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Equivalent electromagnetic parameters for microwave metamaterial absorber using a new symmetry model*

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Transmission line theory uses the complex nature of permeability and permittivity of a conventional magnetic absorber to evaluate its absorption properties and mechanism. However, because there is no method to obtain the electromagnetic parameters of a metamaterial-absorber integrated layer (composed of a medium layer and a periodic metal array), this theory is seldom used to study the absorption properties of the metamaterial absorber. We propose a symmetry model to achieve an equivalent complex permittivity and permeability model for the integrated layer, which can be combined with the transmission line theory to calculate metamaterial absorption properties. The calculation results derived from both the transmission line theory and the high-frequency structure simulator are in good agreement. This method will be beneficial in practical investigations of the absorption mechanism of a metamaterial absorber.

Keywords: metamaterial absorber, equivalent electromagnetic parameters, transmission line theory

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1. Introduction

A metamaterial absorber (MMA), which is composed of an artificial subwavelength periodic metal array, a medium layer, and a backed metal plate, is a novel electromagnetic (EM) wave absorbing material.[1,2] By adjusting the geometric construction of the metal array, EM characters of MMA could be controlled to obtain the desired absorption property,[3–6] which makes it a preferred type of absorber. Several research methods, including finite element method[7] and time domain finite difference method,[8] have been used to study the MMA's absorption mechanism and the underlying absorption phenomena. In previous studies that used simulation software-based analog computations, a group of anti-parallel electric currents were found on the surface metal array and backed metal of the MMA, which, according to the authors, may have resulted in the observed magnetic resonance and the subsequent attenuation of wave energy.[3,9,10] Recently, another research group reported that wave's multiple reflections causes the observed antiparallel electric current on the surface metal array.[11] The authors also pointed out that the absorption peak emerges from destructive interference, which is the same as that in the traditional absorber.[12]

EM parameters including complex permittivity and complex permeability are prerequisite when discussing the absorption properties and mechanism of traditional electromagnetic absorbers. The microwave absorbing characteristics of these absorbers can be obtained using the EM parameters in the transmission line theory for a designed absorber thickness. Furthermore, the change in regularity of the absorption peak frequency and intensity with respect to the absorber thickness can also be measured for a more thorough investigation of the absorption mechanism.[13] For MMA, the backed metal plate is uncoupled with the rest of its parts.[14] The other parts of MMA, which act as an integrated layer, are similar to that in the traditional absorber layer in terms of structure and function. However, the transmission line theory is seldom used to investigate the absorption properties and mechanism of MMA due to the lack of the integrated layer's EM parameters. Several studies have attempted to find out the EM parameters of the integrated layer in the MMA. For instance, Huang *et al.* in his work considered the integrated layer as a homogeneous medium and extracted the equivalent EM parameters.[15] However, their study did not consider the asymmetry in the integrated layer along the EM wave propagation line that causes a significant difference between the values of reflection loss (RL) obtained from transmission line theory and simulation software.[16] This means that the equivalent electromagnetic parameters obtained using the Huang's method cannot be substituted into the transmission line theory to obtain valid microwave absorption performance characteristics. In this paper, we propose a new symmetry model that is used to derive accurate equivalent electromagnetic parameters of the integrated layer in MMAs and solve this problem. Our results reveal a strong consistency between the

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microwave-absorbing performances obtained by substituting the electromagnetic parameters into the transmission line theory and those obtained from the HFSS simulation.

2. Theoretical and experimental methods

Figure 1(a) is a schematic representation of an MMA unit. The figure shows the backed metal plate (bottom layer), medium layer (middle layer), and metal period array (top layer). The integrated layer mentioned above consisting of a metal period array layer and a medium layer is shown in the dashed box in Fig. 1(a). The new symmetry model is constructed through the combination of two integrated composite layers in mirror symmetry, which is shown in Fig. 1(b). The front and back surfaces of the model for a normally incident EM wave are identical. For our symmetry model, the impedance (z) and refractive index (n) can be obtained by HFSS and then the equivalent permeability (μ) and permittivity (ε) are computed by the relations established in Refs. [17]–[19] as follows:

$$\varepsilon = \frac{n}{z}, \quad \mu = nz. \tag{1}$$

When an electromagnetic wave is normally incident on a composite layer, its reflection and transmission characteristics can be described by S parameters (S_{11}, S_{12}, S_{22}, and S_{21}). The symmetry model is symmetrical along the direction of wave propagation, meaning, S_{11} equals to S_{22} and S_{21} equals to S_{12}. For a sample with thickness $2t$, the S parameters can be expressed by the following equations:

$$S_{11} = S_{22} = \frac{1}{\cos(2nkt) - \frac{\mathrm{i}}{2}(z + \frac{1}{z})\sin(2nkt)}, \tag{2}$$

$$S_{21} = S_{12} = \frac{\mathrm{i}}{2}\left(\frac{1}{z} - z\right)\sin(2nkt), \tag{3}$$

where k donates the wave number of the incident wave in free space, and n and z can be described in terms of the S parameters by inverting Eqs. (2) and (3) as

$$z = \sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}}, \tag{4}$$

$$n = \frac{1}{2kt}\cos^{-1}\left[\frac{1}{2S_{11}}(1 - S_{11}^2 + S_{21}^2)\right]. \tag{5}$$

For passive materials, the real part of z (Re(z)) and imaginary part of n (Im(n)) must be larger than zero. The requirement of Re(z) > 0 can fix the sign of Im(z) in Eq. (4). Meanwhile, the limiting condition suggests an unambiguous result for Im(n),

$$\mathrm{Im}(n) = \pm\mathrm{Im}\left(\frac{1}{2kt}\cos^{-1}\left[\frac{1}{2S_{11}}(1 - S_{11}^2 + S_{21}^2)\right]\right). \tag{6}$$

The real part of refractive index n is ambiguous, which can be obtained by

$$\mathrm{Re}(n) = \pm\mathrm{Re}\left(\frac{1}{2kt}\cos^{-1}\left[\frac{1}{2S_{11}}(1 - S_{11}^2 + S_{21}^2)\right]\right) + \frac{2\pi m}{2kt}, \tag{7}$$

where m is an integer. According to formulas (1)–(7), the equivalent EM parameters can be calculated.

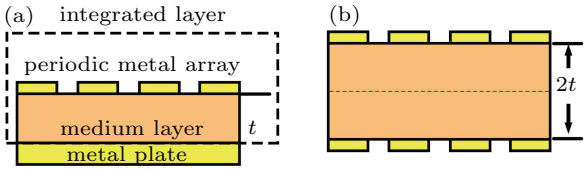


Fig. 1. (a) Schematic of MMA and (b) symmetry model of the integrated layer.

To verify this method, three MMAs with different periodic metal structures are presented in this paper. First, carbonyl iron composite material with a volume fraction of 35% is selected as the MMA medium, whose electromagnetic parameters are shown in Fig. 2. Different periodic metal patterns including round, cross, and concentric ring are exhibited. The geometrical parameters of the three structures are optimized. By optimizing the parameters, the reflection loss curves with different characteristics are obtained. Here, the metal of the periodic array is copper and its thickness is 1 μm. Their diagrams are shown in Figs. 3(a), 3(c), and 3(e), respectively.

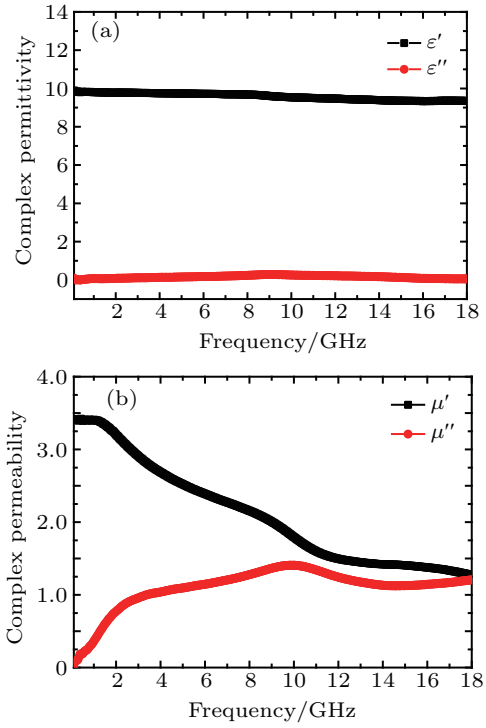


Fig. 2. (a) Complex permittivity and (b) complex permeability of carbonyl iron composite with $V_c = 35\%$.

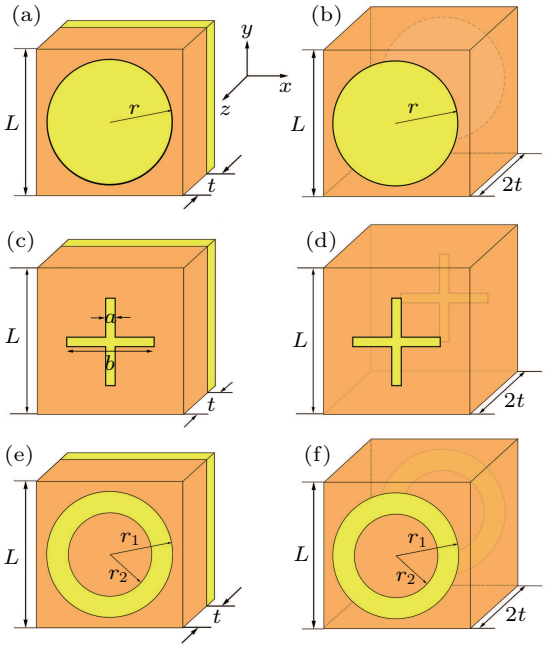


Fig. 3. (a), (c), (e) Diagrams of MMA units with different patterns: (a) round: $L = 10$ mm, $t = 1.5$ mm, and variable r from 0 to 4 mm; (c) cross: $L = 12$ mm, $a = 0.6$ mm, $t = 5.4$ mm, and variable b (1.8 mm, 3.0 mm, 4.2 mm, and 5.4 mm); (e) concentric annulus: $L = 10$ mm, $r_1 = 3$ mm, $t = 1.5$ mm, and variable r_2 from 1.4 mm to 2.6 mm. (b), (d), (f) The symmetry models for the three patterns, respectively.

The RL curves of the structures are generated using HFSS and are shown in Figs. 4(a), 4(c), and 4(e). The geometrical parameters of the MMA with periodic round pattern include the fixed length (L) of 10 mm, thickness (t) of 1.5 mm, and variable radius r. As the radius increases from 0 to 4.0 mm (the curve of $r = 0$ means that there is no round pattern in the medium), the RL peak moves from 10.0 GHz to 3.4 GHz, which can be seen in Fig. 4(a). The absorption peak moves to low frequency with the increase of the radius. It is believed that the increase of the radius will increase the capacitance of the periodic metal array, which leads the absorption peak to move to low frequency. The geometrical parameters of the MMA with periodic cross are $L = 10$ mm, $t = 1.5$ mm, $a = 6$ mm, and a variable length (b) that changes from 1.8 mm to 5.4 mm. The microwave absorption results show that the RL peak of this type of MMA is in the low frequency range and the peak position moves to lower frequency with increasing b. An increase in the length of b will decrease the spacing of the adjacent cross, which will increase the capacitance and shift the resonance to low frequency. The geometrical parameters of the MMA unit with concentric ring pattern are $L = 12$ mm, $t = 1.5$ mm, $r_1 = 3$ mm, and variable inner diameter r_2. Multiple absorption peaks appear in this structure. The low-frequency peak is influenced by the distance of the outer diameter of the circle between adjacent cells, and the high-frequency peak is influenced by the inner and outer diameter distance of the concentric circle in the cell. Because r_1 remains unchanged and r_2 increases from 1.4 mm to 2.6 mm, the absorption peak in the low frequency range is nearly constant and wider in the high-frequency range.

The symmetry models of the corresponding integrated layers are shown in Figs. 3(b), 3(d), and 3(f). The S_{11} and S_{21} of the symmetry models are obtained through HFSS.

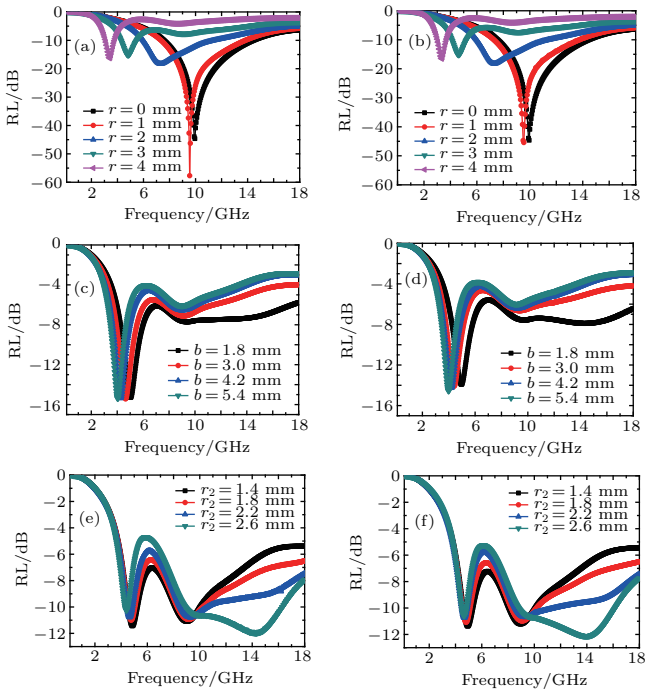


Fig. 4. (a), (c) (e) The RL curves simulated from HFSS and (b), (d),(f) the RL curves calculated by the transmission line theory based on equivalent EM parameters.

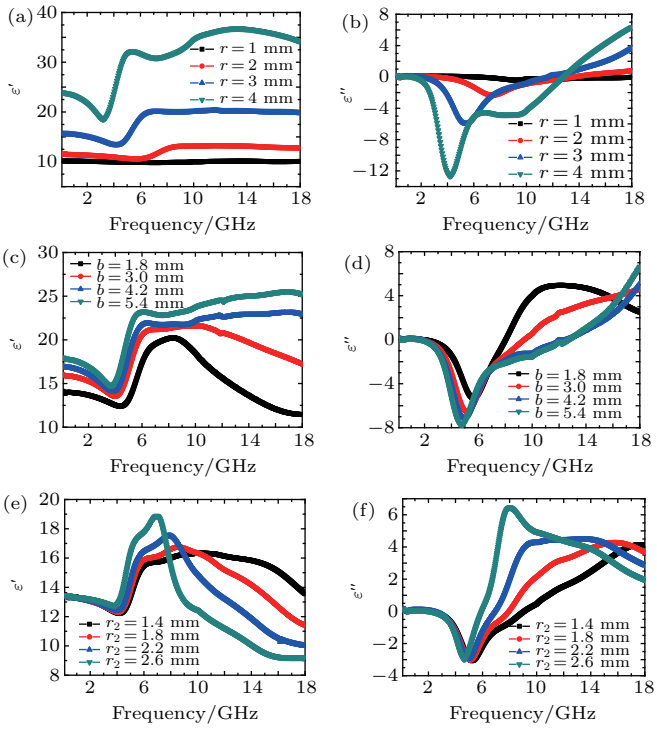


Fig. 5. (a), (c), (e) The real parts and (b), (d), (f) imaginary parts of equivalent complex permittivity in Figs. 3(b), 3(d), and 3(f), respectively.

The equivalent EM parameters for the integrated layer are calculated using S_{11} and S_{21} and the symmetry model's thick-

ness from formulas (1)–(7). The calculated results are shown in Figs. 5 and 6. Based on these equivalent EM parameters, the RL can be calculated using the transmission line theory[13]

$$Z_{\text{in}} = Z_0(\mu_{\text{r}}/\varepsilon_{\text{r}})^{1/2}\tanh\left[j\left(\frac{2\pi ft}{c}\right)(\mu_{\text{r}}\varepsilon_{\text{r}})^{1/2}\right], \quad (8)$$

$$\text{RL} = 20\log|(Z_{\text{in}}-Z_0)/(Z_{\text{in}}+Z_0)|. \quad (9)$$

The calculated RL shown in Figs. 4(b), 4(d), and 4(f) is highly consistent with the results of HFSS simulation shown in Figs. 4(a), 4(c), and 4(e), which indicates that the equivalent EM parameters obtained from the symmetric model are fit to be used with the transmission line theory to investigate the microwave absorption properties of the MMA integrated layer.

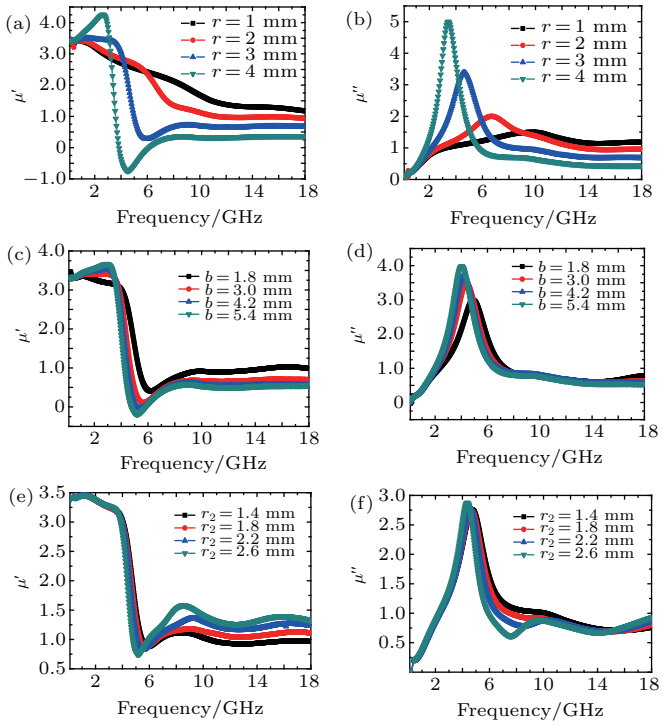


Fig. 6. (a), (c), (e) The real parts and (b), (d), (f) imaginary parts of equivalent complex permeability in Figs. 3(b), 3(d), and 3(f), respectively.

3. Results and discussion

From the EM parameters shown in Fig. 5 and the RL curves in Fig. 4, it can be deduced that ε at the peak frequency of the strong absorption peak is not equal to μ. This conclusion is different from other studies on MMA, in which ε at the absorption peak frequency was found to be equal to μ.[20,21] In these studies,[20,21] the entire structure of the MMA, including backed metal plate, was considered. In this case, the matching electrical impedance means impedance $Z = \sqrt{\mu_{\text{r}}/\varepsilon_{\text{r}}} = 1$ and the electromagnetic waves could enter the microwave absorber unimpeded and without any resistance or losses (reflected wave). However, that method could not reveal the wave energy propagation direction inside the MMA, and hence made understanding the absorption mechanism difficult. A report[11] showed that EM waves cannot completely enter a microwave MMA due to the partial reflection at the front interface. It also showed that the backed metal plate in this case played an important role in the formation of the strong absorption peak, which was caused by the interference cancellation of multiple reflected waves. The origin of the absorption peak in MMA in this case is arguable. To negate these issues in our work, we exclude the backed metal plate from the integrated layer and extract the EM parameters of the rest of the layer. The microwave absorbing characteristics of the metamaterial absorber based on the transmission line theory are calculated accurately using these EM parameters. The results reveal that $\varepsilon \neq \mu$ at the peak frequency, which is consistent with that of the traditional absorber.[22,23] For the traditional absorber, the absorption mechanism based on the transmission line theory was analyzed with respect to the wave energy flow direction and phase.[13] The practical absorption mechanism of MMA needs a more detailed investigation based on the symmetry model and transmission line theory, which will be the subject of our future work.

4. Conclusion

In summary, the EM parameters of the microwave MMA integrated layer were successfully extracted. These EM parameters can be used with the transmission line theory to characterize the MMA microwave-absorption properties at various frequencies. The absorption performance of three MMAs was simulated on HFSS and calculated using the transmission line theory based on the EM parameters. The two sets of results were found to be consistent. The equivalent parameters of the backed-metal-plate-excluded integrated layer of the MMA will help in the scientific understanding of its microwave absorption mechanism and serve as a guide to design the resonance circuit needed for future experimental studies.

References

[1] Liu J, Zhou Q, Shi Y, Zhao X and Zhang C 2013 *Appl. Phys. Lett.* **103** 241911
[2] Bingham C M, Tao H, Landy N I, Averitt R D, Padilla W J and Zhang X 2008 *Opt. Express* **16** 7181
[3] Wang B Y , Liu S B , Bian B R , Mao Z W, Liu X C, Ma B and Chen L 2014 *J. Appl. Phys.* **116** 094504
[4] Zhong M, Liu S J, Xu B L, Wang J and Huang H Q 2018 *Opt. Mater.* **78** 1
[5] Guo L, Ma X, Zou Y, Zhang R, Wang J A and Zhang D 2018 *Opt. & Laser Technol.* **98** 247
[6] Meng T, Hu D and Zhu Q 2018 *Opt. Commun.* **415** 151
[7] Yu Y, Christopher B, Talmage T, Sabarni P, Hand T H, Padilla W J, Smith D R, Marie J N and Cummer S A 2008 *Opt. Express* **16** 9746
[8] Su J, Lu Y, Li Z, Zhang R and Yang Y 2016 *Int. J. Antenn Propag.* **2016** 9
[9] Xu H, Bie S, Xu Y, Yuan W, Chen Q and Jiang J 2016 *Compos. Part. A Appl. Sci. & Manuf.* **80** 111
[10] Shuai S, Yang S, Lu T, Yang L and Cao H 2016 *Aip Adv.* **6** 075203

[11] Chen H T 2012 *Opt. Express* **20** 7165

[12] Zhang J, Peng W, Chen Y, Wang G, Wang D, Liang Q, Tao W and Li F 2018 *J. Electron. Mater.* **47** 1

[13] Wang T, Han R, Tan G, Wei J, Qiao L and Li F 2012 *J. Appl. Phys.* **112** 104903

[14] Chen H T, Zhou J, O'Hara J F, Chen F, Azad A K and Taylor A J 2010 *Phys. Rev. Lett.* **105** 073901

[15] Huang X, He X, Guo L, Yi Y, Xiao B and Yang H 2015 *J. Opt.* **17** 055101

[16] Huang X, Yu S, Chen J and Yang H 2016 11*th International Symposium on Antennas, Propagation and EM Theory (ISAPE)* pp. 640–643

[17] Smith D R, Vier D C, Th K and Soukoulis C M 2005 *Phys. Rev. E* **71** 036617

[18] Smith D R, Schultz S, Markos P and Soukoulis C M 2002 *Phys. Rev. B* **65** 195104

[19] Chen X, Grzegorczyk T M, Wu B I, Pacheco J Jr. and Kong J A 2004 *Phys. Rev. E* **70** 016608

[20] Watts C M, Liu X and Padilla W J 2012 *Adv. Mater.* **24** OP98

[21] Liu X, Starr T, Starr A F and Padilla W J 2010 *Phys. Review Letters* **104** 207403

[22] Wang T, Wang H, Tan G and Wang L 2015 *IEEE Trans. Magn.* **51** 1

[23] Wang B, Wei J, Qiao L, Wang T and Li F 2012 *J. Magn. & Magn. Mater.* **324** 761