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Polarization-Controlled Metamaterial Absorber with Extremely Bandwidth and Wide Incidence Angle

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Abstract In this paper, a three-dimensional metamaterial structure absorber has been analyzed and discussed. The unit of the absorber is composed of nine different size resistive films which are placed vertically on a metal plate. The proposed metamaterial absorber can achieved the perfect absorption for different polarized waves by rotating around the center axis. The simulated results also show that the 3D absorber has the properties of extremely bandwidth, exhibiting the absorption with above 90 % for TM or TE wave from 20 to 55 GHz. In addition, the mechanism of different absorption between TE and TM mode is also discussed based on the E-field and power loss density distributions. The proposed absorber has potential application in polarization detectors, polarizer, sensor, and so on.

Keywords Metamaterial absorber · Ultra-wideband · Polarization-sensitive · Angle independent

Introduction

Various metamaterial (MM) absorbers have been proposed to achieve perfect properties, such as wideband high absorption, angle independent and polarization insensitive since the first MM absorber firstly was proposed by Landy et al. [1]. The traditional three or multi-layers MM absorbers have many advantages. On the one hand, perfect absorption at multi-frequency points can be achieved by changing the geometric parameters of the first metal layer appropriately. On the other hand, a small size is easy to be processed and a wide incidence angle can be obtained compared with the type of grating structure absorber. However, most of these structures are based on the electromagnetic resonances to absorb the incident waves in a thin thickness, and consequently, the bandwidth is very narrow. The narrow band is typically no larger than 10 % with respect to the central frequency. For example, Sun et al. [2] studied a resonant microwave absorber made of meander lines into the resonant cell achieved high absorption and the above 80 % absorption band is about 0.2 GHz. Li et al. [3] investigated a metamaterial absorber (MA) based on E-shaped structure. With about 1 GHz frequency band, more than 86 % absorption efficiency was observed for this E-shape absorber. Cheng et al. [4] worked on a broadband MA, which is composed of the dielectric substrate sandwiched with metal split-coin resonators (SCR) welded with lumped elements and metal film. However, the perfect absorption band is only about 3.5 GHz. In another study, the dual bands [5, 6], triple-band [7, 8], broad-band [9, 10] MA have been proposed in recent years. However, the narrow absorption bands limit their applications in solar-energy harvesting [11], polarization detector [12], light coupling [13], and so on.

To increase the absorption bandwidth, researchers have proposed several methods such as using magnetic medium [14], a multilayer structure [15], resistive film [16], and loading with lumped elements [17]. For example, the multilayer structure can extend the absorption band due to making the different MA unit resonances at several neighboring frequencies. However, multilayer broadband MAs have high thickness and difficult to fabricate. As another branch of the metamaterial absorbers, resistive frequency selective surface (FSS) absorber [18, 19] which is a periodic resistive patches with strong ohmic loss mounted above the metal plate has the

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advantages of lightweight characteristic and achieving broadband absorption.

In this paper, a new 3D metamaterial absorber is presented and the new MA can maintain a high absorption with 90 % for TM or TE polarized wave from 20.0 to 55.0 GHz. The bandwidth of the 3D absorber is wider than that of traditional three or multi-layers planar structure [20–23]. Moreover, current distribution and power loss density of the structure is analyzed to demonstrate the physical mechanism of different absorption between TM mode and TE mode.

Design and Simulation

Figure 1 shows the three views of the metamaterial absorber unit, which consists of nine different size crosses and copper plate. The crosses are placed vertically on the copper plate. The geometric parameters of the absorber are given as follows: $t_1 = 0.02$ mm, $t_2 = 0.1$ mm, $l = 9$ mm, $w = 5$ mm, $g_1 = g_2 = 0.5$ mm, $d = 1$ mm. The electric conductivity of the cross is 1000 S/m and it is regarded as a resistive film. The absorber structure was simulated and optimized using CST software by considering a single unit cell. The open space boundary conditions were used in x and y directions. The absorption is defined as $A = 1 - T - R = 1 - |S_{11}|^2 - |S_{21}|^2$ and we can minimize the reflection and transmission simultaneously at the same frequency for getting the maximize absorption rate. The absorptivity can be refined as $A = 1 - R$ because the electromagnetic wave cannot get through the copper plate.

Results and Discussion Based on High Absorption for TM Mode

The Reflectivity and Absorption

The simulated transmission and absorption spectra for TE and TM polarized waves are compared in Fig. 2. It can be observed that the reflection of TE polarized wave is very high from 20.0 to 55.0 GHz and the case is completely contrary to TM wave. The results for two different polarizations are different, which imply that the proposed metamaterial absorber is sensitive to the polarization of incident EM waves. This is different from other metamaterial absorbers which are concentrated on the study of polarization-insensitive. It is obvious that a very high (greater than 90 %) and flat-top absorption is obtained for TM polarized wave over a frequency range of 31.2 GHz (21.0–52.2 GHz). Relative absorption bandwidth (RAB) is used to describe the absorption performance of MA, defined as $W_{RAB} = 2(f_u - f_l)/(f_u + f_l)$, where f_u and f_l are the upper and lower limits of a frequency range with absorption above 90 %, respectively. The

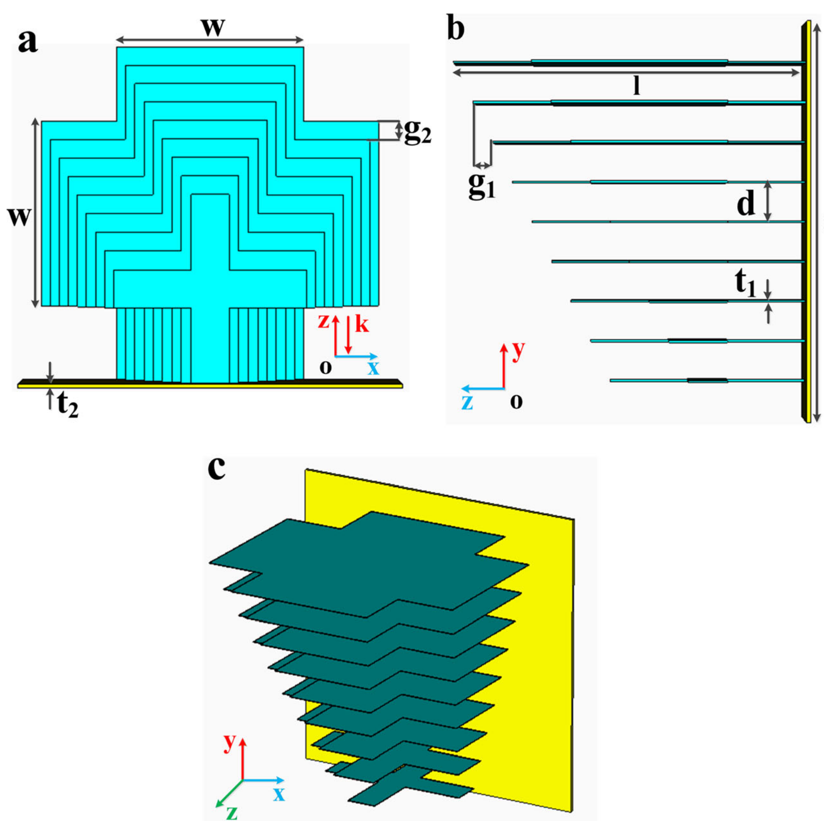


Fig. 1 Schematic of the three-dimensional metamaterial structure. **a** Bottom view. **b** Right view. **c** Perspective view

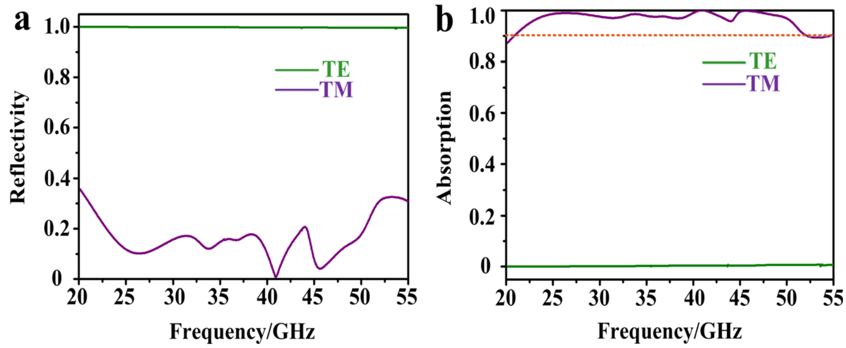


Fig. 2 Simulation results of the extremely bandwidth metamaterial absorber. **a** The reflectivity and **b** absorption of the TM and TE polarized waves

proposed MA shows an excellent absorption performance for TM polarized wave with W_{RAB} equal to 80.8 %, which is much larger than the most of previous reports.

The Mechanism of High Absorption for TM Mode

To better understand the absorption of the separation between TM and TE polarized modes at the 40.9 and 45.6 GHz, in the case of normal incidence, the electric field distributions both for TE and TM modes at these points are depicted in Fig. 3. At the 40.9 GHz frequency, TM polarized wave will change from strong to weak until further attenuation. The intensity of TM polarized wave will become a minimum value when reaching the surface of the metal plate as shown in Fig. 3a. However, the attenuation for TE mode will not change obviously, which implies that the metamaterial absorber is polarization-sensitive at the whole frequency from 20 to 55 GHz. The most notable difference at the two high absorption frequency points (40.9 GHz, 45.6 GHz) lie in the different directions of the current distribution between TE mode and TM mode and it provide a new design thinking in terms of the polarization separation.

To further understand the physical mechanism of the polarization separation at the frequency where the peak absorptions are achieved, power loss density distributions for TM and TE modes are plotted in Fig. 4. Figure 4 shows that the whole power loss density of TM mode is larger than that of TE mode. In addition, the high power losses are concentrated on the edge of the resistive film patches for TM mode at the two resonance frequency points. We can conclude that the attenuation due to resistive film patches is the important stage in the whole absorption process. It clearly implies that the power loss distributions are similar with that of E-field distributions. In other words, the power losses of resistive film patches which are parallel to the electric field direction of propagation are strong. Besides, asymmetric distribution of the nine resistive film patches is the most important reason for the disparate absorption between TE and TM

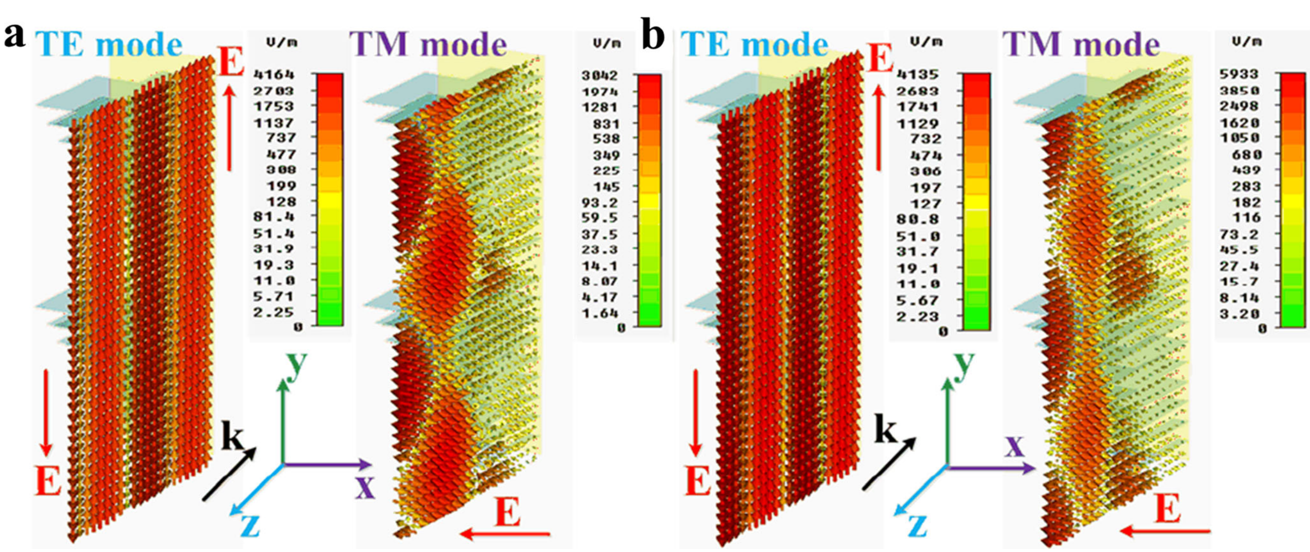
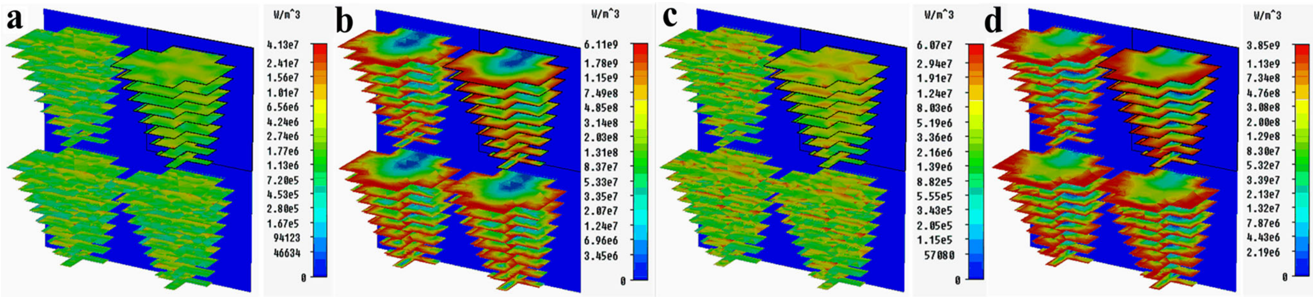


Fig. 3 The E-field distribution for TE and TM mode. **a** At 40.9 GHz. **b** At 45.6 GHz



TE mode, f=40.9GHz TM mode, f=40.9GHz TE mode, f=45.6GHz TM mode, f=45.6GHz

Fig. 4 The power loss density for perspective view. **a** At 40.9 GHz. **b** At 45.6 GHz

modes in terms of normal incidence. We can change the absorption effect easily for TM or TE mode by changing the distribution of the resistive film patches. And, the design ideas pay the way for the polarization detector and polarizer.

The power loss density distributions on the surface of the resistive films are given in Fig. 5. The power loss mainly concentrated in the whole edge of the crosses at 40.9 GHz for TM mode. But, the whole power loss of the TE mode is very weaker than that in TM mode. The results are agreed with the case as shown in Fig. 4.

Design and Discussion Based on High Absorption for TE Mode

Design for High Absorption of TE Mode

Reflectivity and Absorption Curves

Inspired by the difference electric field distribution between TE and TM polarized wave, the unit cell of the extremely bandwidth absorber with high absorption for TE mode is shown in Fig. 6. The MM absorber consists

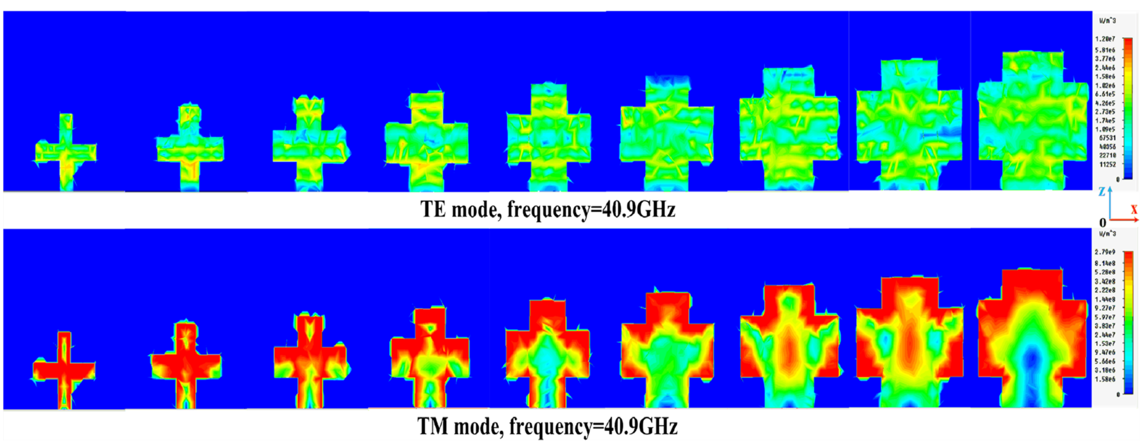
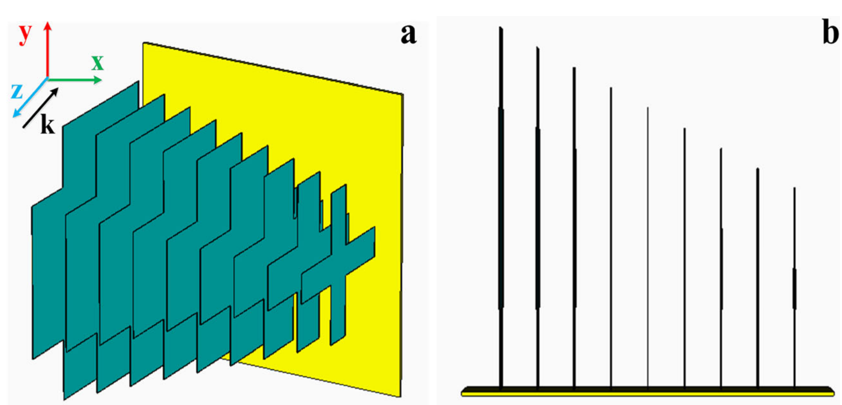


Fig. 5 The power loss density distribution on the surface of the nine different crosses

Fig. 6 The schematic structure of the 3D absorber with high absorption for TE mode. **a** Perspective view. **b** Bottom view



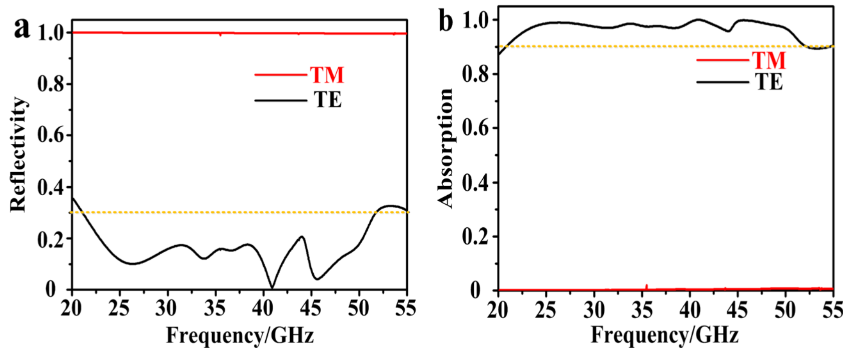


Fig. 7 The simulated results of the absorber with high absorption for TE mode. **a** Reflectivity curves. **b** Absorption curves

of nine resistive film patches and copper plate. The value of geometric parameters of this absorber is same as that in Fig. 1. In other words, the absorber as shown in Fig. 6 can be regard as the structure shown in Fig. 1 which has been rotated 90° around the center of the unit cell. The reflection and absorption curves are plotted in Fig. 7. Figure 7a shows the low reflection of TE mode and fully reflectivity for TM mode. The absorption over 90 % of the structure for TE mode is ranging from 21.0 to 52.2 GHz and the curves shows a reverse trend to that in Fig. 2. The results imply that the proposed absorber can maintain a high absorption for different states of polarization wave by rotation operation.

The Mechanism of High Absorption for TE Mode

In order to explain the phenomenon that the absorption can maintain a high absorption for TE mode, the E-field and power loss density distributions are plotted in Figs. 8 and 9, respectively. The TE polarized wave will be almost loss off completely when getting through the nine resistive film patches from Fig. 8a, b. However, for TM case, the absorber has no effect on the absorption of TM mode from Fig. 8c, d. In addition, the case of power loss density distribution between TM can further clarification the phenomenon of polarization separation as shown in Fig. 9. This is similar with that in Fig. 4.

Results and Discussion Based on Oblique Incidence

The Absorber with High Absorption of TM Mode

Figure 10 exhibits the absorption curves of the absorber which is shown in Fig. 1 based on oblique incidence. The value of the absorption for TE mode is very small, but the absorption will become higher for TM mode with the increasing of incident angle. The trend of the curves between TE mode and TM mode is similar with that in normal incidence. In other words, the 3D absorber will become polarization sensitive with the increasing of the incident angle, and it will have good impact on polarization segregation.

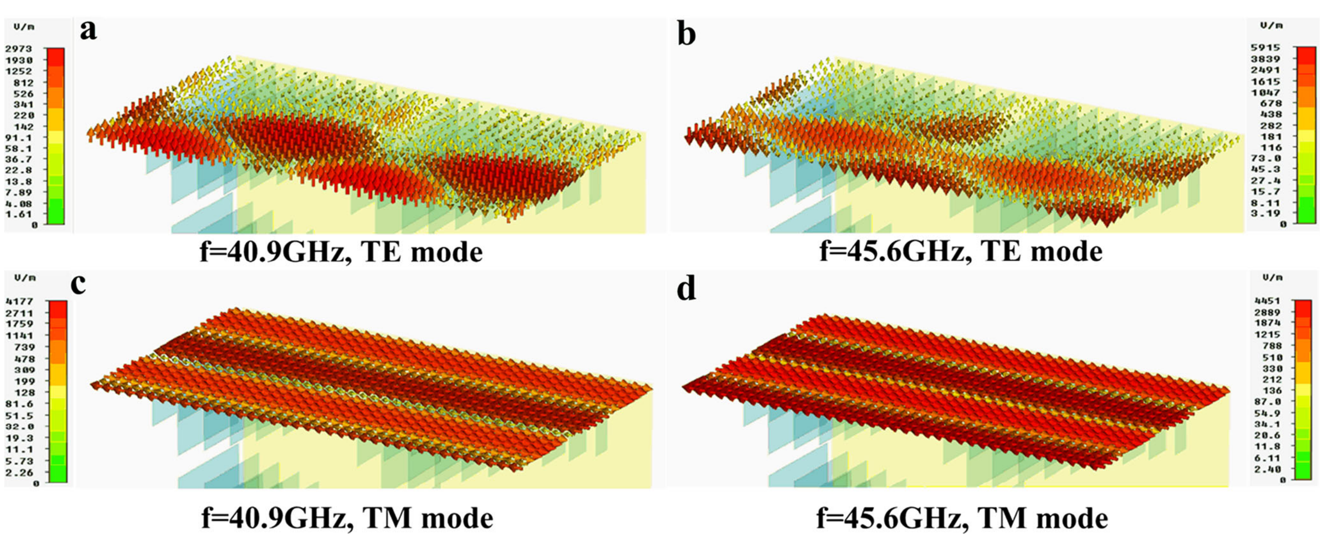


Fig. 8 The current distribution for TE and TM mode. **a** At 40.9 GHz. **b** At 45.6 GHz

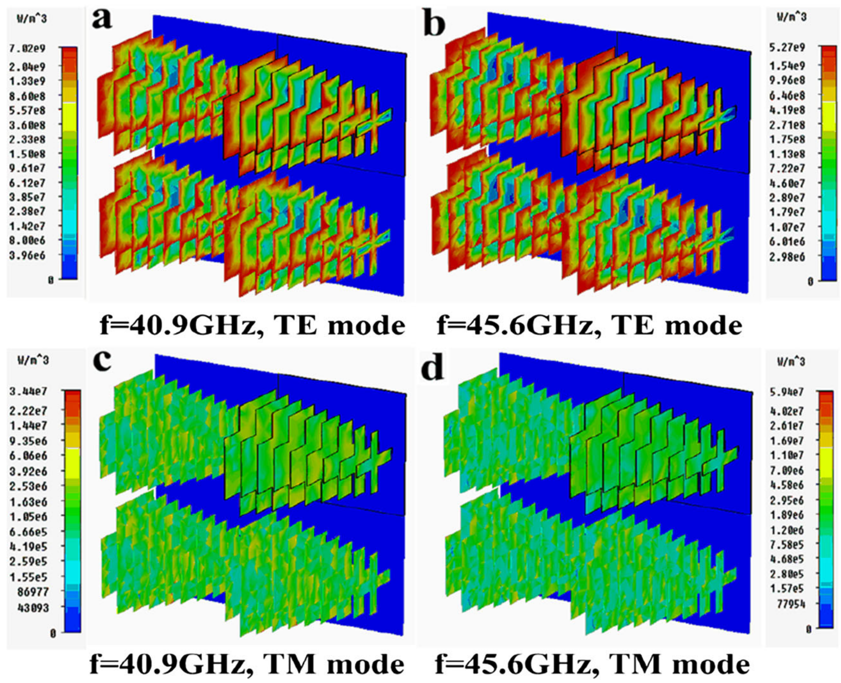


Fig. 9 The power loss density of the absorber with high absorption for TE mode. **a** At 40.9 GHz. **b** At 45.6 GHz

The Absorber with High Absorption of TE Mode

With regard to oblique incidences, incident angles less than 60° have a little influence on the working performance in terms of the absorption with above 90 % for TE mode. For example, the absorption will become wider when the incident angle is 15°. However, the absorption curve marginally drops when the incidence angle is 60°, as shown in Fig. 11a. The absorption curves of TM mode are different significantly from that of TE mode from Fig. 11b. The whole value of absorption will be higher with the increasing of TM incident angle, which is different from the three-layer planar metamaterial absorber. It can be easily seen that the widest absorption bandwidth can be achieved with the incident angle 60° and it exhibits an

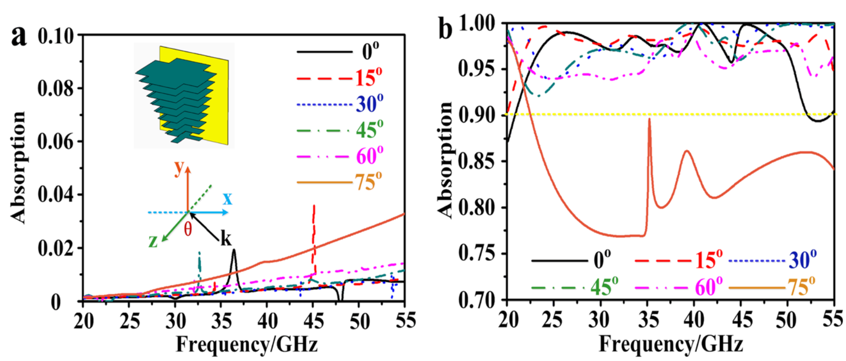


Fig. 10 The absorption of the absorber based on oblique incidence. **a** TE mode. **b** TM mode

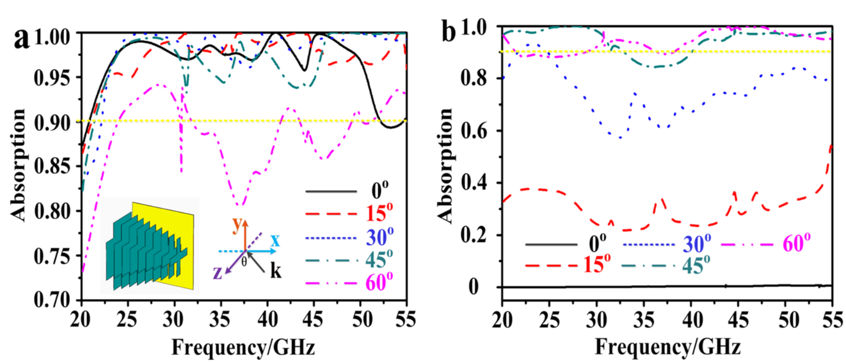


Fig. 11 The absorption of the absorber based on oblique incidence. **a** TE mode. **b** TM mode

extremely bandwidth of absorption more than 90 % from 29 to 55 GHz. As we known, for the normal incidence, the TM electric field is along the x direction and the resistive film patches at the vertical direction have no loss for TM polarized wave. However, for the case of oblique incidence, the direction of electric field has been changed and thus can be decomposed into two components E_x and E_Z which are along x-axis and z-axis direction, respectively. The electric field with parallel to z-axis will be beneficial to the absorption for TM polarized wave.

Conclusion

We proposed a three-dimensional polarization-sensitive matamaterial absorber, which is different from other plane designs. The absorption properties of MA which is composed of resistive film and copper plate are studied and discussed. A bandwidth of 31.2 GHz with absorption of more than 90 % for TM mode or for TE mode was obtained from the extremely bandwidth absorber. It is worth mention that the proposed metamaterial absorber can achieve the perfect absorption for different polarized waves by rotating around the center axis. In addition, the loss mechanism for TM and TE polarized wave is investigated by analyzing the current and power loss density distributions. The presented MA supply a new design ideal for extremely bandwidth absorber and achieving polarization separation. We believe that the new 3D MA can be a good candidate for the application of sensor, polarization detector, medical imaging, and so on.

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