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Dual Tunable Terahertz Metamaterial Absorber Based on Graphene and VO₂ for Switchable Broadband and Triple Band Absorption

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Abstract

We propose an absorber composed of graphene and vanadium dioxide (VO₂). The phase transition of VO₂ enables dynamic switching of the absorption response between a single broadband state and three narrowband states. The results indicate that when VO₂ changes to the metallic state, the absorber exhibits triple narrow band absorption. When VO₂ is in the dielectric phase, the absorber demonstrates single broadband absorption. The absorption can be regulated through the Fermi energy level (E_F) of graphene. Furthermore, the proposed absorber exhibits polarization-independent characteristics and maintains stable absorption performance under wide-angle oblique incidence. The absorber also has high refractive index sensitivity. Impedance matching theory is employed to investigate the physical mechanism governing the absorber. The tuning principle of the device was analyzed and verified successfully by using an equivalent circuit model (ECM).

Keywords: terahertz; metamaterial; absorber; vanadium dioxide; graphene

1. Introduction

Terahertz (THz) waves are electromagnetic radiation in the frequency range of 0.1–10 THz. This band occupies the spectral region between infrared light and microwaves [1,2]. THz waves have attracted significant attention due to their unique properties, including strong penetration capability, high security in communication, and excellent signal integrity [3–5]. However, the development of THz technology is still limited by the lack of suitable natural materials. As artificially engineered media, metamaterials enable tailored electromagnetic properties through the design of subwavelength geometries and lattice configurations [6–8]. The introduction of metamaterials addresses the limited performance of conventional absorbers [9]. In particular, metamaterial perfect absorbers have attracted extensive attention in the THz regime due to their applications in imaging, sensing, and stealth technologies [10–12]. However, the performance of traditional metamaterial devices becomes fixed once fabrication is complete, resulting in limited functionality. This lack of tunability limits their applicability in scenarios requiring dynamic reconfiguration [13,14]. Consequently, achieving tunable metamaterial absorbers has become a key research focus. Therefore, various active materials, such as graphene, photoconductive semiconductors, and phase-change materials, have been widely integrated into THz absorbers [15–17].



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In recent years, VO₂ and graphene have become key materials for dynamically controlling THz waves. VO₂ enables discrete phase-transition switching behavior, whereas graphene provides continuous tunability via E_F adjustment [18–20]. In 2024, Raza et al. demonstrated a tunable multiband terahertz metamaterial absorber. When VO₂ is in the metallic state, the proposed metamaterial exhibits nearly perfect absorption at six distinct frequencies [21]. In 2026, Babu et al. reported a switchable terahertz metamaterial absorber based on VO₂. The designed absorber achieves near-perfect absorption of 99.99% at 4.667 THz with a bandwidth of 0.204 THz [22]. In 2026, Kazim et al. proposed a tunable absorber that can achieve high efficiency absorption over a broad terahertz frequency range. The structure is independent of the polarization angle and maintains perfect absorption efficiency across various incident angles [23]. In 2024, Surajit et al. demonstrated a polarization-independent graphene-based absorber. The absorber exhibits dual broadband absorption with polarization-independent performance at normal incidence, and the broadband absorption is maintained for incidence angles up to 60° [24]. In 2025, Zhang et al. proposed an absorber design based on patterned graphene, demonstrating perfect dual band absorption specifically under TE-polarized incidence [25]. In 2026, Ali et al. proposed a broadband tunable terahertz metamaterial absorber using single-layer graphene structure. The absorber achieves a broadband absorption bandwidth of nearly 2.02 THz with an absorptance exceeding 90% [26]. However, most reported studies are limited to a single tuning mechanism, which restricts the implementation of multifunctional control. Therefore, combining both materials provides a promising route toward multifunctional THz devices [27,28].

We propose a THz absorber based on graphene and VO₂ with a dual control mechanism. It is demonstrated that the proposed device can achieve switching between broadband absorption and triple band absorption within a single structure by combining the continuous tunability provided by graphene with the phase-transition behavior of VO₂. Compared with previously reported absorbers based on a single active material or one tuning mechanism, the proposed structure provides enhanced functional integration by enabling both amplitude modulation and mode switching. The absorption mechanism of the proposed absorber is also analyzed theoretically via impedance matching theory. The proposed absorber exhibits polarization-insensitive behavior and maintains stable performance under wide-angle incidence. Furthermore, the structure exhibits high sensitivity to refractive index changes in the THz range. These characteristics indicate that the device has broad application prospects in modulators, stealth technology, and optoelectronic optical switches.

2. Materials and Methods

The stacked configuration of the proposed metamaterial is illustrated in the schematic of Figure 1a. The absorber structure consists of six layers, as follows: a VO₂ patch, a SiO₂ layer, a graphene patch, a VO₂ layer, a SiO₂ layer, and a silver substrate. As shown in Figure 1b, the graphene layer is patterned into a grating array composed of five parallel strips. The top VO₂ thin film is a regular octagon. The conductivity of silver and the relative permittivity of SiO₂ are $\sigma = 6.3 \times 10^7$ S/m and $\epsilon_t = 3.9$, respectively. The thickness of the top VO₂ thin film is 0.1 μm . The geometrical dimensions given in Figure 1 are as follows: $P_x = P_y = 50$ μm , $h = 5$ μm , $h_1 = 40$ μm , $h_2 = 5$ μm , $h_3 = 40$ μm , $w = 5$ μm , $w_1 = 10$ μm , $r = 25$ μm and $l_1 = 50$ μm .

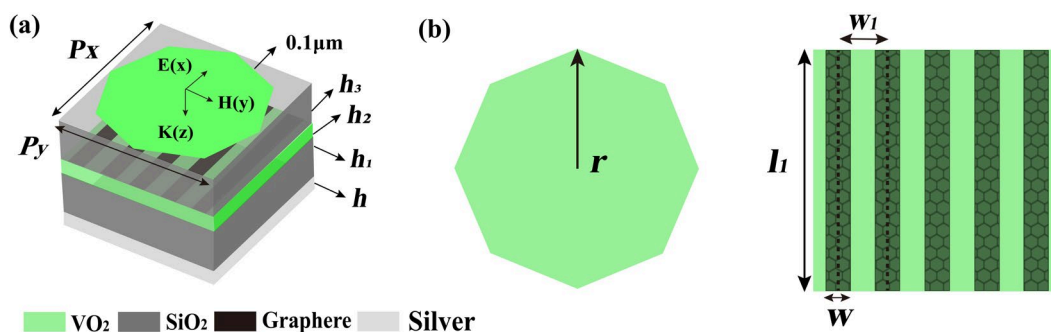


Figure 1. (a) Three-dimensional schematic for the unit of the absorber; (b) top view of the VO₂ layer and the graphene patch layer.

The surface conductivity of graphene σ_g can be described as follows [29,30]:

$$\sigma_g = \sigma_{\text{intra}} + \sigma_{\text{inter}} \quad (1)$$

where σ_{intra} and σ_{inter} correspond to the intraband and interband contributions. According to random-phase approximation theory σ_g can be expressed specifically as follows [31,32]:

$$\sigma_{\text{intra}} = \frac{2e^2 k_B T}{\pi \hbar^2} \frac{i}{\omega + i\tau^{-1}} \ln[2 \cosh(\frac{E_F}{2k_B T})] \quad (2)$$

$$\sigma_{\text{inter}} = \frac{e^2}{4\hbar} [\frac{1}{2} + \frac{1}{\pi} \arctan(\frac{\hbar\omega - 2E_F}{2k_B T}) - \frac{i}{2\pi} \ln \frac{(\hbar\omega + 2E_F)^2}{(\hbar\omega - 2E_F)^2 + 4(k_B T)^2}] \quad (3)$$

where T is the temperature, k_B is the Boltzmann constant, e is the electron charge, ω represents the wave frequency, $\hbar$ is the reduced Planck constant, τ denotes the carrier scattering time in graphene.

The Drude model is used to describe the optical properties of VO₂ in the THz band, which can be formulated as follows [33–35]:

$$\epsilon(\omega) = \epsilon_{\infty} - \frac{\omega_p^2(\sigma)}{\omega^2 + i\gamma\omega} \quad (4)$$

where $\epsilon_{\infty} = 12$ is insulating permittivity at the infinite frequency, $\omega_p(\sigma) = 1.4 \times 10^{15} \text{ rad/s}$ is plasma frequency depending on conductivity, and $\gamma = 5.75 \times 10^{13} \text{ rad/s}$ is collision frequency. The relationship of $\omega_p(\sigma_0)$ and conductivity σ is $\omega_p^2 = \omega_p^2(\sigma_0) \sigma/\sigma_0$, with $\sigma_0 = 3 \times 10^5 \text{ S/m}$. The conductivity of VO₂ is 0 S/m or $2 \times 10^5 \text{ S/m}$ when it is in the insulating or metallic phase. Figure 2a,b depict the real and imaginary components of the relative permittivity of VO₂ under various conductivity conditions.

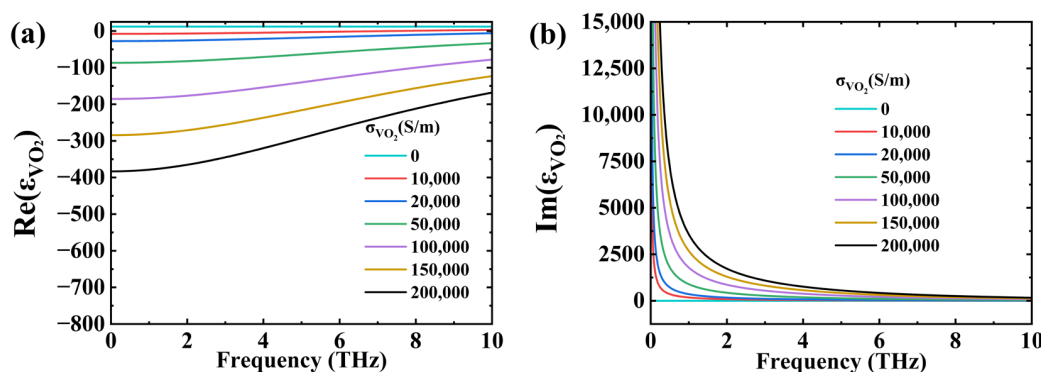


Figure 2. (a) Real parts and (b) imaginary parts of permittivity with different conductivities of VO₂.

To further investigate the modulation mechanism of the metamaterial absorber, an ECM was developed to explain the observed tunable characteristics of the proposed device. The impedance Z_{gra} of the graphene layer is related to the σ_g by the following:

$$Z_{\text{gra}} = \frac{1}{\sigma_g} \quad (5)$$

Figure 3 illustrates the equivalent circuit model of the graphene layer. Within this model, the graphene layer consisting of five parallel graphene strips is described by an equivalent series RLC circuit. The capacitance C_{gap} is introduced to describe the electric coupling between adjacent graphene strips, where strong localized electric fields are generated in the gaps. The gap capacitance between adjacent graphene strips is calculated as follows [36]:

$$C_{\text{gap}} = \frac{\epsilon_0 \epsilon_{\text{eff}} w l_1}{w_1} \quad (6)$$

$$\epsilon_{\text{eff}} = \frac{\epsilon_0 (\epsilon_1 + \epsilon_2)}{2} \quad (7)$$

where ϵ_0 is the vacuum permittivity, ϵ_{eff} is the effective dielectric constant around the graphene layer, ϵ_1 and ϵ_2 represent the permittivity of the medium on top and below the graphene layer, respectively.

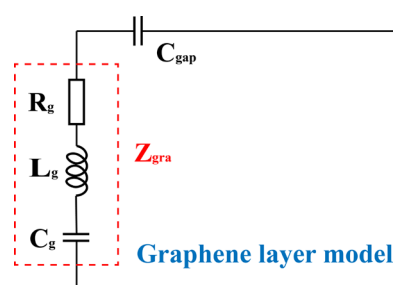


Figure 3. ECM of the graphene layer.

The impedance introduced by the gap capacitance Z_{gap} is as follows:

$$Z_{\text{gap}} = \frac{1}{j\omega C_{\text{gap}}} \quad (8)$$

From the above equation, the total impedance Z_S of the graphene layer mode is calculated as follows:

$$Z_S = Z_{\text{gra}} + Z_{\text{gap}} \quad (9)$$

The ECM of the absorber was developed based on transmission line theory, as presented in Figure 4. In this model, the configuration of the absorber is represented by a parallel RLC circuit. The graphene layer can be modeled as a series RLC circuit (Z_2), while the SiO_2 layers (Z_{d1} and Z_{d2}) are analogized to transmission lines with variable impedances (Z_1 and Z_3), where Z_{in} denotes the input impedance of the absorber system. R_g and R_v are the equivalent resistance, C_g and C_v are the distributed capacitance, and L_g is the distributed inductance. The equivalent impedance of the different parts in the absorber can be expressed as follows [37,38]:

$$Z_1 = jZ_{d1} \tan(\beta_{h1} h_1) \quad (10)$$

$$Z_2 = \frac{Z_1 \times Z_{\text{gra}}}{Z_1 + Z_{\text{gra}}} \quad (11)$$

$$Z_3 = Z_{d2} \frac{Z_2 + jZ_{d2} \tan(\beta_{h3}h_3)}{Z_{d2} + jZ_2 \tan(\beta_{h3}h_3)} \quad (12)$$

$$Z_{in} = \frac{Z_3 \times Z_{VO_2}}{Z_3 + Z_{VO_2}} \quad (13)$$

$$Z_{d1} = Z_{d2} = \frac{Z_0}{\sqrt{\epsilon_t}} \quad (14)$$

$$\beta_{h1} = \beta_{h3} = \frac{\omega \sqrt{\epsilon_t}}{c} \quad (15)$$

$$Z_{VO_2} = \frac{1}{\sigma_{VO_2}} \quad (16)$$

where β_{h_n} signifies the propagation coefficients of the incident wave within each dielectric material, Z_0 is the impedance of free space, ϵ_t is the relative permittivity of SiO₂, c is the velocity of light in vacuum, Z_{VO_2} and σ_{VO_2} represent the equivalent impedance and equivalent conductivity of the top VO₂ patch, respectively.

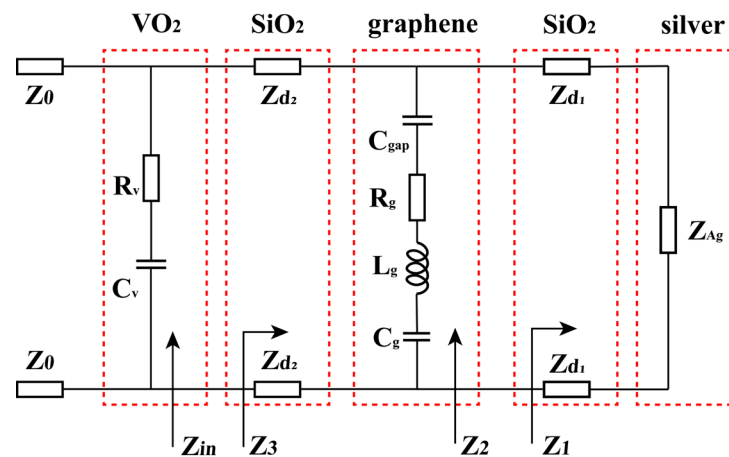


Figure 4. ECM of the designed terahertz absorber.

The performance of the designed absorber is theoretically studied by using CST Studio Suite 2024 (Dassault Systèmes, France). In the CST Microwave Studio simulations, periodic boundary conditions are applied along the x - and y -axis directions, while Floquet ports are assigned along the z -axis direction. The plane wave is set to be incident from the negative direction of the z -axis. The absorption can be measured from the S -parameters as follows: $A(\omega) = 1 - R(\omega) - T(\omega)$, where $R(\omega) = |S_{11}(\omega)|^2$ and $T(\omega) = |S_{21}(\omega)|^2$ is the reflection and transmission, and S_{11} and S_{21} represent the reflection coefficient and transmission coefficient of the THz wave from the normal incidence, respectively. Since the silver film is thick enough that the energy cannot pass through the absorber, the transmission value is equal to zero.

3. Results

As shown in Figure 5, the red, black, and green lines indicate the absorption, reflection, and transmission of the designed absorber, respectively. Figure 5a presents three well-defined absorption peaks at 1.0 THz, 2.95 THz, and 4.8 THz when the E_F of graphene is set to 1.0 eV and VO₂ is in the metallic phase. In Figure 5b, when the E_F of graphene is set to 1.0 eV while VO₂ transitions to its insulating state, a single broadband absorption response can be observed in the 0.5–1.5 THz range. Therefore, regulating the state of VO₂ enables the absorber to flexibly switch between broadband and triple narrowband absorption functions.

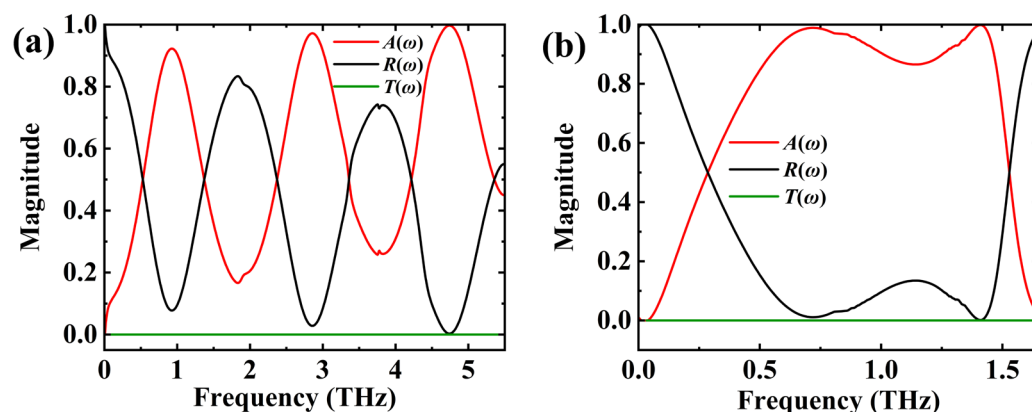


Figure 5. (a) Absorption, reflection, and transmission curves in the VO₂ metallic state and (b) VO₂ insulating state.

Figure 6 illustrates the direction and distribution of the electric field on the grating-like graphene layer. This figure investigates the mechanism behind its broadband absorption. Figure 6a,b shows that at 0.5 THz, the electric field intensity in the central region exceeds that at the edges, whereas at 1.5 THz, the edges exhibit higher intensity than the central region. The electric field vectors in Figure 6c,d exhibit opposite orientations relative to each other. This finding indicates the existence of two separate dipole resonant modes, which are excited at the center and edges of the structure, respectively. The high absorption arises from two distinct dipole resonance modes [39]. Furthermore, when VO₂ is in the insulating phase, the broadband absorption behavior can be controlled by adjusting the E_F of graphene. As shown in Figure 7a,b, at 0.5 THz the amplitude of broadband absorption can be dynamically tuned from 15% to 99% when E_F increases from 0.01 eV to 1 eV.

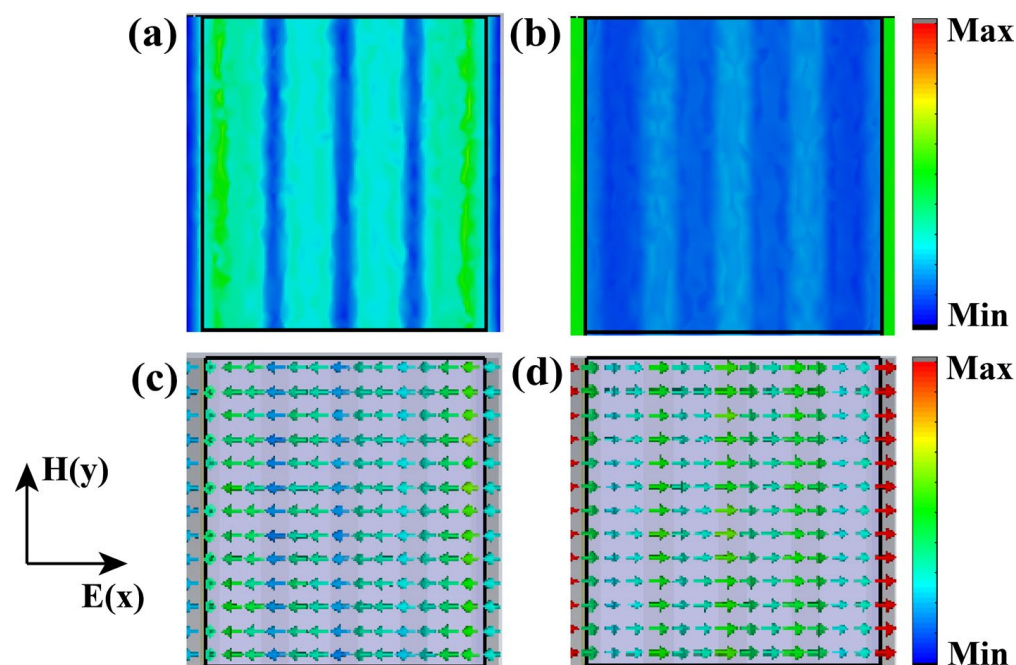


Figure 6. The electric field distribution at (a) 0.5 THz, and (b) 1.5 THz. The electric field directions at (c) 0.5 THz, and (d) 1.5 THz. The arrows indicate the direction of the electric field.

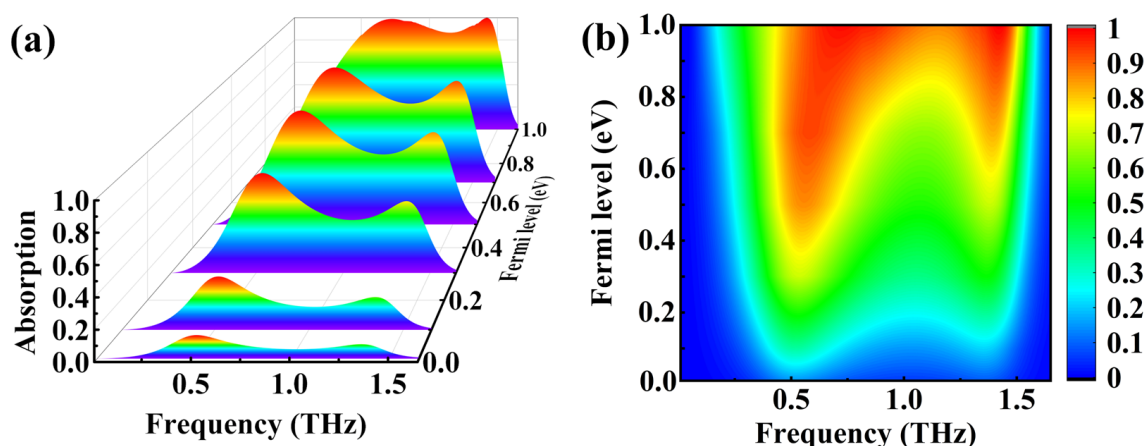


Figure 7. (a) Absorption spectra of graphene for E_F from 0.01 eV to 1 eV, (b) variation in absorption with E_F .

To identify the origin of the three narrowband absorption peaks in the metallic state of VO₂, the electric field distributions at 1.0 THz, 2.95 THz, and 4.8 THz are analyzed in Figure 8. Figure 8a,d reveal that at 1.0 THz, the enhanced electric field concentrates mainly on the four corners of the VO₂ patch. The electric field direction circulates between the gap on the top and bottom. This indicates that the narrowband absorption at 1.0 THz is caused by quadrupole resonances. Figure 8b,e depict the electric field intensity distribution on the VO₂ patch. The field intensity increases from the bottom of the patch and propagates along both sides toward the top, where it converges. This indicates that the narrowband absorption peak at 2.95 THz is attributed to the two field resonances excited within the same unit cell. The bottom-to-top vector field offers definitive evidence for the resonance mechanism. It confirms that the 2.95 THz peak is produced by two concurrent electric field resonances within the unit cell. Figure 8c,f reveals a vertically aligned electric field with a fusiform spatial profile at 4.8 THz. The electric field is directed vertically from the bottom to the top, which means that the narrowband absorption at 4.8 THz arises from the dipole resonance of electric field [40].

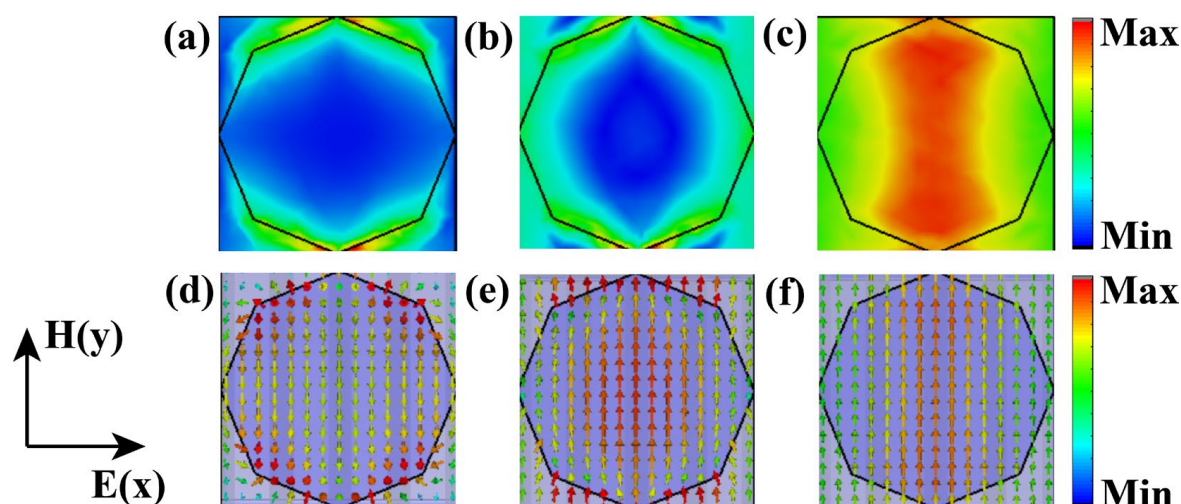


Figure 8. Electric field distribution of the triple narrowband at (a) 1.0 THz, (b) 2.95 THz, and (c) 4.8 THz, respectively. Electric field directions at (d) 1.0 THz, (e) 2.95 THz, and (f) 4.8 THz, respectively. The arrows indicate the direction of the electric field.

To gain further insight into the underlying mechanisms of the resonance modes, a multipole decomposition analysis was carried out based on the induced current distributions. The contributions of electric dipole (ED), magnetic dipole (MD), electric quadrupole (EQ), magnetic quadrupole (MQ), and toroidal dipole (TD) moments are presented in Figure 9. As depicted in Figure 9a, the 1.0 THz resonance is mainly determined by the EQ contribution, indicating that this resonance is induced by electric quadrupole excitation. As shown in Figure 9b, both ED and MD contributions exhibit strong responses at 2.95 THz, suggesting that this resonance is associated with the combined excitation of electric and magnetic dipole modes. In contrast, the resonance observed at 4.8 THz is primarily determined by the ED contribution, as shown in Figure 9c, demonstrating that this mode originates from an electric dipole excitation. Thus, the three narrow absorptions are caused by three different resonance modes of the proposed structure. The evolution of the absorption spectrum with VO₂ conductivity is shown in Figure 10. As the electrical conductivity increases, the absorptivity changes accordingly.

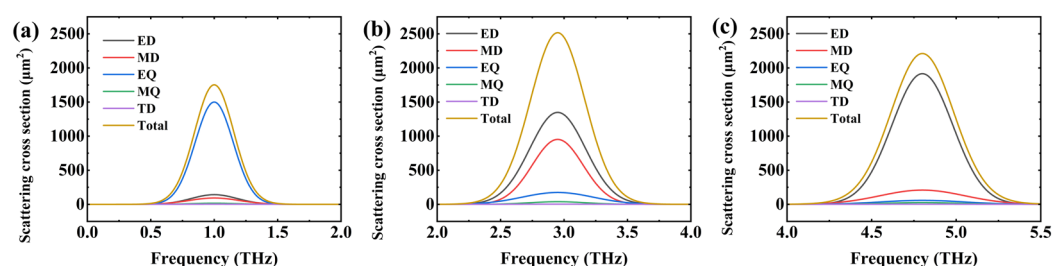


Figure 9. Multipole decomposition analysis of the proposed metamaterial absorber at the resonance frequencies of (a) 1.0 THz, (b) 2.95 THz, and (c) 4.8 THz.

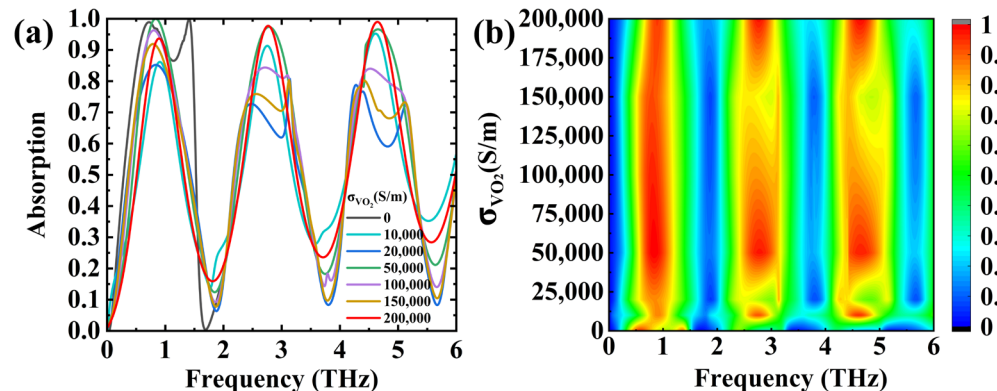


Figure 10. (a) Absorption spectrum of VO₂ increasing from 0 S/m to 200,000 S/m, (b) variation in absorption with different conductivities of VO₂.

To analyze the absorption tuning, we employ impedance matching theory, given by [41–43] as follows:

$$A(\omega) = 1 - \left| \frac{Z - Z_0}{Z + Z_0} \right|^2 = 1 - \left| \frac{Z_r - 1}{Z_r + 1} \right|^2 \quad (17)$$

$$Z_r = \sqrt{\frac{(1 + S_{11}(\omega))^2 - S_{21}(\omega)^2}{(1 - S_{11}(\omega))^2 - S_{21}(\omega)^2}} \quad (18)$$

where Z and Z_0 denote the effective impedance and the impedance of free space, respectively, and $Z_r = Z/Z_0$ represents the relative impedance between the absorber and free space.

Figure 11 presents the real and imaginary components of the relative impedance as a function of frequency. The octagonal resonator introduces multiple current pathways and equivalent LC resonant loops, which enables more flexible adjustment of the effective impedance. As a result, the impedance of the proposed absorber can be better matched to the free-space impedance over the operating frequency range, thereby suppressing reflection and enhancing the absorption performance [44]. Figure 11a,b presents the impedance responses at different values of E_F . As the E_F increases, the real part of the relative impedance gradually approaches 1, while the imaginary part approaches 0 within the frequency range of 0.5–1.5 THz. The optimal impedance matching is obtained at $E_F = 1.0$ eV. According to Equation (17), the absorption reaches its maximum at 0.5–1.5 THz. The results of the above calculations are consistent with the absorption spectra in Figure 5. Figure 11c,d depict the real and imaginary components of the relative impedance of VO₂ under various conductivity conditions. It can be observed that, when the conductivity of VO₂ increases to 200,000 S/m, the real part gradually approaches 1, while the imaginary part approaches 0. At this conductivity, the impedance of the absorber achieves good matching with that of free space. Consequently, the impedance difference between the absorber and free space is reduced, allowing the incident wave to be absorbed to the maximum extent.

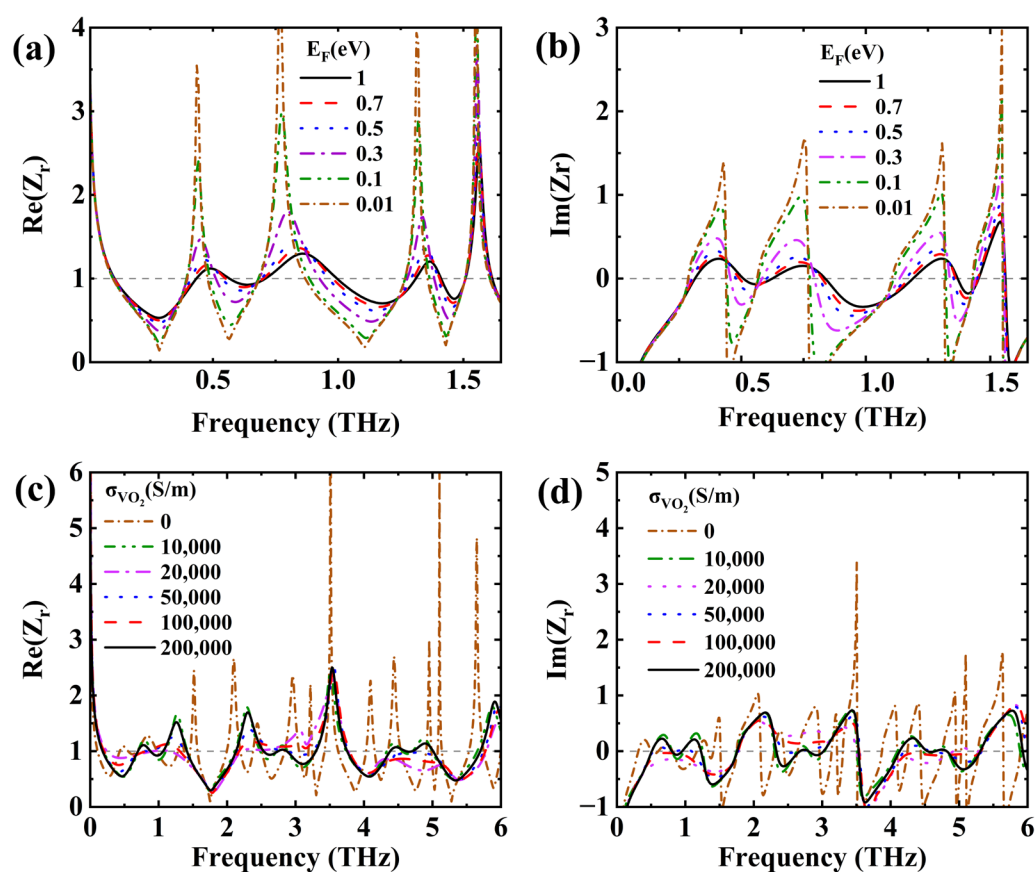


Figure 11. (a) Real parts and (b) imaginary parts for the relative impedance Z_r with different E_F of graphene. (c) Real parts and (d) imaginary parts of the relative impedance with different conductivities of VO₂.

The absorption spectra obtained via the CST microwave studio and the ECM (using MATLAB R2020, MathWorks, Natick, MA, USA) are shown in Figure 12a,b. It can be seen that the results obtained from the two approaches are highly consistent, confirming that the ECM can effectively predict the resonance characteristics of the proposed absorber.

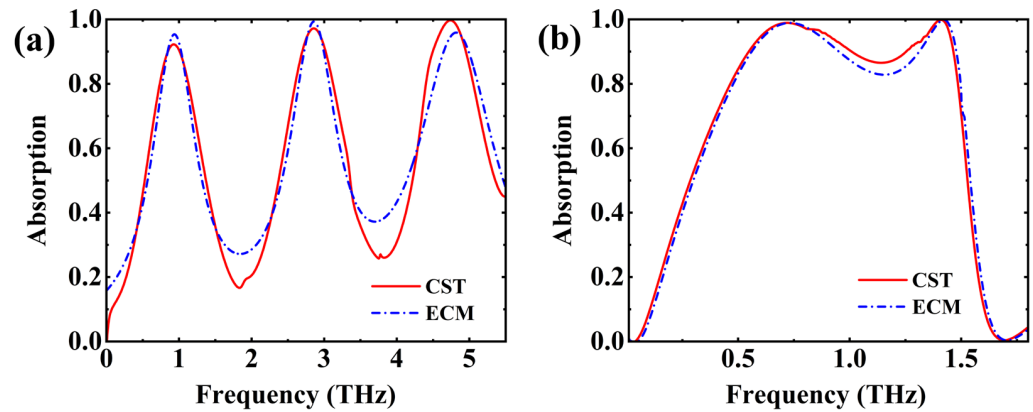


Figure 12. (a) Comparison of CST and ECM results for broadband absorption of the metamaterial absorber. (b) Comparison of CST and ECM results for triple narrowband absorption of the metamaterial absorber.

Furthermore, the angular stability of the proposed absorber is systematically investigated with respect to both polarization and incident angles. The octagonal symmetry of the structure renders the device insensitive to changes in the polarization angle and also enhances the absorption stability at oblique incidence [44]. Figure 13a,d show the absorption responses of the single broadband and triple narrowband states under various polarization angles. The results indicate that the absorption remains nearly constant with increasing polarization angle. This behavior is attributed to the symmetry of the unit cell, which ensures polarization-insensitive performance. Figure 13b,c illustrate the absorption behavior of the single broadband state under TE and TM polarizations, respectively, for different incident angles. The absorber maintains strong absorption up to an incident angle of 80° . Similarly, Figure 13e,f illustrate the angular response of the triple narrowband state under TE and TM incidences. High absorption is preserved for incident angles up to 60° , particularly in the low frequency regime. These results demonstrate that the proposed structure exhibits robust angular stability for both broadband and narrowband operation modes.

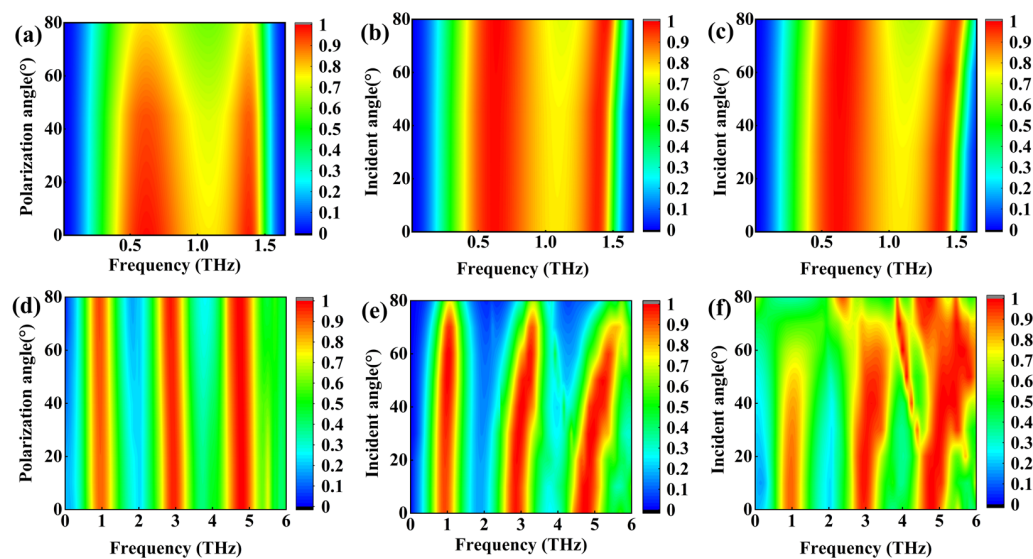


Figure 13. (a) Single broadband absorption spectrum with changing plane wave polarization angle. (b) TE and (c) TM polarization with single broadband absorption at different incidence angles. (d) Triple narrowband absorption spectrum with changing plane wave polarization angle. (e) TE and (f) TM polarization with triple narrowband absorption at different incidence angles.

As illustrated in Figure 14a, the absorption peak shifts as the refractive index of the sensing medium increases from 1 to 1.8 with an interval of 0.2. Figure 14b presents the variation in absorptivity with different refractive indices. Figure 14c demonstrates that the central frequency of the absorption peak gradually red-shifts with increasing refractive index of the sensing medium. For THz sensors, the sensitivity (S) and figure of merit (FOM) are the main factors in testing the value of the sensor for practical applications. The sensitivity is measured as the shift in absorption frequency ($\Delta n = n_2 - n_1$) as the refractive index of the sensing medium changes from n_1 to n_2 [45]. The FOM can be calculated by $FOM = S/FWHM$. We obtain that the refractive index sensitivities of the three are $S_I = 43.5$ GHz/RIU, $S_{II} = 84$ GHz/RIU, and $S_{III} = 66$ GHz/RIU, respectively. After calculation, the FOM values of the three narrowband absorption peaks are determined to be 0.06, 0.11, and 0.07, respectively. These results indicate that the proposed device exhibits high sensitivity to variations in the refractive index of the sensing medium in the THz region. Thus, the structure has promising applications in the field of THz devices.

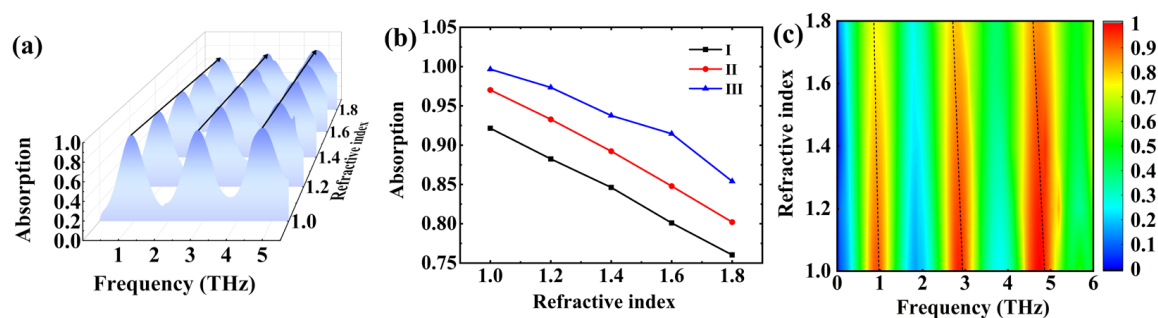


Figure 14. (a) Absorption spectra of the designed absorber at different values of refractive index. (b) The variation in the absorption with respect to the refractive index. (c) The variation in absorption frequency with refractive index.

In the broadband absorption mode, the proposed absorber achieves a modulation depth of 80%, outperforming previously reported designs, including 19% [46], 70% [47], and 50% [48], respectively. The absorber achieves a maximum absorption of 99%, which exceeds the previously reported value of 90%. Improvements are also observed in polarization insensitivity and wide-angle incidence characteristics.

In the narrowband absorption regime, prior studies typically exhibit one or two resonant peaks [49–51], whereas the present design realizes three distinct absorption peaks. In addition, the absorptivity remains stable under polarization angles up to 80° and incident angles up to 60° . A comprehensive comparison with previous absorbers is provided in Tables 1 and 2, highlighting the advantages of the proposed structure in terms of modulation depth, number of resonance modes, polarization insensitivity, and angular stability.

Table 1. Contrasting the broadband absorption properties of multiple absorber types.

Reference	Absorption Bandwidth	Tunable Range	Function	Oblique Incidence (TE/TM)	Polarization Angle
[46]	0.5–1.6	76–95%	Broadband absorption	Not given	Not given
[47]	1.1–2.3	20–90%	Broadband absorption	60°	60°
[48]	1.05–2.35	40–90%	Broadband absorption	Not given	Not given
This work	0.5–1.5	15–99%	Broadband absorption	80°	80°

Table 2. Contrasting the narrowband absorption properties of multiple absorber types.

Reference	Absorption Bandwidth	Absorptance	Function	Oblique Incidence (TE/TM)	Polarization Angle
[49]	0.69	100%	Single narrowband absorption	70°	45°
[50]	0.61, 1.68	98%, 99%	Dual narrowband absorption	Not given	Not given
[51]	0.4, 1	94.5%, 96.3%	Dual narrowband absorption	50°	Not given
This work	1.0, 2.95, 4.8	93%, 98%, 100%	Triple narrowband absorption	80°/60°	80°

In order to provide a guideline for future fabrication, we simply describe the manufacturing process of the absorber. A silver film with a thickness of about 5 μm can be grown by the thermal evaporation method. The SiO_2 layer and VO_2 layer were deposited by magnetron sputtering. Monolayer graphene is deposited on the VO_2 layers through chemical vapor deposition, followed by the fabrication of patterned arrays using UV lithography and plasma etching. The process for preparing the SiO_2 layer on graphene is the same as that employed for SiO_2 layer formation. The top VO_2 film is formed by using standard UV lithography.

4. Conclusions

In summary, we propose a tunable metamaterial THz absorber based on VO_2 and graphene. The results reveal that the device can reversibly switch between broadband and triple-narrowband absorption states by controlling the phase transition of VO_2 . In the metallic state, three distinct absorption peaks are observed at 1.0 THz, 2.95 THz, and 4.8 THz. In the insulating state, a broadband absorption response is achieved in the range of 0.5–1.5 THz. In addition, the broadband absorption amplitude can be continuously tuned by adjusting the E_F of graphene. The absorption and tuning mechanisms of the absorber are analyzed by employing impedance matching theory. It exhibits stable performance under wide-angle incidence and remains insensitive to polarization. The structure has sensitivity of 43.5 GHz/RIU, 84 GHz/RIU, and 66 GHz/RIU for detecting refractive index changes in the THz range at narrowband absorption. This research provides a feasible strategy for designing multifunctional THz absorbers and shows broad application prospects in modulators, stealth technology, and optoelectronic optical switches.

Although this work mainly focuses on the theoretical design and numerical investigation of the proposed absorber, the multilayer structure is compatible with existing micro/nanofabrication technologies, including chemical vapor deposition for graphene transfer, magnetron sputtering for VO_2 thin films, and standard photolithography for pattern fabrication. The experimental fabrication and characterization of the proposed device will be conducted in future work to further validate the theoretical predictions.

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