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THREE-DIMENSIONAL METAMATERIAL MICROWAVE ABSORBERS COMPOSED OF COPLANAR MAGNETIC AND ELECTRIC RESONATORS

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Abstract—In this paper, a 3-dimensional metamaterial absorber operating at 11.8 GHz was presented. The metamaterial absorber is composed of coplanar magnetic and electric resonators, with the latter in the center part of the former. By carefully adjusting structural dimensions of magnetic and electric resonators, absorbance per unit cell can reach up to 96% at 11.8 GHz with a 6% FWHM (Full Width at Half Maximum). The full-wave simulations confirmed nearly equal permeability and permittivity and large imaginary part of the refractive index at 11.8 GHz and thus proved the effectiveness of the proposed 3-dimensional metamaterial absorber for microwave applications.

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1. INTRODUCTION

In 1968, Veselago [1] investigated the characteristics of media with simultaneously negative ε and μ, but his work was neglected for almost 30 years. In 1999, Pendry et al. [2] showed that negative ε can be realized by using conducting wires and negative μ by split-ring resonators (SRRs). In 2000, Smith et al. [3] constructed the wire/SRR structure and demonstrated its negative ε and μ at microwave frequencies. From then on, interests in materials with unnatural ε and μ have been revived. Because of the unnatural ε and μ, such materials were termed metamaterials.

Now many metamaterial-based microwave components have been devised, with much smaller sizes and enhanced performances compared with conventional ones [4–8]. Almost all these applications of metamaterials require the realization of left-handed passband and negative regractive index. Correspondingly, many novel left-handed unit cells, like S-shaped unit cell [9], Ω-shaped unit cell [10], "cross" structure unit cell [11], coplanar magnetic and electric resonator unit cell [12], have been proposed with an aim to expand the left-handed passband and to reduce loss. Although the wave-absorption property of metamaterials has been almost neglected, the use of metamaterials will potentially enhance the performance of microwave absorbers. Due to the diffraction limit, the thickness of conventional absorbers cannot be made thin enough. Moreover, metallic backing plates are necessary in conventional absorbers [13], which may bring about many problems in applications such as stealth technology. As a result, there is an urgent need to design innovative absorbers to overcome the disadvantages of conventional absorbers. Ultra-thin absorbers based on Frequency Selective Surfaces (FSS) [14, 15] were proposed, and the metallic backing plate is still indispensable. To get rid of metallic backing plate problem, Bilotti et al. [16] proposed a SRR-based absorber by arranging SRR arrays behind a resistive sheet, allowing its use in stealth technology due to the absence of metallic backing plates. However, the resistive sheet used to match the impedance of the free space is necessary in such a design. Landy et al. [17, 18] proposed a 1-dimensional metamaterial absorber composed of magnetic and electric resonators without metallic backing plate and resistive sheet. Both the impedance matching and the absorption can be achieved by such an absorber. This opens a brand-new way to the design of smaller and more applicable absorbers.

In this wdork, a 3-dimensional model for metamaterial absorber operating at 11.8 GHz was presented. The metamaterial absorber is composed of coplanar magnetic and electric resonators, with the latter in the center part of the former. By carefully adjusting structural dimensions of magnetic and electric resonators, absorbance per unit cell can reach up to 96% at 11.8 GHz with a 6% FWHM (Full Width at Half Maximum). The full-wave simulations confirmed nearly equal permeability and permittivity and large imaginary part of the refractive index at 11.8 GHz and thus proved the effectiveness of the proposed 3-dimensional metamaterial absorber for microwave applications.

2. DESIGN

In this paper, it is proposed a 3-dimensional model for metamaterial absorber composed of magnetic and electric resonators. The unit cell of the 3-dimensional metamaterial absorber is shown in Figure 1. Metallic patterns of an electric resonator and two C-shaped metal strips are etched on each of the six sides of the substrate cube. The electric resonator is on the center part of each side while the two C-shaped metal strips, which serve as a magnetic resonator and enclose the electric resonator symmetrically. The lossy substrate cube is made of FR4 whose relative dielectric constant is $\varepsilon_r = 4.9$ and loss tangent $\tan\delta = 0.025$. The metal of metallic patterns is copper whose electric conductivity is $\sigma = 5.8 \times 10^7\,\mathrm{S/m}$. The geometrical dimensions are: $a = 4\,\mathrm{mm}$, $b_1 = 3.5\,\mathrm{mm}$, $b_2 = 2.4\,\mathrm{mm}$, $l = 1.6\,\mathrm{mm}$, $c = 0.2\,\mathrm{mm}$, $d = 0.05\,\mathrm{mm}$, $w = 0.2\,\mathrm{mm}$. The electric resonator and the two

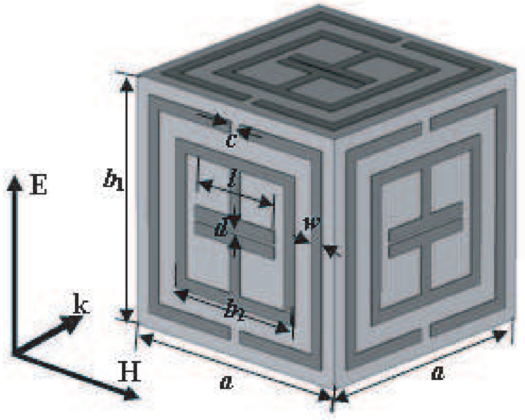


Figure 1. Unit cell of the 3-dimensional metamaterial absorber and polarization of incident EM waves.

C-shaped metal strips couples to electric and magnetic fields of the incident EM waves, respectively.

An absorber must meet two necessary requirements to effectively absorb EM waves. One is that the impedance should match that of the free space, that is, $\mu = \varepsilon$, to minimize the reflection and the other is that the absorber should absorb intensely the transmitted EM wave energy, that is, the imaginary part of refractive index should be large. By carefully adjusting the geometrical dimensions, ε and μ can be tuned so that $\mu = \varepsilon$. Since that the structure is made of metallic resonators and lossy substrates and that it is based on resonances, the imaginary part of the refractive index is expected to be very large, which guarantees strong absorption of transmitted EM waves. Thus, the proposed unit cell is expected to be a good candidate for 3-dimensional metamaterial absorber. In order to testify our predictions, computer simulations were performed using the commercial FDTD solver CST Microwave Studio. Polarization of the impinging plane wave is shown in Figure 1. The impinging wave is incident on the front side of the cube, with the electric vector perpendicular to the up and bottom sides and magnetic vector perpendicular to the left and right sides. Periodic Boundary Conditions (PBC) are imposed on the four lateral sides. Thus, the metamaterial absorber is one-unit-cell thick along the propagation direction and infinite in the other two directions.

Figure 2. Surface current distributions of the unit cell at 11.8 GHz.

3. PHYSICAL UNDERSTANDING OF THE METAMATERIAL ABSORBER

The surface current distributions were monitored to ascertain whether the unit cell behaves as a metamaterial around 11.8 GHz. Figure 2 shows the surface current vector distribution at 11.8 GHz. As shown in Figure 2, surface currents on the left and right halves are counter-clockwise and clockwise, respectively, which means a zero net magnetic flux through the electric resonator. The electric resonator behaves like an electric dipole. For two adjacent C-shaped metal strips near the edge, surface currents are anti-parallel and thus form an effective current loop. The two adjacent C-shaped metal strips near the edge behave like a magnetic dipole. The electric and magnetic dipole moments can be envisioned as the alphabet for making metamaterials [19]. The electromagnetic response of an electric dipole will lead to an electric resonance, resulting in a negative effective permittivity. Similarly, the electromagnetic response of a magnetic dipole will lead to a magnetic resonance, resulting in a negative effective permeability. The electric resonator on the center of each side couples to the electric fields while two adjacent C-shaped metal strips near the edge form a magnetic resonator and thus couple to the magnetic fields. At 11.8 GHz, negative response of both the electric and magnetic resonator occurred simultaneously and thus the metamaterial is realized.

Figure 3 gives the magnitudes of S_{11} and S_{21} parameters of one unit cell along the propagation direction. At 11.8 GHz, both

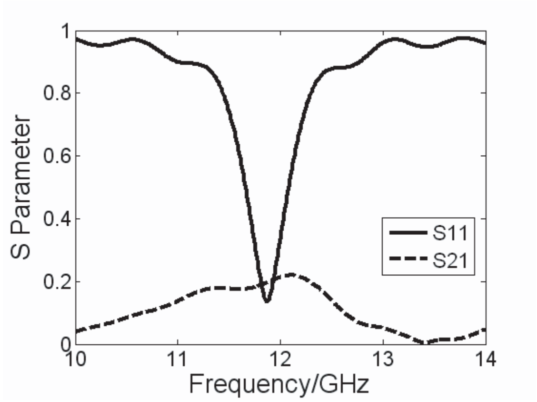


Figure 3. Amplitudes of simulated S_{11} (solid) and S_{21} (dahsed) of one unit cell along the propagation direction.

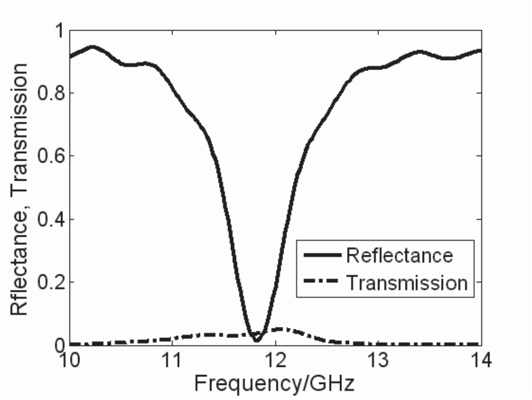


Figure 4. Reflectance (solid) and transmission (dashed) per unit cell.

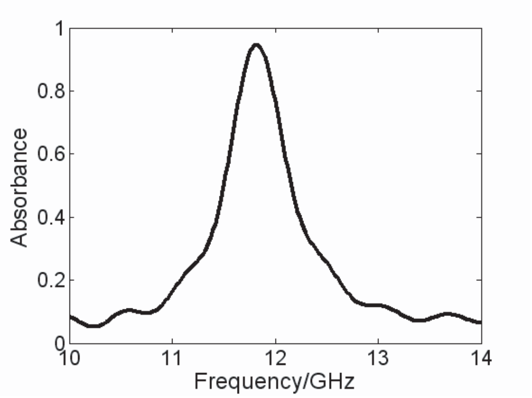
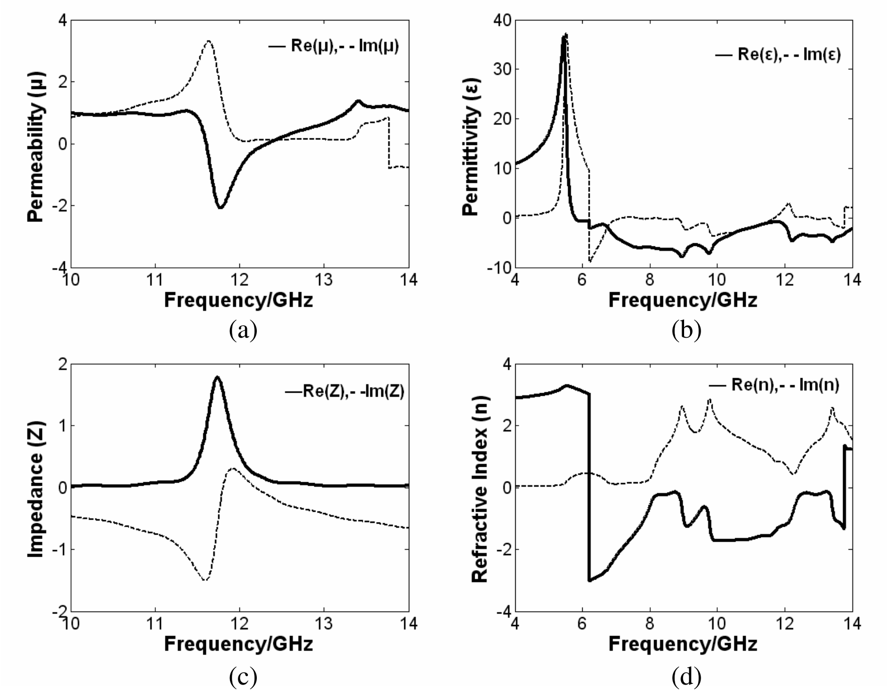


Figure 5. Absorbance of a one-unit-cell layer of the metamaterial absorber.

the reflection and transmission are minor, so a strong absorbance is expected here. According to the magnitudes of S_{11} and S_{21} parameters in Figure 3, we plotted the reflectance $|S_{11}|^2$, transmission $|S_{21}|^2$ and absorbance $A = 1 - |S_{11}|^2 - |S_{21}|^2$ over the frequency range 10–14 GHz in Figures 4 and 5. As shown in Figures 4 and 5, the reflectance and transmission at 11.8 GHz are reduced to 1% and 3%, respectively, very near zero. Accordingly, the absorbance at 11.8 GHz reaches up to 96%, very near unity. The FWHM (Full Width at Half Maximum) is 11.5–12.2 GHz and the relative width is 6% compared to 11.8 GHz.

In order to see whether the two requirements of absorbers are satisfied, the effective constitutive parameters were retrieved from simulated S parameters [20]. Figures 6(a), (b), (c) and (d) show the retrieved effective permeability, permittivity, impedance and refractive index, respectively. As shown in Figures 6(a) and (b), over the frequency range 11–13 GHz, either the effective permeability or the effective permittivity is below unity or both are below unity, so the unit cell can be regarded as a metamaterial unit cell in 11–13 GHz. In Figure 6(c), at the absorbance peak frequency 11.8 GHz, the real and imaginary parts of relative impedance are 1.05 and 0.06, respectively, which means $Z \approx Z_0$ (where Z_0 is the impedance of the free space). The impedance approximately matches that of the free space. Over the FWHM 11.5–12.2 GHz, imaginary part of the refractive index is between 0.5 and 1.6, which means a maximum absorbance of the transmitted waves per unit cell $A = 1 - \exp(-252\pi a) = 96\%$. From this analysis, without metallic backing plate or the resistive sheet, the unit cell can meet the two necessary requirements of a good absorber. At 11.8 GHz, the effective permeability and permittivity



(a) (b)

(c) (d)

Figure 6. Retrieved constitutive parameters: (a) Effective permeability, (b) effective permittivity, (c) relative impedance to the free space and (d) refractive index.

of the unit cell are nearly equal and thus the impedance matches that of the free space approximately, which guarantees maximum reflection. Moreover, because of large imaginary part of the refractive index, the absorption of transmitted EM waves is strong. The unit cell act as an ideal candidate for constructing 3-dimensional metamaterial microwave absorber.

4. CONCLUSIONS

In this paper, by computer simulations and theoretical analysis, we proposed a 3-dimensional metamaterial absorber composed of electric and magnetic resonators and proved its near-unity absorbance. By carefully adjusting the geometrical dimensions of the electric and magnetic resonators, their negative response can occur simultaneously with almost equal effective permeability and permittivity as well as high imaginary part of the refractive index. The maximum absorbance per unit cell reaches up to 96%, with a 6% FWHM. Moreover, the proposed metamaterial absorber isn't limited by diffraction limit and can be made as thin as $\lambda/7$. The absorber doesn't need metallic backing plates and resistive sheet, so the weight as well the thickness of the absorber is greatly reduced and it can be directly used in stealth technology.

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REFERENCES

1. Veselago, V. G., "The electrodynamics of substances with simultaneously negative values of ε and μ," *Sov. Phys. Usp.*, Vol. 10, 509–514, 1968.
2. Pendry, J. B., A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," *IEEE Trans. Microwave Theory Tech.*, Vol. 47, 2075–2084, 1999.
3. Smith, D. R., W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," *Phys. Rev. Lett.*, Vol. 84, 4184–4187, 2000.

4. Lagarkov, A. N., V. N. Kisel, and V. N. Semenenko, "Wide-angle absorption by the use of a metamaterial plate," *Progress In Electromagnetics Research Letters*, Vol. 1, 35–44, 2008.
5. Ourir, A., A. D. Lustrac, and J.-M. Lourtioz, "All-metamaterial-based subwavelength cavities $\lambda/60$ for ultrathin directive antennas," *Appl. Phys. Lett.*, Vol. 88, 084103, 2006.
6. Alù, A., F. Bilotti, N. Engheta, and L. Vegni, "Sub-wavelength, compact, resonant patch antennas loaded with metamaterials," *IEEE Trans. Antennas Propagat.*, Vol. 55, No. 1, 13–25, 2007.
7. Bilotti, F., A. Toscano, L. Vegni, K. B. Alici, K. Aydin, and E. Ozbay, "Equivalent circuit models for the design of metamaterials based on artificial magnetic inclusions," *IEEE Trans. Microwave Theory Tech.*, Vol. 55, No. 12, 2865–2873, 2007.
8. Alù, A., F. Bilotti, N. Engheta, and L. Vegni, "A conformal omni-directional sub-wavelength metamaterial leaky-wave antenna," *IEEE Trans. Antennas Propagat.*, Vol. 55, No. 6, 1698–1708, 2007.
9. Xi, S., H. Chen, B.-I. Wu, and J. A. Kong, "Experimental confirmation of guidance properties using planar anisotropic left-handed metamaterial slabs based on S-ring resonators," *Progress In Electromagnetics Research*, PIER 84, 279–287, 2008.
10. Ran, L., J. Huangfu, H. Chen, X. Zhang, K. Cheng, T. M. Grzegorczyk, and J. A. Kong, "Experimental study on several left-handed metamaterials," *Progress in Electromagnetics Research*, PIER 51, 249–279, 2005.
11. Wongkasem, N., A. Akyurtlu, and K. A. Marx, "Group theory based design of isotropic negative refractive index metamaterials," *Progress In Electromagnetics Research*, PIER 63, 295–310, 2006.
12. Wang, J. F., S. B. Qu, Z. Xu, J. Q. Zhang, Y. M. Yang, H. Ma, and C. Gu, "A candidate three-dimensional GHz lefthanded metamaterial composed of coplanar magnetic and electric resonators," *Photonics Nanostruct.: Fundam. Appl.*, Vol. 6, 183–187, 2008.
13. Kisel, V. N. and A. N. Lagarkov, "Near-perfect absorption by a flat metamaterial plate," *Phys. Rev. E*, Vol. 76, 065601, 2007.
14. Kern, D. J. and D. H. Werner, "A generic algorithm approach to the design of ultra-thin electromagnetic band-gap absorber," *Microwave Opt. Tech. Lett.*, Vol. 38, No. 1, 61–64, 2003.
15. Chakravarty, S., R. Mittra, and N. R. Williams, "On the application of the micro-Genetic Algorithm (MGA) to the design of broadband microwave absorbers comprising frequency selective surface (FSS) embedded in multilayered dielectric media," *IEEE*

Trans. Microwave Theory Tech., Vol. 49, No. 6, 1050–1059, 2001.

16. Bilotti, F., L. Nucci, and L. Vegni, "An SRR based microwave absorber," *Opt. Tech. Lett.*, Vol. 48, No. 11, 2171–2175, 2006.
17. Landy, N. I., S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "Perfect metamaterial absorber," *Phys. Rev. Lett.*, Vol. 100, 207402, 2008.
18. Tao, H., N. I. Landy, C. M. Bingham, X. Zhang, R. D. Averitt, and W. J. Padilla, "A metamaterial absorber for the terahertz regime: Design, fabrication and characterization," *Opt. Express*, Vol. 16, No. 10, 7181–7188, 2008.
19. Ahmadi, A. and H. Mosallaei, "Physical configuration and performance modeling of all-dielectric metamaterials," *Phys. Rev. B*, Vol. 77, 045104, 2008.
20. Smith, D. R., D. C. Vier, T. Koschny, and C. M. Soukoulis, "Electromagnetic parameter retrieval from inhomogeneous metamaterials," *Phys. Rev. E*, Vol. 71, 036617, 2005.