



REGULAR ARTICLE

A Thermally Controlled Tri-Band Metamaterial Perfect Absorber based on Vanadium Dioxide (VO₂) for Terahertz Communication Application

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This article proposes a terahertz metamaterial absorber that uses the phase transition features of vanadium dioxide (VO₂) to achieve broadband characteristics. This paper presents an innovative design for terahertz absorbers that is thinner, has a wider bandwidth, and an expanded adjustable range than existing ones. An electromagnetic wave propagation-preventing bottom conducting layer of gold (Au), a dielectric substrate of silicon dioxide, and a 0.4 μm thick radiating element of vanadium dioxide (VO₂). The proposed structure has dimensions of 16 × 16 × 9.6 μm³. At operational frequencies, the prescribed design achieves wideband absorption with an absorption efficiency of over 96 % and shows outstanding absorption performance across a wide range of polarization angles even at high temperatures. The prescribed structure functions at three distinct frequencies are 3.71 THz, 6.59 THz, and 17.2 THz. The operational frequency ranges have maximum absorption percentages of 98.7 %, 97.8 %, and 97.7 %, ranging from 3.3 to 4.2 THz, 5.6 to 6.9 THz, and 15.5 to 17.5 THz, respectively. In the terahertz spectrum, this one-of-a-kind device provides an innovative contribution by acting as both an absorber and a reflector. The absorber also has wide-angle absorption properties and is insensitive to polarization. It is notable that the absorber being proposed has adjustable properties. For terahertz communication applications, the recommended terahertz tri-band absorbing can be appropriate.

Keywords: Absorber, Broadband, Metamaterial, Terahertz, Tri-band, Vanadium dioxide, Gold.

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1. INTRODUCTION

When compared to naturally existing materials, metamaterials – artificially manufactured composite materials with distinct structures, compositions, and dimensions – display improved electromagnetic and absorption capabilities. As the lower frequency range has been extensively studied, researchers have begun to focus on the higher frequency region of the electromagnetic spectrum. This has led to an increased emphasis on the terahertz (THz) band. Terahertz communication systems are still in the early stages, and every component – emitters, transmitters, and receivers – must operate flawlessly. Among these parts, absorbers are becoming more popular due to their many uses in cloaking, imaging, sensing, and filtering in both commercial and military settings [1]. Because of its distinctive phase-change properties, vanadium dioxide (VO₂) has stood out among the many phase-changing materials investigated by researchers in their pursuit of reconfigurable electromagnetic solutions [2]. Furthermore, scientists are making great strides towards reduc-

ing the impact of electromagnetic radiation on technological devices and people's well-being. Graphene and vanadium dioxide have been extensively used by researchers to improve the structural design of metamaterial absorbers during the past few years. They have tested their absorption capabilities through rigorous theoretical research and computational simulations. One example is the graphene-based tunable broadband metamaterial absorber suggested by Zhang et al. [3]. This absorber was able to obtain a broadband absorption rate of more than 90 % between 3.287 and 5.247 THz, when subjected to normal incidence circumstances of terahertz waves. Vanadium dioxide was also the basis for Li's ultra-broadband terahertz metamaterial absorber, which is both polarization-insensitive and absorption-tunable. According to the results, the prescribed structure could accomplish ultra-broadband characteristics [4]. The adjustable broadband metamaterial absorber that was suggested by Heng Zhang et al. [5] uses a Fabry-Pérot cavity and vanadium dioxide to achieve an absorption rate of more than 90 %. In a similar vein, Pankaj Binda et al. [6] developed a vanadium dioxide broadband absorber with several

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linked, diagonally sliced square rings; the suggested structure exhibited absorption of more than 90 % from 2.85 to 7.51 THz. Xiaojun Huang offered a new metamaterial with a gold conducting ground and a polyimide intermediate layer [7]. Potential applications include energy harvesting, terahertz detection [8], timing, and switches [9] due to its fractional bandwidth of 121.8 % and absorptance of nearly 90 % [10] in the 0.86-3.54 THz range.

There has been significant progress in the design of perfect absorbers, although tri-band absorbers still fall short in several areas. We developed a low-profile THz MMA with a straightforward design and increased absorption peaks at resonance to boost the percentage of absorption at resonance. The standard three-layer absorber relies heavily on the top layer's material and structure. The suggested structure functions at three resonant frequencies, with absorptions of 98.7 %, 97.8 %, and 97.7 %.

2. DESIGN METHODOLOGY OF MMA

The CST tool was used to model the suggested structure using computational modelling. To stop electromagnetic waves from propagating, the bottom layer is composed of 0.2 μm thick gold. The ground layer has an electrical conductivity of $4.56e + 07 \text{ S/m}$ with total size of $16 \times 16 \times 0.2 \mu\text{m}^3$. The upper layer has a circle-shaped patch and several slots that are 0.4 μm thick. This conducting patch has dimensions of $13 \times 13 \times 0.4 \mu\text{m}^3$. A material made of silicon dioxide is sandwiched between the two levels. The SiO_2 material has a height of 7 μm . The total dimensions of the intermediate layer are $16 \times 16 \times 7 \mu\text{m}^3$. The suggested unit cell is seen in Figure 1 in frontal aspect. The prescribed design's dimensions in μm square are $L_{gs} = 16$, $W_{gs} = 16$, $m = 13$, $n = 6$, $s = 8$, $t = 4$, $c = 2$, $d = 2$.

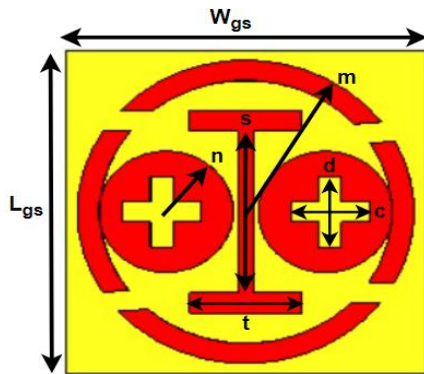


Fig. 1 – A frontal view of the suggested design

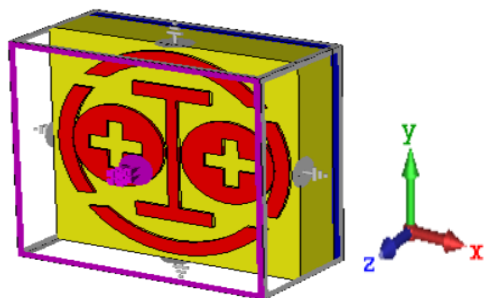


Fig. 2 – Configuration for proposed model

Electromagnetic challenges requiring fast and accurate simulation results are solved with the CST tool. It possible to regulate large radiating structures in an easy and effective way using this tool. By applying ideal E and H boundary conditions along two directions, the electromagnetic wave is impacted differently, as depicted in Figure 2.

3. PARAMETRIC INVESTIGATION

The geometrical form of the structure has an effect on the resonant frequency and absorption coefficient. Therefore, it is crucial to carefully review the parameters and take into account the effects of their changes. The effect of the design's physical dimensions on the absorption performance is addressed in this section. The lowest bandwidth and absorption % are obtained at $m = 12 \mu\text{m}$ and $14 \mu\text{m}$. As seen in Figure 3(a), the three resonant bands only achieved their maximum absorption percentage at $m = 13 \mu\text{m}$. The relative absorption changes similarly when n is increased by 1 μm from 5 to 7 μm . For $n = 5 \mu\text{m}$ and 7 μm , the lowest bandwidth is achieved. As shown in Figure 3(b), the bandwidth and highest absorptivity % for the three bands are only achieved at $n = 6 \mu\text{m}$. In the same way that the geometric parameters c and d are adjusted from 1 to 3 μm , d from 1 to 3 μm with an increment of 1 μm , parametric analysis is also performed using these design parameters. Figure 3(c) and Figure 3(d) respectively show the MMA's relative reactions. The percentage of absorption drops at $c = 1$ and 3 μm . Figure 3(c) shows that the maximum absorption % can only be achieved at $c = 2 \mu\text{m}$ throughout all three resonant bands. According to Figure 3(d), the 3 resonant bands exhibit the largest absorption percentages at $d = 2 \mu\text{m}$, while the lowest absorption levels are attained at $d = 1$ and 3 μm .

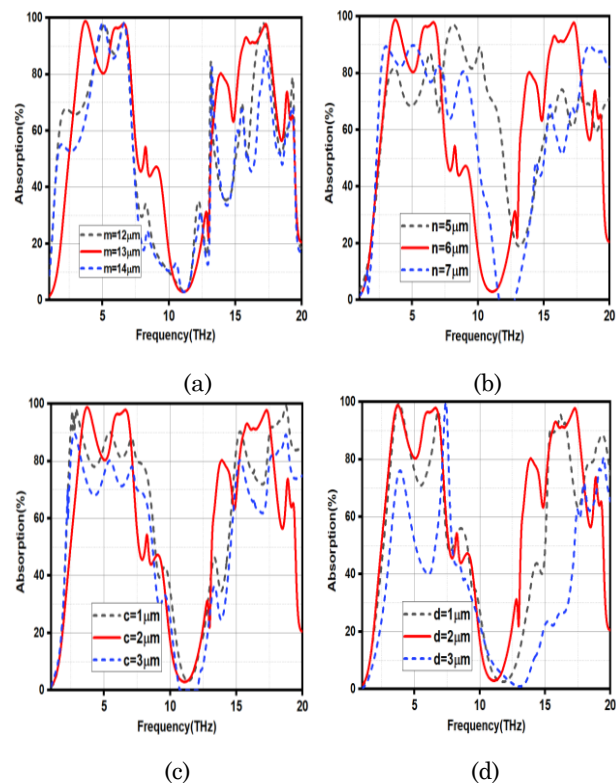


Fig. 3 – Parametric analysis yielded absorption by modifying (a) m (b) n (c) c and (d) d parameters

4. EFFECT OF VO₂ PROPERTIES ON ABSORPTION MECHANISM

This section focuses into the investigation of the external temperature influence on the VO₂ material that would be used in the suggested absorber. The CST simulator was used to examine the temperature-dependent absorption response after the VO₂ conductivity data was imported. This was confirmed by taking into account how temperature affects VO₂ conductivity in experiments. In the metallic state, the VO₂ structure shows substantially greater absorption than in the insulating state, according to the absorption spectra taken at various temperatures. Furthermore, a wider spectrum of frequencies is absorbed in the metallic state due to the broader absorption peaks. Upon reaching a threshold temperature of 68 °C, the VO₂ phase underwent a remarkable transition from insulating to metallic. The fact that this change can be triggered by external stimuli or changes in temperature makes VO₂ highly modifiable. Metamaterial absorbers based on VO₂ are able to dynamically change their electromagnetic response, which allows smart or adaptive materials to adapt their performance to changing environmental conditions.

5. RESULTS AND DISCUSSION

The absorptivity and reflectivity spectra of the suggested model are displayed in Figure 4. The suggested design has two resonance points: the first is at 3.71 THz, with a bandwidth of 0.9 THz (from 3.3 THz to 4.2 THz), and the second is at 6.59 THz, with a bandwidth of 1.3 THz (from 5.6 THz to 6.9 THz). Third resonance at 17.2 THz with a 2 THz bandwidth (15.5 THz to 17.5 THz).

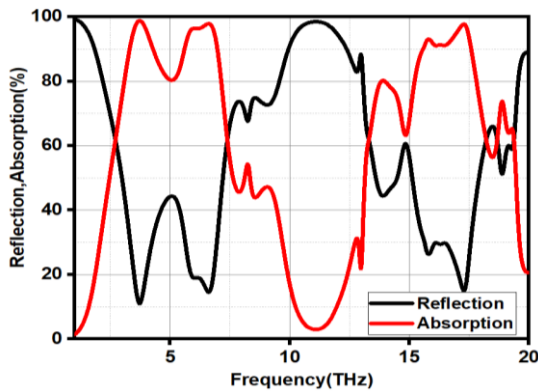


Fig. 4 – Proposed unit cell absorption and reflection spectra

Figure 5(a) displays the absorption response characteristics of the suggested THz MA under polarization angle at $T = 350$ K. Figure 5(b) depicts the color plot of Figure 5(a). The absorption capacity of the suggested THz absorber remains constant as the polarization angle increases. The reason behind this is that the effective magnetic resonance can be excited by varying the polarization angle. Figure 5(a-b) shows that between 3.3 and 4.2 THz, 5.6 and 6.9 THz, and 15.5 and 17.5 THz, for polarization angles up to 80° at TE wave, the suggested THz MMA can maintain the absorption above 96 %.

As illustrated in Figure 6(a), the bandwidth with an absorption rate greater than 96 % stays constant for TM waves as the polarization angle increases. Changing

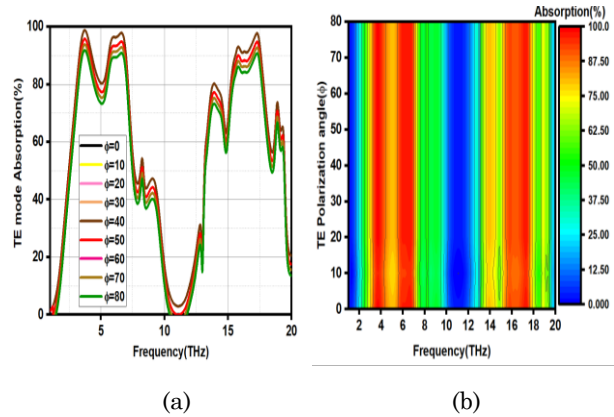


Fig. 5 – The absorption representation in TE mode (a) Spectra and (b) Contour plot

the polarization angle causes a corresponding change in the electric field component of the incident THz wave, which in turn excites the effective electric dipole. Figure 6(b) depicts the contour plot generated from Figure 6(a). The absorption of the TM mode changes with different polarization angles is depicted by Figure 6(b). We attain a 98.7, 97.8 and 97.7 % absorption rate at three distinct resonance frequencies.

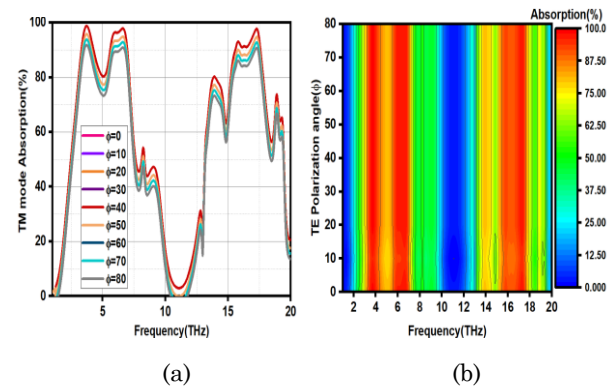


Fig. 6 – The absorption representation in TM mode (a) Spectra and (b) Contour plot

6. FIELD DISTRIBUTION ANALYSIS

The effective characteristics of the E and H field distributions can be used to validate any unit cell structure. The device's design accuracy can be confirmed by analyzing the electric and magnetic fields generated by the unit cell. According to Figures 7 (a-c) and 8 (a-c),

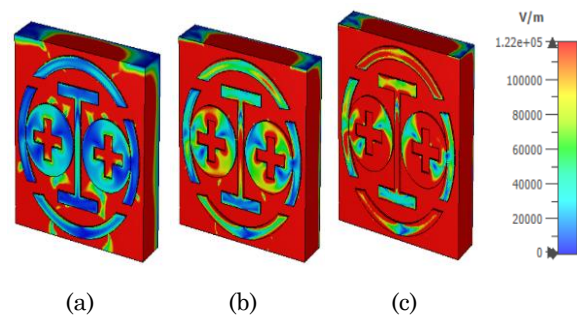


Fig. 7 – An analysis of the proposed unit cell's E field distribution at (a) 3.71 THz (b) 6.59 THz (c) 17.2 THz

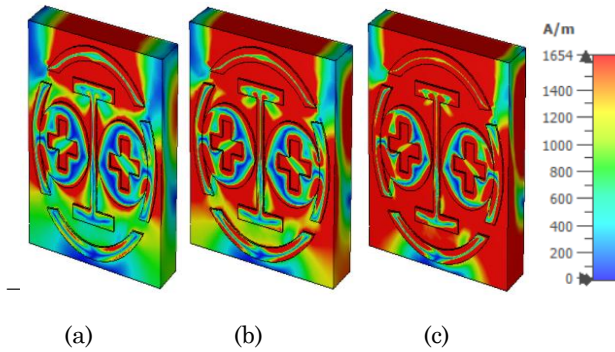


Fig. 8 – An analysis of the prescribed design H field distribution at (a) 3.71 THz (b) 6.59 THz (c) 17.2 THz

the VO₂ patch's E -field is at its peak at 3.71 THz in the patch's inner circle and slots and at its lowest at 17.2 THz in the patch's outer circle and corners. The maximum H -field is detected at 3.71 THz in the horizontal patch and the little inner circle. Both the inner and outer patches exhibit a discernible H -field at 6.59 THz. The fact that the E and H fields are orthogonal to each other is also evident.

7. A COMPARISON OF PERFORMANCE


Table 1 displays a comparison of the current state of the art with research that is currently ongoing. The proposed design has more than 96 % absorptivity, as seen in the comparison table. Table 1 reveals that this microstructure has absorption rates of 98.7 %, 97.8 %, and 97.7 %, respectively.

8. CONCLUSION

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Термокерований трисмуговий метаматеріальний ідеальний поглинач на основі діоксиду ванадію (VO₂) для застосування в терагерцовому зв'язку

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In this article, a VO₂-based metamaterial absorber that is polarization-insensitive is introduced for use in terahertz applications. At resonance frequencies of 3.71 THz, 6.59 THz, and 17.2 THz, the proposed unit cell

Table 1 – Analysis of current research in relation to previous studies

| Ref. | Publication Year | 2D Unit cell size (μm ²) | Conducting Patch | Absorption (%) | Absorption Bandwidth (THz) |
|-----------|------------------|--------------------------------------|------------------------------|---------------------|--|
| [3] | 2025 | 18 × 18 | Graphene | 90 | 3.2-5.2(3) |
| [7] | 2022 | 118 × 118 | Graphene | 98 | 0.86-3.54 (2.68) |
| [8] | 2023 | 65 × 65 | VO ₂ | 90, 90 | Not Mentioned |
| [9] | 2023 | 22 × 22 | VO ₂ | 90 | 3.8-15.6 (11.8) |
| [10] | 2024 | 38 × 38 | Graphene and VO ₂ | 98,96 | 2.05-2.35 (0.3), 3.25-3.6 (0.35) |
| This work | – | 16 × 16 | VO ₂ | 98.7, 97.8 and 97.7 | 3.3 – 4.2(0.9), 5.6 – 6.9(1.3), 15.5 – 17.5(2) |

exhibits three distinct absorption peaks with bandwidths ranging from 3.3 to 4.2 THz, 5.6 to 6.9 THz, and 15.5 to 17.5 THz, respectively. Its dimensions are 16 × 16 × 9.6 μm³. The structure exhibits absorption rates of 98.7 %, 97.8 %, and 97.7 % in the respective triple resonant bands. In both the TE and TM modes, the absorbance is affected by changes in polarization angle, confirming that the proposed design is polarization insensitive. Additionally, Various polarization angles and their effects on absorption are discussed. Consequently, for terahertz communication applications, the proposed triple band VO₂-based absorber is highly recommended.

Запропонований терагерцовий метаматеріальний поглинач, який використовує особливості фазового переходу діоксиду ванадію (VO_2) для досягнення широкосмугових характеристик. У статті представлено інноваційний дизайн терагерцових поглиначів, який є тоншим, має ширшу смугу пропускання та розширений діапазон регулювання, ніж існуючі. Нижній провідний шар із золота (Au), що запобігає поширенню електромагнітних хвиль, діелектрична підкладка із діоксиду кремнію та випромінювальний елемент із діоксиду ванадію (VO_2) товщиною 0,4 мкм. Запропонована структура має розміри $16 \times 16 \times 9,6$ мкм³. На робочих частотах запропонована конструкція досягає широкосмугового поглинання з ефективністю поглинання понад 96 % та демонструє видатні характеристики поглинання в широкому діапазоні кутів поляризації навіть при високих температурах. Запропонована структура функціонує на трьох різних частотах: 3,71 ТГц, 6,59 ТГц та 17,2 ТГц. Робочі діапазони частот мають максимальний відсоток поглинання 98,7 %, 97,8 % та 97,7 %, в діапазоні від 3,3 до 4,2 ТГц, від 5,6 до 6,9 ТГц та від 15,5 до 17,5 ТГц відповідно. У терагерцовому спектрі цей унікальний пристрій робить інноваційний внесок, діючи як поглинач, так і відбивач. Поглинач також має ширококутові властивості поглинання та нечутливий до поляризації. Крім того, запропонований поглинач має регульовані властивості. Для застосувань терагерцового зв'язку може бути доцільним рекомендоване терагерцове тридіапазонне поглинання.

Ключові слова: Поглинач, Широкосмуговий, Метаматеріал, Терагерцовий, Тридіапазонний, Діоксид ванадію, Золото.