Broadband and perfect terahertz absorber based on multilayer metamaterial with cross-ring patterned structures*

WEN Jin[1,2], LIU Zhanzhi[1], WU Zhengwei[1], PAN Yu[1], and ZHANG Ying[1]**

1. School of Science, Xi'an Shiyou University, Xi'an 710065, China

2. Shaanxi Key Laboratory of Measurement and Control Technology for Oil and Gas Wells, Xi'an 710065, China

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Broadband and perfect terahertz absorber based on multilayer metamaterial using cross-ring patterned structures is proposed and investigated. The structure of the absorber is double absorption layers consisting of a chromium cross ring and eight isosceles right triangles. The unique structure of the double absorbing layers excites the electric dipole multimode resonance, giving rise to high absorption performance. Meanwhile, the influence of construal parameters on absorber behavior is also discussed. The numerical results show that the absorption achieves over 90% ranging from 2.45 THz to 6.25 THz and 99% absorption in the range of 3.7—5.3 THz. The realization of broadband and perfect absorber is described using the impedance matching principle. It is obviously found that the absorber is insensitive to the high angle of incidence for both transverse electric (TE) and transverse magnetic (TM) polarizations. Compared with the former reports, this absorber has remarkable improved absorption efficiency and smaller period. The terahertz absorber may be found applications in the fields of energy capture and thermal detection.

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1. Introduction

As known that terahertz waves usually referred to 0.1—10 THz, it situated in the range of frequencies that is between infrared light and microwave. It has garnered considerable attention owing to its immense potential for applications in wireless communication, biomedical imaging, and optical modulation[1]. However, there has been a lack of materials that can generate strong electromagnetic response with terahertz waves in nature. Since the electromagnetic properties of metamaterials, as an artificial "atom", are affected by their structure due to their electromagnetic properties. Thus, various functional devices on the basis of metamaterials have been submitted and employed to facilitate the advancement of these terahertz-based applications, including polarization converters, filters, and perfect absorbers[2,3]. Metamaterials' perfect absorbers represent a crucial subset of the aforementioned metamaterial devices. As a subwavelength-scale artificial electromagnetic material with outstanding capabilities, it finds wide-ranging utility in stealth technology, photovoltaic cells and thermal emitters[4]. To achieve these applications, it is essential to develop a perfect absorber with better performance.

To achieve perfect absorption, the structure of metamaterial units has been widely studied. In 2008, Landy's team reported the first flawless absorber whose structure is three layers[5]. Subsequently, with the idea of coupling multiple resonant peaks, researchers have designed absorbers with complex patterns and multilayer structures or oversized cell structures to extend the bandwidth. FU et al[6] designed the multilayer graphene absorber with more than 90% absorption in 6.98—9.10 THz. QUADER et al[7] reported a three-layer dual-band adjustable broadband absorber on the basis of a graphene pattern with over 90% absorption in 0.1—3.1 THz and 6.25—8.55 THz. KENNEY et al[8] presented an ultra-large unit structure broadband absorber based on gold possessing beyond 83% absorption in 2.82—5.15 THz. Due to the inherent high Q characteristics of electromagnetic resonant modes, the bandwidth and absorption efficiency of the above absorbers cannot be achieved simultaneously. Recently, some broadband absorbers based on plasma effects have been designed, which has promoted the progress of broadband absorbers[9]. Even so, the existing broadband absorbers' bandwidth is not

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** WEN Jin is an associate professor at Xi'an Shiyou University. He received his Ph.D. degree in 2014 from the Chinese Academy of Sciences. His research interests are mainly in ultrafast nonlinear optics and integrated optics. E-mail: wenjin@xsyu.edu.cn.

Optoelectron. Lett. Vol.21 No.1

large enough, and the application areas of these metamaterial absorbers are narrow.

In this research, a broadband and perfect terahertz absorber on the basis of multilayer metamaterial with cross-ring patterned structures is presented. It is comprised of a chromium resonant layer, a silicon dioxide dielectric material layer, a chromium patterned layer and a silicon dioxide dielectric layer with a gold reflector. It has more than 90% absorption in 2.45—6.25 THz, especially more than 99% absorption in 3.7—5.3 THz. Through the distribution of E_z, we can find that the absorption is triggered upon the electric dipole resonance of the two chromium layers, and the impedance matching principle has been used to elaborate the broadband absorption. Moreover, the effect of the structural dimensions of the metamaterial on the absorption results is also analyzed. The absorber is also polarization-insensitive and insensitive to large incidence angles. Compared with other similar research, our absorber improves the absorption efficiency and reduces the period.

2. Structure design and method

The incoming wave is reflected, transmitted and absorbed by the metamaterial structure. For an absorber, the absorption can be obtained from $A=1-R-T$, in which R represents the reflectivity, T represents the transmittance, and A represents the absorptivity. To obtain a high absorption, the reflectance and transmittance of the structure need to be minimized. Since the substrate is a metal sheet whose thickness is far more than the skin depth, the transmittance tends to zero, what needs to be investigated is how to reduce the reflection[10]. According to the impedance matching principle, once the absorber's impedance equals to the free space's impedance, the reflectivity will decrease to 0, which could achieve flawless absorption.

Fig.1 shows the unit sketch of the perfect absorber, which contains three layers. From upwards and downwards, the first floor is the triangular chromium resonator, the second floor is the silicon dioxide layer, which contains the chromium patterned layer, and the third floor is the gold reflection layer. By optimizing the geometrical parameters, the cell period of P=17.8 μm was obtained. The first layer consists of eight isosceles right triangles with SiO_2 filled in the x and y directions and air spacers upward in the southeast/north and southwest/north directions. The waist length of the triangular resonator with the thickness of t_1 is a, and its distance to the boundary is d. The width of the second layer with a thickness of t_3 is P, and it contains a cross-circle with the thickness of t_2 at a distance of h_1 from the first layer, the crosses' length and width are c_1 and c_2, and the circles' inner and outer radius are r_1 and r_2, respectively. The width of the reflective layer with the thickness of t_4 is P. The structure size of the absorber is shown as below: w=0.707 μm, a=5 μm, d=3.4 μm, t_1=4 μm, t_2=0.05 μm, t_3=14 μm, h_1=4.95 μm, r_1=8 μm, r_2=8.9 μm, c_1=18.5 μm, c_2=4 μm, h_3=9 μm, and t_4=0.5 μm. The dielectric constant of chromium in the terahertz band is described by the Drude model:

$$\varepsilon(\omega)=\varepsilon_\infty-\frac{\omega_{\mathrm{p}}^2}{(\omega+\mathrm{i}\gamma\omega)\omega}, \quad (1)$$

where ω is the frequency, ε_∞ is the high-frequency dielectric constant whose value is 3.2, ω_{p} is the plasma frequency whose value is 2.2×10^{16} rad/s, and the collision frequency of Cr is $\gamma=3.8\times10^{15}$ rad/s[11]. The refractive index for silica is 1.45[12]. The gold's conductivity is set to 4.56×10^7 S/m[13]. The finite-difference time-domain approach is used to simulate the electromagnetic properties of this absorber. The periodic boundary conditions have been established in both the x and y directions, and the perfect absorption boundary conditions have been established for the z-direction for numerical simulation.

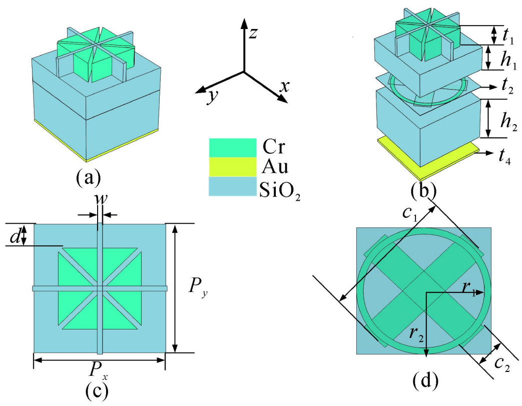

Fig.1 The absorber's structure, composition and three-dimensional view of metamaterial: (a) Sketch diagram of the absorber; (b) Component of the cyclical module; (c) Schematic of the *x*-*y* plane of the top layer; (d) Schematic of the *x*-*y* plane of the middle layer

3. Results and discussion

In Fig.2(a), the absorber obtains flawless absorption in 3.7—5.3 THz and efficient absorption in 2.45—6.25 THz. In addition, due to the device belonging to the centrosymmetric structure, it can be seen that it's insensible to the polarization of the incoming terahertz wave. According to the formula $A=1-R-T$, high absorption can be obtained if the reflection is restrained properly. We first utilize the impedance matching theory to clarify the cause for low reflections by calculating the effective impedance called Z, which is given by the following formula:

$$Z=\sqrt{\frac{(1+S_{11})^2-S_{21}^2}{(1-S_{11})^2-S_{21}^2}}=\sqrt{\frac{\mu}{\varepsilon}}, \quad (2)$$

where S_{11} and S_{21} are the transmission and reflection coefficients. It is necessary to make the absorber's impedance equal to the free space's impedance, which is 1. In Fig.2(b) our absorber has Re(Z)=1 and Im(Z)=0 in a wide range of frequencies, which assists in understanding the mechanism of absorption[14].

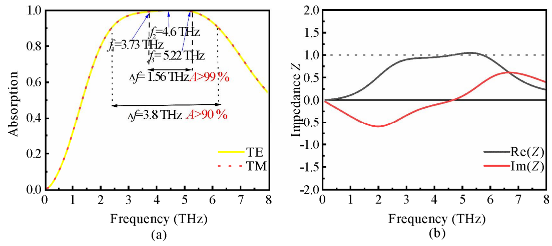

Fig.2 (a) Absorptivity of metamaterial absorber; (b) Impedance comparison in the absorber and free space

Since μ and ε are the magnetic and electrical permeability of the metamaterial, respectively, the distribution of the electromagnetic field at the starting and ending points of the broadband absorption, f_1 and f_2, and at a certain point in the middle, f_3, is investigated further to elucidate the physical absorption mechanism. It is essential to notice that the electric field's direction from incident terahertz waves is in the x direction. E_z distribution can be pointed out to be the polarized charge distribution, with the blue and red regions showing the negative and positive charges under the incident wave, respectively in Fig.3[15]. We notice that the filling of the dielectric makes the charge distribution of the first layer more complicated and the distribution of excitation strengths is not consistent. As seen in Fig.3(b1), there are two heterogeneous charge distributions on each triangular metal. The heterogeneous charges are symmetrically and uniformly distributed around the y-axis, forming multiple pairs of electric dipoles and exciting a multipolar dipole resonance. In Fig.3(b2), it can be seen that the positive and negative charges are uniformly and symmetrically distributed around the y-axis, and the strength of the electric field in the center is smaller than that at the edge. At last, we find that the positive and negative charges are symmetrically distributed on the y-axis and symmetric about the y-axis with the charge distribution from Fig.3(b1).

Overall, the broadband absorber absorbs the incident wave's energy in the form of a simulated electric field. The electric field is mostly enhanced by the resonance of the free electrons of the first and second layers of the metal from Fig.4. Relative to the first layer, the intensity of excited electric field in the second layer decreases along with the increasing frequency of incident wave. In order to explore its consumption mechanism, the impact of the refractive index of the medium on absorptivity was studied and displayed in Fig.5. It's shown in Fig.5(a) that the effect of dielectric loss on the absorption results, and Fig.5(b) shows the influence of the real part of the refractive index of the dielectric on the absorptivity. It can be seen from the results that when the imaginary part of the medium is not zero, the performance of the absorber is significantly degraded. In summary, the power of the incoming terahertz wave is consumed by the ohmic loss from the metal[16].

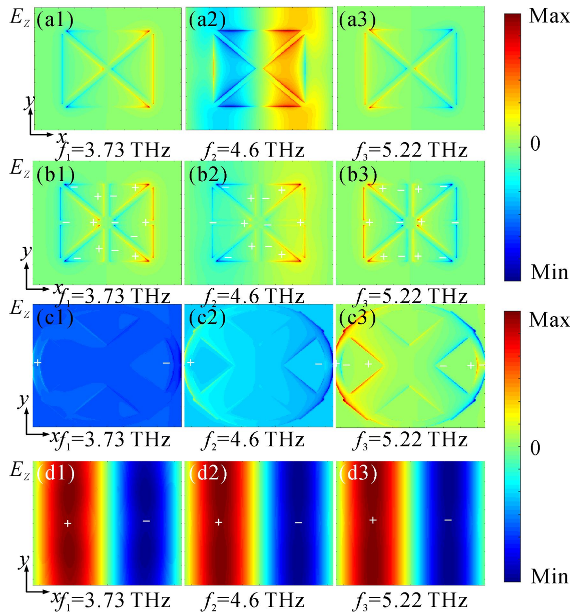

Fig.3 E_z distributions at f_1=3.73 THz, f_2=4.6 THz, and f_3=5.22 THz: (a1)—(a3) The E_z distributions of the first layer without the dielectric crosses; The E_z distributions of (b1)—(b3) the first layer, (c1)—(c3) the second layer, and (d1)—(d3) the bottom layer after the dielectric crosses are placed

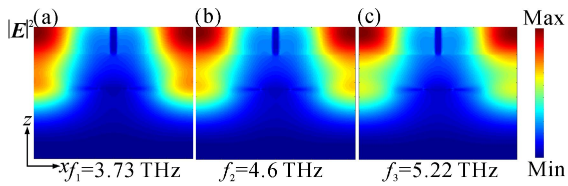

Fig.4 Distributions of electric field intensity in *x-z* plane: (a) f_1=3.73 THz; (b) f_2=4.6 THz; (c) f_3=5.22 THz

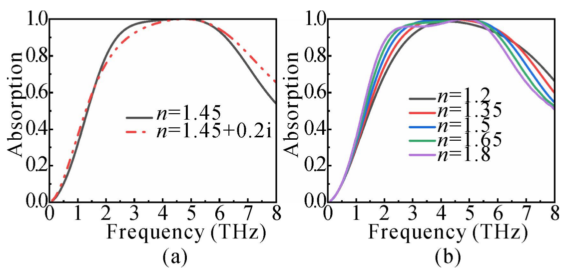

Fig.5 Influence of the medium on the absorptivity of metamaterial absorbers: (a) Influence of presence or absence of dielectric loss on absorption results; (b) Influence of dispersion of the medium on absorption results

Since the structural size has a non-negligible effect on the absorption results, it's critical to study the impact of the structural parameters, which is also conducive to understanding the absorption mechanism. The absorption peak moves to the high-frequency direction after the absorber's period increases, and the bandwidth of the absorber decreases obviously in Fig.6(a). That is because the metal spacing in the adjacent units increases, which weakens the electromagnetic coupling effect of each other, thus influencing the absorption effect. The effects of the second metal pattern layer on the absorber are exhibited in Fig.6(b) and (c). When t_2 is equal to 0, the absorber does not play a role. A broadband perfect absorption phenomenon exists at t_2=0.05 μm, and then the absorption intensity decreases with increasing thickness. It is because the metal's skin depth in the terahertz band is only a few microns.

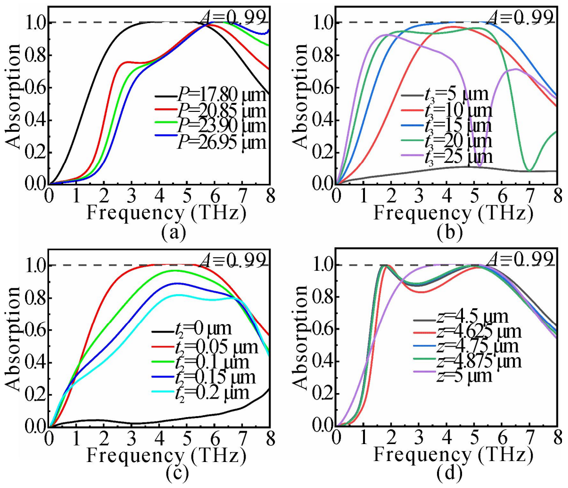

Fig.6 Influence of structural dimensions on the results of metamaterial absorber: (a) *P*; (b) t_3; (c) t_2; (d) Distance *z* of the center of the second layer from the bottom surface of the first layer

When the parameter t_2 exceeds the skin depth, the induced current becomes the surface current, which affects the resonance with the gold bottom plate and the chromium top layer. Since the SiO_2's thickness affects the resonance effect, the t_3 works best for a given value. The significance of the position of the middle layer metal on absorptivity and confirms the above point of view is shown in Fig.6(d). The appropriate distance makes the upper and lower layers have a strong resonance effect and limits the reflection of the terahertz wave. The position and thickness of the interlayer metal have a significant impact on the absorption. It is crucial to notice that the absorption mechanism is mainly electromagnetic resonance. By implementing proper patterning, the resonance effect can be enhanced, leading to an increase in absorption bandwidth and intensity. Therefore, the impact of the geometrical parameters of the rings and metal strips on absorptivity is studied. From Fig.7(a) and (b), the effects of the metal strip's length c_1 and width c_2 on absorption results after a 45° rotation are discussed. From Fig.7(c) and (d), the effect of the inner and outer radius of the ring on absorption results is studied. As a result, we obtained the broadband absorber with better results.

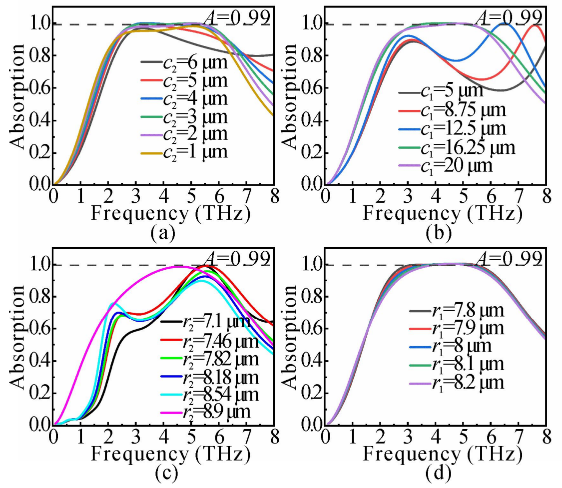

Fig.7 Influence of the dimensions of the cross-ring structure on the results of absorptivity: (a) c_2; (b) c_1; (c) r_2; (d) r_1

It is considered that the top metal pattern not only resonates with the middle metal layer but also its pattern affects its absorption result. Therefore, we explored the effects of thickness t_1 and spacing *w* on the absorption effect. From Fig.8, the intensity of the absorber's absorption increases slightly as t_1 increases, while the high-frequency absorption part decays faster. It could be explained by the truth that the thickness is much greater than the skin depth, which affects the transmission of terahertz waves, and only some currents are present at the surface, where the absorption effect is greatly affected. However, the size of the spacing *w* has little effect on the absorption results. Once there is no spacing, we see a sharp decrease in the absorption intensity and bandwidth. Because the main electromagnetic resonance effect is the resonance with the interlayer which is consistent with the previous point.

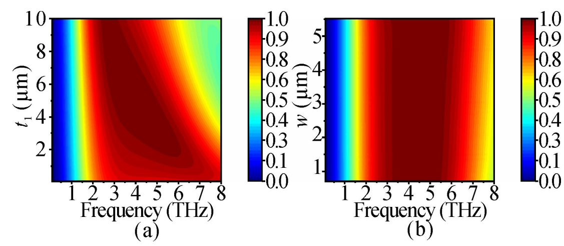

Fig.8 Influence of the first layer's pattern on the absorptivity of the absorber: (a) Influence of t_1; (b) Influence of *w*

The impact of the oblique incidence angle on the absorption band and the peak absorption efficiency of the absorber is studied. From Fig.9, the absorption band of the absorber does not change notably, and the absorption efficiency remains stable over the range of variation of the angle of incidence from 0° to 60°. To better demonstrate the performance of this design, we chose some terahertz absorbers published in recent years to compare with this design. Compared with the terahertz receivers in Tab.1, the absorber submitted in this paper holds a smaller period and a better absorption effect, which reflects the absorber's advantage described in this paper.

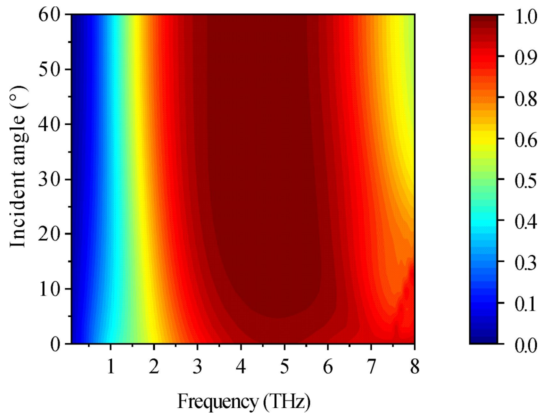

Fig.9 Effect of variation of incident angle of terahertz wave on the absorption results of the absorber

Tab.1 Absorption performance and period size comparison of some published terahertz perfect broadband absorbers in recent years

Reference	Absorption band (THz)	Bandwidth (THz)	Period (μm)	Absorption
[17]	2.6—6.28	3.68	35	>90%
[18]	2.6—7.3	4.7	27	>90%
[19]	1.85—4.3	2.45	75	>90%
[20]	3.4—6.7	3.3	35	>98%
[21]	0.86—3.54	2.68	118	>90%
[22]	2.34—5.64	3.3	30	>99%
This work	3.7—5.3	1.6	17.8	>99%
	2.45—6.25	3.8	17.8	>90%

4. Conclusion

In summary, the chromium-based multilayer broadband absorber with novel structure and great absorption efficiency is demonstrated. It has excellent absorption in 3.7—5.3 THz, and the absorption efficiency exceeds 90% in 2.45—6.25 THz. The physical principle of the absorber is the electric dipole resonance effect, which is proved by impedance matching and electric field distribution. Furthermore, the impact of structural parameters on the results is studied. At the same time, the absorber is insensible to polarization and maintains a high tolerance to the incident angle of electromagnetic waves. The demonstrated absorber has a greater absorption efficiency and smaller period compared to previous devices. This design might have implicit applications in electromagnetic shielding and energy collection.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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