A wideband metamaterial absorber based on a magnetic resonator loaded with lumped resistors*

Cheng Yong-Zhi(程用志), Gong Rong-Zhou(龚荣洲), Nie Yan(聂 彦)†, and Wang Xian(王 鲜)

School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, *China*

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A wideband metamaterial absorber (MA) based on a magnetic resonator loaded with lumped resistors is presented. It is composed of a one-dimensional periodic array of double U-shaped structured magnetic resonators loaded with lumped resistors, a dielectric substrate, and a metal plate. We simulated, fabricated, measured, and analyzed the MA. The experimental results show that the reflectance (S_{11}) is below −10 dB at normal incidence in the frequency range of 7.7 GHz–18 GHz, and the peak value is about −20 dB. Simulated power loss density distributions indicate that wideband absorption of the MA is mainly attributable to the lumped resistors in the magnetic resonator. Further investigations indicate that the distance between two unit cells along the magnetic field direction significantly influences the performance of the MA.

Keywords: wideband, metamaterial absorber, lumped resistors

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1. Introduction

Metamaterials (MM) are novel artificial materials with special properties that arise from their structure rather than their constituent materials. They are created by manipulating extreme magnitudes of physical conditions during synthesis and manufacture. MMs with interesting electromagnetic properties have an inhomogeneity scale that is much smaller than the wavelength of interest, and their electromagnetic (EM) response is expressed in terms of the parameters of homogeneous materials.[1] Interest in MMs has grown in the past decade because they enable unusual manipulations of and interactions with EM waves. MM properties, such as negative refractory indices,[2,3] have led researchers to come up with new types of microwave devices,[4,5] super-lenses,[6,7] and absorbers.[8−11]

Prior to the introduction of MMs, most of the work on EM absorbers was focused on absorptive materials commonly found such as carbon-loaded foam pyramidal absorbers, ferrite tiles, and engineered FSS.[12] However, these absorbers are usually bulky, with larger surface mass density, off-normal incidence, and polarization. These challenges have led to the development of alternative materials and structures that exhibit bulk absorption. Recently, since the concept of a perfect metamaterial absorber (MA) was proposed by Bilotti *et al.*[8] and Mosallaei *et al.*,[9] and first experimentally demonstrated by Landy *et al.*,[10] there has been considerable interest in creating thinner and lighter EM absorbers. Since then, many MAs have been proposed and demonstrated with narrow-band, dual-band, multi-band or wideband absorption.[12−19] Because of simultaneous strong electric and magnetic resonances, the absorption bandwidth is usually narrow. In many practical applications, such as stealth technology and solar energy harvesting, broadband absorption is required. One effective method to extend the absorption band is multi-resonance superposition at several neighboring frequencies.[16−18] Many efforts have been made to extend the absorption band of such MAs in microwave frequency, including multi-resonance superposition technology,[16−18] resistive FSS,[19,20] and lumped elements loaded into MAs.[21,22]

In this paper, we propose a wideband MA in the gigahertz region. Our simulations and experiments demonstrate that the bandwidth of an MA can be greatly enhanced by loading lumped resistors, compared with an MA that works by only using a double U structure magnetic resonator. Further simulation results indicate that lumped resistive elements are the

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†Corresponding author. E-mail: nieyan@mail.hust.edu.cn

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chief contributor of this MA's wideband absorption. We also investigated the influence of the distance between two unit cells along the magnetic field direction.

2. Design, simulation, and experiment

The theoretical basis for the design comes from the effective medium theory; MMs can be characterized by complex permittivity $\tilde{\varepsilon}(\omega)$ and permeability $\tilde{\mu}(\omega)$. In practice, loss is measured by the amount of EM power absorbed, which is defined as $A(\omega) = 1 - T(\omega) - R(\omega)$, where $R(\omega)$ and $T(\omega)$ represent the reflectivity and transmission as functions of frequency ω, respectively. It is possible to absorb both the incident electric and magnetic fields tremendously by properly tuning $\tilde{\varepsilon}(\omega)$ and $\tilde{\mu}(\omega)$, and achieve perfect impedance-matching to free space. To achieve unity absorption of the MA, simultaneously minimizing $R(\omega)$ and $T(\omega)$ to near zero is necessary.

To achieve wideband absorption, our device is composed of a one-dimensional array of double U-shaped magnetic resonators with lumped resistors on a dielectric substrate backed by a metal plate. The unit cell structure model is shown in Fig. 1(a). A similar use of resistors and a backplane design was mentioned by Gu *et al.*,[20] but it was not experimentally tested and did not utilize the concept of impedance-matching. Similar to the behaviour of split ring resonators,[2,3] this unit cell easily achieves a stronger magnetic resonance response when the magnetic field of the incident wave is perpendicular to the plane of the double U-shaped structure. The unit cell loaded with lumped resistors can be regarded as equivalent to a resonant RLC circuit: incident EM energy can be converted into electric energy in the circuit, and then the electric energy can be consumed by lumped resistors.[21,22] The metal elements we selected are 35-μm thick copper film with a frequency-independent conductivity $\sigma = 5.8 \times 10^7$ S/m. We used FR4 lossy dielectric as the substrate with a frequency-independent permittivity of $\varepsilon = 4.9(1 + \mathrm{i}0.025)$. The unit cell structure is optimized, and the geometric parameters are, in millimetres, $a = 10$, $b = 6$, $r = 1.9$, $s = 0.9$, $w = 0.6$, $g = 2$, $t = 0.8$, $t_\mathrm{m} = 0.5$. In addition, the optimal values of the lumped resistors are $R_1 = 241\ \Omega$ and $R_2 = 151\ \Omega$.

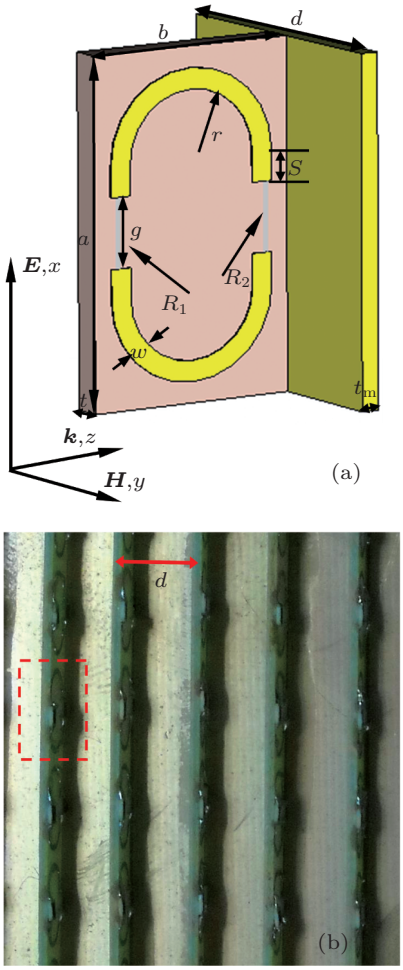


Fig. 1. (colour online) Lumped resistors MA: (a) perspective view of unit cell with TEM wave direction indicated. (b) Detailed photograph of fabricated lumped resistor MA sample with array.

A full wave EM simulation has been performed based on the standard finite-difference time domain (FDTD) method by CST Microwave Studio software. In simulations, we set periodic boundary conditions with the wave vector $\boldsymbol{k}$ parallel to the double U-shaped structure plane and the electric field paralleling the x axis and the magnetic field paralleling the y axis (see the inset of Fig. 1(a)). There is no transmission to be examined for a normal incident TEM plane wave, as it is blocked by the backing metal plate. Thus, only the reflectance needs to be measured in our simulations and experiments.

For the experiments, first, the designed MM structure was fabricated with the optimized structure parameters by conventional PCB technology, and then lumped resistors were loaded by welding technology. The final result is that the plane of the double U structure loaded with lumped resistors is perpendicular to the backing copper plate (see Fig. 1). The distance (d) between two unit cells along the magnetic field

direction can be adjusted easily. The fabricated MA is a one-dimensional array with dimensions of 18 cm ×18 cm, and the detailed photograph of the measurement sample is shown in Fig. 1(b). The complex S-parameters of experimental measurements were carried out in an EM anechoic chamber and described in detail in reference.[11] An Agilent PNA-X N5244A vector network analyzer connected to two standard gain broadband horn antennae that produces microwaves in the range of 2 GHz–18 GHz was used to measure the MA sample.

3. Results and discussion

First we consider the absorbing performance of the MA without lumped resistors. In this case, the distance d between two unit cells along the magnetic field direction is fixed to 10 mm (see the detail ed photograph of fabricated sample shown in the inset of Fig. 2(a)). The measured S_{11} is shown in Fig. 2(a).

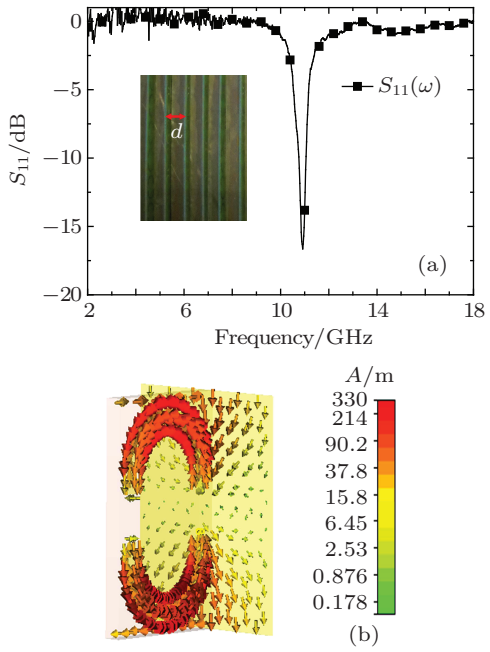


Fig. 2. (colour online) (a) Experimental reflectance (S_{11}) of the designed MA without lumped resistors; (b) the surface current distribution of the unit cell at 10.87 GHz. The inset indicates the testing sample.

It can be observed clearly that there is a reflectance dip at 10.87 GHz, and the reflectance peak value is up to −17 dB. Thus, the corresponding absorption is approximately 98% at resonance frequency. Obviously, this absorption is mainly from strong simultaneous electric and magnetic resonances at 10.87 GHz. The simulated surface current distribution is shown in Fig. 2(b), where it is clear that antiparallel current exists on the double U-shaped structure, forming a current loop which contributes to the magnetic response. The figure further illustrates the resonance absorption mechanism. The absorption band of the above-mentioned structure of MA is very narrow and the full width at half maximum (FWHM) bandwidth is about 0.9 GHz.

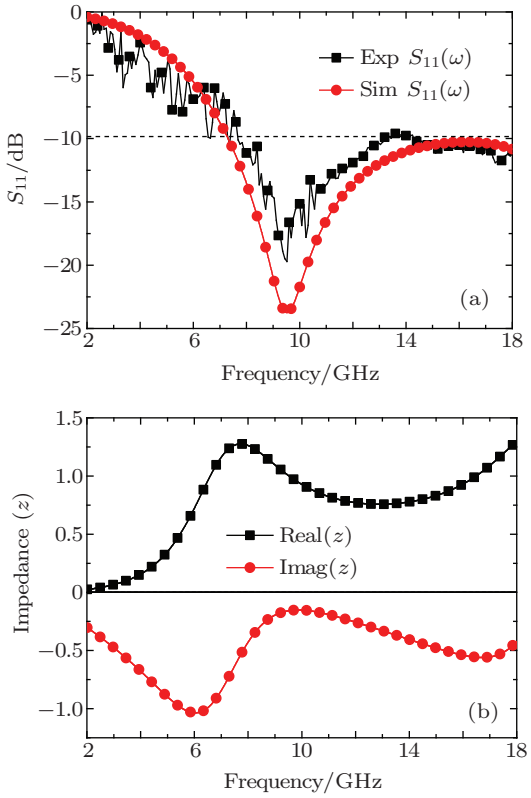


Fig. 3. (colour online) (a) Simulated (red line) and experimental (black line) reflectance (S_{11}); (b) the corresponding relative wave impedance (z) from simulated S parameters.

Below we will report our investigation of the absorption of the designed structure with welded lumped resistors. In this case, the distance d between two unit cells along the magnetic field direction is fixed to 9 mm. The measured and simulated results are shown in Fig. 3(a); one can see that the agreement between the experimental (black line) and simulated (red line) results is very good, considering the tolerances in fabrication and assembly. It can be observed that the reflectance (S_{11}) is below −10 dB at normal incidence in the frequency range of 7.7 GHz–18 GHz, and the measured dip value of S_{11} is about −20 dB and simulated dip value is about −24 dB. Thus, the corresponding absorption of experiment and simulation exceeds 90% from 7.7 GHz to 18 GHz, and peak value

of absorption is about 99% and 99.6%, respectively. These results indicate that this MA has strong broadband absorption. To better understand the reason for the high absorption, the relative wave impedance for normal incidence was retrieved from the simulated S parameters.[23] The relative wave impedance ($\tilde{z}(\omega)$) is presented in Fig. 3(b). The real part of relative impedance is near unity ($\mathrm{Re}(z) \approx 1$) which is consistent with our intent to match the impedance of the free space from 7.7 GHz to 18 GHz. These results indicate that the impedance of our MA can be tuned to approximately match the impedance of the free space at a wideband absorption frequency range.

It is also interesting to explore the power loss in the MA since it can provide information about how and where the absorption happens. Figure 4 shows the simulated reflectance of the designed MA on Fr4-lossfree substrate (black line) and FR4-lossy substrate (red line), respectively. It can be seen that the reflectance is below −10 dB from 7.7 GHz to 21.7 GHz when Fr4 substrate is lossy. However, when using the Fr4-lossfree substrate, the reflectance is nearly the same as that under lossy conditions, and these results are similar to the design by Gu *et al.*[20] Thus, we conclude that the absence of dielectric substrate cannot significantly affect the absorption of the MA loaded with lumped elements.

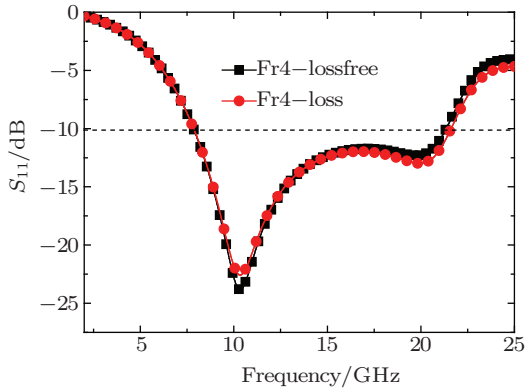


Fig. 4. (colour online) Simulated reflectance of the designed MA on FR4-lossfree substrate (black line) and FR4-lossy substrate (red line), respectively.

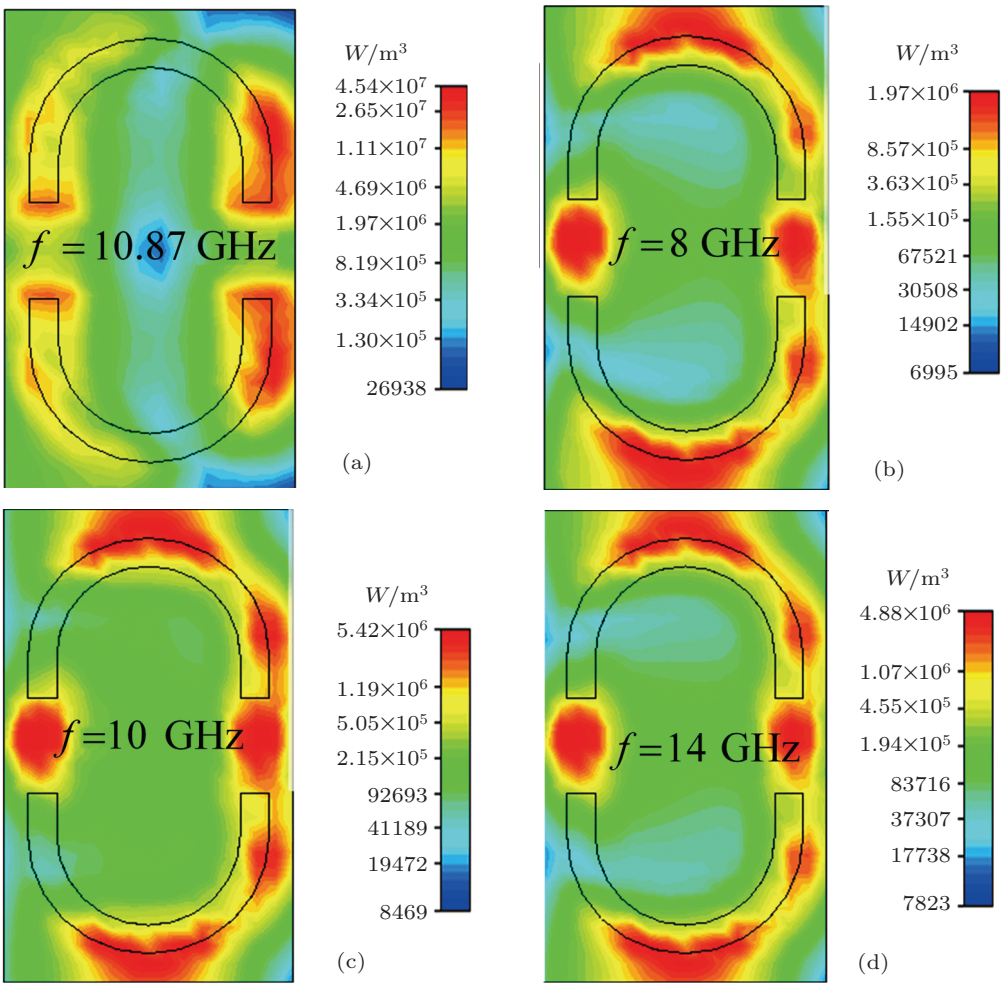


Fig. 5. (colour online) Simulated power loss density distributions for designed MA with (a) unloading, (b), (c), and (d) loading lumped resistors at 10.87 GHz, 8 GHz, 10 GHz, and 14 GHz, respectively.

To illustrate intuitively where the absorption happens in the designed MA, the power loss density distributions of designed MA with and without lumped resistors were also simulated numerically, respectively. From Fig. 5(a), it can be seen that the power loss is mainly focused on the edges of the double U-shaped structure in the absence of lumped resistors. As shown in Figs. 5(b), 5(c), and 5(d), with lumped resistors, it is clear that the power loss is mainly focused on the middle part (the place where lumped resistors are loaded) and the top and bottom edges of the double U-shaped structure (see the red area which represents the maximal power loss density). From these physical pictures of the intriguing absorption features, we propose that the wideband absorption of this MA is mainly attributable to the lumped resistors in the magnetic resonator.

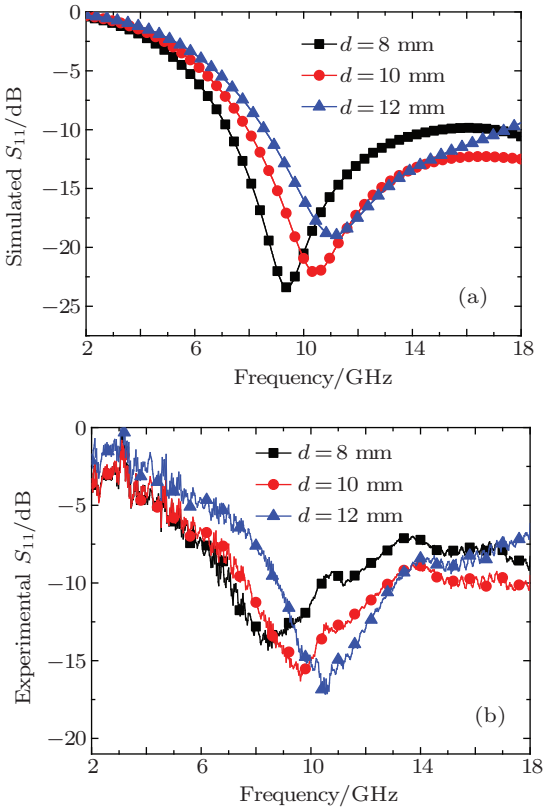


Fig. 6. (colour online) (a) Simulated and (b) measured reflectances (S_{11}) at different distances (d) between two unit cells along the electric field direction.

Taking a further step, we will consider the influence of the distance (d) between two unit cells along the magnetic field direction, the simulated and measured reflectances for different values of d are shown in Fig. 6. In simulations, the frequency of the peak value of reflectance increases with the increase of d, which could be mainly due to a magnetic coupling effect.[24] From Fig. 6(a), we also can see that the bandwidth of -10 dB is widest when $d = 10$ mm. The corresponding measured reflectance is shown in Fig. 6(b); we can see that the magnitudes of reflectance are less than those in the simulation, and the frequency of the peak value also increases accordingly. Especially, comparing with the simulation, when $d = 8$ mm and 12 mm, the bandwidth of -10 dB becomes narrow. These discrepancies may be due to the following reasons: first, in the simulations the proposed MAs are regarded as infinite for the normal incident plane. However, in the experiments, the dimension of the fabricated sample is of course finite, thereby resulting in edge diffraction. Thus, edge diffraction can create discrepancies between the simulated and experimental results. Secondly, the tolerances in fabrication and assembly of the designed MA also could account for some discrepancy. However, these experiments indicate that the bandwidth of -10 dB could be adjusted by properly changing the distance between two unit cells along the magnetic field.

4. Conclusion

In conclusion, we have designed, simulated, and experimentally verified the performance of a wideband MA loaded with lumped resistors. The experimental results show that the reflectance (S_{11}) is below -10 dB, and the corresponding absorption exceeds 90% at normal incidence in the frequency range of 7.7 GHz–18 GHz. In addition, the wideband absorption of the proposed MA is mainly attributable to the lumped resistors in the magnetic resonator and is insensitive to the loss of the dielectric substrate. Furthermore, we can obtain a wider bandwidth of -10 dB by properly adjusting the distance between two unit cells along the magnetic field. One other advantage of this MA is its relative thinness ($\approx \lambda/5$ of peak value of absorption) in the propagation direction, compared with the typical ($\approx \lambda/2$) or greater thickness of carbon loaded foam pyramidal absorbers. Therefore, the proposed absorber has potential application in the design and development of high-performance absorber structures in stealth technology.

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