Polarization insensitive metamaterial absorber based on E-shaped all-dielectric structure

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In this paper, we designed a metamaterial absorber performed in microwave frequency band. This absorber is composed of E-shaped dielectrics which are arranged along different directions. The E-shaped all-dielectric structure is made of microwave ceramics with high permittivity and low loss. Within about 1 GHz frequency band, more than 86% absorption efficiency was observed for this metamaterial absorber. This absorber is polarization insensitive and is stable for incident angles. It is figured out that the polarization insensitive absorption is caused by the nearly located varied resonant modes which are excited by the E-shaped all-dielectric resonators with the same size but in the different direction. The E-shaped dielectric absorber contains intensive resonant points. Our research work paves a way for designing all-dielectric absorber.

Keywords: Absorber; all-dielectrics; E-shaped; microwave ceramics.

1. Introduction

Metamaterial perfect absorber attracts all over the world researchers since it was proposed by Landy et al. in 2008. Metamaterial absorbers based on metallic patterns develop rapidly in recent years, the metamaterial perfect absorber was designed, fabricated, measured in different working bands, such as microwave, terahertz, infrared and optical absorbers. The absorbers have many their own different advantages. Polarization-independent is a character of the absorbers which attracts many researchers to study. Cao et al. used a phase-change metamaterial to achieve a mid-infrared tunable polarization-independent perfect absorber. Wang et al. used a double-layered composite structure on a metallic board to achieve an ultra-broadband and polarization insensitive terahertz metamaterial absorber. Yang et al. designed a broadband polarization insensitive absorber whose unit cell is composed of resonators mounted crosswire and gradient split ring resonator. Mao et al. proposed a multi-band polarization-insensitive metamaterial absorber based on Chinese ancient coin-shaped structures. Bhattacharyya and Srivastava used electric field-driven LC resonator to achieve a triple-band polarization-independent ultra-thin metamaterial absorber, however, most of the metamaterial perfect absorbers contain metallic patterns. Although metal has many advantages, it has deficiency in oxidation and corrosion resistance, as well as not suitable for applications in high temperature and high power compared to high permittivity ceramics. On the other hand, dielectric materials have more resonant modes than metal, so we want to design a polarization insensitive all-dielectric metamaterial absorber. In recent years, the research of dielectric metamaterial is just developing, and remarkable progress is achieved in theory, experimental methods and applications. These provide a good foundation for the study of dielectric absorbers.

A perfect absorber via placing high dielectric cubes on a metal plate was proposed by Liu, and he studied the effects on absorbing properties with changing edge length and the permittivity for the cubes of the dielectric material. The perfect absorber achieves a single frequency absorbing in the X-band. In this paper, we design complex E-shaped structure which is abundant in resonant modes and achieve a band enhanced polarization insensitive all-dielectric absorber at microwave frequency regime. The average absorption rate of the absorber can reach above 86% at bandwidth 1 GHz for both TE and TM polarization. Our work provides new ideas and methods for future studies of absorbers with all-dielectric structures and expands the application of high permittivity dielectric ceramics.

2. Modeling and Simulation

The schematic of the dielectric metamaterial absorber is shown in Fig. 1. The structure is made of Sr,BaTiO3 whose relative permittivity is 300, and the loss is 0.005. The unit cell contains 16 E-shaped resonators which are oriented in different directions. These 16 E-shaped resonators are in the same size, for which the geometrical parameters are shown in Fig. 1(a). In order to describe the size of the structure, we disassemble the E-shaped resonator to one vertical edge and three horizontal edges. The length (y-direction) of the vertical edge is 5 mm, and the width (x-direction) of the vertical edge is 1 mm. The length (y-direction) of each horizontal edge is...
1 mm, and the width (x-direction) of each horizontal edge is 4 mm. The thickness (z-direction) of the whole structure is 0.4 mm. The 16 E-shaped resonators are placed at the copper plate to makes up the minimum unit cell with size $28 \times 28$ mm$^2$, as shown in Fig. 1(b). The arrangement of the periodic absorber is shown in Fig. 1(c).

The E-shaped structure is simulated by the commercial finite difference frequency-domain solver Microwave Studio (CST). The performance of the absorber can be characterized by the formula:

$$A(\omega) = 1 - R(\omega) - T(\omega) = 1 - |S_{11}(\omega)|^2 - |S_{21}(\omega)|^2,$$

where $R(\omega) = |S_{11}|^2$ is the reflectance and $T(\omega) = |S_{21}|^2 = 0$ is the zero transmittance due to the presence of the ground plane in the metallic film. As shown in Fig. 2, when the incident wave is TE polarization, the reflection loss is below $-5$ dB between 12.96 and 13.80 GHz, in which average absorption rate is 86.4%. There are five resonant points in this range. They are located at 13.03, 13.16, 13.22, 13.33 and 13.48 GHz. The resonant points at 13.03 and 13.48 GHz are stronger than other points. The reflection loss of 13.03 GHz can reach about $-34.05$ dB; and that of 13.48 GHz can reach about $-45.4$ dB, their absorption rate can reach 99.96% and 99.997%, respectively. When the frequency is at 12.99–13.67 GHz, the average absorption rate can reach 91.48%. When the incident wave is TM polarization, the reflection loss is below $-5$ dB between 12.88 and 13.78 GHz and its average absorption rate can reach about 86.66%. In this range, there are seven resonant points located at 12.92, 13.01, 13.16, 13.25, 13.47, 13.63, and 13.76 GHz, respectively. The resonant peak reaches maximum at 13.47 GHz. Its reflection loss can reach about $-30$ dB and absorption rate can reach 99.9%. When the frequency is at 13.07–13.61 GHz, the average absorption rate can reach 92.19%.

### 3. Theoretical Analysis

In our previous work, we used effective medium theory to analyze the metamaterial absorbers, and explained that impedance matching and strong interior absorption could be achieved simultaneously. In this paper, we also use the theory to analyze and discuss the E-shaped structures.

The distribution of the electric and magnetic fields at the strongest resonant point for both TE and TM polarization are investigated to analyze the mechanism of the absorption. Figure 3 is the electric and magnetic fields distribution at 13.03 and 13.48 GHz when the incident wave is TE polarization. It is shown that every E-shaped structure inspired by the incident wave behaved some kind of special distribution resonant modes. The resonant modes and resonant frequencies are relative with the directions of the E units. It can be seen from Fig. 3(a), for different E-shaped units there are different resonant modes and the inner displacement current behaves a very strong localization effect. There are many differences in every resonant area. Different E-shaped structures take effects in different resonant points, which can be seen from Fig. 3, different E units take effect at 13.03 and 13.48 GHz. The directions of magnetic fields are vertical to the electric fields. A different E unit has different resonant mode. Many different resonant modes result in the increase of the localization field so that the loss of the incident wave increase. This is why the absorption band forms.
For different polarization incident wave, although the resonant modes and the frequencies of every E-shaped resonator can be changed, because of the distribution of E-shaped resonator in every direction, the whole structure is insensitive to the polarization. Figures 3 and 4 can support the view. Every E-shaped resonator in different direction but in the same size consist of the disorder structure contains many different resonant modes, and behave a polarization insensitive absorption.

Fig. 3. The electric and magnetic fields at 13.03 and 13.48 GHz when the incident wave is TE polarization. (a) The electric field distribution at the phase of 0° at 13.03 GHz. (b) The magnetic field distribution at the phase of 90° at 13.03 GHz. (c) The electric field distribution at the phase of 0° at 13.48 GHz and (d) the magnetic field distribution at the phase of 90° at 13.48 GHz.

Fig. 4. The electric and magnetic fields of TM polarization at 13.47 GHz. (a) The electric distribution at the phase of 0° at 13.47 GHz and (b) the magnetic distribution at the phase of 0° at 13.47 GHz.
Only one E-shaped structure is simulated. The size of E-shaped structure is the same as Fig. 1(a). The size of metal plate is $7 \times 7 \text{mm}^2$, as shown in Fig. 5(a). The frequency dependence of the absorption under different polarization angles is depicted in Fig. 5(b). In the simulation, the polarization angle is varied by $3^\circ$ from $0^\circ$ to $90^\circ$. The 16 E-shaped structures can be seen as eight pairs of E and the direction of every pair E is opposite. So although 1 E-shaped structure has cross polarization, the cross polarization of the whole structure is canceled. The frequency dependence of the absorption under different incident angles is depicted in Figs. 5(c) and 5(d). The full wave simulations are performed to verify the angle dispersion for both TE polarization (Fig. 5(c)) and TM polarization (Fig. 5(d)). In the simulation, the incident angle is varied by $3^\circ$ from $0^\circ$ to $75^\circ$. It can be seen from Fig. 5 that only 1 E-shaped all-dielectric structure can result in many different resonant modes, especially at 13–14 GHz. So when the structure contains 16 E-shaped structures in different directions, the resonant modes work together enhanced absorption band and because the 16 E-shaped structures are along different directions, the whole structure can be seen as a symmetrical structure, which makes the structure insensitive to polarizations.

The E-shaped structures have many resonant modes. The resonant modes shown in Figs. 3 and 4 did not contain all the resonant modes. There are many different resonant modes appear at working band for both TE and TM polarization, sometimes some complex resonant modes even can change with the phase. In order to illustrate the structure contained many different resonant modes, the eigen modes of only one E-shaped structure (Fig. 5(a)) are simulated. The difference between the 16 E- and 1 E-shaped structures is the direction, their eigen modes are the same. We selected some representative eigen modes of the 1 E-shaped structure listed in Fig. 6.

Figure 6 shows six resonant modes appear in the working band of 1 E-shaped structure, it can be seen that the resonant modes in Figs. 6(a) and 6(b) also appeared in Fig. 3(a). It is not mean that the 16 E-shaped structure only contains six resonant modes, Fig. 6 just list the part of eigen modes of 1 E-shaped structure. There are many resonant modes in the resonant points for TE and TM polarization. It is also difficult to identify some complex resonant modes. The resonant modes in 16 E-shaped structure have some differences from the eigen modes in 1 E-shaped structure. This is because these 16 E-shaped structures are located closely; the distribution of the electric fields can be influenced by each other. So it is verified that the basic of the 16 E structure comes from 1 E-shaped structure, and E-shaped structure contains many resonant modes which form the absorption band.

In order to analyze the stability of the incident angle of the whole structure, we simulated the angle of incident wave from $0^\circ$ to $60^\circ$. Figure 7(a) shows when the incident wave is TE polarization, with the angle increased, the reflectivity is decreased. When the angle is $15^\circ$, it is nearly the same as the angle is $0^\circ$. When the frequency is between 12.98 and 13.87 GHz, the reflection is below $-5 \text{dB}$. The average absorption rate is about 86.65%. When the angle is $30^\circ$, the reflection is below $-5 \text{dB}$ at 12.94–13.78 GHz.
The average absorption rate is about 85.50%. When the angle is 45°, the average absorption rate is about 78.98% between 12.94 and 13.74 GHz. When the angle is 60°, the average absorption rate is about 71.49% between 12.94 and 13.52 GHz. The two deepest resonant points are also reduced when the incident angle becomes larger. Figure 7(b) shows when the incident wave is TM polarization, with the angle increased, the reflectivity is increased. When the incident angle is 15°, the reflection is below -5 dB between 12.89–13.71 GHz. The average absorption rate is 89.49%. When the angle is 30°, the reflection is below -5 dB at 12.89–13.92 GHz. The average absorption rate is about 89.12%. When the angle is 45°, the reflection is below -5 dB at 12.91–13.94 GHz. The average absorption rate is about 91.09%. When the angle is 60°, the reflection is below -5 dB at 12.94–13.96 GHz. The average absorption rate is about 91.17%. It is obvious that if the incident angle increased, for TM polarization, the reflection loss will decrease but its average absorption rate can still be above 70%. These results demonstrate that the metamaterial absorber could achieve high absorption under wide incident angles for both TE and TM polarization.

4. Conclusion

In this paper, we design a kind of all-dielectric metamaterial absorber based on E-shaped high-permittivity ceramics; its absorbing property is insensitive for incident angles and polarization of incident wave. The absorber’s average absorption can achieve 86% with the bandwidth of 1 GHz, and in this absorption band there is about 0.60 GHz bandwidth the average absorption rate can reach above 90% for both TE and TM mode. High-permittivity ceramics have the advantages in antioxidant, corrosion resistant, especially in high power and high temperature application. The high-permittivity dielectrics also have more resonant modes than metal so we
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