Metamaterial absorbers realized in an X-band rectangular waveguide*

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In this paper, we demonstrate six types of metamaterial absorbers (MMAs) by measuring their absorptivities in an X-band (8–12 GHz) rectangular waveguide. Some of the MMAs have been demonstrated previously by using the free space measurement method, and the others are proposed firstly in this paper. The measured results show that all of the six MMAs exhibit high absorptivities above 98%, which have similar absorbing characteristics to those measured in the free space. The numerically obtained surface current densities for each MMA show that the absorbing mechanism is the same as that under the free space conditions. Such a demonstration method is superior to the conventional free space measurement method due to the small-scale test samples required, the simple measure device, and its low cost. Most importantly, the proposed method opens a way to enable MMAs to be used in microwave applications such as matched terminations.

Keywords: metamaterial, absorber, electric resonator, rectangular waveguide

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1. Introduction

Metamaterials are macroscopic composites having manmade three-dimensional periodic cellular architectures designed to have optimized combinations of two or more responses to specific excitations not available in nature. Metamaterials usually gain their properties from their structures rather than their compositions, using small inhomogeneities to create effective macroscopic behavior. The first metamaterial was experimentally realized in 2000,[1] and the negative refraction phenomenon was observed at the microwave frequencies in 2001.[2] Since then, more and more studies have been focused on the metamaterials, including their fabrication methods and applications.[3−10] In the various applications of metamaterials, due to the controllable effective electromagnetic parameters (permittivity $\varepsilon(\omega)$ and permeability $\mu(\omega)$, especially the imaginary parts of these two parameters $\mathrm{Im}[\varepsilon(\omega)]$ and $\mathrm{Im}[\mu(\omega)]$), the metamaterial absorber (MMA) reported by Landy *et al.* in 2008[11] has attracted considerable attention in recent years. Potential applications include the perfectly matched layer (PML) and the bolometer.[11,12] Various kinds of MMAs are reported at microwave,[13−19] terahertz,[20−23] infrared,[24] and optical frequencies.[25,26] Quite recently, dual-band and multi-band MMAs based on different electric resonators or the same resonators with different sizes,[27−33] ultra-broadband MMAs,[34,35] ultra-thin broadband MMAs,[36] and tunable MMAs[37,38] have also been introduced to extend the operating bandwidth and reduce the thickness.

Most of the MMAs are realized using metallic electric resonators to absorb the incident electric fields and metallic plate layers with loss of dielectric layers to absorb the incident magnetic fields. By adjusting the structure sizes of the metallic electric resonators and the distances between the electric resonators and the plate layers to achieve the conditions of effective permittivity $\varepsilon(\omega)$ equaling effective permeability $\mu(\omega)$,

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big dielectric loss $\tan\delta_\varepsilon$, and big magnetic loss $\tan\delta_\mu$, the MMAs can be impedance-matched with the free space and completely absorb the incident electromagnetic (EM) waves. Such nearly perfect absorptivities are realized with the help of numerical optimization methods, such as the commercial finite difference time domain (FDTD) solver Microwave Studio and the finite-element based electromagnetic solver (HFSS, Ansoft).

To experimentally demonstrate these MMAs, the most conventional method is the free space measurement method, which needs large-scale samples placed onto the focus of two horn antennas and two horn antennas with or without focusing a dielectric lens to receive the transmitted and the reflected signals. The entire measurement process should be performed in a chamber, and therefore the free space measurement method is too complex and costly. Furthermore, there may be a part of energy that is scattered in other directions, which cannot be detected by the two horn antennas, although large-scale test samples are used.[39] So Li *et al.* proposed a new waveguide measurement method (a closed system) to verify the absorption. It only needs small-scale test samples, and the measurement system is also simple, i.e., standard or non-standard waveguides.[39]

In this paper, based on the new measurement method, we experimentally demonstrate six types of MMAs. Some of them have been demonstrated previously by using the free space measurement method,[17,21,28,32] others are introduced in this paper. Because these MMAs placed in a shorted rectangular waveguide can be considered as matched loads, the proposed method opens up a way for MMAs to be used in such microwave applications.

2. Models

The unit cells of the six MMAs discussed in this paper are all shown in Fig. 1, the structure sizes are given in units of millimeters. The structure sizes are optimized to meet the requirement that the resonances or absorbing frequencies are in the X band (8–12 GHz), then the rectangular waveguide can operate properly, and the absorption characteristics of these MMAs can be measured. The unit cells of the MMA shown in Figs. 1(a), 1(c), 1(e), and 1(f) are associated with those in the previous publications.[17,21,28,32] The unit cell of the MMA shown in Fig. 1(b), which can be called the snowflake shaped MMA, is a new structure proposed in this paper. The unit cell of the MMA shown in Fig. 1(d) is from the electric LC resonator.[40] Finally, each MMA is fabricated on an FR4 substrate, which has the measured relative dielectric constant $\epsilon_r = 4.0$ and loss tangent $\tan\delta = 0.02$, with the dimensions 22.86 mm × 10.16 mm × 0.8 mm. The fabricated samples are shown in the insets of Fig. 2.

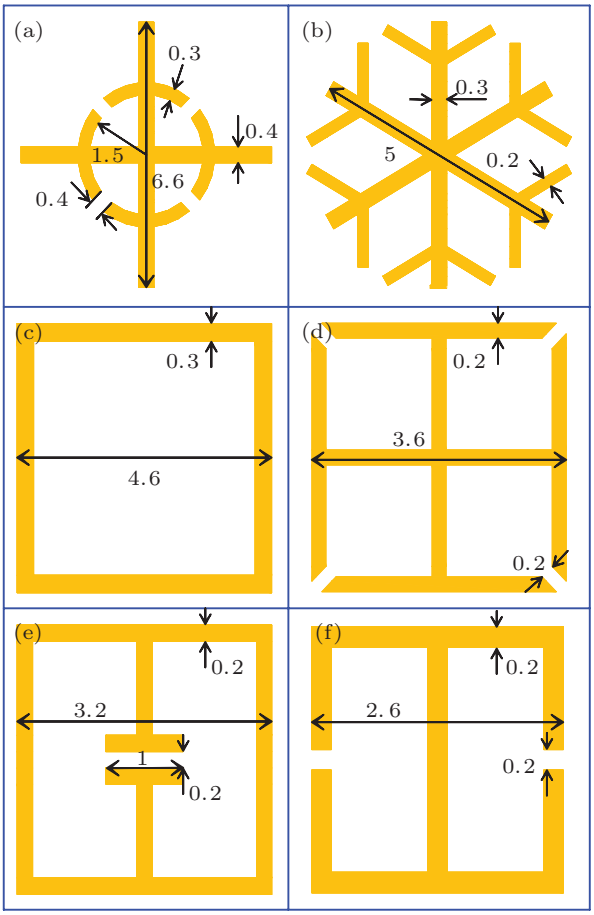


Fig. 1. (colour online) Unit cells of the six proposed MMAs ((a)–(f)). The structure sizes are shown for each MMA in units of millimeters.

Each sample is placed in the end of an X-band rectangular waveguide, and a metal plate is used to tightly cover the waveguide port, as shown in Ref. [39]. A vector network analyzer (Agilent N5230A) and a coaxial to the rectangular waveguide transition operated at the X band are used in this measurement system. There is no wave energy transmitted through the MMAs because of the back metal plate, so the absorptivity for each MMA can be completely decided from the measured reflection S_{11} with $A = 1 - |S_{11}|^2$.

3. Demonstration and discussion

The measured results compared with the simulated results of each of the proposed six MMAs are all shown in Fig. 2 and Table 1. For each MMA, the simulated absorptivity of unit cell inclusion placed in the free space and under the transverse electromagnetic (TEM) wave incidence is also presented for comparison. As shown in the left of each subplot of Fig. 2, the measured and the simulated absorptivities of each MMA placed in the X-band rectangular waveguide agree with each other very well except for some displacements of peak absorption mainly due to the fabrication tolerance. The measured peak absorptivity of each MMA is more than 98%, as shown in Table 1. The simulated absorptivity of unit cell inclusion is lower than that in the X-band rectangular waveguide. This is because that the sizes for each structure are optimized in the X-band rectangular waveguide under the transverse electric (TE) wave incidence rather than in the unit cell condition under the TEM wave incidence, leading to the mismatch of impedance in the latter conditions.

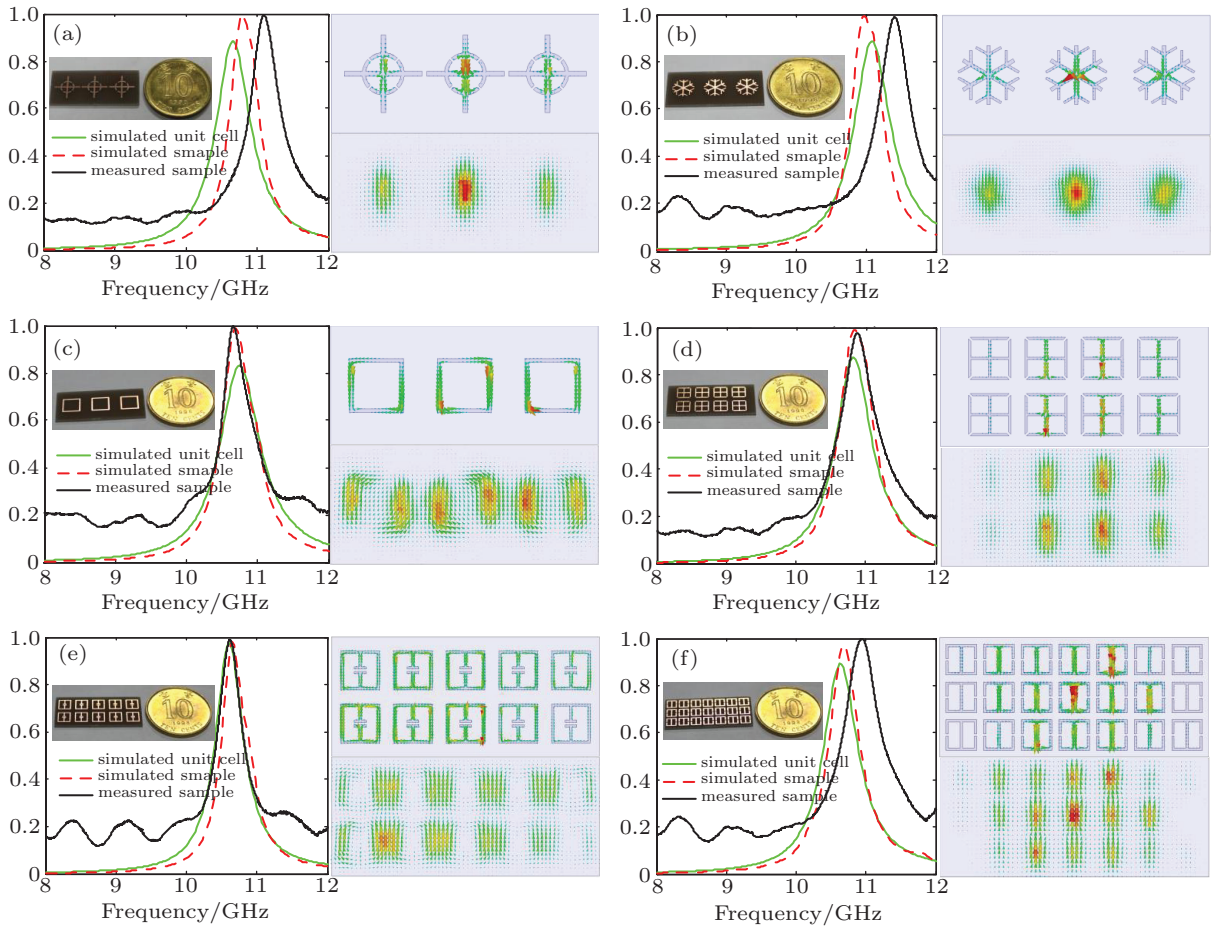


Fig. 2. (colour online) ((a)–(f)) Absorptivity characteristics of each MMA obtained experimentally and numerically. The inset in each subplot is the fabricated sample. The surface current densities in the resonator and the back metal plate in each MMA are also presented.

For each MMA, the surface current densities in the resonator and the back metal plate at the resonance frequency are shown in the right of each subplot of Fig. 2. It can be seen that for each MMA under the TE wave normal incidence, the current densities in the resonators placed in the rectangular waveguide have similar characteristics to that of the corresponding MMA under the TEM wave incidence in the free space,[17,21,28,32] and so provide the electric response. In addition, there is also a magnetic response associated with the currents on the ground plane. This means that the electric and magnetic responses appear simultaneously at the given frequency, so the MMA can absorb the incident electric and magnetic fields.

Therefore, we can conclude that the waveguide system demonstration method used in this paper pos-

sesses a similar effect and validity compared to the free space demonstration method. The main electric and magnetic field polarizations in the waveguide are similar to those of the TEM wave in free space. The waveguide system demonstration method is superior to the conventional free space measurement method, due to the small-scale test samples required, the simple measurement method, and its low cost. The most important thing is that these MMAs placed in the shorted rectangular waveguide can be considered as matched loads, so the proposed method opens a way to make the MMAs used in microwave applications.

On the other hand, it is demonstrated that the new structures proposed in this paper shown in Figs. 1(b) and 1(d) can also be used to achieve the MMAs. Moreover, both of the two structures have highly symmetric characteristics, so it can be expected that these two MMAs also have polarization independent properties for the incident EM waves, even though we can not measure directly the absorptivities for different polarization waves in the X-band rectangular waveguide. We have proven that the same results were achieved for the absorptivities measured in the rectangular waveguide and the free space, and that similar symmetric structures have been demonstrated previously.[18,22,23,29,32,39] Based on the new measurement method, we can further investigate the broadband and the ultra-thin MMAs in a simple way.

Table 1. The simulated and the measured peak absorptivities and the corresponding frequencies of the six MMAs proposed in this paper. Column 2 shows the unit cell size for each MMA. Column 3 shows the peak absorptivity ($A_{\rm uc}$) and the corresponding frequency of the MMA unit cell inclusion simulated in the free space. Columns 4 and 5 show the simulated and the measured peak absorptivities ($A_{\rm ss}$ and $A_{\rm ms}$) and the corresponding frequencies of the MMA sample placed in the X-band rectangular waveguide. The frequency is given in units of GHz.

MMA	Size/mm	$A_{\rm uc}/f$	$A_{\rm ss}/f$	$A_{\rm ms}/f$
(a)	7	88.2%/10.7	99.5%/10.8	99.5%/11.1
(b)	7.5	89.3%/11.1	99.6%/11.0	98.8%/11.4
(c)	7.5	83.5%/10.7	99.2%/10.7	99.8%/10.7
(d)	4.8	87.3%/10.8	99.0%/10.8	98.0%/10.9
(e)	4.5	98.6%/10.6	98.0%/10.7	98.8%/10.6
(f)	3.2	89.4%/10.6	97.5%/10.7	99.8%/10.9

4. Conclusion

In conclusion, we have demonstrated six types of MMAs using the waveguide system demonstration method. Some of the MMAs have been demonstrated previously, and the others have been studied first in this paper. The measured and the simulated results prove that the waveguide system demonstration method has a similar validity compared to the free space demonstration method, and also prove the validity of the two new MMAs. The proposed method opens up a way for the use of MMAs in microwave applications such as matched terminations. Moreover, based on the new measurement method, we can further investigate the broadband and the ultra-thin MMAs in a simple way.

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