THz Wideband Metamaterial Absorber for Different Applications

Riya, Surendra Kumar Gupta, and Amit Bage(✉)

Department of ECE, NIT Hamirpur, Hamirpur 177005, Himachal Pradesh, India
{22mec108,surendra,abage}@nith.ac.in

Abstract. This paper presents, a THz wideband metamaterial absorber using combination of one circular and two hexagonal rings. The absorber is the composition of vanadium dioxide (VO_2), silicon dioxide (SiO_2) and gold (Au) layer. The resonators has been designed on the top layer i.e. on vanadium dioxide (VO_2). The numerical analysis of the proposed THz metamaterial absorber is carried out using CST microwave studio (electromagnetic field simulation software). The numerical analysis shows, absorption exceeding 97% across a bandwidth of 1.7 THz (2.9–4.6 THz). The detailed designed procedure with necessary diagram has been presented. The parametric analysis also carried out to understand the absorptance phenomena. A table also provided to compare the proposed absorber with those already available in literature. This THz absorber is used to elucidate the restricted bandwidth problem of the internet of things backhaul networks. Proposed THz absorber can also be used in landscape, energy, biology etc.

Keywords: Absorber · Metamaterial · vanadium dioxide · wideband · THz

1 Introduction

The metamaterial are the artificial materials, showing non-existing electromagnetic features when they interact with the electrometric (EM) waves. The theoretical studies of materials showing negative permittivity and permeability simultaneously has been studied by Veselago in 1967 [1]. The terahertz (THz) ranging from 0.1 to 10 THz, offers a vast, relatively unexplored frontier for technological innovation. This spectral window bridges the gap between mature microwave and optical technologies, holding immense potential for the burgeoning Internet of Things (IoT), landscape, communication, energy, biology etc. However, traditional materials often struggle in this regime, lacking the necessary control over electromagnetic wave manipulation. This is where metamaterials come into play. These engineered materials, meticulously crafted with sub-wavelength structures, possess the remarkable ability to tailor light-matter interactions. Researchers have harnessed this power to design versatile THz components, including absorber [2, 3], modulators [4], wave front controllers, polarization converters and sensors [5–8]. Notably, metamaterial perfect absorbers (MPAs) have emerged as a game-changer due to their exquisite control over THz wave absorption [9–14].

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However, conventional THz MPAs often suffer from limitations like narrow bandwidth and a fixed response [15, 16]. This research tackles these challenges by introducing a novel metamaterial design on vanadium dioxide (VO_2). The dynamic nature of VO_2 allows absorption characteristics, paving the way for a new generation of “active” THz meta-devices [17]. The implications for IoT are particularly exciting. Traditional backhaul networks, responsible for data transfer within the IoT ecosystem, face bandwidth limitations imposed by WiFi and cellular networks. Here, optical connections offer a compelling alternative due to their superior bandwidth capabilities. Interestingly, metamaterials can be designed to act as efficient light absorbers, making them ideal candidates for THz sensors. Integrating such sensors with an optical IoT backhaul network unlocks a future of enhanced sensing capabilities, leading to more efficient and effective data collection within the IoT landscape [18].

In this paper, a wideband metamaterial absorber has been presented. The absorber is designed on vanadium dioxide (VO_2) and the resonating structure is combination of circular and hexagonal concentric rings. The analysis shows, absorption exceeding 97% across a bandwidth of 1.7 THz (2.9–4.6 THz). In essence, this research explores the synergy between metamaterials and the terahertz spectrum, with a specific focus on its transformative potential for the future of IoT devices and networks.

2 Design and Analysis of Absorber

Figure 1 explains the fundamental building block of the proposed wideband terahertz absorber. The top, middle and bottom layer is made of VO_2, SiO_2 and Au. The middle layer of the absorber is made of silicon dioxide (SiO2) with a depth of 12 µm and a relative dielectric constant of 3.8. The bottom layer is a thin layer of gold (Au) with a thickness of 1µm. Gold is chosen due to its excellent conductivity, which in this case is 4.56×10^7 S/m.

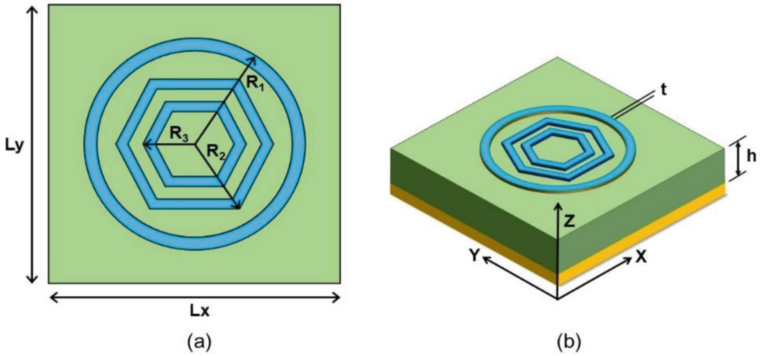

Fig. 1. (a) front view and (b) 3D schematic of the absorber.

The top layer is VO_2 and consists of combination of one circular and two hexagonal rings based resonator. These rings are crucial for achieving the desired absorption properties. A continuous metal layer is situated on the bottom of unit cell. This layer plays a energetic role in confining and manipulating the terahertz waves. Separating the top layer and the metal ground layer is a thin dielectric spacer. This spacer serves to control interaction among the electromagnetic waves and the VO_2 rings. The complete dimensions of the proposed metamaterial absorber is tabulated in Table 1.

Table 1. Optimized parameters of the proposed absorber.

Parameter	Value	Parameter	Value
P	30 μm	w	1.5 μm
R1	11.5 μm	h	12 μm
R2	8 μm	t	0.2 μm
R3	4 μm		

The optical characteristics of VO2 in the THz range is described by using Durde mode and can be expressed as [8]:

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

Where $\varepsilon_\infty = 12$ is permittivity at high frequency, collision frequency $(\gamma) = 5.75 \times 10^{12}$ rad/s. The relationship between the conductivity and plasma frequency can be expressed as using [8]:

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

In proposed metamaterial absorber has considered $\sigma_0 = 3 \times 10^5$ S/m, $\omega_p^2(\sigma_0) = 1.4 \times 10^{15}$ rad/s, and conductivity of vanadium dioxide changes from 200 S/m to 2×10^5 S/m when it turns into insulator to metal phase. At the metal state, the conductivity has been chosen $\sigma = 2 \times 10^5$ S/m. To analyze the absorption and reflection performance of the designed absorber, CST microwave studio has been chosen. The boundary condition set as unit cell in x and y direction and perfect matching layer at Z-direction. Since the thickness of the metal ground plane is much greater than the skin depth, the transmittance will become equal to 0. Under these conditions, absorbed power can be defined as using [8]:

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

Where $R(\omega)$ represents the reflectance, and $S_{11}(\omega)$ denotes the reflection coefficient in the S-parameter.

3 Results and Discussion

Figure 2 shows the reflection and absorption characteristics of the designed absorber. The figure reveals that, a remarkable absorption bandwidth exceeding 97% across a wide frequency range of 3 THz, spanning from 2.9 THz to 4.6 THz under normal incidence. The maximum absorption peak is located at around 2.9 THz. The variation of SiO_2, VO_2 thickness and R_1 and R_2 radius parametric analysis has been carried out to enhance absorptance performance.

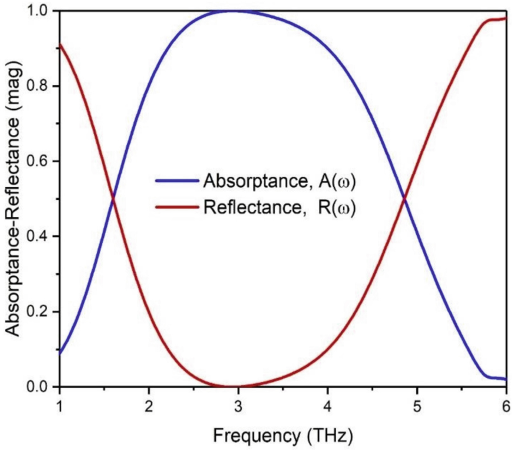

Fig. 2. Simulated frequency Vs absorptance-reflectance response of Fig. 1.

Initially, thicknesses of SiO_2 is varied and all other parameters are remains unchanged. Under normal incidence, the computed absorptance as a function of SiO_2 thickness and frequency is displayed in Fig. 3. The figure reveals that, as SiO_2 thickness increased, resonant peak moves at the lower side and the absorption performance also decreases. The SiO_2 acts as a cavity, and for different thickness different field distributions and has different effective impedances.

When the thickness is small, the interaction with VO_2 is very strong and when the thickness is large interaction is very weak. The small change in thickness large changes on the absorption can be observed. At optimized values of $h = 12$ µm, maximal broadband absorption is achieved. Figure 4 shows the variation of VO_2 Vs frequency and absorptance. The picture illustrates how the coupling between VO2 and metallic is very weak at very thin thicknesses, and the related impedance is not equal to that of vacuum. When the thickness is sufficient, electromagnetic waves will be significantly reflected. The figure reveals that, at optimized value of $t = 0.2$ µm the wideband absorptance with maximum absorption has been achieved.

The parametric analysis has also been carried out for variation of R_1 and R_2 and shown in Fig. 5 and Fig. 6. Figure 5 reveals that, the absorption percentage and bandwidth increases as the R_1 increases and Fig. 6. Reveals shows, as radius R_2 increases the absorption bandwidth and absorption percentage is increasing. A comparison of the

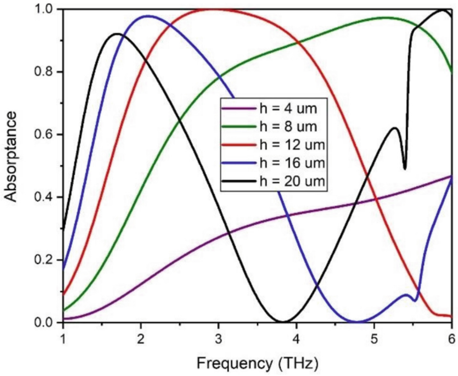

Fig. 3. Absorption spectrum variation of absorber with variation in SiO2 thickness.

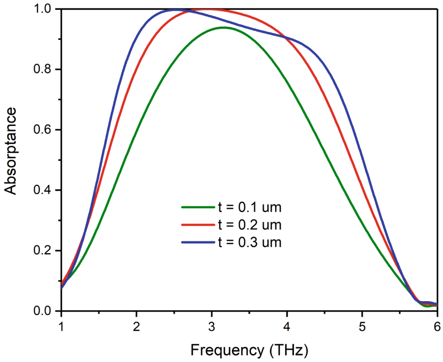

Fig. 4. Thickness variation of VO_2 Vs frequency and absorptance.

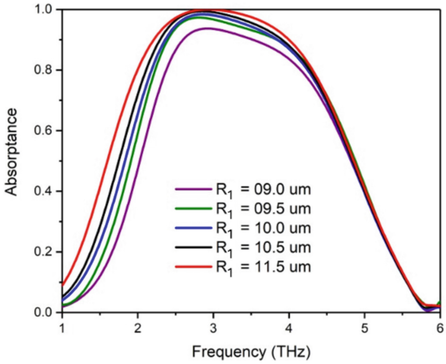

Fig. 5. Radius R_1 variation Vs frequency and absorptance.

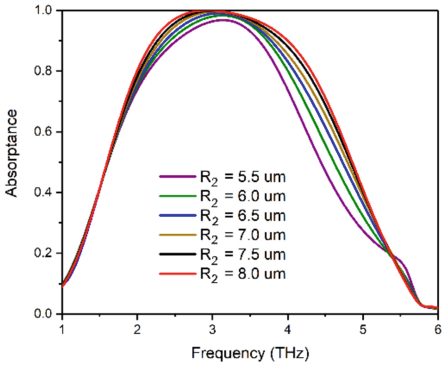

Fig. 6. Radius R_2 variation Vs frequency and absorptance.

proposed work with literature is tabulated in Table 2. The table shows the absorptance is more as compared to Ref. [10–13] and absorption bandwidth is more as Ref. [10–11 and 13].

Table 2. Comparison of proposed metamaterial absorber with the Ref. [10–13].

Reference	Absorption BW	Absorptance
[10]	0.33 THz	>90%
[11]	0.65 THz	>90%
[12]	2.44 THz	>90%
[13]	0.52 THz	>90%
Proposed Work	1.7 THz	>97%

4 Conclusion

This work introduces a novel wideband terahertz (THz) absorber design. The design incorporates a unique arrangement of one circular and two hexagonal resonating rings made of VO2, separated from a metallic ground plane by a SiO2 spacer. Simulations reveal absorption performance exceeding 97% across a broad bandwidth of 3 THz (2.9 THz to 4.6 THz). This superior bandwidth surpasses those reported in previous studies. Furthermore, the design exhibits strong absorption even for non-perpendicular light incidence, making it suitable for real-world applications. The wide bandwidth, high efficiency, and wide-angle absorption of the suggested metamaterial absorber make it a viable option for a number of THz technologies, including as optical devices, sensors, and modulators..

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