The design of tunable terahertz absorber realized by phase change film

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Based on the phase transition characteristics of vanadium dioxide, a multi-resonant tunable terahertz absorber is designed in this paper by combining vanadium dioxide with terahertz metamaterials. With the change in ambient temperature, the conductivity of vanadium dioxide will also change. When the critical value is reached, vanadium dioxide will change from semiconductor state to metallic state. The results show that when the temperature is 40 ℃, the absorber has three absorption peaks, the peak frequencies are 0.613THz, 1.183THz and 1.742 THz, respectively, and the absorptivity at each peak frequency is more than 90%. When the temperature is 67℃, the absorber has two absorption peaks, the peak frequencies are 0.615THz and 1.314THz, respectively, and the absorption effect is good at each peak frequency. This novel type of multi-resonant tunable terahertz waves absorber is expected to play an important role in the future multi-frequency imaging, electromagnetic stealth and other fields.

(Received August 23, 2018; accepted August 18, 2020)

Keywords: Terahertz, Absorber, Phase, Tunable

1. Introduction

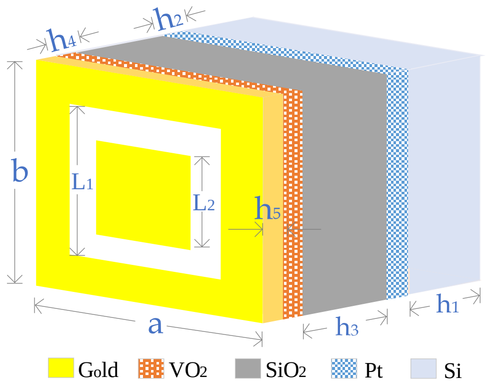
In recent years, with the rapid development of high efficiency radiation sources and high sensitivity detection technology, the unique properties of terahertz waves have attracted extensive attention in the scientific community. Terahertz waves / waved science and technology have also been developed rapidly. It has broad application prospects for wireless communication [1], sensing [2-3], medical detection and diagnosis [4] and so on. However, in order to promote the further development and practical application of terahertz technology, it is also essential to provide a variety of high-performance terahertz waves functional devices that make up terahertz application systems. Such as: terahertz wave switches, beam splitter, filter, modulator, absorber and so on. Because there are few materials in nature that can produce electromagnetic response to terahertz band, which seriously hinders the development and development of terahertz wave functional devices, which make the progress of terahertz practical research slowed. The emergence of artificial electromagnetic metamaterials solves the problem of material shortage and is one of the best candidates to fill the "terahertz gap", which also provides a new idea of the application of terahertz bands functional devices [5-11].

At present, a series of important achievements have been recorded in the study of terahertz wave absorbers based on metamaterials [12-15]. However, the absorption frequency of these absorbers is often single and not adjustable. In order to realize the dynamic control of terahertz waves functional devices, the common method is to add semiconductor or superconductor materials to the metal array. The frequency response characteristics of these materials are tailored by external heating, magnetism, electricity, light and so on, to realize the purpose of dynamically adjusting terahertz. In recent years, vanadium dioxide (VO_2) has served for terahertz wave devices, such as modulator [16], switch [17] and so on. VO_2 is a type of metal oxide with picosecond insulator-metal phase transition characteristics. It can be changed from insulator state to mental state under the action of heat, light or stress. With the transformation of phase, its physical properties will also change inversely [18-19].

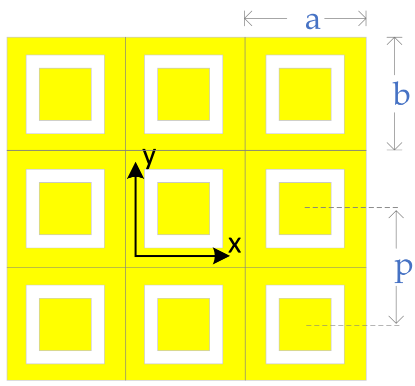
Based on the phase transition characteristics of VO_2, a multi-spectrum tunable terahertz absorber that can realize the strong absorption of terahertz is designed in this paper. The proposed absorber has simple structure design and diversified functions. It has great application potential and development space in the fields of multi-spectrum stealth, multi-spectrum detection and communication.

2. Structural design

The terahertz wave absorber structure designed in this paper is shown in Fig. 1. Fig. 1 (a) and (b) presents the schematic diagrams of the five-dimensional structure of the absorber unit and array size of the structural unit, respectively. The substrate is high resistivity silicon(Si, thickness h1=180nm), which plays a supporting role in the structure; This paper selects the continuous metal platinum (Pt) thin film (thickness is h2 = 150nm) as a metal reflective layer tuned metamaterial absorber, h2 is greater than the corresponding tunable metamaterial absorber of the normal work of the electromagnetic skin depth, it is mainly used for blocking the transmission of electromagnetic waves; The dielectric layer is SiO_2 film (thickness h3 = 500nm); phase change material layer is selected as VO2 film (h4 = 150nm), with insulator-metal phase transition characteristics; metamaterial layer (thickness is h5 = 400nm) is located in the surface layer of VO_2 phase change material, which is formed by the periodic arrangement of the metal (Gold) artificial structural units with sub-wavelength scales. The artificial metal structure unit as shown in Fig. 1 (b), the length of the array unit is (a=b=80μm), the cycle is p=80μm. Other parameters are as follows: L1=50μm, L2=30μm.



(a) Absorber structure



(b) Absorber cell array

Fig. 1. Structure and cell array of tunable electromagnetic metamaterial absorber (color online)

A layer of VO_2 film with insulation-metal phase transition characteristics is included between the metamaterial layer and the dielectric layer of a three-layer electromagnetic metamaterial absorber. The absorption of the electromagnetic metamaterial absorber is supervised by the phase change process of VO_2 film triggered by heat, electricity or light. The VO_2 film layer acts as a dielectric layer when the VO_2 film is in an insulating state, by properly designing the structure and size parameters of the metamaterial, the impedance matching ($\varepsilon_{eff} = \mu_{eff}$) between the metamaterial and the free space can be achieved, at this time we can obtain a terahertz absorber that can achieve perfect absorption of electromagnetic waves in certain frequency bands. In the external field stimulation, when the VO_2 phase-change film layer changes from an insulating state to a metallic phase, the impedance matching conditions are destroyed resulting in electromagnetic waves is strongly reflected. As a result, the absorption rate is significantly reduced. As the VO_2 film changes from a mental state to an insulating state, it will revert to a super electromagnetic material absorber with a high absorptive.

3. Theoretical and experimental analysis

When terahertz incident vertically on the absorber designed in this paper, in addition to the usual LC resonance, there is also a dipole resonance. According to the characteristic parameters of vanadium dioxide material in reference [8], it is known that when the temperature is 40ºC, the conductivity of VO_2 is 130 S/m, the VO_2 is in semiconductor state, the conductivity is very weak, and there is a strong capacitance effect between the inner square and the outer square. Under the action of incident electromagnetic wave, the absorber structure has three resonance modes, namely, the dipole resonance of the outer square, the dipole resonance of the inner square and the LC resonance of the inner and outer squares. The resonant frequencies are expressed by f_{d1}, f_{d2} and f_{o1}, respectively, which are related to the structural parameters of the device [20]:

$$f_{d1} \propto \frac{c}{2L_1\sqrt{\varepsilon_{eff1}}} \tag{1}$$

$$f_{d2} \propto \frac{c}{2L_2\sqrt{\varepsilon_{eff2}}} \tag{2}$$

$$f_{o1} \propto \frac{c}{2\pi\sqrt{LC}} \tag{3}$$

where c is expressed as the speed of light in vacuum; L_1 and L_2 are the structural parameters of the absorber; ε_{eff1} and ε_{eff2} are the equivalent dielectric constant near the outer square arm and the equivalent dielectric constant near the inner square arm, respectively. L and C represent equivalent inductance and capacitance of inner and outer square structure, respectively.

When the temperature rises from 40ºC to 80ºC, Vanadium dioxide materials undergo a phase transition from semiconductor state to metal state, and the conductivity changes from 130S/m to 21700 S/m, and the electrical conductivity of vanadium dioxide material changes from semiconductor state to metal state, and the conductivity changes from semiconductor state to metal state, and the conductivity is significantly enhanced, which led to the disappearance of the original capacitance effect. At this time, under the action of incident terahertz, the original LC resonance mode of the absorber will disappear, that is, the original three resonance modes will become two: the dipole resonance of the outer square(the resonant frequency is expressed as f_{d1}') and the dipole resonance of the inner square(the resonant frequency is f_{d2}') . according to formula (1) and formula (2), we can know that f_{d1} and f_{d1}' are equal, but f_{d2}' moves to high frequency compared to f_{d2}.

It can be seen from the above analysis that when the temperature is 40ºC (corresponding to the conductivity of vanadium dioxide is 130 S/m), the proposed absorber has three absorption peaks. When the temperature changes to 80ºC (corresponding to the conductivity of vanadium dioxide is 21700 S/m), the designed absorber has only two absorption peaks. The absorber structure unit model shown in figure 1 is simulated and verified by CST Microwave Studio software, where the terahertz incident vertically on the absorber surface. Due to the thickness of the metal plate is much greater than the terahertz skin depth, so the terahertz cannot pass through the metal plate in the whole simulation frequency band. The transmittance of the absorber $T = |S_{21}|^2 = 0$. At this point, the formula for calculating the absorptivity of the absorber can be simplified as follows:

$$A=1-R=1-|S_{11}|^2 \tag{4}$$

where R is the reflectivity of the absorber; S_{11} represents the reflection parameter of the absorber. Fig. 2 shows the normalized reflection parameters of the absorber at temperatures of 40ºC and 67ºC.

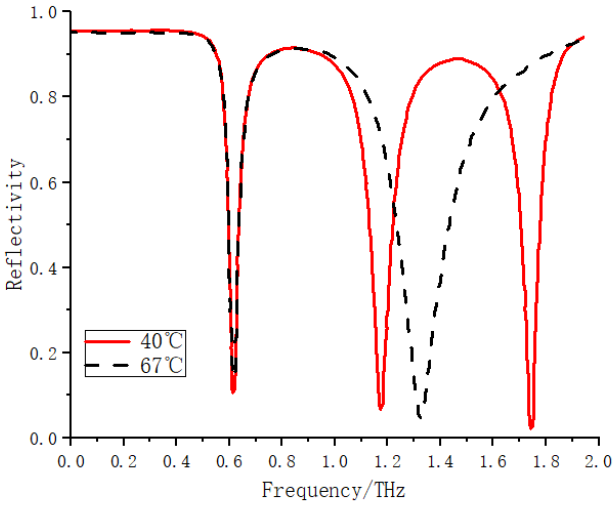


Fig. 2. Normalized reflection parameters of terahertz wave absorbers at different temperatures (color online)

It can be observed in Fig. 2 that when the temperature is 40ºC, the reflection parameter S_{11} of the absorber has a trough at 0.613THz, 1.183THz and 1.742 THz, and the minimum values are 0.113, 0.112 and 0.032, respectively. Which indicates that at these three frequency points, the metamaterial absorber can basically achieve good impedance matching with the surrounding space. The reflectivity of the incident electromagnetic wave is very low, and the absorptivity of the absorber is high. When the temperature is 67ºC, the normalized reflection parameters of the absorber appear a trough at 0.615THz and 1.314THz, the minimum values are 0.127 and 0.095, respectively. This indicates that at these two frequency points, the absorber and the surrounding environment basically satisfy the impedance matching condition and the most terahertz is absorbed. By comparing the reflection parameter curves of the absorber at two temperatures, there is the same resonant frequency point at both different temperatures, which indicate that the resonant frequency of 0.613 THz corresponds to the dipole resonance of the absorber. When the temperature rises to 67ºC, the resonance peak with a resonant frequency of 1.314 THz disappears, which indicates that the resonant frequency corresponds to the LC resonance of the absorber. Furthermore, it can be known that the second resonant frequency of the absorber at 40ºC is 1.183 THz corresponding to the internal square dipole resonance of the absorber, and when the temperature changes to 67ºC, the resonant frequency moves in the direction of high frequency. This is consistent with the results of the preceding theoretical analysis. The absorptivity curve of terahertz wave absorber calculated from the reflection parameters is given in Fig. 3.

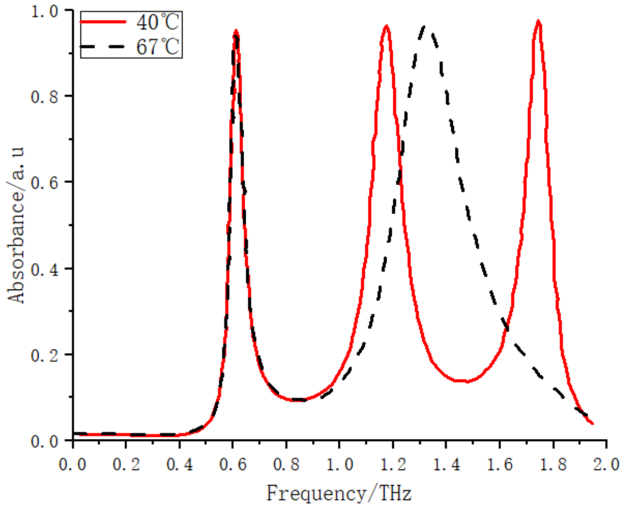


Fig. 3. Absorptivity of terahertz wave absorbers at different temperatures (color online)

It can be seen from Fig. 3 that when the temperature is 40 ℃, the absorber has three obvious absorption peaks. When the temperature is 67 °C, the peak frequency, and half power absorption bandwidth of the first absorption peak remain basically unchanged, while the peak frequency of the second absorption peak shifts to high frequency by 51 GHz, and the half-power absorption bandwidth increases, and the third absorption peak disappears. By changing the temperature of the environment, the absorption frequency band of the terahertz wave absorber can be adjusted and the dynamic control of the absorber can be realized.

In order to further analyze the performance of the designed tunable terahertz metamaterial absorber, in this paper, the influence of the thickness of silica and vanadium oxide on the absorptivity of the absorber is analyzed and calculated. Keep other parameters unchanged, and change the value of thickness of SiO_2 (parameter is h_3), make it decreased sequentially by 0.2μm 0.4μm, 0.6μm，0.8μm, then carry out simulation, and the gained absorption spectrum is shown in Fig. 4. As can be observed in Fig. 4, the h_3 in SiO_2 dielectric layer is a key parameter. With the decrease of h3, the absorption rate decreases gradually and each absorption peak moves to the low frequency, this is due to the decrease of the dielectric layer thickness causing the equivalent impedance of the top layer of a resonator relative to free space enhanced, therefore, the reflectivity increases and the absorption decreases.

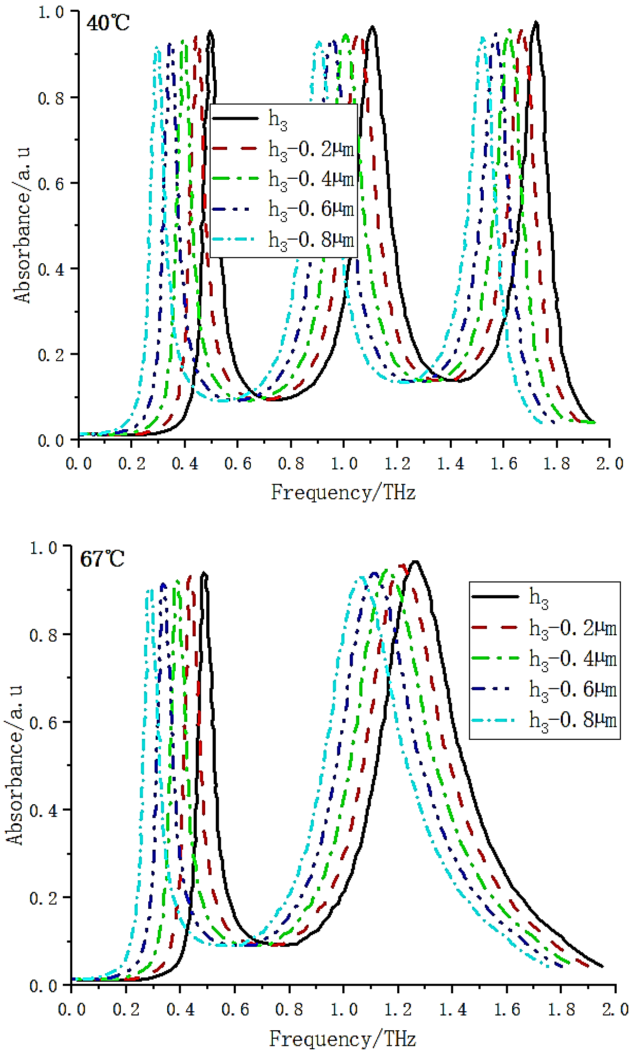


Fig. 4. Effect of thickness h_3 of silica on the absorption characteristics (color online)

Keeping the other parameters constant, changing the value of vanadium oxide thickness (the parameter is h_4), making it decreased sequentially by 0.1μm, 0.2μm, 0.3μm, 0.4μm, the absorption spectrum of the absorber is shown in Fig. 5. As can be seen from Fig. 5, with the increase of the thickness of vanadium dioxide, the absorption rate decreased and each absorption peak moves to the low frequency, the effect of the thickness h4 of vanadium dioxide on resonance frequency is relatively obvious.

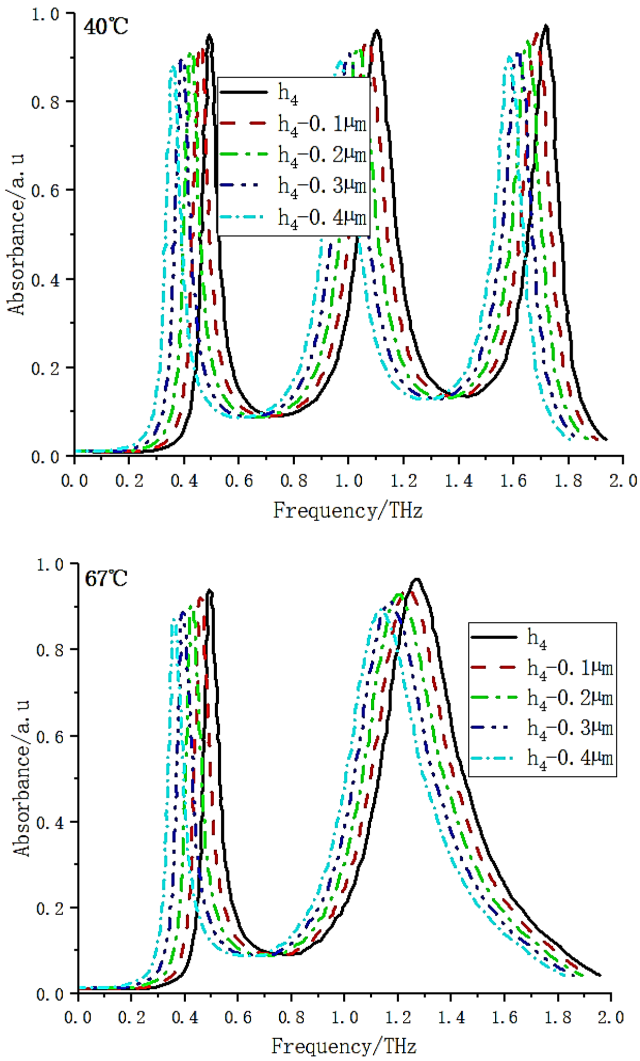


Fig. 5. Effect of thickness h_4 of vanadium dioxide on absorption characteristics (color online)

4. Conclusions

Based on the insulator-metal transition characteristics of VO_2 material and the three-layer type electromagnetic metamaterial absorber, this paper inserts a layer of VO_2 film between SiO_2 dielectric layer and top layer metamaterial, VO_2 and metamaterials are made into effective integration for the construction of THz electromagnetic tunable metamaterial absorber, and phase transition of thermally triggered VO_2 thin films is used to control the absorption rate of metamaterial absorber. In this paper, the effect of phase transformation on the resonant properties of metamaterials and absorber, and forms a technical scheme for adjusting electromagnetic wave by thermal trigger material phase transformation. The effects of the thickness of VO_2 and SiO_2 on the absorption peaks at 40ºC and 67ºC degrees, respectively, are also analyzed. The results show that their new type of multi-resonant terahertz absorber is expected to play an important role in multi-frequency imaging and electromagnetic stealth.

Acknowledgments

This work is supported by Support for scientific research projects (scientific research projects in colleges and universities) (No. 2019sn066); supported by Foundation Funded Project of doctoral (No. 99000617) ; supported by Characteristic Innovation projects of Colleges and Universities in Guangdong Province(No. 2019KTSCX165); supported in part by research grants from the Science and Technology Program of Shaoguan City, China, under Grant 2019sn056, in part by the Key platforms and major scientific research projects of Universities in Guangdong, China, under Grant 2017KQNCX183, and the Key Project of Shaoguan University of China under Grant SZ2017KJ08.

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