

Article

Ultra-Broadband Terahertz Metamaterial Absorber Utilizing High-Efficiency Absorbing Materials

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Abstract

We propose a dual-band/broadband terahertz (THz) metamaterial absorber based on a simple vanadium dioxide (VO₂) design. The absorber achieves high absorption (>90%) within two frequency bands: 4.5–6.8 THz and 10.98–12.54 THz at a VO₂ conductivity of 2×10^5 S/m, while broadband absorption of 8.2 THz can be achieved at a VO₂ conductivity of 1.5×10^5 S/m. By tuning the VO₂ conductivity, absorption can be continuously adjusted from 20% to over 90%. Furthermore, the absorber exhibits polarization insensitivity and maintains high performance over a wide range of incident angles. The dual-band/broadband absorption mechanism is analyzed through electric field distributions, providing deeper insights into its operation. This work presents a promising approach for developing tunable and broadband THz absorbers.

Keywords: metamaterial; perfect absorber; THz; dual-broad band; vanadium dioxide

1. Introduction

The terahertz (THz) frequency range (0.1–10 THz), situated between the microwave and optical regions, remains one of the least developed spectral bands due to the scarcity of natural materials exhibiting strong THz responses. However, the emergence of metamaterials has revolutionized THz device development, enabling the realization of functional components such as absorbers, antennas, filters, and switches. Among these, THz metamaterial absorbers (MMAs) have attracted significant attention for applications in imaging, sensing, and detection [1–10].

Traditional MMAs often suffer from inherently narrow bandwidths due to strong electromagnetic resonance at specific frequencies, limiting their practical utility. To overcome this limitation, researchers have explored two primary approaches for bandwidth expansion: (1) integrating multiple resonators with varying dimensions into a coplanar structure [11–17] and (2) vertically stacking multiple metallic layers [18–26]. However, the first approach increases the unit cell size, hindering miniaturization, while the second presents fabrication challenges due to the complexity of multilayer structures. Consequently, considerable efforts have been directed toward designing broadband MMAs with simplified resonant structures [27–33]. Despite these advancements, most broadband MMAs lack tunability, as their absorption characteristics remain fixed after fabrication. For practical applications, tunable broadband absorption is highly desirable, posing a sig-

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nificant challenge in designing MMAs with both wide tunability and structural simplicity [34,35].

Recently, tunable phase-transition materials, such as vanadium dioxide (VO₂), have emerged as promising candidates to address these challenges. For instance, Liu et al. [36] developed a dynamically tunable broadband THz absorber using a hybrid VO₂-based metamaterial, achieving a 1.0 THz absorption bandwidth with tunable absorption ranging from 3% to over 90%. Gandhi et al. [37] proposed a VO₂-based metasurface absorber with a circular and cross-shaped geometry, demonstrating absorption exceeding 90% over the 2.54–5.54 THz range, with continuously adjustable absorption from 10% to nearly 100%. Kwang-Jin RI [27] introduced a simplified ultra-broadband MMA design with over 90% absorption in the 2.65–6.76 THz range and above 80% absorption at incident angles up to 40°. Field and current analyses revealed the absorption mechanism, and the ultra-thin, broadband design proved adaptable to other frequency ranges, including microwaves. Wang et al. [38] designed an ultra-broadband absorber using hexagonal VO₂ patches, achieving absorption above 90% from 3.5 to 8 THz. Additionally, Jiao et al. explored similar tunable absorber designs. He et al. (2026) [39] built a mechanically tunable metasurface for broadband camouflage—by shifting the vertical displacement of a slotted structure, they could adjust reflectivity across 2.7 to 19.1 GHz, a 150% fractional bandwidth. That is about as extreme as structural actuation gets for tunable absorption. The other work [40] took a different route, integrating graphene into a THz absorber and tuning its resonances by adjusting the graphene's conductivity with an applied bias; changing the voltage let them continuously shift both the resonance frequency and the absorption amplitude.

To address these challenges, we propose an enhanced dual-band/broadband THz metamaterial absorber using a simple VO₂ resonator. This design features a significantly simplified structure, facilitating easier fabrication. By incorporating the VO₂ resonator within the dielectric layer, oxidation and deformation are effectively mitigated, ensuring stable absorption performance. The proposed absorber achieves high absorption (>90%) within two frequency bands: 4.5–6.8 THz and 10.98–12.54 THz at a VO₂ conductivity of 2×10^5 S/m, while broadband absorption of 8.2 THz is realized at a VO₂ conductivity of 1.5×10^5 S/m. Furthermore, the absorber maintains stable absorption across a wide range of incident angles. The underlying physical mechanism of dual-band/broadband absorption is analyzed using H-field distributions and surface current analysis, while the influence of geometric parameters on absorption performance is systematically examined. Given its simple structure, tunable broadband characteristics, polarization insensitivity, and wide-angle stability, the proposed absorber holds great potential for applications in filters, modulators, detectors, and sensors.

2. Design and Simulation

The design of a metamaterial absorber requires careful selection of structural parameters, including dimensions, shape, and resonator configuration. Previous research has proposed a tunable THz metamaterial absorber incorporating a ring-shaped resonator [38]. Additionally, Chen et al. [41] suggested that a complementary graphene structure could be an effective approach for tunable absorbers. Inspired by these studies, we developed a simplified design using a VO₂ resonator with a meandered structure.

Figure 1 illustrates the unit cell of the proposed dual-band/broadband tunable metamaterial absorber, which consists of a VO₂ resonator embedded in SiO₂, with a gold ground plane at the bottom. The gold layer has a thickness of $T_1 = 0.5 \mu\text{m}$ and a conductivity of $\sigma = 4.561 \times 10^7$ S/m. The silicon dioxide (SiO₂) layers have a thickness of $T_2 = 6 \mu\text{m}$, with a dielectric constant of $\varepsilon = 3.8$ [42]. The VO₂ resonator has a thickness of $T_3 = 0.2 \mu\text{m}$, and its permittivity is described using the Drude model [43]:

$$\varepsilon(\omega) = \varepsilon_{\infty} - \frac{\omega_p^2(\sigma)}{\omega^2 + i\gamma\omega} \quad (1)$$

where $\varepsilon_{\infty} = 12$ represents the permittivity at infinite frequency, and $\gamma = 5.75 \times 10^{13}$ rad/s denotes the collision frequency. The plasma frequency is given by:

$$\omega_p^2(\sigma) = \frac{\sigma_v \sigma_0}{\sigma_0} \omega_p^2(\sigma_0) \quad (2)$$

where $\sigma_0 = 3 \times 10^5$ S/m and $\omega_p^2(\sigma_0) = 1.4 \times 10^{15}$ rad/s. The conductivity of VO₂ varies with temperature, measured as 2×10^5 S/m at $T = 350$ K and 200 S/m at $T = 300$ K [44].

In particular, VO₂ is insulating below about 68 °C and metallic above it, and that switch comes with a huge jump in electrical conductivity—roughly four to five orders of magnitude. To make the tuning more concrete: this phase change is not limited to temperature alone. In practice, people switch VO₂ several ways—heating it directly with a heater or a thermal pulse, or hitting it with light or an electric field to push it through the transition. Liu et al. [36], for instance, found that electrical, optical, and thermal stimulation can all drive that same multi-order-of-magnitude jump in conductivity. We have added specific numbers here (roughly 200 to 200,000 S/m), so it is clear which conductivity range lines up with which phase, and what actually triggers the switch between them.

The unit cell has a periodic length of $P = 25$ μm , and the geometric parameters of the VO₂ resonator are $L = 22$ μm , $r = 5.5$ μm , and $r_c = 3$ μm .

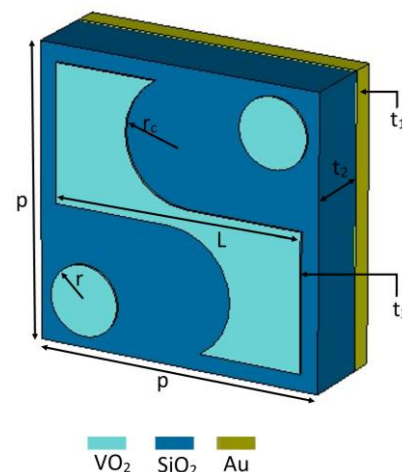


Figure 1. Perspective view of the unit cell structure of schematic diagram of the unit cell structure for tunable dual-broadband/broadband THz.

To analyze the absorption performance, we conducted numerical simulations using CST Microwave Studio, employing the frequency-domain solver. Periodic boundary conditions were applied along the X- and Y-directions, while an open boundary condition (add space) was set along the Z-direction. The incident electromagnetic waves were classified into transverse electric (TE) and transverse magnetic (TM) waves. In the TE mode, the electric field aligns with the Y-axis, and the magnetic field aligns with the X-axis, whereas in the TM mode, the electric field aligns with the X-axis, and the magnetic field aligns with the Y-axis [44].

The absorptivity $A(\omega)$ of the metamaterial absorber is calculated as:

$$A(\omega) = 1 - |S_{11}(\omega)|^2 - |S_{21}(\omega)|^2 \quad (3)$$

where $|S_{11}(\omega)|^2$ and $|S_{21}(\omega)|^2$ correspond to the reflection and transmission coefficients, respectively. Since the metallic ground plane prevents wave transmission as explained by [3,9] ($|S_{21}(\omega)|^2 \approx 0$), the absorption simplifies to:

$$A(\omega) \approx 1 - |S_{11}(\omega)|^2 \quad (4)$$

This formulation allows for precise characterization of the absorber's performance.

3. Results

Figure 2: Evolution of the wideband metamaterial absorber through a four-step iterative design process and the corresponding absorption spectra. Design 1 (red): A single square ($L \times L$) exhibits narrow absorption peaks at 2.51 THz and 10.24 THz. Design 2 (green): Two overlapping squares ($L/2 \times L/2$) enhance the bandwidth to 4.4–7.47 THz and 11.5–14 THz. Design 3 (blue): Partial cuts on opposite edges reduce the bandwidth but retain dual absorption bands. Design 4 (orange): Adding diagonal circular elements significantly broadens the absorption to 8.21 THz (from 4.4 THz to 12.61 THz) with five distinct absorption peaks. The tunability of the absorber was further investigated by varying the conductivity of vanadium dioxide (VO_2), which is temperature-dependent.

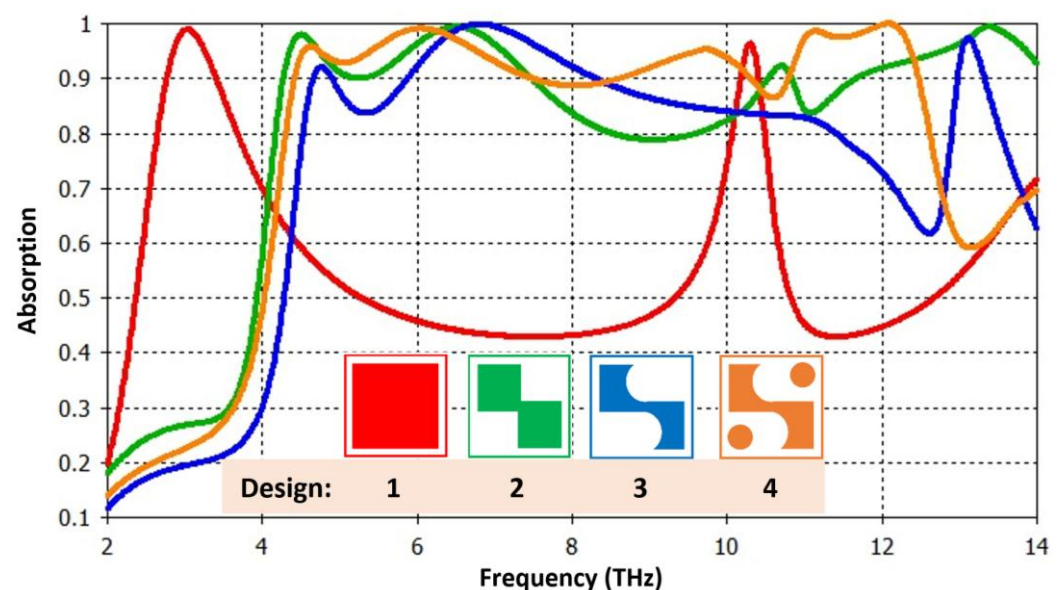


Figure 2. Iterative design evolution of the wideband metamaterial absorber and corresponding absorption spectra, demonstrating progressive bandwidth enhancement through structural modifications.

Figure 3 comprehensively illustrates the impact of structural and material parameters on the performance of the proposed wideband metamaterial absorber. Figure 3 demonstrates the effect of VO_2 conductivity (σ) on absorption, revealing that increasing σ from 100 S/m to 2×10^5 S/m significantly enhances absorption, with the highest performance observed at $\sigma = 1.5 \times 10^5$ S/m, where absorption exceeds 90%. As shown in Figure 3, when VO_2 conductivity increases from 100 S/m to 2×10^5 S/m, absorption can be continuously tuned from 20% to over 90%, while the central absorption frequencies remain unchanged. Optimal absorption is achieved at a VO_2 conductivity of 1.5×10^5 S/m, exceeding 90%.

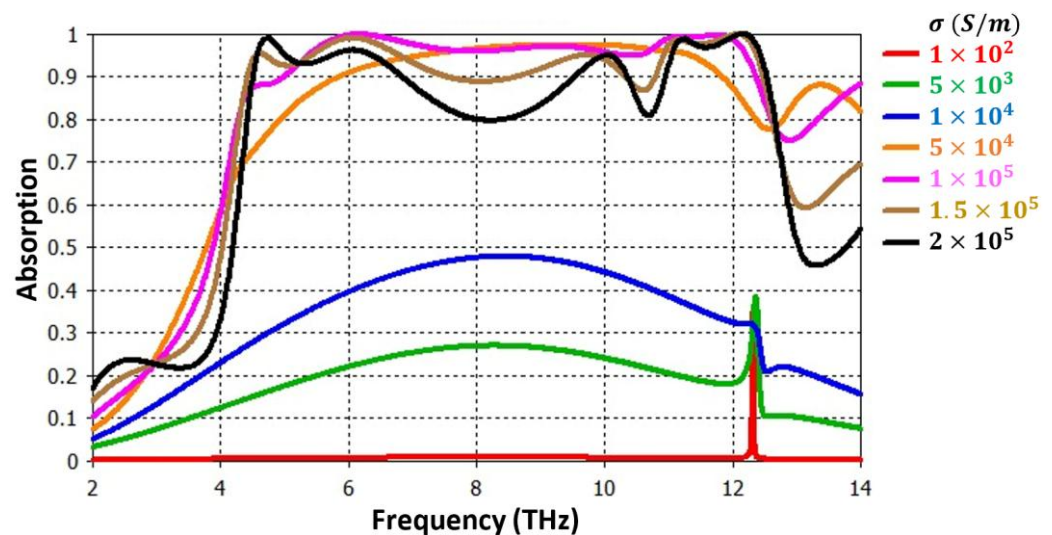


Figure 3. Effect of VO₂ conductivity on the absorption performance of the wideband metamaterial absorber.

Figure 4 explores the effect of the dielectric layer thickness (h) on absorption, showing that increasing h from 4 μm to 8 μm adjusts the absorption intensity and slightly shifts the peak positions, emphasizing the critical role of thickness in enhancing absorption properties. A thicker dielectric layer tends to redshift the resonance frequencies due to the increased optical path length, which in turn affects the impedance matching between free space and the metamaterial structure.

A thicker dielectric layer lengthens the effective optical path between the resonator and the metallic ground plane. That changes the equivalent inductance and capacitance of the resonant structure, so the resonance frequencies shift gradually lower. It also alters the impedance matching between the absorber and free space, which shows up as real changes in both absorption bandwidth and magnitude.

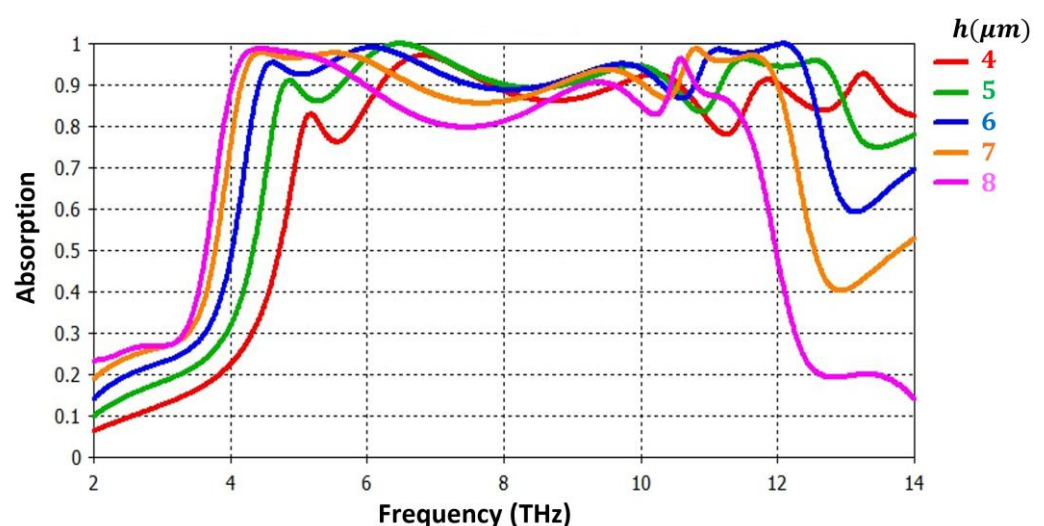


Figure 4. Effect of dielectric layer thickness (h) on the absorption performance.

Figure 5 examines the impact of resonator length (L) on the absorption spectrum, where varying L from 18 μm to 26 μm changes the peak positions and bandwidth, with optimal absorption at $L = 22$ microns. This indicates that fine-tuning the resonator dimensions directly influences the coupling efficiency between the incident Terahertz waves and the metamaterial structure, enhancing the wideband absorption. Resonator length sets the effective current path the incident wave excites. A longer resonator means a longer elec-

trical path, which—by the LC resonance principle—pulls the resonant frequency down; shorter resonators push it up. Getting the resonator length right matters for both broad-band absorption and absorption efficiency.

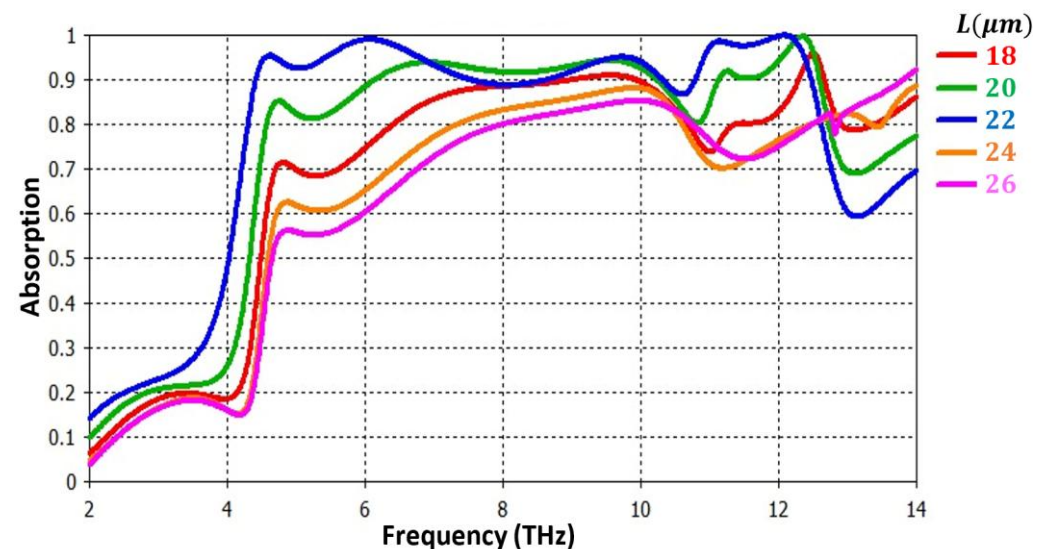


Figure 5. Effect of resonator length (L) on the absorption spectrum.

Furthermore, Figure 6 investigates the effect of unit cell periodicity (p) on absorption, revealing that increasing p from 25 μm to 40 μm shifts the absorption peaks and modifies the overall absorption efficiency. A larger periodicity leads to a broader absorption range, attributed to the interaction between adjacent unit cells and the resulting collective resonance effects. Unit-cell periodicity controls the electromagnetic coupling between neighboring resonators: increase it and the near-field interaction weakens; decrease it and mutual coupling strengthens. Those coupling changes feed into the collective resonant behavior, which shifts the impedance matching condition, resonance bandwidth, and overall absorption performance. So periodicity needs careful tuning to strike the right balance between resonance coupling and broadband absorption.

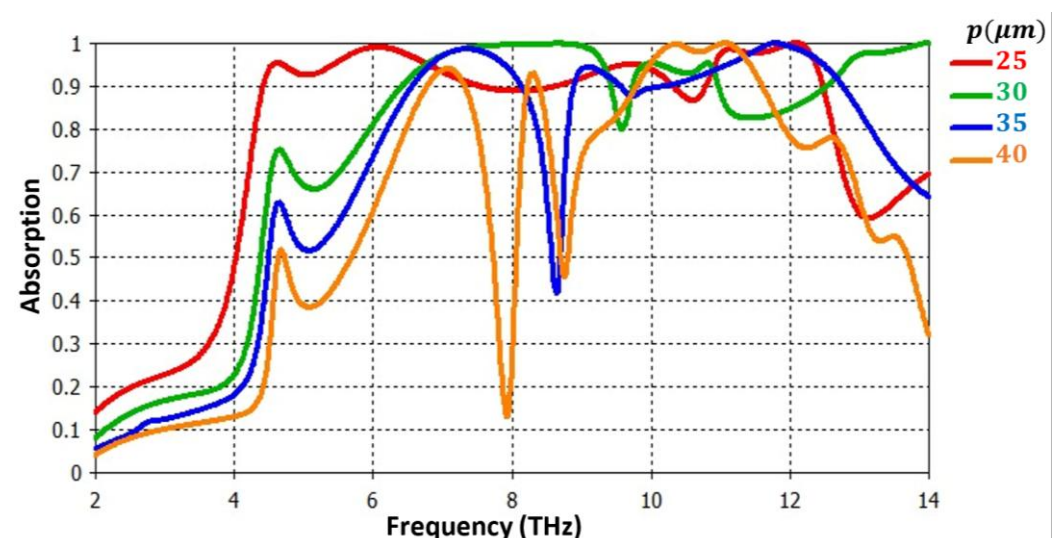


Figure 6. Effect of unit cell periodicity (p) on the absorption performance.

These results collectively highlight that both material properties and geometric parameters must be carefully optimized to achieve high absorptivity over a broad frequency range. The interplay between the structural design and the material response of VO_2 ena-

bles precise control over absorption characteristics, making the proposed absorber highly suitable for adaptive terahertz applications, including imaging, sensing, and stealth technology. The ability to dynamically tune the absorption response through external stimuli, such as temperature variations, further enhances its potential in reconfigurable and smart electromagnetic devices.

These trends make sense through resonance and impedance matching. As VO₂ conductivity rises, it drives stronger surface currents, which strengthen the electric and magnetic resonances and bring the absorber closer to impedance matching with free space—so less power reflects back, and absorptivity goes up. Dielectric thickness works on the propagation path: a thicker layer lengthens it and shifts the equivalent inductance and capacitance of the resonant structure, which pushes the resonance frequencies lower. Resonator dimensions mainly change the effective current path length, so they shift the resonance condition and the absorption bandwidth. And adjusting the unit-cell periodicity changes the near-field coupling between neighboring resonators, which feeds back into both the collective resonant behavior and the impedance matching. Put together, the broadband absorption comes from tuning resonator geometry, dielectric properties, and VO₂ conductivity in tandem—each pulling in resonances from a different angle and pushing the overall impedance match across a wider band. The surface current distributions (Figure 7) and magnetic-field distributions (Figure 8) explain where these absorption peaks come from. At each resonant frequency, the incident wave excites localized currents on the VO₂ resonator, and opposite currents form on the metallic ground plane at the same time. Those anti-parallel currents set up current loops, which build strong localized magnetic fields inside the dielectric spacer—the signature of magnetic resonance, and the main reason reflection gets suppressed through impedance matching with free space. At the lower-frequency resonance, the surface currents mostly circulate around the outer sections of the resonator, forming fairly large loops. These loops raise the structure's effective inductance, while the narrow gaps between adjacent metallic regions add capacitive coupling—so this resonance behaves as an LC resonance, with the frequency set by the resonator's equivalent inductance and capacitance. Figure 8 backs this up: the magnetic field is tightly localized within the dielectric layer, just as this mechanism would predict. Push the frequency higher and the current shifts toward the corners, narrow gaps, and inner edges of the resonator. Opposite charges pile up at these spots and form localized electric dipoles, while the anti-parallel currents between resonator and ground plane produce magnetic dipoles alongside them. With electric and magnetic resonances both present, impedance matching improves sharply and absorption climbs with it. At the highest resonance, the current pattern breaks up further, with several localized loops scattered across different sections of the resonator. These higher-order paths create multiple localized magnetic hot spots (again visible in Figure 8), pointing to higher-order resonant modes. Coupling between these modes is what stretches the absorption spectrum out and produces the ultra-broadband response. Other work on broadband terahertz metamaterial absorbers built from combined LC and dipolar resonances shows the same kind of evolution. So the broadband absorption is not coming from one resonance doing all the work—it is the superposition and coupling of several mechanisms: LC resonance, electric dipole resonance, magnetic dipole resonance, and higher-order localized resonances. Together they give broadband impedance matching with free space, which is what keeps reflection down and absorption high across the band.

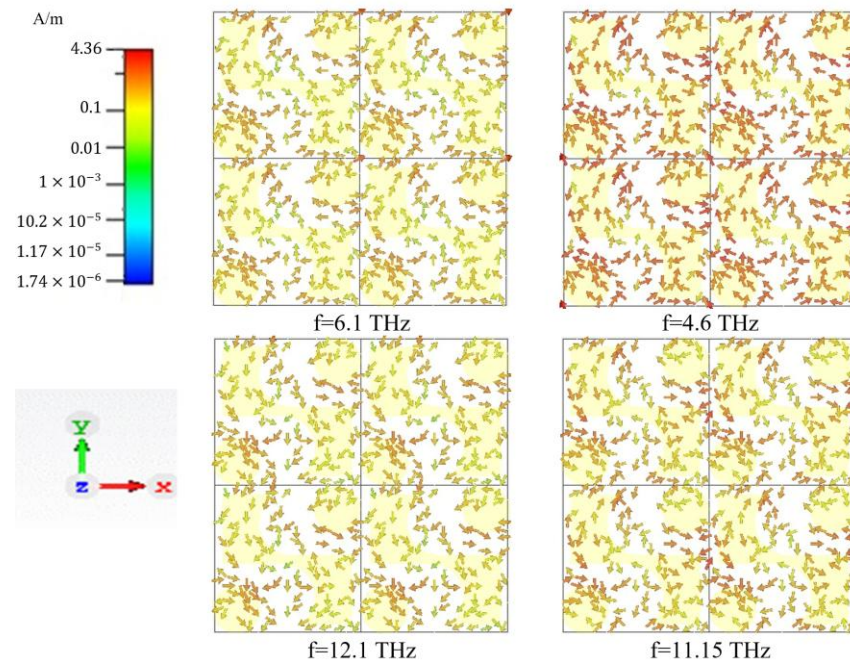


Figure 7. Absorption mechanism analysis of the metamaterial absorber through surface current distributions at different resonant frequencies.

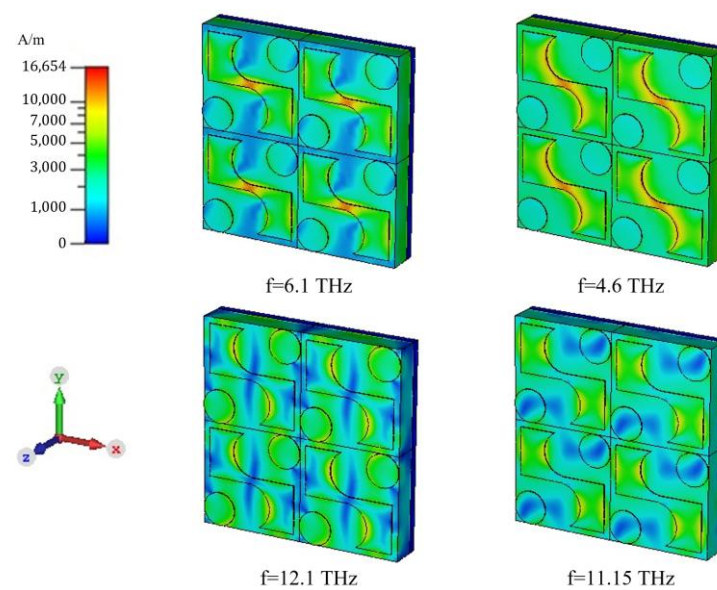


Figure 8. Absorption mechanism analysis of the metamaterial absorber through magnetic field distributions at different resonant frequencies.

The metamaterial unit cell exhibits mu-negative (MNG) properties within the X-band and C-band frequency ranges. The material properties were analyzed through simulations under Z-axis field excitation, revealing unique electromagnetic characteristics. The metamaterial properties of the unit cell can be derived by computing the reflection (S_{11}) and transmission (S_{21}) coefficients, which serve as the foundation for extracting effective permittivity, permeability, impedance, and refractive index. These properties can be determined using the following equations [45]:

$$\varepsilon = \frac{n}{Z} \quad (5)$$

$$\mu = nz \quad (6)$$

$$\eta = \frac{1}{kd} \cos^{-1} \left[\frac{1}{2S_{21}} (1 - S_{11}^2 + S_{11}^2) \right] \quad (7)$$

$$z = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \quad (8)$$

where

- ε is the effective permittivity;
- μ is the effective permeability;
- η represents the propagation constant;
- z is the impedance;
- kd is the wave propagation constant;
- S_{11} and S_{21} are the scattering parameters obtained from simulations.

Figure 9a shows the frequency-dependent permittivity curve, indicating a positive real permittivity in the transverse electromagnetic (TEM) mode at the resonant frequencies within the absorption range. This confirms the dielectric nature of the material at these specific frequencies. Additionally, Figure 9b shows the effective permeability, displaying negative values at the resonant frequencies, consistent with the behavior of the MNG metamaterial. To accurately extract these metamaterial properties, the Nicolson–Ross–Weir (NRW) method [4] was used. This technique derives the actual electromagnetic properties by using the S-parameter data obtained from CST simulations. Subsequent data processing ensures precise determination of the material parameters, which are crucial for validating the absorber's performance, transmission, and resonance behavior. These results highlight the potential applications of the designed material in areas such as wave manipulation, radar absorption, and electromagnetic shielding, where engineered material responses play a critical role in controlling wave propagation at specific frequencies.

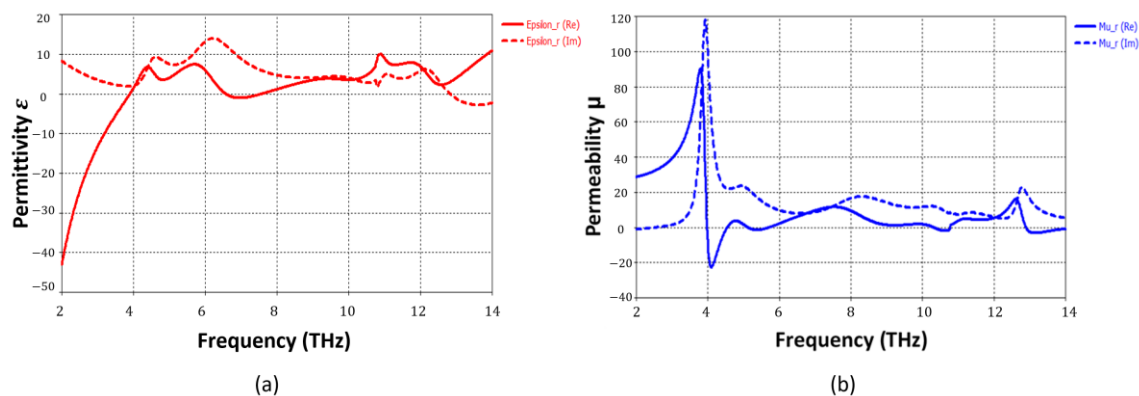


Figure 9. Electromagnetic properties of the proposed material: (a) frequency-dependent permittivity curve, indicating positive real permittivity in the transverse electromagnetic (TEM) mode at resonant frequencies, and (b) effective permeability showing negative values at resonant frequencies, consistent with MNG metamaterial behavior.

4. Conclusions

In conclusion, the proposed dual-band/broadband THz absorber, based on the simple vanadium dioxide (VO₂) design, demonstrates significant potential for a wide range of applications. The absorber achieves high absorption efficiency (>90%) within two distinct bands, 4.5–6.8 THz and 10.98–12.54 THz, and provides broadband absorption of 8.2 THz by tuning the VO₂ conductivity. This tunability allows for continuous control of absorption from 20% to over 90%. Furthermore, the absorber exhibits excellent polarization insensitivity and consistent performance across a wide range of incident angles. The ab-

sorption mechanism, clarified through electric field distributions, provides valuable insights into the operation of the device. Overall, this work presents a promising approach for the development of tunable THz absorbers, with applications in wave manipulation, radar absorption, and electromagnetic shielding.

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Abbreviations

The following abbreviations are used in this manuscript:

VO ₂	Vanadium Dioxide
MM	Metamaterial
THz	Terahertz
MMAs	Metamaterial Absorbers
TE	Transverse Electric
TM	Transverse Magnetic

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