

Article

Tunable Broadband Terahertz Absorber Based on Triangular-Patterned Graphene with Sandwich Configuration

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Abstract

A terahertz (THz) metamaterial broadband perfect absorber featuring a simple sandwich structure with a top layer composed of a triangular-patterned graphene film is presented. The graphene pattern is designed to exhibit a pronounced surface plasmon resonance (SPR) effect, which locally enhances the internal electric field's intensity, leading to broadband absorption of 2.8 THz above 90% and a peak absorption rate of 99.99% at 6.05 THz. The broadband tunability of the absorber was further investigated by modulating the Fermi level of the graphene, demonstrating an adjustment in the absorption rate from 6.18% to 99.99% via an external voltage. This study shows that the absorber demonstrates excellent angular tolerance by maintaining an absorption rate above 90% across incident angles ranging from 0° to 50°. The absorber's broadband perfect absorption properties were examined using relative impedance theory. Additionally, to reveal the fundamental physics behind this absorption, detailed analyses of the electric field distributions were carried out. Consequently, the origin of the absorption peaks is elucidated. This absorber enables noise suppression for optoelectronic integration and THz communications.

Keywords: surface plasmon resonance; broadband tunable; terahertz perfect absorber; polarization insensitive

1. Introduction

THz technology is a highly significant cutting-edge interdisciplinary field, encompassing optics, electronics, optoelectronics, and semiconductor research [1–4]. As a key enabling technology, THz devices have attracted significant research interest due to their excellent performance within this band [5]. Among these devices, THz absorbers, which achieve near-perfect absorption across specific frequencies, are particularly notable. This characteristic makes them widely applicable in imaging [6], sensing [7], and communications [8]. As a class of artificially synthesized material structures with unique electromagnetic properties, metamaterial perfect absorbers (MPA) in classical designs typically consist of three thin-film layers: the top and bottom metal layers mainly serve to support the excitation of surface plasmon resonance (SPR), while the intermediate dielectric layer plays a key role in tuning absorption frequency, bandwidth, and other structural performance parameters [9,10]. From the perspective of working mechanism, the excellent absorption performance of MPA



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for incident electromagnetic waves stems from its multiple resonant responses. When electromagnetic waves of specific frequencies reach the material surface, they excite surface free electrons to form surface plasmon waves, which can confine electromagnetic energy within the metamaterial structure. Subsequently, through energy conversion pathways such as Ohmic losses and dielectric losses, the confined electromagnetic energy is transformed into thermal energy, ultimately achieving near-perfect absorption close to 100%.

The performance advantages of MPA are also remarkably significant. Firstly, it exhibits strong design flexibility. Researchers can precisely control the position of absorption peaks, absorption bandwidth, and absorption intensity by adjusting the structural parameters (such as size, shape, periodicity, etc.) of the metamaterial and the properties of the constituent materials, thereby adapting to application requirements in different scenarios [11]. Secondly, MPA covers a broad range of absorption frequencies, enabling electromagnetic absorption from the microwave band to the terahertz band, infrared band, and even the visible light band [12,13]. Early absorber designs were typically narrowband and non-tunable, limiting their practical utility [14]. In contrast, broadband absorbers offer greater versatility by mitigating absorption failure caused by source frequency drift or environmental variations. Tunability, the ability to dynamically control absorption via external stimuli, further allows devices to adapt their response to specific requirements. To transcend the limitations of conventional absorbers, recent research has focused on dynamically tunable metamaterials, advancing the development of intelligent THz absorbers for complex application scenarios.

Graphene, a two-dimensional carbon allotrope, possesses a monolayer hexagonal honeycomb lattice. The surface conductivity of graphene can be flexibly modulated through electrostatic gating or an external bias voltage [15], a property that has prompted extensive research into tunable graphene-based absorbers for the THz band. Several strategies have been developed to achieve broadband absorption, such as utilizing multi-layer stacks [16,17], continuous-patterned [18], or unpatterned graphene configurations [19]. This work employs a discrete-patterned graphene structure, with an external voltage applied via indium tin oxide (ITO) electrodes to modulate the Fermi level of the graphene [20]. The interaction of THz waves with this patterned graphene excites surface plasmon polariton (SPP) [21,22] modes. The patterning significantly enhances this plasmonic effect [23,24], leading to improved absorption of THz waves.

To achieve tunability in the wide band, researchers in recent years have adopted approaches such as utilizing the electrical tunability of graphene, employing novel absorbing materials [25,26], or designing new structures [27,28], leading to the development of various THz absorbers integrating these dual characteristics. Gu et al. proposed a dynamically tunable terahertz perfect absorber based on surface patterned graphene nanofilm, where the absorption efficiency is controlled by adjusting the graphene's Fermi level through an applied external voltage [29]. Utilizing the phase-change properties of VO₂, Wang et al. developed a metamaterial absorber featuring an annular-square open geometry. This device achieves ultra-wideband absorption in the mid-infrared spectrum, where thermal regulation allows for the active modulation of its absorption performance [30]. Within this research framework, the novel graphene-based absorber is proposed to facilitate continued advancement in this field.

Notably, dynamic THz modulation in graphene-based devices has been successfully demonstrated in recent experimental advances. For example, approximately 40% ultrafast absorption modulation in graphene thin films was achieved through optical pumping experiments employing the negative photoconductivity effect, as reported by Tasolamprou et al. [31]. Furthermore, it was shown that graphene absorbers can be self-modulated via hot carrier dynamics by intense THz fields, while the effectiveness of electrostatic gating using ionic liquids for Fermi-level control was also confirmed, as demonstrated by Koulouklidis et al. [32]. Although the potential for ultrafast temporal modulation using continuous

graphene sheets is highlighted in these experimental studies, the present work is focused on the extension of spectral bandwidth and the enhancement of absorption efficiency.

This work presents a THz metamaterial perfect absorber constructed from graphene. The device features a top layer of patterned graphene, which integrates a combination of two distinct isosceles triangles, squares, and cross-shaped elements. Across the 0.1–10 THz frequency band, this design generates a broad absorption band, achieving a peak absorption of 99.99%. A silicon dioxide (SiO_2) dielectric spacer and a gold film substrate form the remaining parts of the structure. The adherence of the device to classical physical theory was confirmed by examining the absorption spectra for both TE and TM polarizations and verifying the effective impedance matching principle. To understand the origin of the broadband absorption, the corresponding electric field distributions were scrutinized. Furthermore, the excellent tunability inherent to graphene was leveraged. By modulating Fermi energy of the graphene, the dynamic adjustability of the absorber was successfully demonstrated. Finally, the insensitivity to the incident light angle was established, showing consistent performance across a wide angular range from 0° to 60° .

2. Materials and Methods

For the research and analysis of the performance of metamaterial devices, we employed the Finite Element Method (FEM) in simulating the electric field. When setting the boundary conditions, the x -axis and y -axis were defined with unit cell boundaries, while the z -axis was set with an open boundary (with added space). Here, the x -axis and y -axis represent the direction of the electric field and magnetic field, respectively. The z -axis is the direction of the incident wave.

The schematic diagram of the designed THz absorber, utilizing graphene, is illustrated in Figure 1. At the bottom, a gold layer constitutes the substrate, which functions as a metallic reflector ($H_1 = 0.5 \mu\text{m}$, electrical resistivity $4.561 \times 10^7 \text{ S/m}$), ensuring zero transmission of THz waves and thus promoting effective absorption of incoming radiation. Above this, an intermediate dielectric functional layer of SiO_2 ($H_2 = 6.5 \mu\text{m}$) is designed, which has an average relative permittivity of $\epsilon = 3.9$ [33], and demonstrates low-loss properties within the THz band. The top layer is a patterned graphene sheet of 1 nm thick. A hybrid geometry combining rectangular and triangular motifs is employed in this graphene layer to maximize the absorption bandwidth. The entire structure has a unit cell period of $p = 10 \mu\text{m}$. For this design, the structural constants are defined by the following measurements, $L_1 = 1 \mu\text{m}$, $L_2 = 6 \mu\text{m}$, $L_3 = 2 \mu\text{m}$, $L_4 = 3 \mu\text{m}$, $L_5 = 5 \mu\text{m}$.

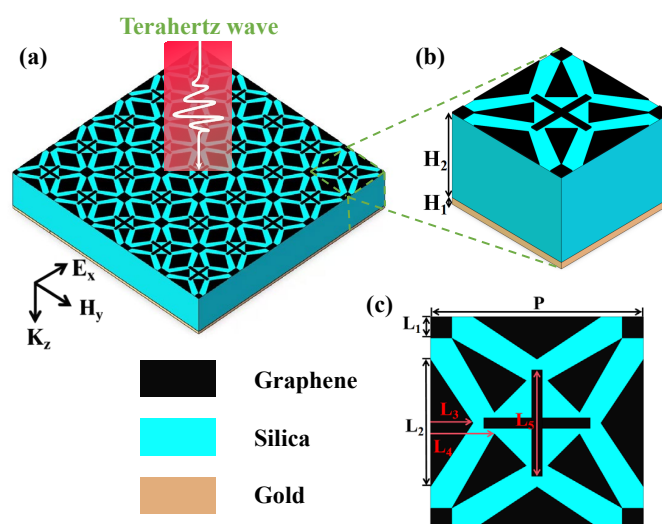


Figure 1. Schematic structure of tunable multifunctional device; (a) 3D structural view; (b) cell structural view; (c) top view of the device periodic row cell.

3. Theoretical Principles

The following Maxwell equations are employed to establish the connection between the dielectric constant of silicon dioxide and its refractive index [34]:

$$n = \sqrt{\epsilon_r \mu} \quad (1)$$

In the expression above, the variables n , ϵ_r and μ denote the refractive index of silicon dioxide, the dielectric constant, and the magnetic permeability, respectively.

The Drude model formula for gold as described in the above text is as follows [35]:

$$\epsilon_{Au} = 9 - \frac{\omega_p^2}{\omega_p^2 + i\omega\gamma} \quad (2)$$

In this expression, ω denotes the angular frequency and i signifies the imaginary unit. Furthermore, the parameters for the damping constant and plasma frequency are set to $\gamma = 1.23 \times 10^{14} \text{ S}^{-1}$ and $\omega_p = 1.37 \times 10^{16} \text{ S}^{-1}$ [34–36].

The absorption rate of the absorber can be calculated by the formula $A(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2$, where S_{11} and S_{21} correspond to the reflection and transmission coefficients of the incident wave. Standard calculations indicate that at a frequency of 10 THz, gold possesses a skin depth of 25 nm. Since the basal gold layer is significantly thicker than this value, transmission is effectively negligible. Consequently, the absorption formula for this device simplifies to $A(\omega) = (1 - |S_{11}|^2)$ [37].

The electromagnetic penetration depth for gold is defined by the following expression [38]:

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} \quad (3)$$

In this expression, ω denotes the angular frequency, defined as $2\pi f$, while μ signifies magnetic permeability. Regarding material properties, gold exhibits a relative permeability of unity at room temperature. We also define the vacuum permeability constant as $4\pi \times 10^{-7} \text{ H/m}$. Additionally, the specific electrical conductivity for gold is set to $\sigma = 4.52 \times 10^7 \text{ S/m}$.

The Kubo formalism characterizes graphene's surface conductivity, which arises from the interplay between intra-band and inter-band electron transitions [39]:

$$\sigma_g = \sigma_{\text{inter}} + \sigma_{\text{intra}} \quad (4)$$

$$\sigma_{\text{intra}} = \frac{ie^2 K_B T}{\pi \hbar^2 (\omega + i2\Gamma)} \left[\frac{E_f}{K_B T} + 2 \ln \left(e^{-\frac{E_f}{K_B T}} + 1 \right) \right] \quad (5)$$

$$\sigma_{\text{inter}} = \frac{ie^2}{4\pi \hbar} \ln \left(\frac{2|E_f| - (\omega + i2\Gamma)\hbar}{2|E_f| + (\omega + i2\Gamma)\hbar} \right) \quad (6)$$

In this expression, ω denotes the radiation frequency, while μ_c and T refer to the graphene's chemical potential and absolute temperature, respectively. We define the phenomenological scattering rate as $\Gamma = (2\tau)^{-1}$, dependent on the relaxation time τ . Furthermore, the equation incorporates standard physical constants: the elementary charge e , the Boltzmann constant k_B , and the reduced Planck constant $\hbar$. When certain conditions are met, interband conductivity can be neglected. The surface conductivity can be effectively described by the Drude model [40].

$$\sigma = \frac{e^2 E_f}{\pi \hbar^2} \frac{i}{\omega + i\tau^{-1}} \quad (7)$$

In the above formula, E_f depends on the concentration of the charge. In this paper, the graphene with a thickness of 1 nm and a Fermi energy level of $E_f = 1.1$ eV is utilized. It is worth noting that the Fermi energy level of graphene can be changed as needed through chemical doping technology or electrostatic casting technology. Equation (8) demonstrates a significant relationship connecting surface conductivity with the Fermi energy level. Furthermore, the Fermi level (E_f) exhibits a distinct dependence on the applied bias voltage (V_{bias}).

$$|E_f| = \hbar V_f \sqrt{\pi |a_0 V_{bias}|} \quad (8)$$

With a_0 defining the capacitance constant and V_f standing for the Fermi velocity, the relationship shows that the Fermi level is tunable. Specifically, it responds to changes in the bias voltage applied from an external source.

4. Results and Discussion

Under conditions of normal incidence, the device's absorption profile appears in Figure 2. A bandwidth of 2.8 THz is achieved when E_f is 1.1 eV, maintaining greater than 90% efficiency from 4.43 to 7.23 THz. A broader spectrum, ranging from 4.22 to 7.58 THz, sustains rates higher than 80%. Specifically, the structure generates two separate peaks at 5.16 THz and 6.05 THz, which correspond to intensities of 99.26% and 99.99%.

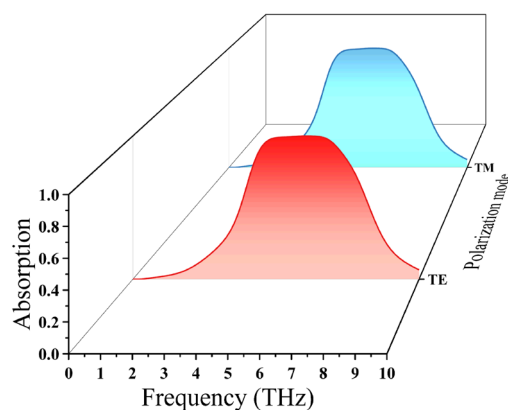


Figure 2. Absorption rates of the absorber in TE and TM modes, respectively.

Figure 3 displays the calculated relative impedance (Z), derived via the effective impedance matching principle to elucidate the absorption mechanism. The plotted curve highlights how impedance at the absorption maxima depends on the frequency of the incident wave. Achieving 100% absorption requires satisfying the critical coupling condition; this implies that the device's impedance must equal that of a vacuum, resulting in a unitary relative impedance ($Z = 1$). The mathematical expression for Z is [41]

$$Z = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 + S_{21}^2}} \quad (9)$$

The real and imaginary components of the impedance data presented in Figure 3 are illustrated with blue and black lines. Across the 4.43–7.23 THz absorption band, the real part is observed to approach 1 while the imaginary part remains close to 0. This behavior is particularly evident at 5.16 THz and 6.05 THz. The enhanced absorption at the noted frequencies, shown in Figure 2, is comprehensively explained by the observed impedance properties. This is due to the strong impedance matching achieved between the absorber's design and free space.

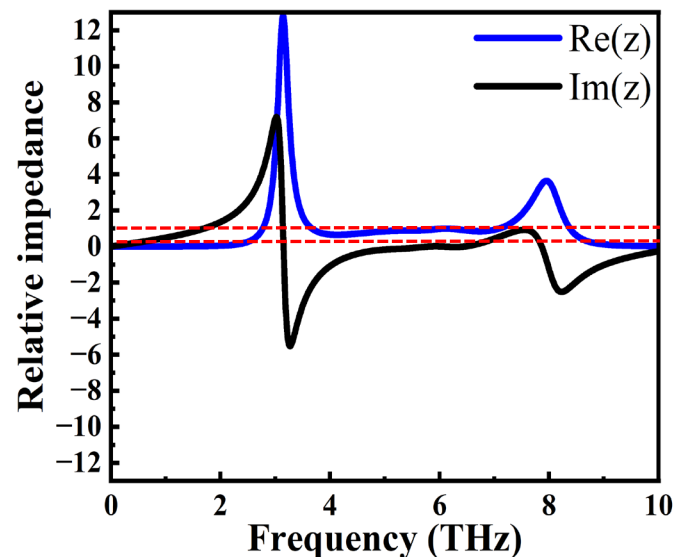


Figure 3. Relative impedance of the absorber (real part and imaginary part).

4.1. The Impact of Patterned Graphene on Absorption Efficiency

The geometric configuration of the top-layer graphene was systematically adjusted to enhance the structural absorption performance. As shown in Figure 4a, an absorption rate of only 3% was observed without a graphene layer. In contrast, the application of a continuous graphene film (Figure 4b) increased the absorption rate to 60%. Further introduction of small square patterns (Figure 4c) achieved an absorption rate of 30%. With the optimized specific graphene patterns (Figure 4d), an absorption rate exceeding 90% was attained, and the final optimal design (Figure 4e) reached over 99%.

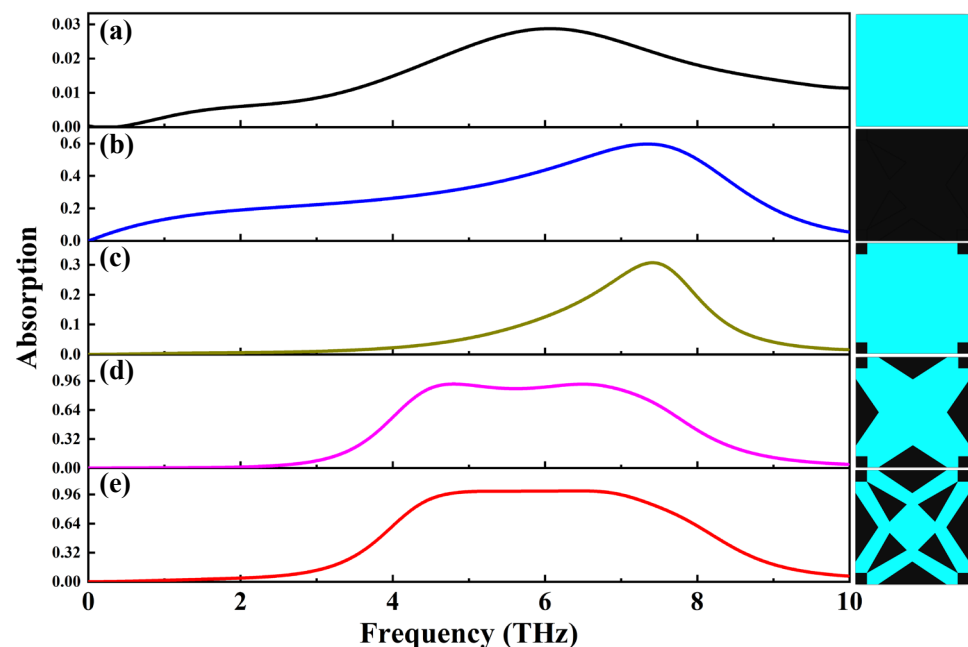


Figure 4. The influence of different patterns of graphene on the absorber (a) without graphene and (b) with fully covered graphene. (c) A group of squares. (d) A group of squares and triangles. (e) A group of squares and two groups of triangles.

It can be intuitively seen in Figure 4b,e that the introduction of the triangular elements transformed the absorption curve from a single peak into a broad, flat-topped absorption peak. Furthermore, the incorporation of a cross-shaped structure, as indicated in

Figures 2 and 4e, enhanced the absorption rate at 6.05 THz to 99.99%. Unlike common single patterns (such as circles, squares, or crosses), we propose a top-layer graphene pattern composed of two sets of isosceles triangles with different sizes, integrated with square and cross-shaped units. This symmetric and multi-scale composite design effectively and tenably excites and modulates multiple localized surface plasmon resonance (LSPR) modes. Through the coupling and superposition of these modes, narrowband resonances are broadened into a continuous wideband. A clear comparison between Figures 2 and 4b–e demonstrates that this specific patterned design—rather than simple continuous graphene or basic square arrays—increased the absorption rate from below 60% to over 99%.

4.2. Effects of Different Parameters on Absorption Efficiency

Polarization insensitivity is recognized as a critical characteristic of THz absorbers. This property was verified through analysis of the symmetrical structure performance under vertical incidence in both transverse electric and transverse magnetic modes. As shown in Figure 5a, highly consistent curves of absorption are observed across different polarization angles. The coincidence of absorption spectra between TE and TM modes is further demonstrated in Figure 5b, indicating excellent polarization insensitivity. This feature is considered highly valuable for practical applications in THz communications and radar systems, where stable performance is maintained regardless of variations in the incident wave polarization state, thereby effectively overcoming the absorption efficiency degradation caused by polarization uncertainty.

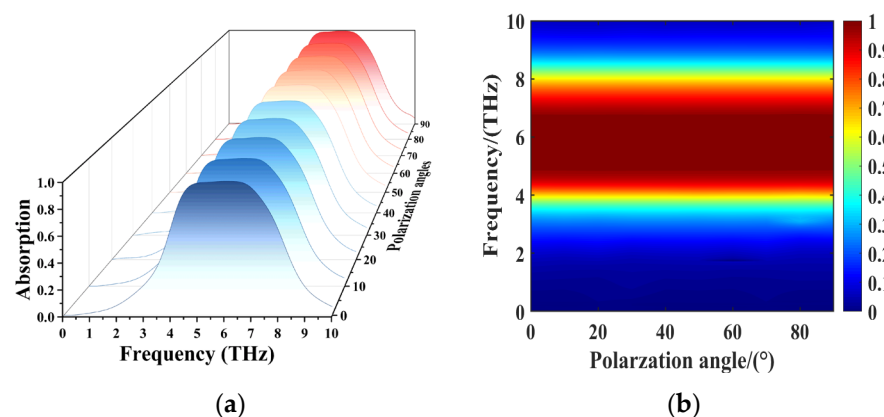


Figure 5. Absorption rate under different polarization angles (a) varies with the change in polarization angle; (b) absorption spectra at different polarization angles.

The application of distinct bias voltages allows for the precise modulation of graphene's Fermi level. As illustrated in Figure 6, increasing the potential from 0 eV up to 1.1 eV results in a progressive upward trend in absorptivity. This improvement occurs because the plasmon resonance effect becomes significantly stronger. At $E_f = 0.8$ eV, an absorption rate of 93.37% is achieved at 5.41 THz, while at $E_f = 1.1$ eV, 99.99% absorption is reached at 6.05 THz. By modulating the Fermi level from 0 eV to 1 eV, the absorption rate is enhanced from 6.18% to 99%. These results demonstrate that graphene Fermi level adjustment enables satisfaction of specific frequency requirements for different applications.

The relationship between absorption rate and oblique incidence angles is demonstrated in Figures 7 and 8. Under transverse electric (TE) mode (Figure 7), absorption rates exceeding 80% are maintained within specific frequency bands at incidence angles ranging from 0° to 60° . At 50° incidence, over 90% absorption is preserved across the 5.15–6.57 THz band. Beyond the angle of 50° , the absorption bandwidth decreases significantly, which is caused by enhanced electric field resonance parallel to the graphene surface and simultaneous reduction in the magnetic field component transferred to the absorber.

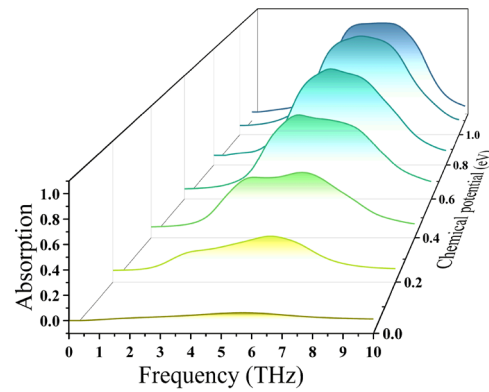


Figure 6. The regulating effect of Fermi energy level on absorption rate.

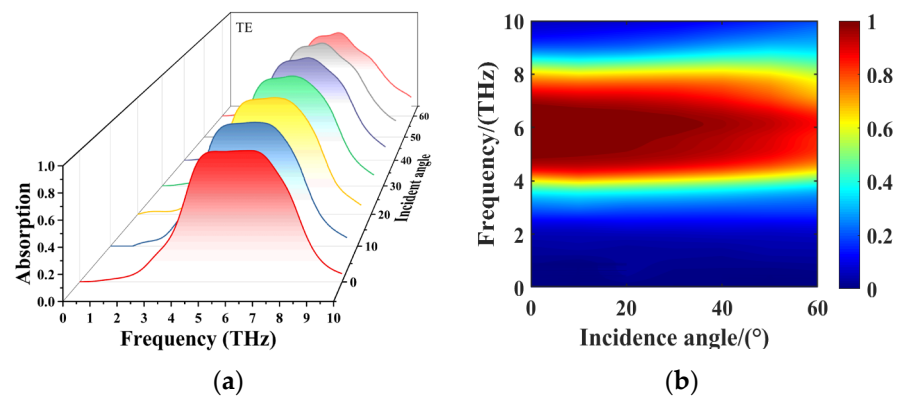


Figure 7. TE mode: (a) Absorption efficiency varying with the incident angle. (b) Absorption spectra at different incident angles.

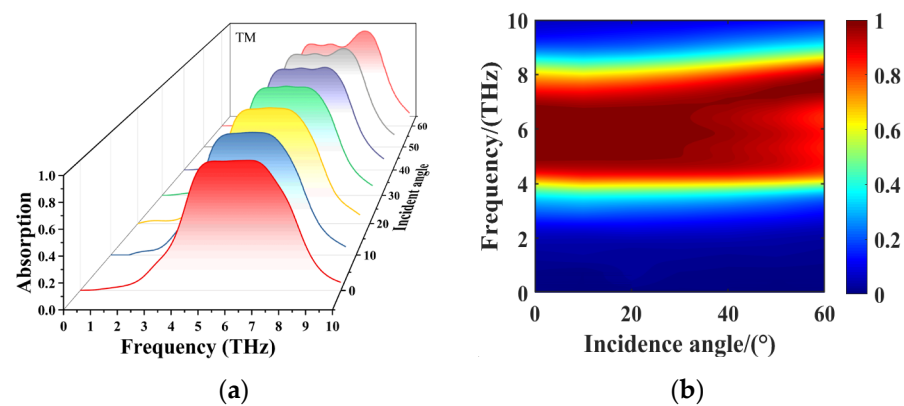


Figure 8. TM mode: (a) Absorption efficiency varying with the incident angle. (b) Absorption spectra at different incident angles.

The influence of incident angle on absorption rate in transverse magnetic (TM) mode is demonstrated in Figure 8. At incidence angles increase to 60° , over 80% absorption is maintained across 4.38–8.36 THz, demonstrating excellent angular stability. Although absorption degradation is observed beyond 50° , the increased angle in TM mode promotes effective excitation of surface dipoles, thereby enhancing absorption. In contrast, fast absorption decay in TE mode originates from angular variation in the electric field orientation, while the electric field direction in TM mode remains consistent regardless of incidence angle.

The geometric parameters of the structural design will influence the absorption performance. The influence of slight variations in key structural parameters on the absorption

performance will be discussed next, with the corresponding simulation results presented in Figure 9. As the length of L_3 increases from $0.5\ \mu\text{m}$ to $2.5\ \mu\text{m}$, both the absorption bandwidth and absorption efficiency of the absorber improve steadily. This is because the increase in the height of the surrounding triangular patches reduces the distance between the graphene layer and both the inner cross-shaped structure and the other set of triangular structures, thereby enhancing resonance coupling and consequently improving the absorber's absorption rate and bandwidth. When the length of L_3 reaches $2.5\ \mu\text{m}$, the outer triangular patches connect with the cross-shaped structure, leading to weakened resonance coupling and thus a decline in absorption performance. Therefore, the length of L_3 is carefully set to $2.0\ \mu\text{m}$ to achieve optimal absorption performance.

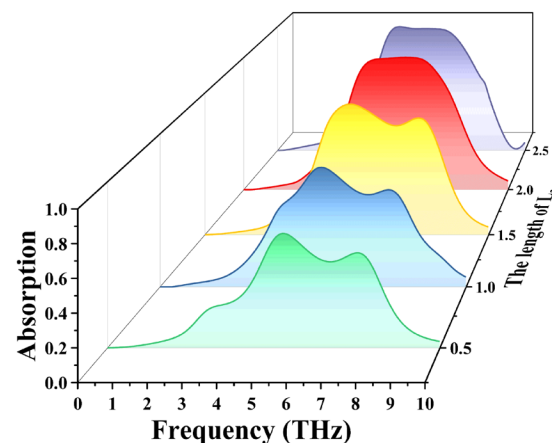


Figure 9. Absorption rates at different L_3 lengths.

Figure 10 illustrates the dependence of the absorption spectra on the relaxation time of graphene. As observed, at a relaxation time of $0.1\ \text{ps}$, the system enters a high-damping state due to frequent carrier scattering. This high-loss effect causes significant broadening of the resonance peaks, resulting in the overlapping of adjacent resonance modes, which effectively fills the spectral dips between resonance points. Consequently, the absorption spectrum exhibits a flat and continuous broadband profile. As the relaxation time increases to $0.5\ \text{ps}$, the damping decreases due to the freer movement of electrons. The originally merged broadband spectrum splits into multiple distinct and sharp absorption peaks with significantly deepened valleys, demonstrating strong multi-frequency oscillatory characteristics. Notably, although variations in the relaxation time drastically alter the shape and sharpness of the peaks, the central frequencies of the primary resonance modes remain substantially unchanged.

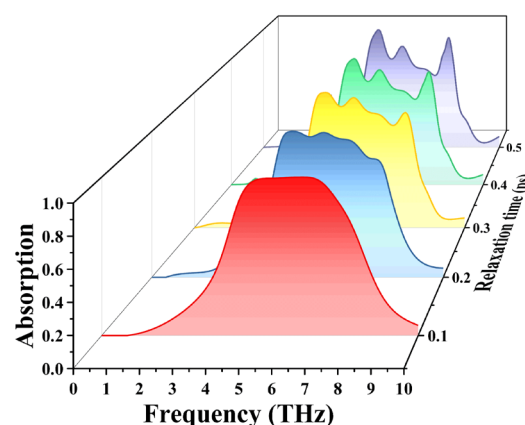


Figure 10. Absorption rates of different relaxation times.

As shown in Figure 11, simulation results demonstrate that adjusting the periodicity of the absorber unit and varying the SiO₂ interlayer thickness enables an evolution from single-peak to dual-peak absorption behavior without compromising wideband performance. With the period expanded progressively from 20 μm to 50 μm and the SiO₂ layer thickness correspondingly increased from 9.5 μm to 17.5 μm , absorption levels remain above 90% throughout the 1.51–5.20 THz spectrum, achieving near-ideal peak values of approximately 99.9% at several discrete frequencies. Each tested variant displays consistent wideband absorption stability, accompanied by a progressive redshift of resonance peaks under dimensional enlargement, thereby validating the configuration's structural adaptability and spectral tuning capability.

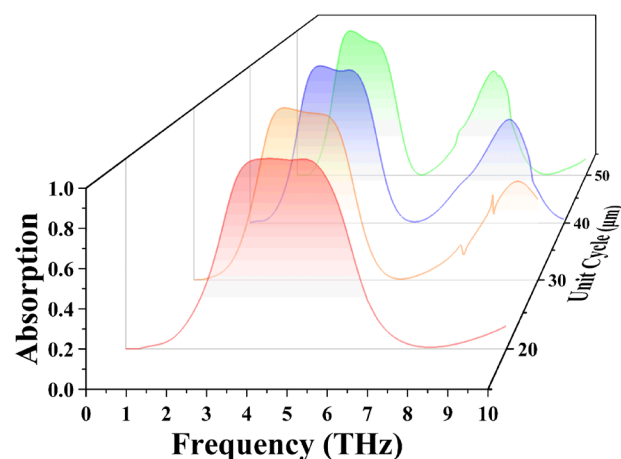


Figure 11. Absorption rates of different unit periodic absorbers.

4.3. Electromagnetic Field Analysis and Feasible Preparation Process

To elucidate the physical basis of the broadband absorption, we monitored the profiles of both the magnetic (H) and electric (E , E_z) fields. As illustrated in Figure 12a,b, surface plasmons triggered at the structural margins create dipole patterns that parallel the incident field vector. The intense coupling between these dipoles and the external field induces powerful resonance, leading to substantial absorption rates. Furthermore, Figure 12c,d reveals that field intensity concentrates mainly along the perimeters of the inner and outer triangular geometries. Upon matching the THz wave frequency with the device's resonance, localized surface plasmon resonance (LSPR) activates. This effectively traps energy near the surface, thereby boosting absorption efficiency. Finally, Figure 12e,f depicts magnetic confinement within the SiO₂ dielectric spacer, indicating a microcavity mechanism driven by magnetic dipoles [42]. Consequently, the broadband and high absorption characteristics are attributed to the combined effects of graphene dipoles, magnetic resonance, and LSPR [43].

Given its uncomplicated geometry and the accessibility of its constituent components, this absorber is ideal for scalable production. Figure 13 illustrates the step-by-step assembly process we have conceptualized for this periodic structure. The protocol commences by thoroughly washing the silicon wafer with acetone and isopropanol, after which it is dried using a stream of pure nitrogen gas. Next, a gold layer is coated onto the substrate via electron beam physical vapor deposition (E-beam PVD) [44] at room temperature. A silica spacer is then added through spin-coating; its thickness is subsequently measured with a stylus profiler to confirm it matches the design specifications. Finally, a graphene sheet is synthesized on a copper catalyst using chemical vapor deposition (CVD) [45,46]. Once the graphene is formed, the specific geometric patterns are defined using photolithography.

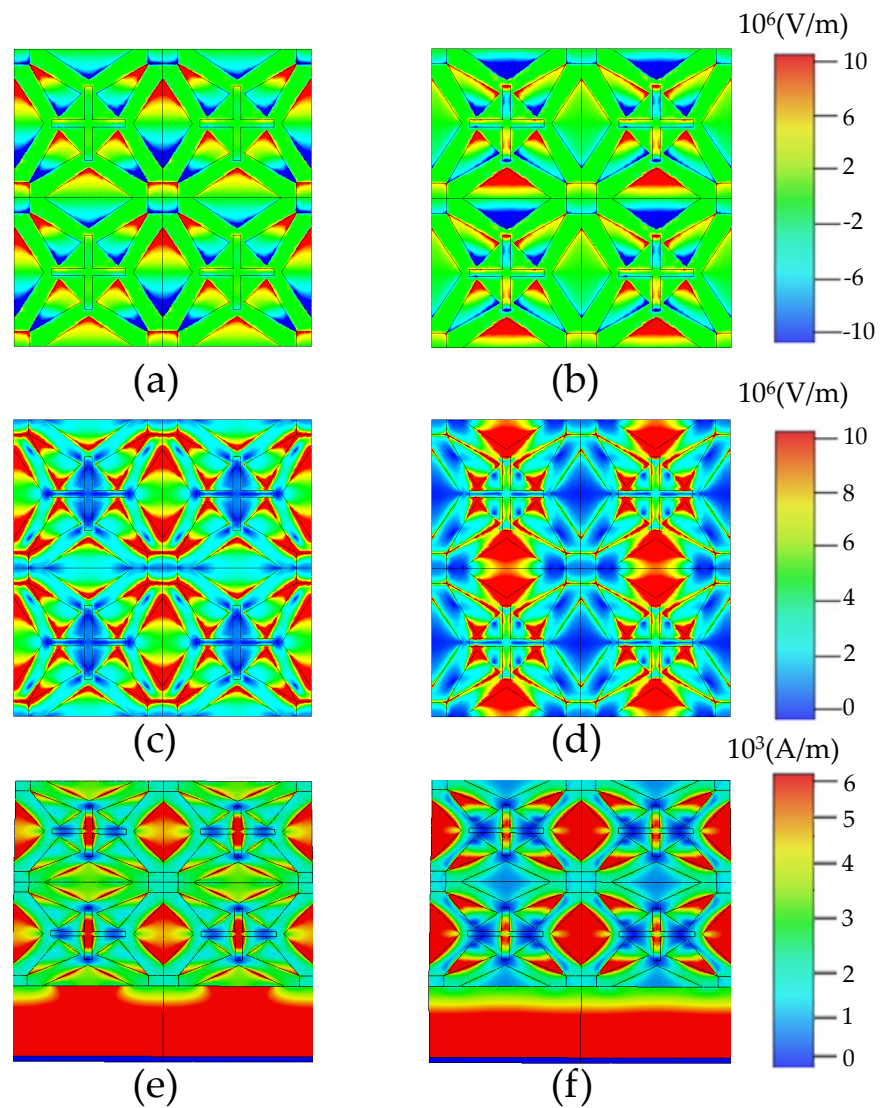


Figure 12. Z-component electric field (E_z) (a,b), electric field (E) (c,d) on the x-y plane, and magnetic field (H) (e,f) of the absorber at 5.16 THz and 6.05 THz.

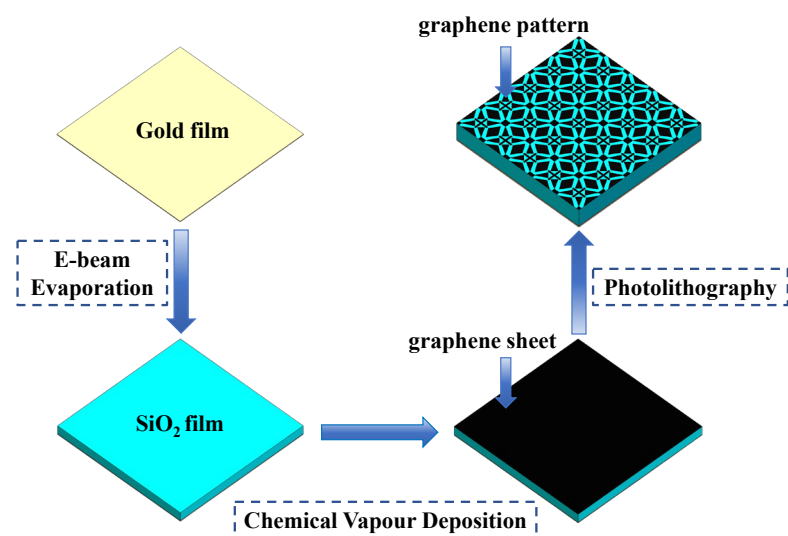


Figure 13. Preparation process diagram of the proposed metamaterial absorber.

Table 1 demonstrates that, compared to other academic literature, the absorber structure designed in this paper is relatively simple, employing only a basic three-layer configuration. It achieves a peak absorption rate of up to 99.99%, features a relatively straightforward fabrication process, and exhibits wide-bandwidth characteristics.

Table 1. Performance comparison of the tunable perfect absorbers.

Type	Maximum Absorption/%	Range of Work (≥ 0.9)	Structure Number of Layers
Multilayer graphene structure [47]	>90	1.12–3.78	5
Periodical arrays of stepped rectangle dielectric structure [48]	>90	1.6–4.2	4
Graphene-based proportional structure [49]	>99	3.1–6.97	3
Cross and an external square frame graphene [50]	99.00	1.53–2.16	3
Patterned single-layer triangular graphene (This study)	99.99	4.43–7.23	3

5. Conclusions

In this work, we present a broadband tunable graphene-based absorber operating in the THz regime. The designed graphene layer pattern can effectively excite SPR effect, thereby making its absorption rate adjustable over a broad frequency range. The designed absorber achieves a peak absorption of 99.99% at 6.05 THz and maintains over 90% absorption across a frequency range of 4.43–7.23 THz. The polarization insensitivity of the structure was verified, and the underlying mechanism for broadband absorption was investigated through the principles of effective impedance matching and electric field distributions. Excellent agreement was observed between the theoretical and simulation results. The superiority of our specific design was demonstrated by modifying the top-layer graphene patterns, while the structure's excellent tunability was confirmed by adjusting the graphene Fermi level. The absorber exhibits insensitivity to incident angles up to 60°. Additionally, by altering the structural periodicity, a modified device was simulated and shown to achieve favorable dual-band absorption characteristics within the same frequency range. The proposed structure shows potential for applications in highly sensitive sensors, detectors, optical filters, and can contribute to fields such as photoelectric detection, optical communications, and photoelectric sensing.

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Data Availability Statement: Data will be made available on request.

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