An ultrathin wide-band planar metamaterial absorber based on a fractal frequency selective surface and resistive film*

Fan Yue-Nong(范跃农)[a)b)], Cheng Yong-Zhi(程用志)[a)†], Nie Yan(聂 彦)[a)], Wang Xian(王 鲜)[a)], and Gong Rong-Zhou(龚荣洲)[a)]

[a)] School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
[b)] Department of Mechanical and Electronic Engineering, Jingdezhen Ceramic Institute, Jingdezhen 333403, China

(Received 29 August 2012; revised manuscript received 30 October 2012)

We propose an ultrathin wide-band metamaterial absorber (MA) based on a Minkowski (MIK) fractal frequency selective surface and resistive film. This absorber consists of a periodic arrangement of dielectric substrates sandwiched with an MIK fractal loop structure electric resonator and a resistive film. The finite element method is used to simulate and analyze the absorption of the MA. Compared with the MA-backed copper film, the designed MA-backed resistive film exhibits an absorption of 90% at a frequency region of 2 GHz–20 GHz. The power loss density distribution of the MA is further illustrated to explain the mechanism of the proposed MA. Simulated absorptions at different incidence cases indicate that this absorber is polarization-insensitive and wide-angled. Finally, further simulated results indicate that the surface resistance of the resistive film and the dielectric constant of the substrate can affect the absorbing property of the MA. This absorber may be used in many military fields.

Keywords: wide-band, metamaterial absorber, fractal frequency selective surface, resistive films

PACS: 78.20.Ci, 41.20.Jb **DOI:** 10.1088/1674-1056/22/6/067801

1. Introduction

Electromagnetic (EM) metamaterial (MM) is known as a class of artificial media. The unit cell of MM usually possesses high geometrical symmetry, which is made of periodically arranged metallic structures, and is treated as a homogeneous medium. According to the effective medium theory, MM can be characterized by a complex permittivity $\tilde{\varepsilon}(\omega) = \varepsilon_1 + \mathrm{i}\varepsilon_2$ and permeability $\tilde{\mu}(\omega) = \mu_1 + \mathrm{i}\mu_2$. The effective EM parameters ($\tilde{\varepsilon}(\omega)$ and $\tilde{\mu}(\omega)$) can be tuned and controlled by designing the resonance structure of the unit cell of MM. Thus, MM can achieve many exotic EM properties or phenomena by designing the unit cell, including negative refraction,[1,2] perfect lenses,[3] invisibility cloaks,[4,5] perfect absorption,[6–8] and so on.

Recently, the idea of a metamaterial absorber (MA) was first proposed by Bilotti *et al.*[9] and Mosallaei *et al.*,[10] and realized by Landy *et al.*[6] in the gigahertz (GHz) regime. The perfect absorption of MA is mainly due to the local EM resonance mechanism. The electric and magnetic response can be tuned independently and the impedance of the structure can be matched to free space by varying the geometry of the unit cell of the MA. Based on this mechanism, from the microwave region to visible frequencies, various MAs, each of which are of resonance structure consisting of two or more sandwiched layers, have been proposed and investigated widely.[6–8,11–13] However, the absorption bandwidths of these MAs are very narrow, and may restrict practical applications. Thus, the performance of MA, in particular the bandwidth and the sensitivity to the polarization of the incident wave, has attracted more and more attention. Several attempts to achieve broadband absorption have been made, including loading lumped elements onto MAs,[14–16] adopting a resistive frequency selective surface (FSS) directly,[17–20] or multi-type composite technology.[21–24] These technologies allow the physical limitations regarding the thickness-to-bandwidth ratio to be approached.[19] However, the use of lumped elements leads to complex structures because of manufacturing complexity.

In all the above-mentioned MAs, a perfect conduct (copper or aluminum) film or resonance structure is usually used as the ground plane. In contrast to the techniques used for the previous MAs, an attractive alternative approach is introduced in this work, that is, a continuous resistive film is used as the ground plane. On the other hand, to achieve stronger wide-band absorption, the conventional single-band split-ring structure is also substituted by a multiband Minkowski (MIK) fractal loop structure electric resonator. Finally, an ultrathin MA, which is composed of the MIK fractal loop resonator, a dielectric substrate, and a backing of continuous resistive films, is presented. Then the finite element method (FEM) is used to explore the performance of the MA. The simulated results show that the absorber has a strong wide-band absorption in a range from 2 GHz to 20 GHz, and is polarization-insensitive and wide-angled.

*Project supported by the National Natural Science Foundation of China (Grant No. 51207060) and the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20090142110004).

†Corresponding author. E-mail: cyz0715@126.com

© 2013 Chinese Physical Society and IOP Publishing Ltd

2. Design and simulation

A schematic diagram of the unit cell of the MA is shown in Fig. 1. Arranged sequentially from the top layer to the bottom layer are a metal MIK fractal loop structure electric resonator, the dielectric substrate and continuous resistive films. The dielectric type and the thickness between the MIK electric resonator and the resistive ground plane determine the magnetic response. We are then able to tune the EM response by changing the dimension of the MIK and the separation between them. To maximize the absorption, the impedance ($\tilde{z}(\omega) = \sqrt{\tilde{\mu}(\omega)/\tilde{\varepsilon}(\omega)} \approx 1$) of the MM structure must be matched to that of the free space. On the other hand, the unit cell can be regarded as an equivalent RLC resonance circuit, which can be tuned by changing the size of the metal MIK electric resonator, the dielectric constant of the substrate and the surface resistance of the resistive film. Through RLC resonance, the EM energy in the space can be converted into electric energy in the circuit, and electric energy can subsequently be consumed by the resistive films.[15,17,19,24]

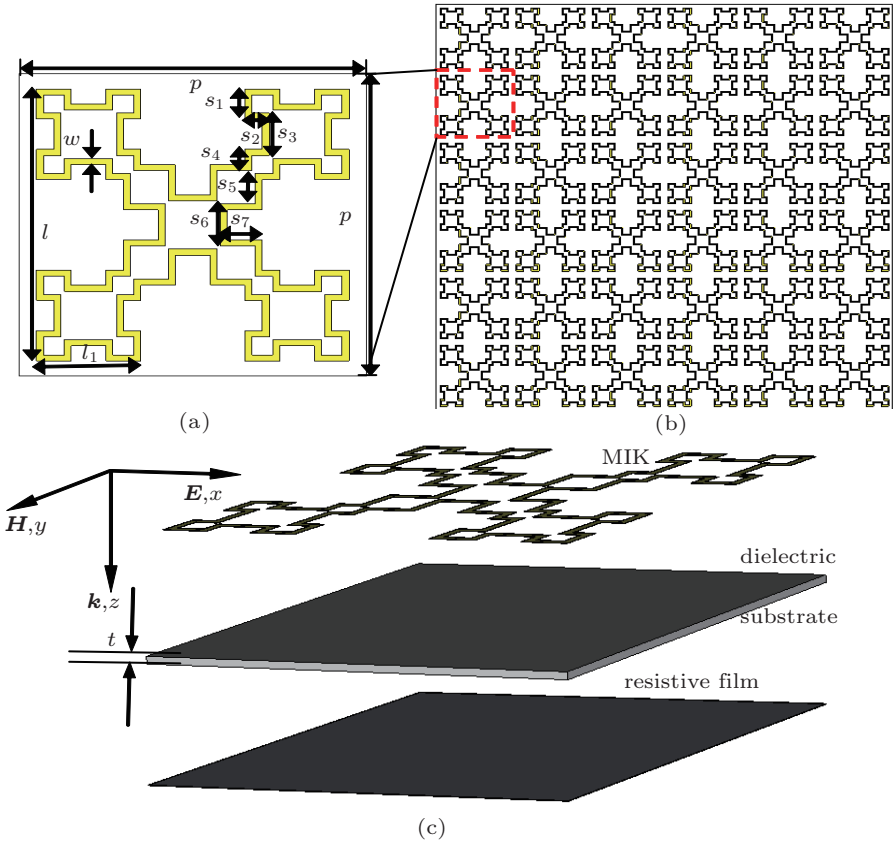


Fig. 1. (color online) Schematic diagram of the unit cell of the MA, showing (a) the MIK fractal loop structure electric resonators, (b) a square array of the MA, and (c) a bird's eye view of the unit cell from the top layer to the bottom layer.

We perform computer simulations of the MA using the FEM with the CST Microwave Studio software, and then set the periodic boundary conditions with the wave vector $\boldsymbol{k}$ perpendicular to the absorber plane, the electric field parallel to the x axis and the magnetic field parallel to the y axis, as shown in the inset of Fig. 1(c). Rapid convergence to a near optimal design can then be readily achieved. For the simulation model of the unit cell of the proposed MA, the MIK metal structure is selected to be copper, whose conductivity is $\sigma = 5.8 \times 10^7$ S/m and thickness $t_{\rm m} = 0.02$ mm. The unit cell structure is optimized and the geometric parameters are as follows: $p = 20$, $l = 18$, $l_1 = 6$, $s_1 = s_3 = s_5 = s_6 = s_7 = 2.15$, $s_2 = s_4 = 1.15$, and $w = 0.3$ (all in units of mm). We use FR-4(loss) with the relative dielectric constant $\varepsilon_r = 4.9$ and the loss tangent $\tan\delta = 0.025$ as the dielectric substrate, and its thickness is only 0.4 mm. The surface resistance and the thickness of the square resistive patch are 475 kΩ and 0.03 mm, respectively. The absorption is calculated by the equation $A(\omega) = 1 - R(\omega) = 1 - |S_{11}|^2$, and the simulated reflection and absorption of the composite structure MA are shown in Fig. 2.

3. Results and discussion

Figure 2(a) shows that the reflection is lower than 10% and that the corresponding absorption exceeds 90% in a range from 2.2 GHz to 20 GHz. These results indicate that the pro-

posed MA has a strong broadband absorption. The relative wave impedance for the normal incidence is retrieved from the simulated S parameters,[12] and the relative wave impedance ($\tilde{z}(\omega)$) is shown in Fig. 2(b). The real part of the relative impedance is near unity ($\mathrm{Re}(z) \approx 1$), and the imaginary part is minimized ($\mathrm{Im}(\tilde{z}) \approx 0$), which is consistent with our intent to match the impedance of the free space in a range from 2 GHz to 20 GHz. The result indicates that our MA can be tuned to approximatively match the impedance to that of the free space in a wide-band absorption frequency range. We conjecture that the wide-band low-reflection high-absorption performance is mainly due to the multiband resonance properties of the MIK fractal loop structure and the Ohmic loss properties of the resistive films.[11,12,18,19] That is to say, the MA with a simultaneously large electric and magnetic resonance loss may result in strong absorption in a wide-band frequency range.

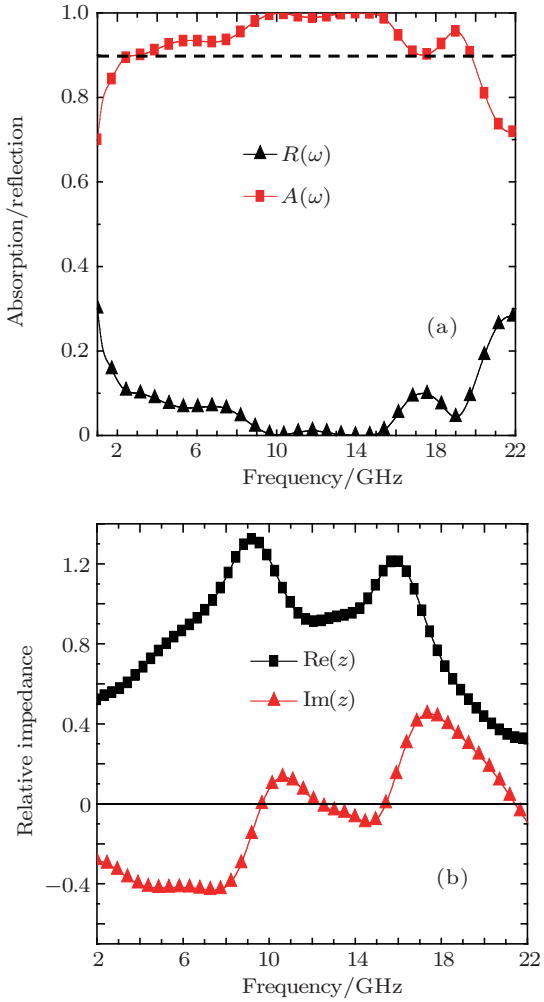


Fig. 2. (color online) (a) Simulated reflection and absorption of the designed MA, and (b) the corresponding relative impedance.

To validate the above conjecture, we should perform a study by comparing the proposed MA with a conventional MA. Here, the conventional MA is composed of an MIK structure resonator and continuous copper films separated by the FR-4 dielectric substrate with a thickness of 0.8 mm (see the inset of Fig. 3(a)). From Fig. 3(a), it can be observed that there are nine absorption peak values in a frequency range between 2 GHz and 22 GHz, which mainly originate from EM coupling resonance.[21] Hence, this conventional MA can achieve stronger multi-band absorption by tuning the structure parameters properly and by using a relatively thick FR-4 dielectric substrate as well. It is also necessary to explore the power loss in the composite structure MA since it can provide information about where the absorption happens for practical applications. Simulated absorptions of composite structure MA under two different loss conditions of the FR-4 substrate are shown in Fig. 3(b). When the FR-4 substrate is lossy, the absorption exceeds 90% in a frequency range from 2.2 GHz to 22 GHz, and the corresponding absorption bandwidth from the central frequency occupies up to 163.6%. When the FR-4 substrate is loss-free, the absorption of the MA is almost unchanged. These results further indicate that the wide-band high absorption is mainly due to the resistance of the resistive film.

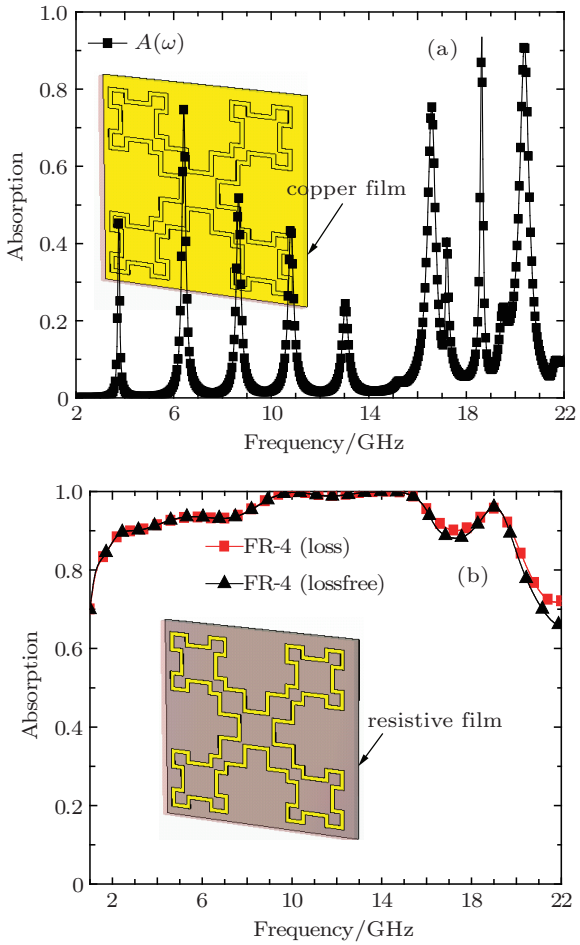


Fig. 3. (color online) (a) Simulated absorption of the conventional MA, and (b) simulated absorptions of the designed MA under two different loss conditions.

To gain a better physical insight into the high absorbing properties of the conventional and our proposed metamaterial absorber, the power loss density distributions of different

type metamaterial absorbers at different frequencies are examined, as shown in Fig. 4. For a conventional metamaterial absorber (see the inset of Fig. 3(a)), as shown in Figs. 4(a) and 4(b), the power losses (see the deep-colored area, which indicates a maximum power loss) are mainly concentrated in the central area of the MIK loop structure at resonance frequencies (e.g. typically, 6.2 GHz and 10.4 GHz), which is due to the strong magnetic coupling and consistent with the corresponding absorption.[12,13,21] Conversely, for the proposed MA, as shown in Figs. 4(c) and 4(d), the power loss is mainly focused in the outside area of the Minkowski loop structure (see the deep-colored area). On the other hand, the area of the power loss density distributions of the designed metamaterial absorber is larger than that of the corresponding conventional metamaterial absorber. Therefore, from the physical pictures of the intriguing absorbing feature, we can deduce that the wide-band high absorption property of the designed metamaterial absorber originates mainly from both the resonance property of the Minkowski fractal loop structure and the Ohmic loss property of the resistive film.

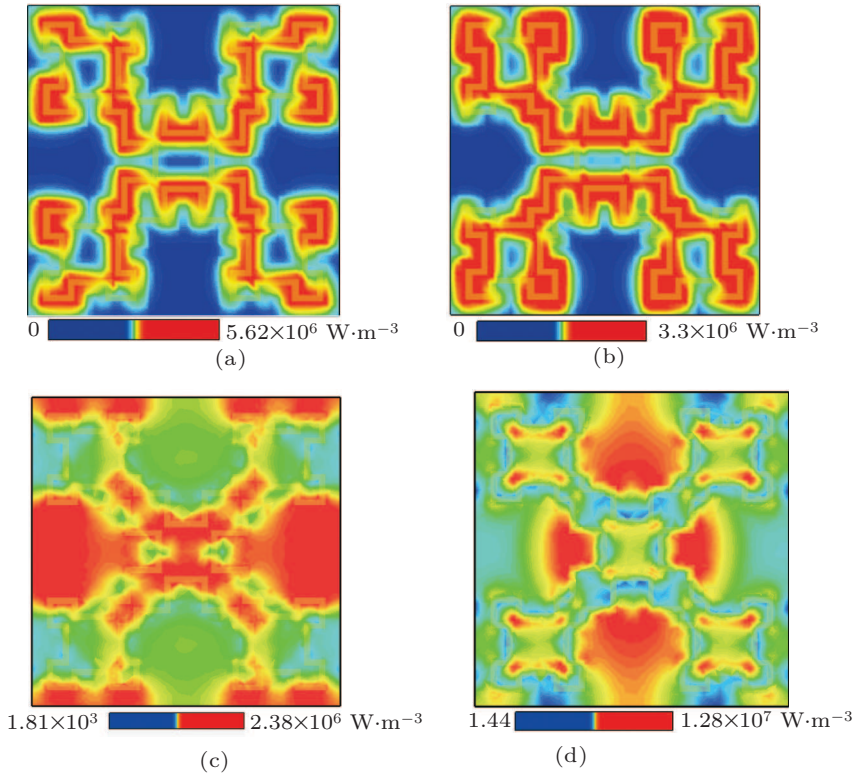


Fig. 4. (color online) The power loss density distributions of different MAs at frequencies of (a) 6.2 GHz and (b) 10.4 GHz for the conventional MA, and at (c) 6.2 GHz and (d) 10.4 GHz for our designed MA.

Next, we further investigate the polarization-insensitive and wide-angle properties of the MA, and the simulated results are shown in Fig. 5. From Figs. 5(a) and 5(b), the absorptions under different polarization angles for the TE and TM waves are almost unchanged. Figures 5(c) and 5(d) show the simulated absorptions of our MA at various angles of oblique incidence for the TE and TM modes, which indicate that the absorptions are not significantly influenced. For the TE wave, the absorption band is almost unchanged when the angle of incidence is under 50°. For the TM wave, the absorption band is almost not influenced when the angle of incidence is under 40°. These results indicate that the composite structure MA is polarization-insensitive and wide-angled.

Further, we study the absorption performances for the cases of optimal substrate thickness and MIK structure geometric parameters, under different values of the dielectric constants of the substrate and surface resistance of the resistive film. The simulated results are displayed in Fig. 6. From Fig. 6(a), we can see that the absorption properties are not significantly changed when the relative dielectric constant of the substrate is below 3. However, the absorption bandwidth of 90% will gradually become narrower with the increase in the dielectric constant (when $\varepsilon_r > 4$). From Fig. 6(b), it can be observed that the absorption frequency of 90% gradually shifts toward a higher frequency range with the decrease in the surface resistance of the resistive film. These results indicate that the proposed MA can achieve high-absorption in different frequency ranges by varying the dielectric constant of the substrate and the surface resistance of the resistive film.

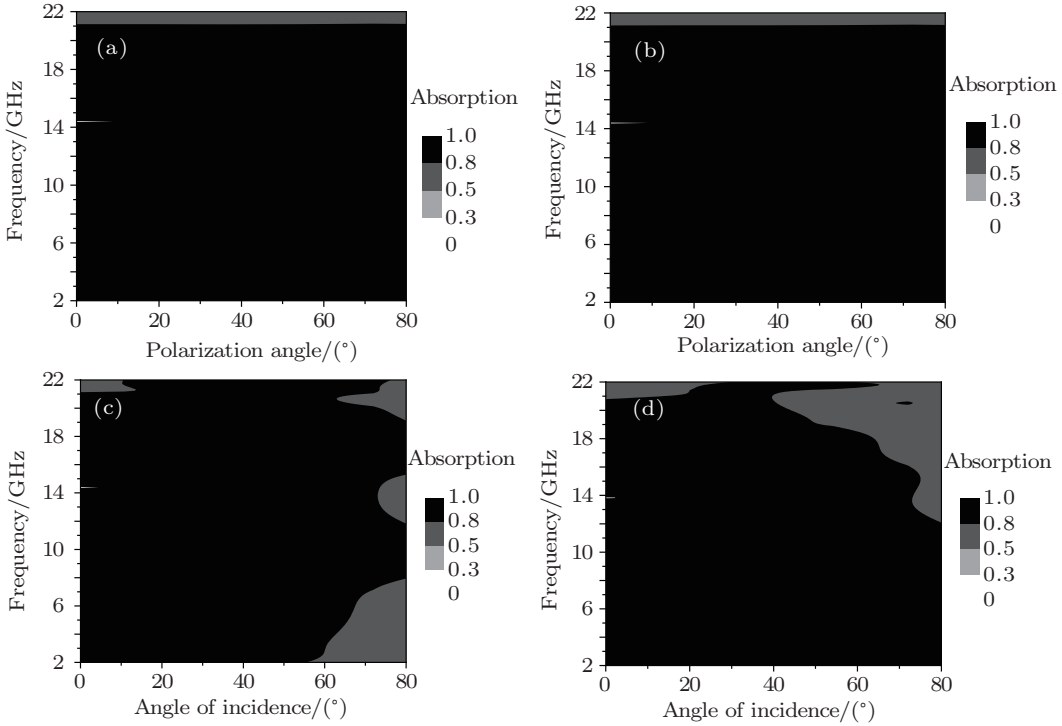


Fig. 5. (color online) Simulated absorptions at different polarization angles: (a) TE, (b) TM; and simulated absorptions at different angles of incidence: (c) TE, (d) TM.

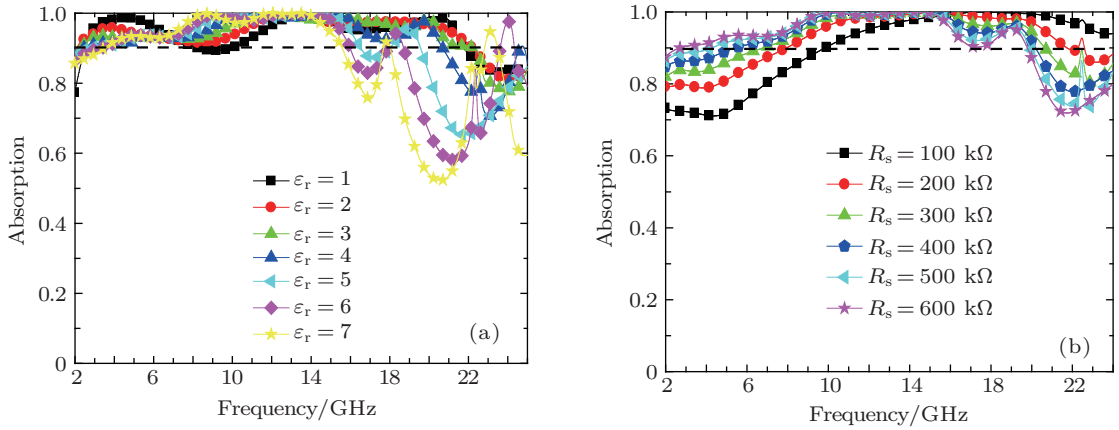


Fig. 6. (color online) Simulated absorptions versus frequency under different dielectric constants of substrate (a), and different surface square resistances of resistive films (b), for the designed MA structure.

4. Conclusion

In this paper, we present a wide-band polarization-insensitive and wide-angle planar MA, which is composed of the dielectric substrate sandwiched with MIK fractal loop structure electric resonators and continuous resistive films. The simulated results demonstrate that the absorption of the proposed MA is greater than 90% in a frequency range from 2.2 GHz to 20 GHz, and is also polarization-insensitive and wide-angled. The numerically investigated results indicate that the wide-band high absorption is mainly due to the multi-band resonance property of the MIK fractal loop structure and the Ohmic loss of the surface resistance of the resistive film. The further investigated results indicate that the proposed MA can achieve high-absorption in different frequency ranges by changing the type of substrate and the surface resistance of the resistive film. Compared with the previously designed MA,[14,15,19–23] our proposed MA has an ultra-thin thickness and broader high absorption band. Furthermore, the proposed MA is easy to realize experimentally. First, we adopted the conventional PCB technology or standard optical lithography process to fabricate an MIK copper or aluminum structure on a dielectric substrate surface. Then, a thin resistive film was deposited on the substrate backed by a grounded plane using silk-screen printing technology, and the surface resistance tuned by controlling the thickness of the resistive film. So the

purpose of this work is to present a new type of ultrathin high-performance MA, and to offer theoretical support for future experiments.

References

[1] Veselago V G 1968 *Sov. Phys. Usp.* **10** 509
[2] Shelby R A, Smith D R and Schultz S 2001 *Science* **292** 177
[3] Pendry J B 2000 *Phys. Rev. Lett.* **85** 3966
[4] Pendry J B, Schurig D and Smith D R 2006 *Science* **312** 1780
[5] Schurig D, Mock J J, Justice B J, Cummer S A, Pendry J B, Starr A F and Smith D R 2006 *Science* **314** 977
[6] Landy N I, Sajuyigbe S, Mock J J, Smith D R and Padilla W J 2008 *Phys. Rev. Lett.* **100** 2074021
[7] Cheng Y Z, Yang H L, Cheng Z Z and Wu N 2011 *Appl. Phys. A: Mater. Sci. Process.* **102** 99
[8] Li M H, Yang H L, Hou X W, Tian Y and Hou D Y 2010 *Progress in Electromagnetics Research* **108** 37
[9] Bilotti F, Alu A, Engheta N and Vegni L 2005 in: *Proceedings of the Nanoscience and Nanotechnology Symposium*—NN 2005, Frascati, Italy, p. 4
[10] Mosallaei H and Sarabandi K 2005 *IEEE Antennas and Propagation Society International Symposium*, 2005, p. 615
[11] Landy N I, Bingham C M, Tyler T, Jokerst N, Smith D R and Padilla W J 2009 *Phys. Rev. B* **79** 125104
[12] Liu X L, Tatiana S, Starr A F and Padilla W J 2010 *Phys. Rev. Lett.* **104** 207403
[13] Hu C G and Luo X G 2009 *Opt. Express* **17** 19
[14] Gu S, Barrett J P, Hand T H, Popa B I and Cummer S A 2010 *J. Appl. Phys.* **108** 064913
[15] Gu C, Qu S B, Pei Z B, Zhou H, Xu Z, Bai P, Peng W D and Lin B Q 2010 *Chin. Phys. Lett.* **27** 117802
[16] Mias C and Yap J H 2007 *IEEE Trans. Anten. Propag.* **55** 1955
[17] Costa F, Monorchio A and Manara G 2007 *Proc. IEEE International Symposium on Antennas and Propagation*, June 10–15, 2007, Honolulu, Hawaii, USA, p. 861
[18] Liu H T, Cheng H F, Chu Z Y and Zhang D Y 2007 *Materials & Design* **28** 2166
[19] Filippo C, Agostino M and Giuliano M 2010 *IEEE Trans. Anten. Propag.* **58** 1551
[20] Pang Y Q, Zhou Y J and Wang J 2011 *J. Appl. Phys.* **110** 023704
[21] Liao Z Q, Gong R Z, Nie Y, Wang T and Wang X 2011 *Photon. Nanostruct. Fundam. Appl.* **9** 287
[22] Sun L Q, Cheng H F, Zhou Y J and Wang J 2012 *Chin. Phys. B* **21** 055201
[23] Yang Y J, Cui Y J, Wen G J, Zhong J P, Sun H B and Oghenemuero G 2012 *Chin. Phys. B* **21** 038501
[24] Cheng Y Z, Wang Y, Nie Y, Zheng D H, Gong R Z, Xiong X and Wang X 2012 *Acta Phys. Sin.* **61** 134103 (in Chinese)