Orthogonal bidirectional modulation of terahertz absorber based on phase change principle

JIANJUN LIU *, FAN DING
School of Intelligent Engineering, Shaoguan University, Shaoguan Guangdong 363000, China

A kind of temperature-controlled terahertz absorber based on metamaterial was proposed by using the phase transition characteristics of vanadium dioxide film in this paper. The transmission and temperature-controlled tunability characteristics of phase change metamaterials were investigated in the terahertz band. When the incident terahertz wave is in a horizontally polarized or vertically polarized, the transmittance spectrum of the absorber exhibits two independent transmission broadband around 1.2THz, which the center frequencies are 1.15THz and 1.37 THz respectively and the bandwidth is 0.2THz and 0.3 THz respectively. When the temperature changes from 40℃ to 80℃ the transmittance of the two broadbands is drop apparently, especially at the phase transition temperature of Vanadium dioxide (68℃). For the two polarization states of incident light, the modulation depths of the designed absorber are more than 65%, and achieve a good modulation effect.

(Received August 5, 2019; accepted June 16, 2020)

Keywords: Absorber, Phase, Bidirectional, Terahertz

1. Introduction

Terahertz wave is an electromagnetic wave with a frequency range between 0.1THz and 10 THz. It is located between the microwave and the visible wave in the electromagnetic spectrum. In the past it was difficult to generate and detect THz waves, so people know very little about terahertz [1]. In recent years, with the rapid development of THz radiation sources and detection technology, the applications of THz are also rapidly developing. Especially in wireless communication [2], biological sample spectral detection [3-6], radar imaging [7] and sensing [8] have been applied in practical applications, the unique superiority of terahertz has also been widely recognized. However, as an indispensable part of the THz application system the research of terahertz functional devices such as THz switching filtering modulation polarization and other functional devices is still relatively backward. The main reason is the lack of natural materials that react with THz waves which directly restricts the further development of THz technology. The emergence of artificial structure electromagnetic materials solves this problem in which metamaterials are expected to achieve efficient regulation of terahertz waves. Metamaterials are periodic structural materials with man-made structures that exhibit extraordinary physical properties not found in natural materials. Because it can respond strongly to terahertz waves it can control THz waves [9,10].

In order to achieve the regulation of THz waves a common method is to add semiconductor materials to the metal array of metamaterials [11,12]. In recent years phase change materials such as vanadium dioxide (VO_2) films have been widely used in the structure of THz metamaterials to achieve the tuning function of metamaterials. A vanadium dioxide (VO_2) film is a metal oxide having an insulator-metal phase transition property that can be converted from an insulator state to a metallic state under the action of light heat or stress [13]. With the phase change, the physical properties of VO_2 film also undergo reversible mutation [14].

At present the metamaterial structure made by combining the VO_2 phase change principle has been applied to smart windows [15], microbolometers [16], light modulators [17] and so on. Wen et al. [18] used VO_2 thin film lithography to form the unit structure of electromagnetic metamaterial, through the thermal excitation of the film to produce a phase change, in this way up to 65% terahertz transmission modulation can be obtained. Choi et al. [19] fulfill the all-optical switch of terahertz radiation using a nano-resonator structure which is grown on a vanadium dioxide film to form a metal film and form a submicron-sized antenna structure. The ultra-fast control of the transmitted THz wave is achieved by the phase transition characteristic of the VO_2 film due to the appearance of the desired transmission characteristics at its resonant frequency. So far there have been few reports on metamaterial devices capable of efficiently modulating THz waves incident in two polarization directions. This polarization-independent modulation function can significantly enhance the control of terahertz waves and has important applications in terahertz broadband communication. This paper proposes a metamaterial absorber that can achieve independent modulation of horizontal polarization (p-polarization) and vertical polarization (s-polarization) with modulation depths of 65% and 70% respectively.

2. Instruments and equipment

The terahertz time-domain spectrum system used in this paper consists of a pump light source (fiber femtosecond laser, TOPTICA Photonics company, Germany) and a terahertz time-domain spectrum optical system (American Zomega company, model Z3-XL). Fig. 1 is the reflection detection mode schematic diagram of the terahertz time-domain spectrum system. In the reflection mode, the generated terahertz wave is focused on the sample through the convex lens after passing through the silicon wafer (the transmittance and reflectivity are both 50%). After passing through the convex lens, the reflection signal is reflected again by the silicon wafer and finally reaches the detection crystal. The reflection detection system uses semi-transparent and semi-reflective silicon wafers to achieve the effect of vertical reflection detection. Because the metamaterial absorber is used in the experiment, a metal layer is sputtered on the absorber as an anti-reflection layer, and the terahertz wave cannot pass through the metamaterial absorber, so the reflection spectrum of the terahertz metamaterial absorber needs to be obtained through the reflection mode.

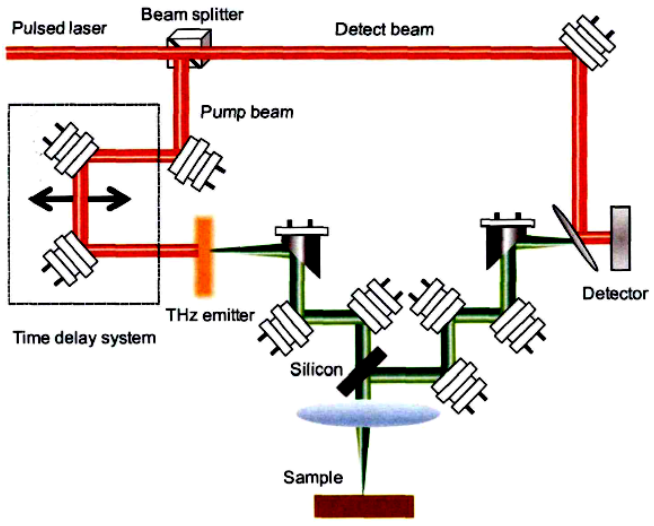

Fig. 1. Reflection detection mode of terahertz time domain spectroscopy system (color online)

3. Theoretical analysis of phase transition of VO_2 materials

3.1. Structure of VO_2 material

Under the thermal excitation condition the phase transition temperature of VO_2 film is about 68 ℃. During the process from low temperature to high temperature the structure of VO_2 molecules is slightly distorted which from a monoclinic lattice structure of an insulator phase to a tetragonal lattice structure of a metal phase. During this process, the VO_2 atoms did not undergo extensive rearrangement. The phase change of VO_2 is completed in the hundred femtosecond time, the optical, electrical and magnetic properties of VO_2 have undergone reversible mutations before and after phase transition [20]. For thermal excitation phase transitions, the phase transition curves are not exactly same during heating and cooling, and there is a phenomenon of thermal hysteresis. According to the relevant research, this phenomenon is related to the distribution and size of VO_2 particles [21].

3.2. Theoretical analysis

It is assumed that in an infinite medium substrate with a dielectric constant of ε_D, there are random composite systems composed of metal particles with a dielectric constant of ε_M. When the volume fraction f of the metal particles is large (generally greater than 20%), the distance between the particles is small, so it is necessary to consider the interaction between the particles. In this case, the dielectric function ε_C of the composite system can be expressed as follow [22]:

$$\varepsilon_C = \frac{1}{4}\left\{\varepsilon_D(2-3f)+\varepsilon_M(3f-1)+\sqrt{[\varepsilon_D(2-3f)+\varepsilon_D(3f-1)]2+8\varepsilon_D\varepsilon_M}\right\} \tag{1}$$

where f is the volume fraction of the metal component, and ε_D and ε_M are the dielectric functions of the insulating phase component and the metal phase component in the VO_2 film, respectively.

For the insulator component in VO_2 film, it can be regarded as the dielectric with dielectric constant $\varepsilon_D = 9$, and for the metal component in VO_2 film, the dielectric function ε_M can be described by the Drude model.

$$\varepsilon_M(\omega) = \varepsilon_\infty - \frac{\omega_P^2}{\omega^2 + i\omega/\tau} \tag{2}$$

where ω is the circular frequency of the THz wave; ε_∞ is the high-frequency limit dielectric constant of the VO_2 material; $\tau = 2.2\,fs$ is the carrier collision time; ε_P is the plasma frequency, expressed as follow:

$$\omega_P = \sqrt{Ne^2/\varepsilon_0 m^*} \tag{3}$$

It depends on the carrier concentration N inside the

medium, the effective mass m∗ and the vacuum dielectric constant ε_0. For the VO_2 film [23], $\varepsilon_\infty = \varepsilon_D = 9$, the carrier concentration $N = 1.3\times10^{22} cm^{-3}$, effective mass $m^* = 2m_e$.

In addition, the correspondence between the volume fraction f of the VO_2 metal component and the temperature can be described by the Boltzmann function:

$$f(T) = f_{\max}(1 - \frac{1}{1+\exp[(T-T_0)/\Delta T]}) \quad (4)$$

The critical temperature of the temperature rise phase transition point is $T_0 = 68°C$, and the transition temperature is $\Delta T = 2°C$. $f_{\max}$ is the maximum volume fraction of the metal component in the VO_2 film at the highest temperature. The experimental results show that $f_{\max}$=0.95[24].

By using Bruggeman effective medium theory (Formula 1), Drude model (Formula 2,3) and Boltzmann function (Formula 4), and combining with the relationship between dielectric function and conductivity [25] $\sigma = -i\varepsilon_0\omega(\varepsilon_c - 1)$, the conductivity of VO_2 thin films corresponding to different temperatures during phase transition can be calculated, where σ is the conductivity of the composite system. The corresponding relationship between the conductivity and the temperature change is drawn in Fig. 2, and the relevant data are recorded in Table 1.

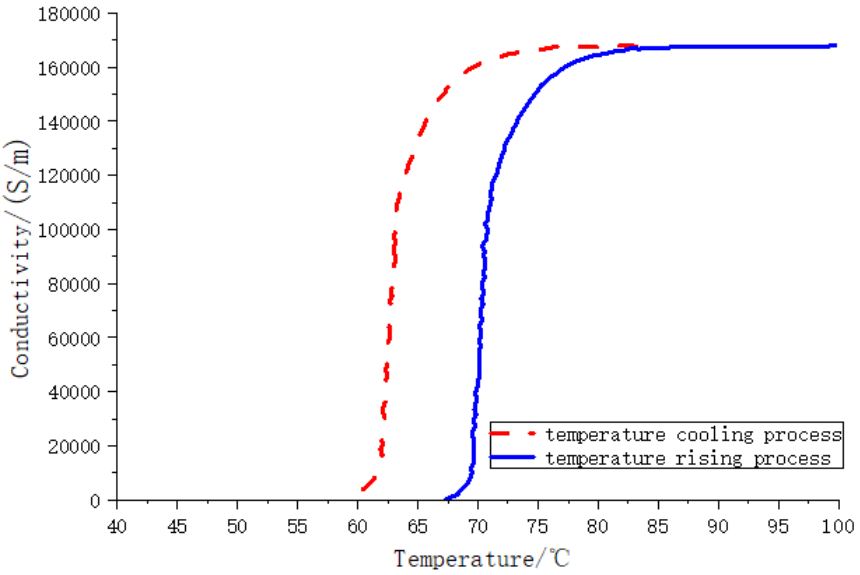

Fig. 2. Relationship between conductivity and temperature of VO_2 film (temperature rising process T_0 = 68 ℃, cooling process T_0 = 62℃) (color online)

Table 1. Correspondence between conductivity and temperature during temperature rising

Temperature/℃	Metal component volume fraction/%	Conductivity/(S/m)
40	0.000086	107
60	2.17	381
67	21.16	$0.83*10^3$
70	73.53	$1.53*10^5$
80	97.61	$1.69*10^5$

4. Results and analysis

The metamaterial absorber proposed in this paper is a three-layer dielectric structure. The schematic diagram of a structural unit is shown in Fig. 3(a): The material in the middle as the substrate is quartz glass, whose refractive index n = 1:96, The front surface of the substrate is plated with a layer of gold foil and etched the grooves shown in Fig. 3 (b), On the other side of the substrate, a layer of VO_2 thin film with a thickness of h = 180 nm is grown. Compared with the traditional method of plating metal film on the same side of VO_2, the advantage of this method is that avoids preparing periodic metal array structure directly on VO_2 film, which not only reduces the difficulty of absorber realization, but also provides an idea for absorber design in the future. The side length of the substrate is a =60 μm, b=50 μm, thickness H = 400 μm, air groove width x = 2.0 μm, other parameters: m = 20 μm, n = 15 μm, d = 10 μm. The THz wave is incident from the front of the absorber, and Fig. 3 (c) is a schematic diagram of the metamaterial absorber.

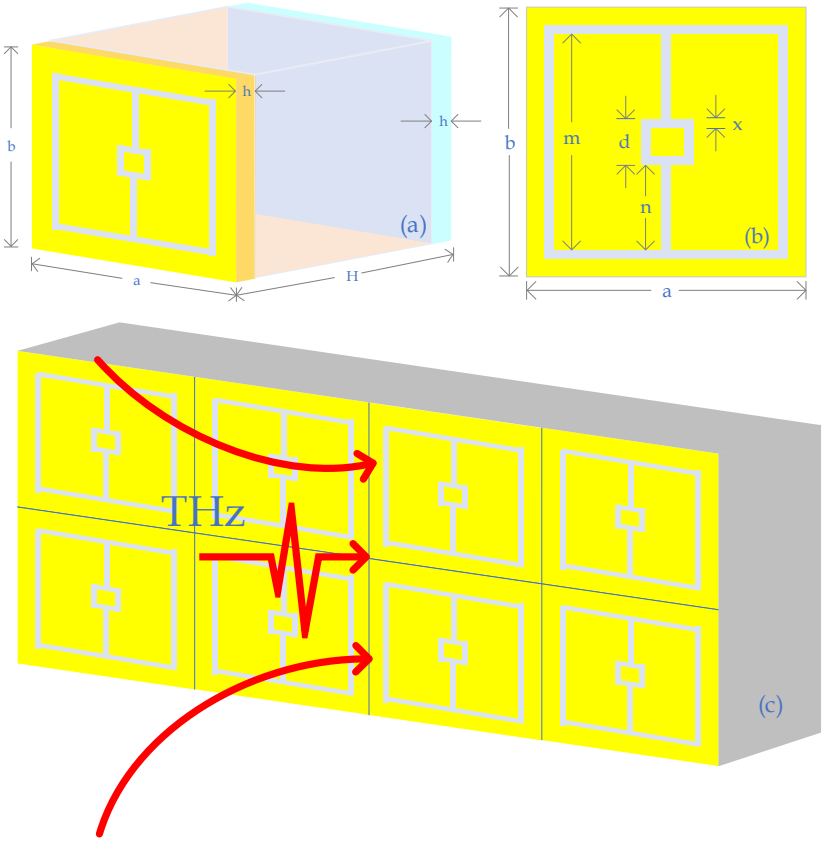

Fig. 3. The structure of metamaterial unit device (a) unit cell structure; (b) unit cell front structure; (c) metamaterial absorber schematic (color online)

Fig. 4 shows the transmission spectrum of a metamaterial absorber at different temperatures calculated by the FDTD method. When the incident THz wave is horizontal polarization (p polarization) shown by Fig. 4 (a), a transmission peak appears near 1.37 THz at 40 ℃, the transmittance is close to 80%, and the bandwidth is about 0.2 THz. With the increase of the external temperature, the transmittance decreases gradually. When the temperature reaches 67 ℃ before the phase transition, the peak transmittance is 63%. However, when the temperature exceeds the phase transition temperature and reaches 70 ℃, the peak transmittance drops to 20%. Thereafter, as the temperature increases, the peak transmittance changes little, and when the outside temperature reaches 80 ◦C or above, the transmittance of the line is stabilized at 12% with little change. Also, at 40 ℃, when the incident THz wave is the vertical polarization (s polarization) shown in Fig. 4 (b), a passband with a peak transmittance of 82% appears near the frequency of 1.15 THz, with a bandwidth of about 0.3 THz. With the increase of temperature, the

transmittance of THz wave decreases gradually, the transmittance is 63% at 67 ℃ before phase transition and 19% at 70 ℃ after phase transition. When the temperature reaches 80 ℃ or higher, the transmittance is basically stable at 13%. It can be seen from the above that the absorber is well modulated in both polarization states.

Because of the phase transition temperature of VO_2 thin film is 68 ℃ and the time of phase transition is very short, when the external temperature changes in the range of 40- 60 ℃ and 70 - 80 ℃, the change range of transmittance is very small. But when the temperature changes near the phase transition temperature (68 ℃), the transmittance changes greatly. In this paper, a more sensitive THz broadband absorber is designed by using this characteristic of VO_2 thin film. compared with the control methods of electricity, light, magnetic field and so on, the temperature control is undoubtedly more convenient and easier to realize.

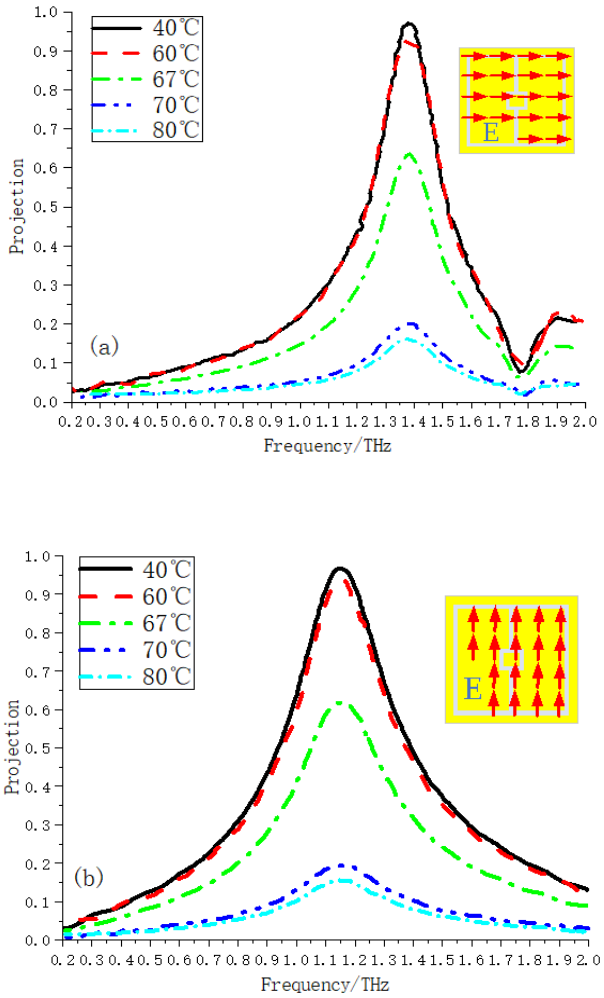

Fig. 4. Transmission line of two polarization incident THz waves at different temperatures (a) P polarization; (b) S polarization (color online)

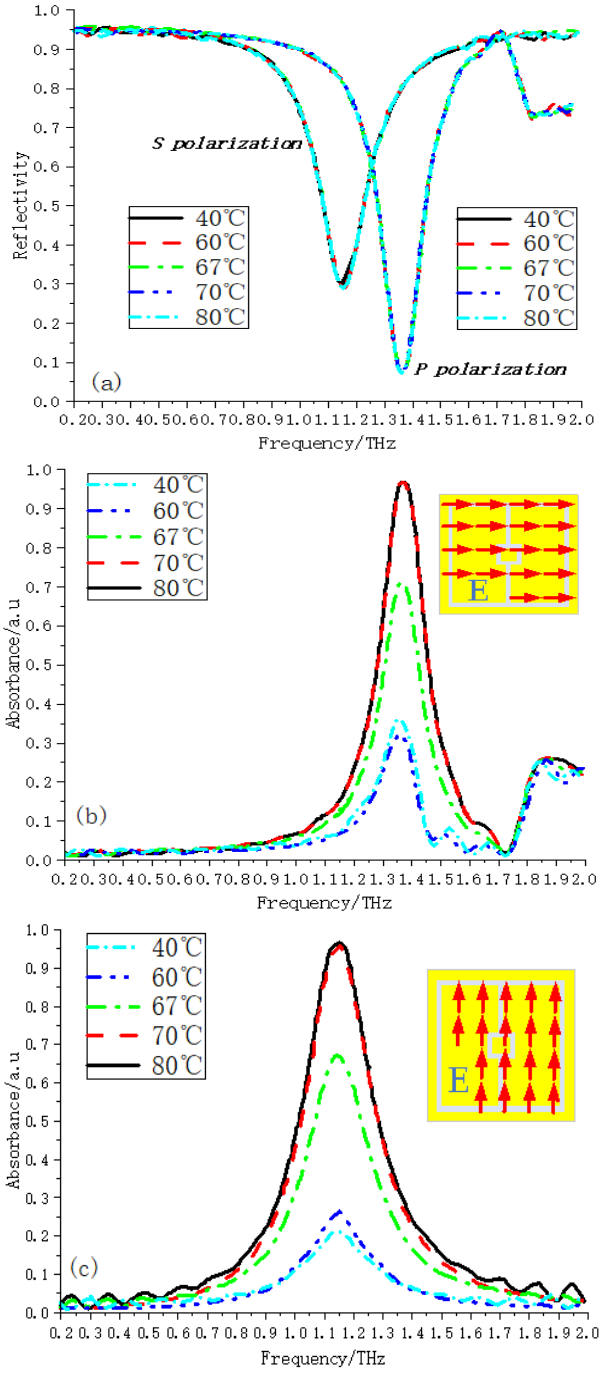

Fig. 5. Reflection and absorption lines of two polarization incident THz waves at different temperatures. (a) absorption line; (b) absorption line of P polarization; (c) absorption line of S polarization (color online)

In addition, as shown in Fig. 5, the reflection and absorption lines of absorber in two polarization states are analyzed in this paper. It can be seen from the reflection spectral line Fig. 5(a) that the reflection spectral lines of the two polarized incident terahertz waves do not change much when the phase transition and carrier concentration of VO_2 thin films increase with the increase of temperature. This is because the reflection of terahertz wave by the

absorber is mainly caused by the metal material on the front side, but the structure and properties of the metal material have not changed during the phase transition of VO_2 material. It can be seen from Fig. 5(b) and (c) that with the phase transition of the VO_2 film, the absorption of the THz wave by the absorber gradually increases from about 25% of 40 ℃ to more than 95% of 80 ℃. It can be seen from above that the decrease of the transmittance of the two polarized incident waves in a specific frequency band is caused by the absorption enhancement of the absorber, but the fundamental reason is that the reflection of the terahertz wave is enhanced after the VO_2 film becomes a metal phase. Therefore, the loss of terahertz waves in the substrate medium is increased.

5. Conclusions

In this paper, a three-layer medium absorber structure is proposed. When the incident terahertz wave is in two states of horizontal polarization and vertical polarization, the transmittance spectrum exhibits two independent transmission broadbands around 1.2 THz, and the center frequencies are 1.15 THz and 1.37 THz, respectively. Based on the phase transition principle of VO_2, the transmittance modulation in two polarization states can be realized by temperature control, and the modulation depth are all more than 65%. With the continuous development of THz technology, the absorber has a great application prospect in the future.

Acknowledgments

This work is supported by Support for scientific research projects (scientific research projects in colleges and universities) (No. 99000332); supported by Foundation Funded Project of doctoral (No. 99000617).

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*Corresponding author: liujianjun8888@hotmail.com