maximum (FWHM) of 4.8 nm, resulting in an impressive Figure of Merit (FoM) of 160.47. In comparison, previously reported configurations—such as the E-shaped resonator with a nominal sensitivity of 2453.75 nm/RIU—exhibit significantly broader resonance linewidths, yielding FoM values of approximately 22.8, which correspond to FWHM values near 107 nm.

This distinction highlights a key performance advantage of the present design: although earlier sensors demonstrate higher absolute sensitivity, their broad resonance spectra drastically reduce the precision with which resonance shifts can be measured. The narrow resonance peak of the proposed MIM structure enables far superior wavelength resolution and lower detection limits, allowing even minute refractive index variations to be accurately quantified. Thus, the device achieves an optimal balance between sensitivity and spectral sharpness, making it particularly suitable for high-precision biosensing and the detection of early-stage biomarkers.

To further contextualize the sensing capability of the proposed MIM-based biosensor, a comparative analysis with previously reported plasmonic and waveguide-based designs is presented in Table 4. As shown, despite the diversity of resonator geometries, including Si rings, semi-elliptical/rectangular rings, E-shaped and H-shaped structures, tapered waveguides, and cavity-based configurations, the proposed hexagonal cavity design achieves highly competitive performance. This comparison underscores the superior resonance confinement and low-loss characteristics of the present structure, confirming its suitability for high-precision biosensing applications.

Table 4: Comparison of the sensing performance of the proposed biosensor with previously reported

Topology	Max sensitivity(nm/RIU)	Max FoM	References
Si ring resonator	636	211.3	[40]
Semi-elliptical and rectangular ring resonant	1384	28.4	[41]
E-shaped resonator	2453.75	22.8	[42]
H-shaped resonator	1960	15.2	[27]
tapered WG	1132.14	48.17	[43]
Hexagonal Cavity-Based resonator	770.27	160.47	This work

Conclusion

In this study, a high-performance plasmonic Metal-Insulator-Metal waveguide refractive index sensor was designed and optimized for the detection of Carcinoembryonic Antigen (CEA) using Surface Plasmon Resonance (SPR) principles. The proposed biosensor, featuring a hexagonal cavity with a rectangular slit, demonstrated superior sensitivity and enhanced resonance characteristics, making it a promising candidate for biomolecular sensing applications. A comprehensive numerical analysis was conducted using the FDTD, ensuring accurate performance evaluation. The optimized sensor achieved a remarkable sensitivity of 770.27 nm/RIU and a FoM of 160.47, surpassing several existing designs in plasmonic biosensing research.

The results indicate that the strategic optimization of key geometric parameters significantly enhances the sensor's detection capabilities, ensuring precise and efficient biomarker identification. The strong field

confinement, high Q-factor, and minimized energy dissipation contribute to its applicability in real-time, label-free biosensing. The ability to detect even minor refractive index variations underscores the sensor's potential for clinical diagnostics, particularly in the early detection of CEA-associated cancers. Future research may focus on experimental validation and further structural enhancements to broaden its applicability in biomedical and environmental monitoring.

Declarations

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare no competing interests.

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