



Triple-band terahertz plasmonic refractive index sensor based on an octa-arm graphene metamaterial absorber

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ABSTRACT

This work introduces a triple-band terahertz plasmonic sensor for refractive index monitoring, featuring an octa-arm graphene metamaterial absorber. The sensing functionality is driven by the interaction between electromagnetic field distributions and resonance modes, enabling the detection of subtle dielectric changes in the analyte environment. Structurally, the device is configured as a four-component stack: a gold base-layer, a SiO₂ spacer, a patterned graphene monolayer, and the target analyte. Computational analysis reveals three distinct absorption peaks located at 5.32, 7.66, and 9.43 THz. The calculated performance metrics include a peak sensitivity of 1740 GHz/RIU, a Q-factor of 34.40, and a Figure of Merit (FoM) reaching 5.91. To investigate the structure's electromagnetic response, numerical modeling was executed within the CST Microwave Studio environment, while the underlying physical coupling and resonance behavior were validated through Coupled Mode Theory (CMT). These findings suggest that the proposed architecture is highly effective for multi-band sensing applications in the THz regime.

1. Introduction

In recent years, research into terahertz (THz) electromagnetic radiation-spanning the spectral gap between the microwave and infrared regions-has expanded significantly [1]. Due to its non-ionizing nature THz radiation enables the non-destructive investigation of biological cells without inducing chemical damage or altering their native structures [2]. Consequently, THz -based configurations have become instrumental in diverse applications, including imaging [3], spectroscopy [4], sensing, and switching [5–11]. Among the structures that have attracted considerable attention in the terahertz region are THz absorbers. Examples of such absorbers have been reported in Refs. [12–14]. To implement these devices, various materials are utilized, among which graphene has emerged as one of the most prominent due to its extraordinary electrical and plasmonic properties.

Graphene comprising a single-atom-thick planar sheet of carbon atoms arranged in a two-dimensional honeycomb lattice and is recognized as the fundamental building block for carbonaceous materials of various dimensions. It can be wrapped into one-dimensional carbon nanotubes as well as stacked into three-dimensional graphite structures [15]. Since the successful isolation of stable graphene on a silicon

substrate in 2004, this material has garnered immense research interest due to its remarkable properties and has become an important subject of scientific studies [16]. In the THz domain, graphene has assumed a pivotal role, emerging as a highly promising platform for the generation and detection of terahertz waves. This capability originates from a set of intrinsic and unique properties of graphene. Most notably, both the plasmonic resonance frequency of graphene, and the bandgap of its nanoribbon derivatives fall precisely within the THz spectrum [17–24].

As a cutting-edge discipline within nano-optics and photonics, plasmonics investigates how optical fields couple with collective free electron oscillations at the boundaries of conducting materials. Leveraging excitation states like surface plasmon polaritons (SPPs) and localized surface plasmons (LSPs), this domain provides a mechanism to manipulate, concentrate, and boost electromagnetic energy well below the classical diffraction limit. Graphene-based terahertz plasmonic networks benefit significantly from the intense spatial energy localization offered by these SPP modes [25], with diverse configurations documented in literature [26–31].

This exceptional capacity for subwavelength light localization positions plasmonics as an essential foundation for engineering next-generation nanophotonic components, high-sensitivity detection

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schemes, imaging modalities, optical networks, and biological sensors. Furthermore, recent breakthroughs driven by integration of innovative 2D materials—most notably graphene—have unlocked novel pathways for developing actively tunable, low-dissipation, and highly efficient optoelectronic architectures.

Metamaterials are defined as artificial, engineered materials formed by the periodic arrangement of subwavelength unit cells. An important characteristic of these structures is that the dimensions of each unit cell are much smaller than the operating wavelength [32]. Such an arrangement leads to unusual electromagnetic behaviors that are rarely observed in natural materials. Among these properties are including a negative refractive index and backward wave propagation [33–36]. Owing to these capabilities, metamaterials have provided a suitable platform for designing various types of THz absorbers, including dual-band, multiband, and broadband structures [1,37–40].

In recent years, considerable research effort has been devoted to the design and development of various graphene-based metamaterial absorbers. These structures aim to optimize absorption characteristics while exploiting the unique properties of graphene. In the following, some of the most notable examples of these structures are reviewed. Designing absorbers using graphene resonators with elongated geometries—such as elliptical nanodisk structures [41] or arrow-shaped configurations [42] facilitates enhanced absorption at longer wavelengths. However, a major challenge in employing these topologies is their high sensitivity to the polarization of the incident wave, which constitutes an operational limitation. In contrast, employing resonators with high geometric symmetry provides an effective approach to overcome this drawback and achieve polarization-independent responses. Structures such as circular ring and disk resonators [43,44] and vertically stacked elliptical rings [45], exhibit excellent operational stability against polarization variations due to their symmetric nature [46].

This work develops a graphene-enabled, triple-resonance plasmonic sensor for refractive-index measurement. The proposed unit cell consists of a graphene circular resonator integrated with eight radial arms, placed above an SiO₂ spacer and backed by a gold ground plane. Its electromagnetic behavior was evaluated numerically using the finite-difference time-domain (FDTD) technique. The simulation results reveal three clearly separated resonances located at 5.32, 7.66, and 9.43 THz. The device provides a peak refractive-index sensitivity of 1740 GHz/RIU, while the highest quality factor reaches 34.40. These results suggest that the proposed platform can offer satisfactory spectral selectivity for monitoring changes in the dielectric environment. The rest of the manuscript is arranged as follows. Section 2 describes the underlying theory and formulates the conductivity model used for graphene. The device architecture, material stack, and computational procedure are specified in Section 3. Section 4 discusses the simulated spectral response and evaluates the main performance characteristics of the proposed sensor. In Section 5, the resonance shifts and sensing metrics are examined for different refractive indices of the surrounding analyte. A summary of the principal findings is given in Section 6.

2. Graphene conductivity

The electromagnetic behavior of the proposed configuration is characterized by representing graphene conductivity through the Kubo formalism. In this framework, the overall surface conductivity of graphene, (σ_g), is determined by combining the intraband term, (σ_{intra}), with the interband term, (σ_{inter}), as given in Eq. (1):

$$\sigma_g(\omega, \mu_c, \Gamma, T) = \sigma_{\text{intra}} + \sigma_{\text{inter}} \quad (1)$$

These two components are defined by Eqs. (2) and (3):

$$\sigma_{\text{intra}}(\omega, \mu_c, T) = \frac{iq_e^2 k_B T}{\pi(\omega + i2\Gamma)\hbar^2} \left(\frac{\mu_c}{k_B T} + 2 \ln \left(e^{-\frac{\mu_c}{k_B T}} + 1 \right) \right) \quad (2)$$

$$\sigma_{\text{inter}} = \frac{iq_e^2}{4\pi\hbar} \left(\frac{2|\mu_c|}{(\omega + i2\Gamma)\hbar} + \frac{(\omega + i2\Gamma)\hbar}{2|\mu_c|} \right) \quad (3)$$

here, e denotes the elementary charge, k_B is Boltzmann's constant, $\hbar$ refers to the reduced Planck constant, and ω is the angular frequency of the incoming electromagnetic wave. The simulations were performed at $T = 300$ K, with a carrier relaxation time of $\tau = 1$ ps and a graphene chemical potential of $\mu_c = 1$ eV.

Within the investigated THz band, the relation $\mu_c \gg \hbar\omega$ is satisfied. Consequently, interband carrier transitions are strongly suppressed by Pauli blocking, and their effect on the graphene surface conductivity is insignificant relative to the intraband contribution. Hence, graphene conductivity is modeled using the intraband Drude approximation, as expressed in Eq. (4):

$$\sigma_g(\omega) = \frac{ie^2|\mu_c|}{\pi\hbar^2(\omega + i\tau^{-1})} \quad (4)$$

Finally, the absorption performance of the structure is evaluated based on the scattering parameters (S-parameters). The total absorption $A(\omega)$ is obtained from the following relation:

$$A(\omega) = 1 - T(\omega) - R(\omega) = 1 - |S_{21}|^2 - |S_{11}|^2 \quad (5)$$

Since the thickness of the bottom metallic layer (gold) is much greater than the skin depth at these frequencies, the transmission is zero ($|S_{21}|^2 = 0$), and therefore the absorption expression simplifies to $A(\omega) = 1 - |S_{11}|^2$.

These equations provide the theoretical framework for modeling the graphene-based metamaterial absorber and analyzing its absorption characteristics in the terahertz frequency range.

3. Absorber theory and design

Fig. 1 illustrates the architecture of the suggested sensor, which comprises a tri-layer configuration. The uppermost stratum features a 0.35-nm-thick graphene metasurface characterized by a symmetrical arrangement; specifically, a central disk integrated with eight equidistant L-shaped resonators. This specific topography is engineered to trigger surface plasmon resonances and tailor the spectral response across the intended frequencies. Beneath this, a silicon dioxide (SiO₂) spacer of height H_{SiO_2} functions as the dielectric medium, while a base layer of gold (Au) with thickness H_{Au} acts as an electromagnetic back-plane to suppress transmission. Finally, a 2- μm analyte coating is deposited atop the entire assembly. In this section, the geometric parameters are considered as follows:

The selection of the final optimized dimensions $S1 = 0.4 \mu\text{m}$, $S2 = 0.4 \mu\text{m}$, $P1 = 1.5 \mu\text{m}$, $P2 = 1.7 \mu\text{m}$, and $R = 1.5 \mu\text{m}$ in Table 1 was guided by rigorous multi-objective optimization criteria to ensure superior sensing performance. Specifically, these parameters were tuned to prevent spectral degeneration and mode collapse (maintaining well-separated triple-band responses without merging), satisfy the critical coupling condition ($\gamma_e \approx \delta$) for near-unity absorption exceeding 98% across all three frequencies (5.32, 7.66, and 9.43 THz), and minimize the resonance FWHM to maximize sensitivity, quality factor ($Q = 34.40$), and figure of merit (5.91 RIU^{-1}), thereby establishing the ideal structural configuration for the proposed sensor.

Electromagnetic simulations were conducted using the frequency-domain solver in CST Studio Suite. To model the periodic nature of the structure, Floquet ports were applied along the x- and y-axes. Furthermore, perfectly matched layers (PML) were employed as open-space boundary conditions along the direction of wave propagation (z-axis) to eliminate spurious reflections and ensure the accuracy of the results. Regarding the discretization process, a surface-based tetrahedral meshing scheme was utilized within CST Studio Suite 2025. By setting the mesh density to 10 cells per maximum model box edge, a total of 27,400 tetrahedral elements were generated.

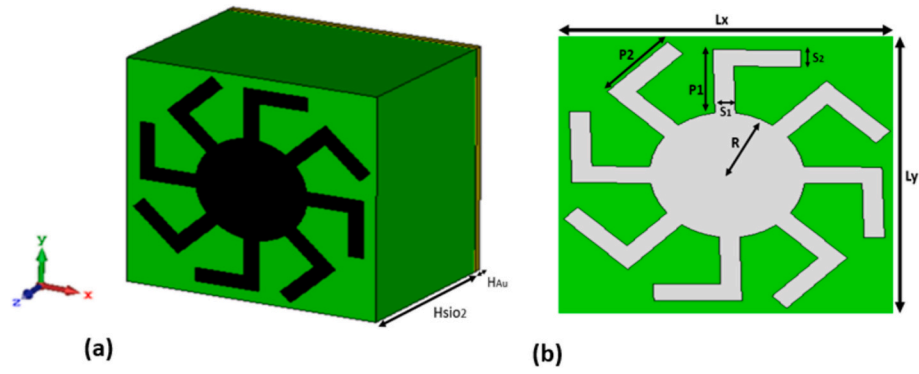


Fig. 1. (a) Perspective representation of the designed THz absorber. (b) Its X-Y view.

Table 1

Proposed absorber parameters.

Parameter	Value	Parameter	Value	Parameter	Value
HAu	0.2(μm)	P1	1.5(μm)	R	1.5(μm)
HSiO2	4.75(μm)	P2	1.7(μm)	ϵ_r	3.9(μm)
Lx	6.7(μm)	S1	0.4(μm)	τ	1(ps)
Ly	6.7(μm)	S2	0.4(μm)	μ_c	1(eV)

4. Results and analysis

The geometric evolution of the proposed graphene metasurface is illustrated in Fig. 2. The design process initiates with a simple graphene disk as the central core (Fig. 2a) to establish the fundamental plasmonic response. The absorption spectrum shown in Fig. 2b exhibits a single peak at 6.463 THz with relatively low absorption.

In the second stage, as shown in Fig. 2c, eight straight arms were symmetrically added around the perimeter of the disk to enhance the impedance matching and excite higher-order resonant modes. The corresponding absorption spectrum in Fig. 2d shows two distinct absorption

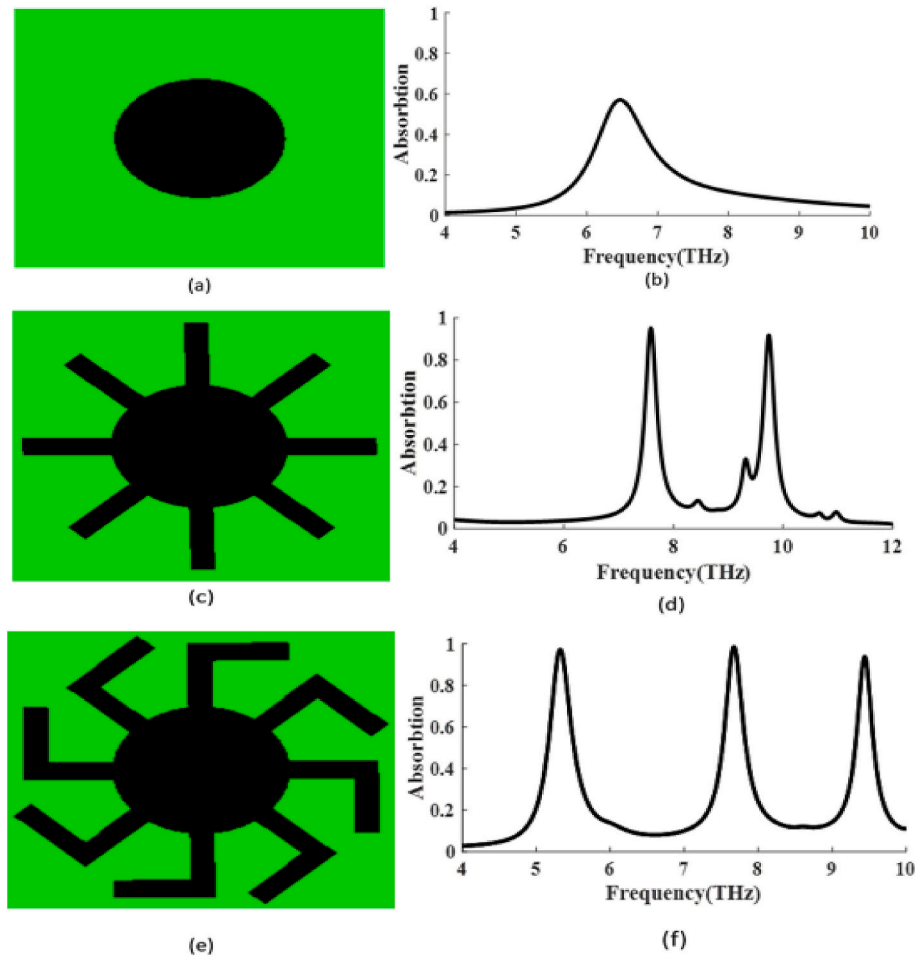


Fig. 2. (a) Structure 1, (b) absorption spectrum of structure 1, (c) structure 2, (d) absorption spectrum of structure 2, (e) Structure3, (f) absorption spectrum of structure 3.

peaks at 7.565 THz and 9.710 THz.

Finally, to further optimize the device performance and achieve a triple-band response, these arms were modified into L-shaped configuration, as illustrated in Fig. 2e. The corresponding absorption spectrum in Fig. 2f presents three peaks at 5.32 THz, 7.66 THz, and 9.43 THz. This strategic modification increased the effective electrical length thereby introducing additional inductive and capacitive components that strengthen the light-matter interaction within the target terahertz regime.

To examine the resonance mechanism, Fig. 3 illustrates the surface electric-field patterns of the proposed graphene structure at 5.32, 7.66, and 9.43 THz. For the lowest-frequency mode, occurring at 5.32 THz, pronounced field localization is observed at the rims of the L-shaped segments and in the regions where these segments merge with the central graphene region Fig. 3(a). Such field confinement is characteristic of localized surface-plasmon excitation in the outer resonant features. As a result of the collective oscillation of graphene charge carriers, strong near-field hot spots are formed around these areas.

At the intermediate frequency of 7.66 THz, the field concentration shifts toward the central graphene disk and the initial sections of the arms. This phenomenon suggests the occurrence of strong electromagnetic coupling between the central core and the surrounding arms, resulting in a constructive near-field interference that significantly enhances field localization within the inner structural cavities.

Finally, at 9.43 THz, the field distribution shifts toward the outer edges and the tips of the L-shaped arms. The meaningful variation in the spatial pattern of hotspots as frequency increases confirms the crucial role of the arm geometry in shaping the triple-band response. These results clearly demonstrate that by optimizing the geometric parameters and increasing the effective electrical length, the proposed structure can efficiently confine the incident electromagnetic energy on the graphene surface at the targeted frequencies.

In geometric parameters S_1 , S_2 , P_1 , P_2 , and R were varied, and different absorption spectra were obtained. As shown in Fig. 4(a), varying the parameter S_1 significantly alters the spectral behavior of the structure. When S_1 increases from 0.2 to 0.6, the first peak remains unchanged, while the second and third peaks shift toward higher frequencies due to the increased arm thickness. Moreover, for $S_1 = 0.6$, only two absorption peaks appear.

In the next step, by increasing the thickness S_2 , the first and second peaks shift to higher frequencies, whereas the third peak shifts to lower frequencies as S_2 increases from 0.2 to 0.6. In addition to the frequency shift, it is observed that increasing S_2 also modifies the bandwidth and absorption intensity. The absorption efficiency of the third peak is initially very low, then increases, and later decreases slightly. For $S_2 = 0.4$ and $S_2 = 0.6$, the high-frequency absorption peaks tend to merge or come closer together, which can lead to high-performance multiband responses. This geometric tunability allows the designer to adjust the operating frequency of the absorber according to application requirements without altering the constituent materials.

Fig. 4(c) compares the absorption spectra for different values of P_1 . As P_1 increases, the resonance peaks exhibit a redshift toward lower frequencies. In addition, the first absorption peak becomes stronger, the second peak weakens, and the third peak increases again. The influence of P_2 is shown in Fig. 4(d); increasing P_2 also shifts the absorption peaks to lower frequencies. Finally, the radius of the central disk was varied, as illustrated in Fig. 4(e). When R increases, the first peak shifts to a higher frequency, the second peak shifts to a lower frequency, and the third peak moves to a higher frequency as well.

The impact of adjusting the graphene chemical potential (μ_c) on the device's absorption characteristics between 4 and 10 THz is depicted in Fig. 5. A noticeable blueshift in all three resonance frequencies is observed as μ_c rises from 0.6 to 1.0 eV. This phenomenon originates from the enrichment of charge carrier concentration in the graphene layer, which modifies the real permittivity (ϵ) and consequently shortens the resonant wavelength. Beyond the spectral displacement, higher chemical potentials generally boost the absorption magnitude and tune the bandwidth of the peaks. Such active reconfigurability renders the sensor suitable for dynamic environments and frequency-agile applications.

Furthermore, Fig. 6 presents the absorption spectra under TE and TM polarizations across the 4–10 THz band. As observed, three peaks appear at approximately 5.4, 7.7, and 9.5 THz, where the absorption in all cases reaches values close to unity (1). The complete overlap of the TE and TM curves indicates an identical absorber response for different polarization states of the incident wave. This polarization-independent behavior arises from the high geometric symmetry of the designed unit cell.

The absorption profiles of the suggested sensor under oblique incidence from 0° to 60° are illustrated in Fig. 7. Assessing operational stability relative to θ variations is important for practical applications, particularly when the source orientation is variable. The results indicate that the three resonance peaks (at 5.32, 7.66, and 9.43 THz) remain stable as the angle increases to 60° . Within this range, the absorptivity is maintained above 90%, with small frequency shifts. This angular stability is related to the sub-wavelength dimensions of the unit cell and its symmetric design. This response supports the sensor's suitability for sensing and imaging applications.

Due to the four-fold rotational and mirror symmetry of the octa-arm L-shaped unit cell, the proposed absorber exhibits complete polarization independence, demonstrating identical spectral responses for both TE and TM polarizations across the entire 4–10 THz window with peak absorption deviations of less than 0.5% (Fig. 6). Furthermore, the device demonstrates remarkable angular stability under oblique illumination up to $\theta = 60^\circ$ (Fig. 7), maintaining absorptivities above 90% across all three modes (specifically 93.5%, 91.2%, and 90.5% at $\theta = 60^\circ$ for Modes 1, 2, and 3, respectively) along with negligible frequency shifts ($\Delta f < 0.08$ THz). Because the underlying mechanism relies on sub-wavelength localized surface plasmon (LSP) confinement rather than angle-sensitive resonances, the effective modal overlap and sensing integrity remain highly stable under realistic oblique incident beams.

Although the present study is based on rigorous numerical

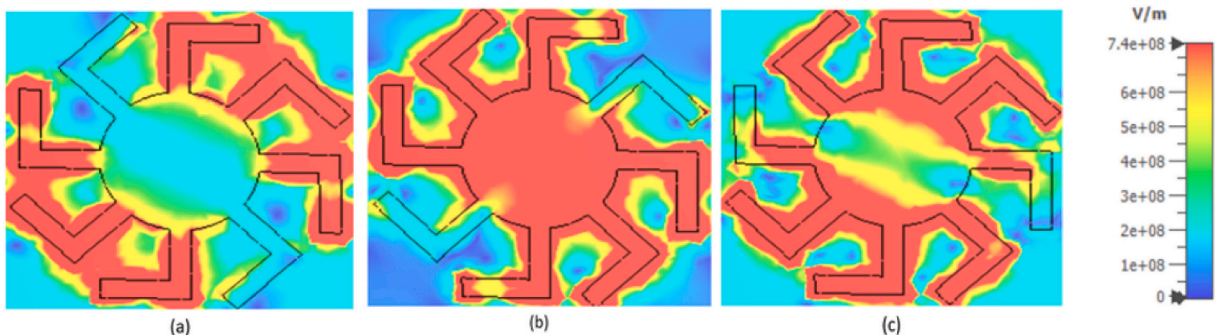


Fig. 3. The electric field distribution ($|E_z|$) in the proposed sensor structure at (a) 5.32 THz, (b) 7.66 THz, (c) 9.43 THz.

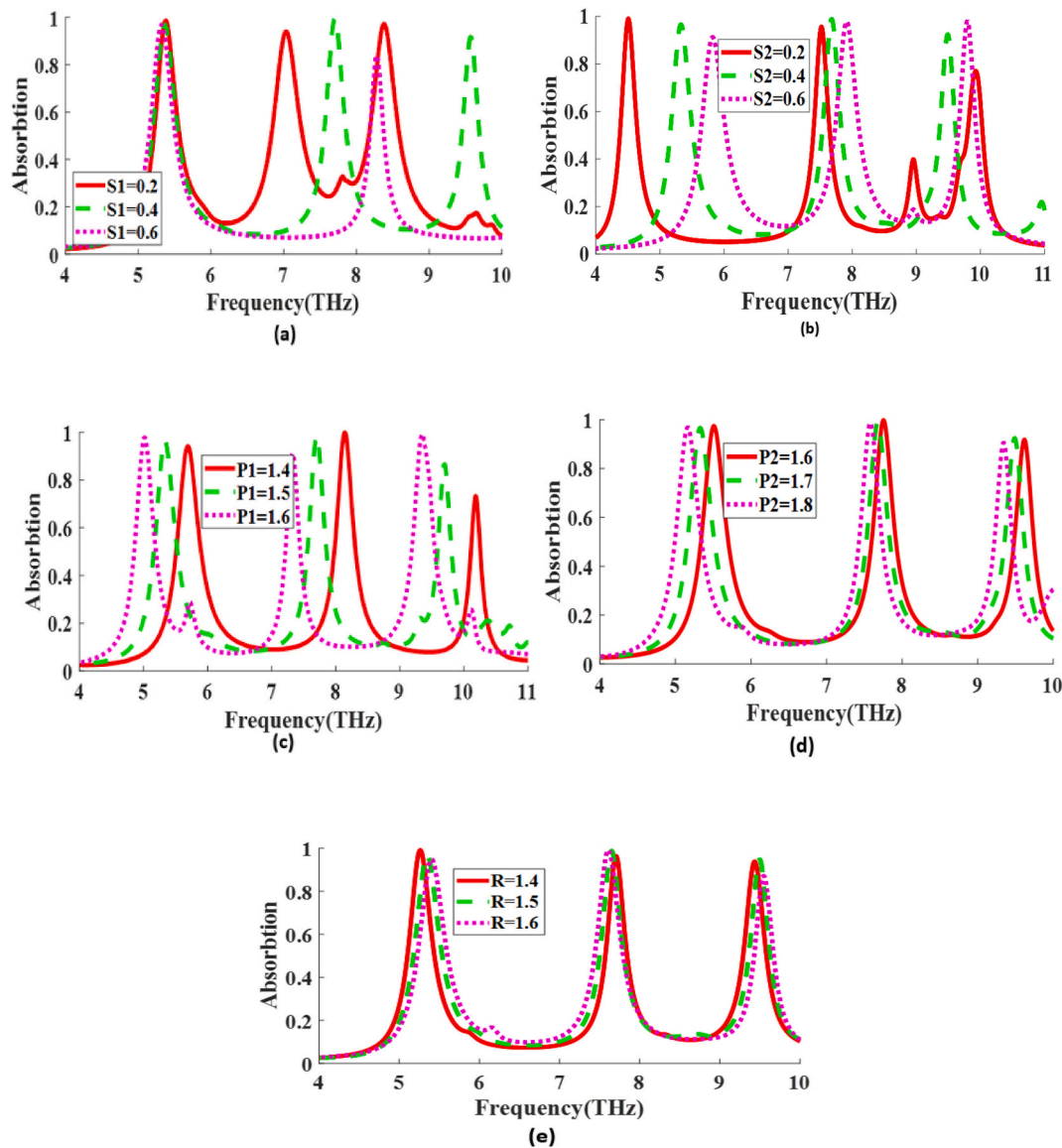


Fig. 4. Sensor absorption diagram: (a) when $S1$ is changed, (b) when $S2$ is changed, (c) when $P1$ is changed, (d) when $P2$ is changed, (e) when R is changed.

simulations, the practical realization of the proposed octa-arm graphene metamaterial absorber relies on well-established, standard micro- and nanofabrication techniques. First, monolayer graphene can be synthesized via Chemical Vapor Deposition (CVD) on copper foils and subsequently transferred onto the SiO_2/Au substrate using a standard PMMA-assisted wet-transfer method, where the copper layer is etched with FeCl_3 and PMMA is dissolved in acetone. Second, the underlying thick gold reflector and SiO_2 spacer are readily deposited onto the silicon substrate via standard RF magnetron sputtering or electron-beam evaporation. Finally, given the micrometer-scale dimensions (such as the $6.7\text{-}\mu\text{m}$ unit cell), the precise L-shaped octa-arm patterns can be reliably transferred onto the graphene sheet using standard photolithography or electron-beam lithography combined with Oxygen Reactive-Ion Etching (O₂ RIE), ensuring high experimental feasibility and reproducibility [47–49].

5. Refractive index sensor

Fig. 8(a–d) presents the spectral behavior of the designed sensor. It is evident that modifying the refractive index (RI) of the surrounding medium from 1.0 to 1.6 noticeably alters the optical response of the

device. As the analyte index increases, the resonance peaks associated with the three modes migrate toward lower frequencies, corresponding to a clear redshift. This shift originates from the elongated effective optical path inside the structure caused by the larger refractive index of the background medium.

In Figs. 8(b–d), the resonant frequency versus RI is plotted for Modes 1, 2, and 3, respectively. The quantitative assessment of these curves confirms that the structure retains stable behavior while providing adequate sensitivity. The sensing performance is characterized using three figures: sensitivity (S), full width at half maximum (FWHM), and figure of merit (FOM):

Mode 1 achieves a sensitivity of 830 GHz/RIU , an FWHM of 396 GHz , and an FOM of 2.09 RIU^{-1} .

Mode 2: With the increase in resonance frequency, the sensitivity improves to 1040 GHz/RIU , while the FWHM decreases to 350 GHz , resulting in an FOM of 3 RIU^{-1} .

Mode 3: This mode demonstrates the highest sensitivity among the investigated modes, reaching 1740 GHz/RIU . Additionally, with the lowest FWHM (280 GHz), it offers the highest resolution and achieves an FOM of 5.91 RIU^{-1} .

To establish the practical applicability of the sensor, the investigated

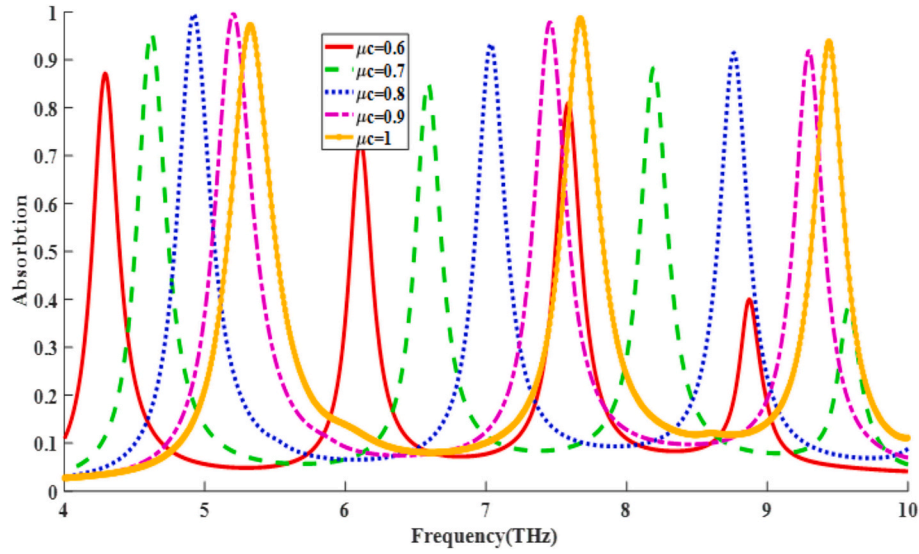


Fig. 5. Simulated absorption responses corresponding to different chemical potential (μ_c) values.

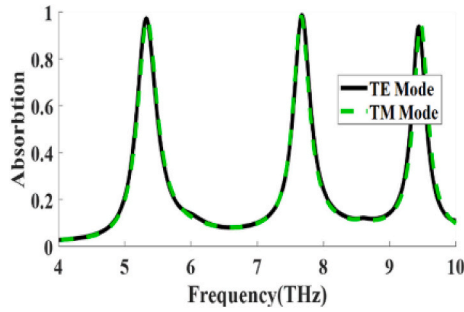


Fig. 6. Polarization-independent absorption response of the suggested design across the 4–10 THz band for both TE and TM waves.

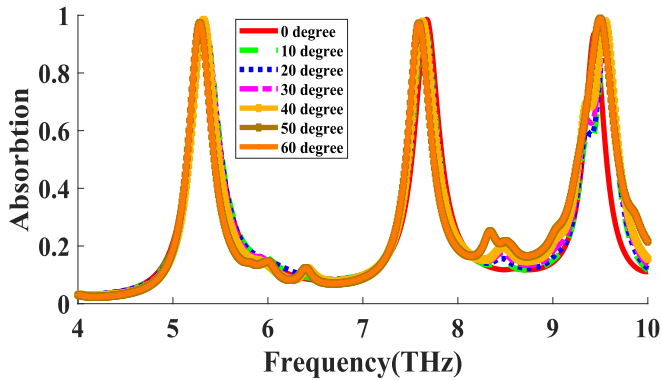


Fig. 7. Absorption response of the proposed sensor under different incidence angles (θ) from 0° to 60°.

refractive index (RI) range of 1.0–1.6 covers a comprehensive spectrum of real-world environments—ranging from air and gas baselines (RI $\approx$ 1.0) and aqueous buffer solutions (RI $\approx$ 1.33) to biological targets such as protein solutions, lipid membranes, viral suspensions, and cell cytoplasm (RI = 1.35–1.45), as well as denser biomolecular and DNA/RNA matrices (RI = 1.45–1.55).

To quantify the sensor response, three performance indicators are considered: sensitivity (S), quality factor (Q), and figure of merit (FOM). Their values are obtained using the following equations:

$$s = \frac{\Delta f}{\Delta n} \quad (6)$$

$$Q = \frac{f_r}{FWHM} \quad (7)$$

$$FOM = \frac{S}{FWHM} \quad (8)$$

In these expressions, Δf denotes the spectral frequency shift, whereas Δn represents the RI variation of the surrounding analyte. Additionally, f_r is the center frequency and $FWHM$ signifies the resonance line-width at half-maximum.

To verify the findings of the full-wave simulations, a theoretical model leveraging Coupled Mode Theory (CMT) was applied. Fig. 9 compares the absorption spectra obtained from the simulations (red dashed line) and the CMT model (solid blue line) across the 4 to 10 THz band. As shown in the figure, the theoretical results exhibit a close correspondence with the simulation data.

All three resonance peaks at frequencies of 5.32, 7.66, and 9.43 THz exhibit high correlation in terms of both spectral position and line-width. The absorption levels at all three peaks are reported to be near unity (perfect absorption) for both methods.

The negligible discrepancies observed in the off-resonance regions can be attributed to the approximations made regarding the coupling parameters in the CMT model. Nevertheless, the high degree of consistency at the resonance points confirms the validity of the physical modeling and the accuracy of the extracted parameters for the proposed structure. This alignment demonstrates that the CMT model effectively describes the physical behavior of the absorber/sensor and can serve as a reliable tool for predicting the optical responses of the structure during the design phases.

The absorption spectrum obtained from the Coupled Mode Theory (CMT) framework is compared with the results derived from full-wave simulations. The findings demonstrate a strong agreement between the analytical CMT approach and numerical simulations, validating the proposed theoretical model.

The decay-rate parameters, γ_e and δ , essential for calculating the absorption spectrum, were determined using Lorentzian fitting. The values employed for the three resonant modes are $\gamma_{e1} = 5 \times 10^{11}$, $\gamma_{e2} = 4 \times 10^{11}$, and $\gamma_{e3} = 3 \times 10^{11}$, alongside the corresponding intrinsic decay rates of $\delta_1 = 3 \times 10^{11}$, $\delta_2 = 4 \times 10^{11}$, and $\delta_3 = 3.5 \times 10^{11}$. Based on these parameters, the absorption response was calculated using the

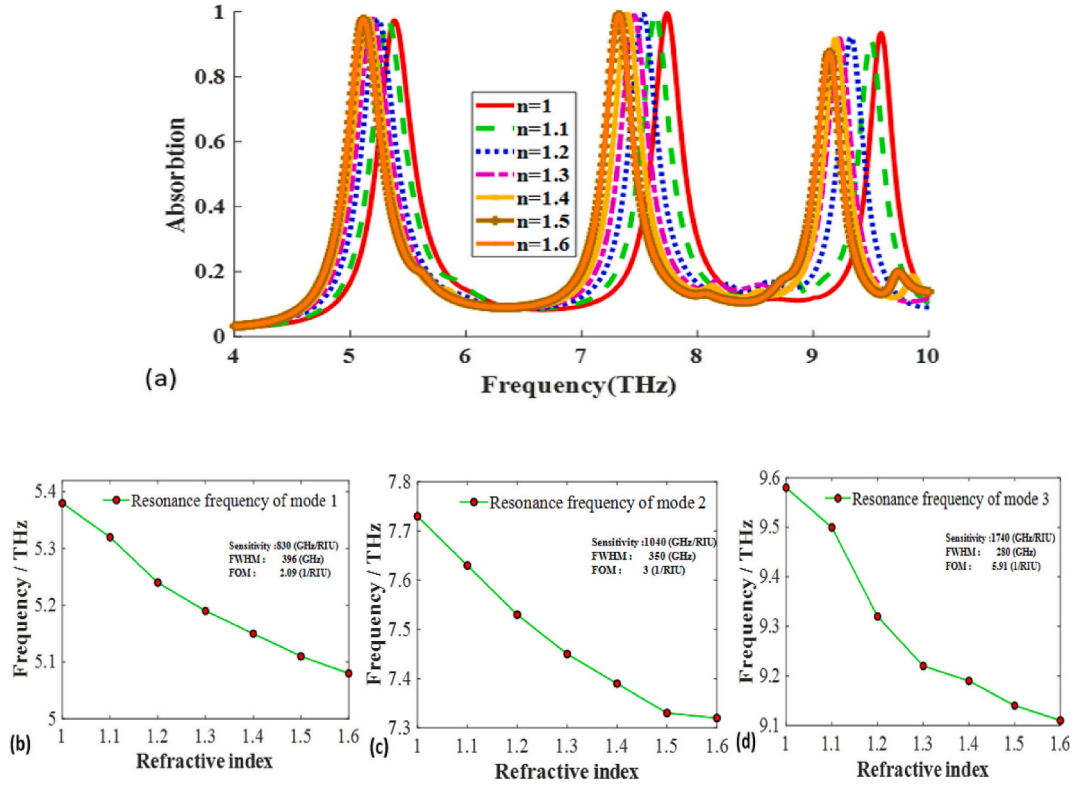


Fig. 8. Refractive-index sensing characteristics of the proposed structure. (a) Absorption spectra for refractive indices ranging from 1.0 to 1.6. (b–d) Dependence of the resonance-frequency shifts of Modes 1–3 on the refractive index, along with the corresponding sensitivity (S), full width at half maximum (FWHM), and figure of merit (FOM).

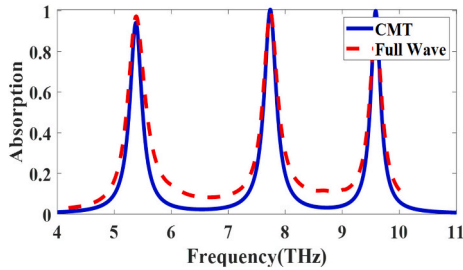


Fig. 9. Comparison and correlation between the circuit model and simulated data.

following CMT expression:

The results obtained from the Coupled Mode Theory (CMT) are presented below, which clearly demonstrate the good agreement between the full-wave simulation results and those derived from this theoretical approach. The values of the two parameters, δ and γ_e , used in the formula for calculating the absorption curve based on the Coupled Mode Theory (CMT) (as shown below), were obtained from a Lorentzian fitting procedure, which is fully described in Reference [3,78]. Since critical coupling occurs at the resonance frequency, the values of these two parameters become equal at 5.29, 6.66, 8.02, and 11.44 THz. The value of γ_e and δ for each frequency are: $\gamma_{e1}=3 \times 10^{11}$, $\gamma_{e2}=4 \times 10^{11}$, $\gamma_{e3}=3 \times 10^{11}$, $\gamma_{e4}=3.5 \times 10^{11}$, $\delta_1=3 \times 10^{11}$, $\delta_2=4 \times 10^{11}$, $\delta_3=3 \times 10^{11}$, $\delta_4=3.5 \times 10^{11}$.

$$A = \sum_{i=0}^N \left(\frac{4(\gamma_e(i)\delta(i))}{(\omega - \omega(i))^2 + (\gamma_e(i) + \delta(i))^2} \right) \quad (9)$$

In this relation, ω_i denotes the resonant frequency of the i -th mode, while $\gamma_e^{(i)}$ and $\delta^{(i)}$ represent the external and intrinsic decay rates,

respectively. The analytical curves effectively reproduce the primary resonant features observed in the full-wave simulation, confirming that the interactions between the modes are accurately described by this theoretical framework.

The physical origin of the three distinct absorption resonances at 5.32, 7.66, and 9.43 THz is governed by the excitation of localized surface plasmon (LSP) modes within the hybrid structure, where the central disk primarily dictates the fundamental lowest-frequency mode, while the L-shaped octa-arm branches introduce additional inductance-capacitance (LC) pathways to excite higher-order plasmonic modes. To analytically substantiate this mechanism, a temporal Coupled-Mode Theory (CMT) framework was implemented, demonstrating that the extracted intrinsic and radiative decay rates satisfy the critical coupling condition ($\gamma_e \approx \delta$) at each resonance peak to achieve near-unity absorption in the absence of transmission $S_{21} \approx 0$ due to the gold ground plane. The excellent quantitative agreement between the CMT analytical curves and full-wave CST simulations across the operational band confirms that these three peaks arise from distinct, well-defined modal pathways rather than numerical artifacts.

To highlight the novelty and advanced performance of the proposed design, the structural evolution from conventional circular disk/ring resonators to the symmetrical eight-arm L-shaped configuration successfully excites higher-order localized surface plasmon (LSP) modes, yielding a well-defined triple-band absorption response at 5.32, 7.66, and 9.43 THz with near-unity absorption. Unlike many multi-band or high-sensitivity graphene structures that rely on asymmetric geometries and suffer from polarization-dependent degradation, our high geometric symmetry ensures complete polarization independence and wide-angle stability. Furthermore, as corroborated by our performance evaluation, while previous works typically achieve isolated high sensitivities or Q-factors in narrow bands (e.g., Refs. [50–53]), the proposed sensor delivers an optimal engineering compromise—featuring a high sensitivity of 1.740 THz/RIU, a desirable Q-factor of 34.40, and an FOM of

5.91 across a broad 4–10 THz operational window, establishing it as a highly robust multi-functional platform for advanced terahertz biosensing. To conduct a precise evaluation of the proposed structure's performance, a comprehensive comparison between the key parameters of this sensor and several previous studies is presented in Table 2. As the results indicate, the sensor designed in this study, which operates in the 4–10 THz frequency range, achieves a significant sensitivity of 1.740 GHz/RIU. This sensitivity value demonstrates a remarkable superiority over most previous studies, including references [50–53]. Furthermore, the obtained quality factor (Q-factor) of 34.40 and figure of merit (FOM) are at a desirable level, indicating a suitable balance between bandwidth and sensitivity. Although some references have reported higher sensitivity or Q-factors in a specific parameter, the proposed structure—by offering a stable multi-band response and high sensitivity across a wide terahertz range—establishes itself as an efficient and competitive option for advanced biosensing applications.

6. Conclusions

In this study, a triple-band graphene-based plasmonic sensor operating in the THz region was designed and comprehensively investigated. The proposed structure consists of a graphene disk with attached arms placed on a gold layer, with a SiO₂ dielectric layer incorporated into the design. Simulation results showed that the structure is capable of simultaneously identifying three frequency bands and exhibits satisfactory performance in detecting refractive index variations, achieving a sensitivity of 1740 nm/RIU and a quality factor of 34.40. These characteristics demonstrate the capability of the proposed structure for accurate and selective sensing at multiple frequencies. Overall, the combination of a multiband response, high sensitivity, and the electro-optic tunability of graphene renders this a promising candidate for next-generation THz biosensors, integrated photonic circuits, and optical communication systems.

Use of AI tools

The authors declare that AI tools were used to improve the English content of this paper.

CRedit authorship contribution statement

Mohadese Imani: Writing – original draft, Software, Investigation, Data curation. **Seyed Amin Khatami:** Validation, Project administration. **Shiva Khani:** Writing – review & editing, Validation. **Mohammad Danaie:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization.

Ethical approval statement

The authors confirm that the submitted paper has not been submitted to any other journal and that this version is original and has not been published elsewhere. Additionally, all listed authors affirm the integrity of the study, data, information, and analyses, ensuring that no manipulations have been made. Furthermore, we confirm that no other individuals meet the authorship criteria for this paper beyond those listed as authors.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

Table 2

Performance summary of the proposed sensor contrasted with previously reported works.

Ref.	Year	Frequency Range [THz]	Sensitivity [THz/RIU]	FOM	Q-factor
[50]	2019	3.82	0.16	62.81	1432
[54]	2019	0.8–1.2	0.28	NR	NR
[55]	2019	5–15	22.720	34.96	14.32
[56]	2020	2.1–6.25	1.57	11.75 & 24.5	40.1 & 80
[51]	2020	0.4–2.5	0.5	15	NR
[57]	2020	0.1–1.9	0.28	8.54	30.5
[52]	2021	1–2.4	0.152	1.5	106
[58]	2022	2.5–4.5	1.6498	NR	11.33
[53]	2023	1.3	0.473	16.9	NR
This work	2026	4–10	1.740	5.91	34.40

NR: not reported.

the work reported in this paper.

Data availability

All the data, designs, and relevant information associated with this paper are accessible and will be shared upon a reasonable request to the corresponding author.

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