Broadband metamaterial absorber

Xia Ma$^1$, Feng Tian$^{1*}$, Xiaoyan Li$^2$, Liang Guo$^3$ and Xiaojun Huang$^{1,*}$

1 College of Communication and Information Engineering, Xi’an University of Science and Technology, Xi’an, Shaanxi, 710054, People’s Republic of China
2 College of Physical Science and Technology, Northwestern Polytechnical University, Xi’an, Shaanxi, 710129, People’s Republic of China
3 College of Physics and Electrical Engineering, Kashi University, Kashi 844007, People’s Republic of China

* Authors to whom any correspondence should be addressed.

E-mail: tianfeng@xust.edu.cn and hxj@xust.edu.cn

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Abstract

In this paper, we present a broadband metamaterial absorber with excellent performances of oblique incidence and polarization insensitivity for enhancing the absorbance of electromagnetic waves at oblique incidence. Simulated results show that absorbance is larger than 0.9 in 1.61–4.45 GHz with the full width half maximum is 122.44%, and absorbance can be maintained stably as the incidence angle increases to 45° both in the case of transverse electric and transverse magnetic waves. The simulated results are successfully verified by microwave experiment in the anechoic chamber. The physics of absorption are revealed by the electric and magnetic fields energy distribution. We believe that the proposed absorber has many promising applications in electromagnetic stealth and energy harvesting.

1. Introduction

Electromagnetic (EM) metamaterial absorber (MMAs), usually composed of periodic sub-wavelength cells [1], have extensive applications in EM civil and military fields because of their unique properties not existed in natural materials [2]. C M Watts et al summarized the design methods, applications, and the performance of MMAs ranging from microwave to visible light [3]. MMAs have the clear advantages of bandwidth, geometry and fabrication compared with the conventional absorber [4–8], thus MMAs have been widely used in thermal radiation, sensors, EM stealth, energy harvesting and other fields [9–18]. Recently, all-dielectric and nonlinear saturated materials with 3D printing technology have been used to implement MMAs [9, 19–25]. So far, MMAs still suffer from the narrow bandwidth, polarization sensitivity and non-ideal oblique incidence, which greatly limit the applications of the MMAs [26–28]. The absorption bandwidth can be extended by iterating on a single cell with different geometric dimensions or stacking multiple layers on a single cell, but the disadvantages of this artistry are robust geometry and thickness [3, 29, 30]. High impedance surface (HIS) and lumped elements are also the effective ways to enhance the bandwidth of the MMAs [31–39]. Due to the difference of resonance and coupling response, the huge challenge of the MMAs is that the absorbance is quite unstable in the case of transverse electric (TE) and transverse magnetic (TM) wave oblique incidence.

In this paper, we present a broadband MMA by loading lumped resistor into double loop split-ring and sector shaped resonators, which shows the remarkable performance of the absorbance enhancement of the oblique incidence and polarization insensitivity. The simulated results show that the absorbance is larger than 0.9 in 1.61–4.45 GHz covering the S and L bands with the full width half maximum is 122.44%. Moreover, the absorbance remained stable at 0.9 when the incident angle increased to 45°. Microwave experiments accurately verify the simulation, and the experimental results are coincided with the simulated results. The effects of geometry and resistors on the absorbance are analyzed in detail during the simulation and optimization. The physics of the absorption of the designed MMA is investigated by using the electric and magnetic fields energy distribution. The proposed MMA has a good application prospect in electromagnetic stealth and energy harvesting, especially in the case of very sensitive to oblique incidence.

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2. Structure design, simulation and experiments

The designed MMA is illustrated in figure 1, which consists of four layers, the top layer is composed of double loop split-rings and a set of metal sector. The lumped resistors are inserted into the gaps of the loop split-rings and sectors for expanding the absorption bandwidth shown in figure 1 (a), and the cross-polarization reflectance will not exist due to the symmetric structure. The second layer is the dielectric of FR-4, whose relative permittivity, loss tangent and thickness are 4.3, 0.025, and 1 mm, respectively. The third layer is the air, and the significance of which is matching impedance in the free space via adjusting the thickness of the layer. A copper plate with $\sigma = 5.8 \times 10^7$ S m$^{-1}$ and thickness of 0.03 mm serves as the bottom reflector to block the transmission. The final optimized dimensions of the unit cell are shown in table 1. For the sake of detail, figures 1 (a)–(c) depict the top view, side view and perspective view of the unit cell, respectively. Herein, the absorbance is calculated as $A(\omega) = 1 - R(\omega) = 1 - |S_{11}|^2$, $A(\omega)$, $R(\omega)$ stand for the absorbance and co-polarization reflectance, and $S_{11}$ is the reflection coefficient of the electromagnetic wave.

In the simulation, the commercial software CST Microwave Studio is used for numerical simulation. We first model a single cell structure on x-y plane, and then the unit cell boundary condition is set along x- and y-axis, this means the structure is modelling on the infinite plane (xoy plane). In addition, open add space boundary is applied in z-axis, and transverse electric (TE) and transverse magnetic (TM) waves are normally incident on the metamaterial, respectively. The boundary conditions of unit cell are applied in x- and y-directions and open (add space) boundary condition is applied in z-direction, and the tetrahedron mesh with the size of $\lambda/10$ (\lambda is the center wavelength of the working frequency) is also used in the simulation. In the

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**Table 1.** Optimized dimensions of single sub-cell.

| Parameter | $t_1$  | $t_2$  | $R_1$  | $R_2$  | $R_3$  |
|-----------|--------|--------|--------|--------|--------|
| Dimension | 2 mm   | 16 mm  | 250 $\Omega$ | 250 $\Omega$ | 450 $\Omega$ |
| Parameter | $L$    | $r_1$  | $r_2$  | $r_3$  | $g$    |
| Dimension | 40 mm  | 16 mm  | 12 mm  | 9 mm   | 1 mm   |
experiment, the experimental and measurement methods are the same as those in [40]. We fabricate the experimental sample with the identical geometry in the simulation by using print circuit board (PCB) technology, and a part of the fabricate sample which is shown in figure 1(d). Because of the limitation on fabrication techniques, we just fabricate the sample with the geometry of 480 × 480 mm² (10 × 10 units). In the anechoic chamber, the vector network analyzer (R&S ZNB40) connects two horn antennas through the coaxial line, one antenna is used as the transmitter and the other is used as the receiver. We first use the same size metal plate to test the reflectance for normalization after calibration, and then the sample was put on the same position to measure the reflectance.

### 3. Results and discussion

First of all, we simulate the absorptance of loading resistors and no loading resistors, and the results for the two different cases are presented in figure 2. From the results in figure 2, we can see that there are three resonances located at 2.48, 3.89 and 4.91 GHz with the absorptance of 0.12, 0.78 and 0.90 without lumped resistors loaded, respectively. With the lumped resistors loaded, there are two resonance obviously located at 2.01 and 4.12 GHz respectively. With the lumped resistors loaded, there are two resonance obviously located at 2.01 and 4.12 GHz with the absorptance of 0.99 and 0.95, respectively. Meanwhile, the bandwidth of the absorptance greater than 0.9 is 1.61–4.45 GHz with the full width half maximum (FWHM) is 122.44%. Therefore, we can conclude that the achievement of broadband and high absorptance MMA is basically due to the addition of the lumped resistors.

Figure 3 shows the simulated and measured results of absorptance under TE wave. It can be seen that both the simulated and measured absorptances are larger than 0.9 in 1.61–4.45 GHz when the incident angle increasing from 0° to 45° in figures 3(a) and (c). For the TM wave, the simulated and measured absorptance also exceeded to 0.9 at 1.61–4.45 GHz when the incident angle reaches 45° in figures 4(a) and (c). Distributed diagrams of the absorptance are visually showed in figures 3(b), (d), 4(b), and (d). Specifically, we need to emphasize the difference between the EM coupling of TE and TM waves, and the absorptance of the MMA is mainly due to magnetic coupling. The H-field direction of TE wave along y-axis, and the coupling in this case, so the magnetic coupling will not be weakened as the incident angle increases. For the TM wave, the H-field direction along x-axis, and the absorptance decreases gradually with the increase of the incident angle because of the decrease of magnetic coupling. However, it is satisfied that the absorptance does not decrease as the incident angle increases in the case of TM waves in figures 4(c) and (d). It means that the proposed MMA can well overcome the defect of oblique incidence of TM wave and has the same performance as TE wave in the case of oblique incidence. We can see that the simulation results are consistent with the experimental results from figures 3 and 4.

Figure 5 shows the simulation and measurement absorptance with different polarizations. The simulation result from figure 5(a) shows that the bandwidth is 1.21–5.04 GHz with the relative bandwidth of 122.83% for TE wave normal incidence. The absorptance of the measurement in FWHM shown in figure 5(b) is 1.15–5.21 GHz with the relative bandwidth of 127.67%. It is obviously seen that the absorptance is completely stable when changing the polarization angle from 0° to 45°. We can conclude that the MMA has an excellent performance of polarization insensitivity.

To visualize the mechanism of the absorption of the designed MMA, electric and magnetic fields energy distributions are examined in 1.8, 3.0 and 4.0 GHz, respectively, as illustrated in figure 6. From figures 6(a)–(c), it is found that the electric field energy is gradually concentrated toward the center of the unit as the frequency
Figure 3. Absorptance under oblique incidence in TE wave. (a), (b) simulated and (c), (d) measured results.

Figure 4. Absorptance under oblique incidence in TM wave. (a), (b) simulated and (c), (d) measured results.
increases. The electric field energy at 1.8 GHz in figure 6(a) is mainly concentrated on the outermost ring and a strong energy concentration is distributed at the resistance position. As the frequency increases to 2.5 GHz, the electric field energy concentration is moved on the two rings in the middle and gradually disappears on the outermost ring. Similarly, the electric field energy is mainly concentrated in the center of the unit when the frequency rises to 4 GHz. The magnetic field energy distributions are depicted in figures 6(d)–(f), we can see that the magnetic field energy distributions at 1.8, 3.0 and 4.0 GHz are the same as that of electric field energy distributions. The reason is that the wide bandwidth of the designed MMA is realized by combing the individual response of different geometric dimensions, and each geometric dimension has a resonant frequency. In addition, although the absorbance with larger geometry is dominant at lower frequencies, and the smaller geometry is dominant at higher frequencies within the operating bandwidth, the mutual coupling between adjacent structures has great significance in enhancing absorbance and enlarging the bandwidth. It is also
indicated in figure 6 that most of energy dissipation for the designed MMA originates from Ohmic loss in lumped resistors.

In what follows, we discuss in-depth the design procedure for optimizing the proposed MMA to reach a perfect absorptance with different geometric parameters. To avoid design complications, the significant parameters including the thickness of the air and substrate and the value of resistors are set as variable and their effects on the absorptance are optimized. Figure 7(a) shows the absorptance with different thickness of the FR-4 layer ($t_1$). In the simulation, we change the thickness of FR-4 from $t_1 = 0$ mm to $t_1 = 2$ mm by the step of 0.5 mm while fixing the thickness of the air of 18 mm. When changing $t_1$, the absorptance remains basically stable while the bandwidth changes significantly. From the figure, we can see that the bandwidth is gradually narrowed and red shift occurs with the increase $t_1$. Figure 7(b) shows the absorptance with different thickness of the air ($t_2$). Similarly, we change $t_2$ from $t_2 = 10$ mm to $t_2 = 26$ mm while fixing $t_1 = 1$ mm. In addition to the bandwidth narrowing and red shift, the absorptance decreases significantly when $t_2$ increases from $t_2 = 10$ mm to $t_2 = 26$ mm.

Figure 7. Simulated absorptance with different thickness. (a) the FR-4 layer, (b) the substrate of air layer.

Figure 8. Simulated absorptance with different resistors. (a) $R_1$, (b) $R_2$, (c) $R_3$. 
We simulated the resistor values of $R_1$, $R_2$ and $R_3$, as shown in figures 8(a)–(c), respectively. We can find that when other parameters remain unchanged and either $R_1$, $R_2$ or $R_3$ is changed, the absorptance of the absorber will not change significantly. Thus, it is concluded that the designed absorber has sufficient resistance tolerance.

4. Conclusions

In conclusion, we have proposed a broadband metamaterial absorber with the excellent performances of polarization-insensitivity and wide oblique incidence covering the S and L bands. The simulated and measured results demonstrated that the absorptance of the designed MMA was beyond 90% in 1.61–4.45 GHz. The absorptance keeps high value for both under TE and TM polarizations with the incident angle up to 45°. The physics of the absorptance was revealed by the electric–fields energy distributions and magnetic–fields energy distributions. We believe that our design can improve the design for achieving the broadband, low-frequency absorbers, and the proposed absorber also has the potential applications in electromagnetic stealth and energy harvesting.

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ORCID iDs

Xiaojun Huang https://orcid.org/0000-0002-7685-2678

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