Simultaneous realization of the single-band and broadband terahertz perfect absorber using one piece of metamaterial resonator

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Received: 30 September 2019 / Accepted: 5 February 2020 / Published online: 12 February 2020
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Abstract

A kind of terahertz metamaterial absorber, made of only an Au closed-ring resonator and a dielectric layer deposited on a continuous Au film, is presented to achieve bifunctional absorption characteristic. Unlike traditional absorbers having the single-functional absorption features of single-band or broadband, the designed device exhibits not only the single-band absorption response at frequency of 1.45 THz, but also a broadband absorption performance, which is caused by the superposition of three adjacent frequencies that are all localized at right side of the single-band absorption. Importantly, the relative absorption bandwidth of the broadband performance of the device over absorption rates of 50% and 80% can, respectively, reach 47.22% and 35.97%, which is very close to (and even exceed) the performance of previous single function of broadband absorbers that require several different lengths of metallic elements. The designed bifunctional absorber has the comprehensive advantages of the single functions of the single-band and broadband absorbers, and therefore, this work can offer an inspiring method to obtain a bifunctional absorber through using only one piece of metamaterial.

Keywords Metamaterials · Perfect absorber · Broadband absorption · Terahertz

1 Introduction

Metamaterials with subwavelength lattice structures have been extensively used to control and manipulate the essential characteristics of electromagnetic (EM) waves, and the manipulation of the EM waves can be used to realize a variety of functional devices for different purposes, including electromagnetically induced transparency [1], Fano resonance [2], slow light effect [3], modulators [4], absorbers [5]. Metamaterial absorbers (MAs) [5–30], as one of them, have received a wide range of attention for their potential applications in thermal imaging and thermal emitter, solar cells, sensing, detecting, etc. Compared with traditional light absorbers [8], the MAs possess some outstanding advantages, which are mainly embodied in

ultra-thin dielectric sheet thickness, scalable structure size, and controllable resonance performance. Therefore, since the first presentation of the microwave MA in 2008 [5], various styles of MAs at spectrum ranges of visible, infrared, terahertz, and microwave have been studied [8–11]. Nevertheless, the designs of these MAs can only achieve the perfect absorption of single frequency point, i.e., the single-band absorption. This is unfavorable in many application aspects.

To expand the application scopes of the MAs, some approaches have been put forward to achieve multiple-band and broadband absorption features. These suggested methods can be summarized into three categories: (a) Integrate a number of resonant structures with different sizes into a super-lattice coplanar structure [12–14];

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(b) integrate several different sizes of metallic elements into a stacked structure [15–18]; and (c) use the combination methods of the (a) and (b) [19, 20]. Although these methods can achieve excellent performance of the MAs, the starting point of these designs is the same, which combines several different frequencies of single-band absorption peaks, each of which resonance peak corresponds to a certain length of metallic element. More importantly, these obtained MAs only have specific functions, including the absorption response of single-band, multiple-band, or broadband, which cannot achieve the combination of any two functions, that is, the simultaneous realization of the single-band and broadband absorption or the simultaneous realization of the multiple-band and broadband absorption, i.e., the bifunctional absorption response.

Because the use of resonators with different dimensions is easy to design the multiple-band and broadband MAs, there are two basic things we have to get clear on: First, is it possible for us to break this kind of conventional design method that must employ multiple metallic resonators? If yes, how do we design? Second and most important, can we design a kind of MA with bifunctional (or multiple-functional) absorption performance?—for example the absorption features of the simultaneous realization of single-band and broadband in a unit cell, instead of designing two single functions of single-band and broadband MAs, respectively. If these two concerns can be effectively solved, the designed MA will find more application prospects.

This paper is committed to studying a kind of bifunctional terahertz MA using a new type of structure design consisted of only one metallic ring resonator. Simulation

results show that besides a large absorption rate of single-band resonance peak at frequency of 1.46 THz, a wide absorption range across a continuous bandwidth of 1.70 THz (in absorption larger than 50%) with central resonant frequency of 3.60 THz is also realized. That is to say, bifunctional absorption features of single-band and broadband can be realized simultaneously in this resonance structure. The relative bandwidth of the broadband response of the device can reach 47.22%, which is very close to and even greater than the absorption performance of previous single-functional broadband MAs that integrate several different dimensions of resonators into a unit structure. Moreover, we found that the performance of the presented bifunctional MA can be controlled by reshaping the parameters of the metallic ring resonator.

Compared with previous MAs, the designed MA has the following advantages: Firstly, the structure of the MA is only consisted of one metallic resonator, which presents a new design approach to obtain broadband absorption response, rather than using multiple different lengths of resonators. From this point of view, it can greatly simplify the design complexity of the structure, reduce construction costs, and eliminate the strong interaction encountered in multiple resonators. Secondly, the simultaneous realization of single-band and broadband absorption (or bifunctional absorption) can integrate the respective advantages of the single functions of the single-band MA and broadband MA (see Table 1 for the comparison between this work and the previous reports), and therefore, the bifunctional MA will find more application prospects than single-functional devices of single-band and broadband.

Table 1 Performance comparison between this work and the previous reports

References	Published years	Working frequencies	Number of resonators	Absorption types	Absorption functional
[6]	2018	Infrared	1	Single-band	Single-functional
[7]	2018	Terahertz	1	Multiple-band	Single-functional
[9]	2019	Terahertz	5	Dual-band	Single-functional
[10]	2018	Infrared	2	Single-band	Single-functional
[11]	2019	Near-infrared	4	Single-band	Single-functional
[12]	2018	Infrared	4	Multiple-band	Single-functional
[13]	2018	Microwave	4	Multiple-band	Single-functional
[14]	2019	Microwave	13	Multiple-band	Single-functional
[15]	2018	Visible	6	Broadband	Single-functional
[16]	2019	Terahertz	3	Multiple-band	Single-functional
[17]	2019	Microwave	4	Broadband	Single-functional
[18]	2019	Microwave	25	broadband	Single-functional
[19]	2016	Terahertz	4	Multiple-band	Single-functional
[20]	2015	Terahertz	9	Broadband	Single-functional
This work	Present	Terahertz	1	Single-band + broadband	Bifunctional

2 Structure design

Figure 1a and b, respectively, gives the top view and side view of the bifunctional metamaterial absorber. As revealed, this absorption device is consisted of the top square metallic ring resonator, the middle insulating medium layer, and the bottom metallic ground placed on a substrate. The bottom metallic board layer has the thickness greater than the skin depth of the incident beam; therefore, the transmission of the designed metamaterial structure should be completely suppressed. Since the transmission of the metamaterial structure is zero, the substrate materials can be selected arbitrarily. The silicon or silicon dioxide can be selected here. The top square metallic ring resonator has the outside length of $l = 40 \mu\text{m}$ and the inside length of $g = 24 \mu\text{m}$, which indicates that the width of the square metallic ring is equal to $8 \mu\text{m}$, i.e., the $(l-g)/2$. The square metallic ring resonator is placed on the basic cell with the period dimensions of $P_x = P_y = 60 \mu\text{m}$. The middle insulating medium layer has the thickness of $t = 15 \mu\text{m}$, and its refractive index is $1.733 + i0.1$. The top and bottom metallic layers are both made of gold with conductivity of $4.09 \times 10^7 \text{ S/m}$.

Numerical simulation software FDTD solutions version 8.6 based on finite-difference time-domain method is employed to analyze the absorption properties and resonance mechanisms of the MA. In the concrete analysis process, a plane electromagnetic wave with electric field parallel to x-axis is irradiated to the basic cell. In the light propagation direction, we employ perfectly matched layers to eliminate the unnecessary scattering, while in both

directions of x and y , periodic boundary conditions are utilized to represent the periodic arrangement of resonant structures.

3 Results discussion

Figure 1c provides the absorption spectra of the presented bifunctional MA. It is clearly observed that four near-perfect resonance absorption peaks in this structure are obtained, which is different from previous multiple-band or broadband MAs that typically require several different dimensions of metallic elements. Particularly, we found that the last three peaks are far from the first resonance peak, i.e., the off-resonance (A point of Fig. 1c) absorption rate of the first peak and the last three bands is considerable low, about 32%, while the off-resonance absorption rates of the last three peaks (see B and C points) are, respectively, 80.77% and 78.79%, which indicates that a broadband absorption bandwidth is realized by combining the three adjacent resonance peaks. For the broadband absorption response, larger than 50% (or 80%) absorption can be achieved over a continuous spectra range of 1.70 THz (or 1.32 THz), where its central resonance frequency is 3.60 THz (or 3.67 THz). The relative resonance bandwidths of the broadband response (in absorption > 50% and 80%) are, respectively, 47.22% and 35.97%, which are very close to and even larger than the performance of previous broadband MAs that combine several different lengths of metallic elements. From this point, the broadband absorption function of the designed MA has the ability to simplify the design complexity of the structure, reduce fabrication steps and costs, and eliminate the strong interaction in the multimetric structure.

On the basis of the above analysis, we know that the presented device exhibits not only the single-band absorption characteristic but also the broadband resonance response, i.e., the bifunctional absorption property. This kind of resonance feature will provide more application prospects than single-functional absorption devices. Additionally, because the Au ring resonator has the high degree of structure symmetry, the absorption performance of the device in two orthogonal polarization states (TE and TM) should remain unchanged. As shown in Fig. 1d, the device absorption response is indeed insensitive to the polarization states of incident wave.

The corresponding field distributions of the four resonance modes of the bifunctional MA are provided to reveal its resonance mechanism. Figure 2a–d is, respectively, the field distributions of the first, the second, the third, and the fourth mode of the MA. Subscripts 1, 2, and 3 of (a), (b), (c), and (d) are, respectively, the fields of $|E|$, real E_z ,

Fig. 1 **a** and **b** Are, respectively, the top view and side view of the structure schematic of the designed bifunctional MA; **c** is the absorption spectra of the presented MA; **d** gives the absorption spectra of the bifunctional MA in TE and TM polarization states of the incident waves

Fig. 2 **a₁–a₃** Are, respectively, the $|E|$, real E_z , and $|H_y|$ field distributions of the first mode of the MA; **b₁–b₃** are, respectively, the $|E|$, real E_z , and $|H_y|$ field distributions of the second mode of the MA;

c₁–c₃ are, respectively, the $|E|$, real E_z , and $|H_y|$ field distributions of the third mode of the MA; **d₁–d₃** are, respectively, the $|E|$, real E_z , and $|H_y|$ field distributions of the fourth mode of the MA

and $|H_y|$. For the first mode of the MA, its $|E|$ field is mainly clustered in both sides of the outside of the square metallic ring resonator (see Fig. 2(a₁)). The real E_z distribution of this mode shown in Fig. 2a₂ is very similar to that of the $|E|$ field in Fig. 2a₁. These two field distributions demonstrate that the first mode of the MA should be originated from the fundamental mode resonance (FMR) of the square metallic ring resonator. As we know, $|H_y|$ field of the FMR is primarily focused on middle insulating dielectric layer (especially the area below the metallic resonator) of the MA. The $|H_y|$ shown in Fig. 2a₃ proves that the first mode of the MA is indeed due to the FMR. That is to say, the single-band absorption function of the MA is attributed to the FMR.

However, compared with the case of the first mode of the MA, the field distributions of the last three modes have nothing in common. We found that the $|E|$ field distributions of the last three modes are concentrated not only at both sides of the outside of the square metallic ring resonator but also at both sides of the inside of the resonator (see Fig. 2b₁, c₁, and d₁), which means that the broadband absorption function of the designed MA can be controlled

by the outside length (l) and the inside length (g) of the square metallic ring resonator. This is why the changes of the inside length g and outside length l have large effect on the frequencies of the last three modes of the MA, as shown in Fig. 3a and b, while the resonance frequency of the first mode of the MA has no significant shift when the inside length g of the Au resonator is changed, which can be attributed to the weak $|E|$ distribution in both sides of the inside of the square metallic ring resonator (see Fig. 2a₁).

In fact, although the field distributions of the last three modes of the MA are completely different from the case of the first one, the $|E|$ distributions of the last three modes are also different. For example, for the second mode of MA in Fig. 2b₁, in addition to the strong field distributions at the edges of the square metallic ring resonator, the spatial regions of the outside of the square metallic ring also own obvious distribution. For the third mode of the MA in Fig. 2c₁, the $|E|$ distribution intensities in inside of the square metallic ring are larger than that of the case of the outside. However, for the fourth mode in Fig. 2d₁, the $|E|$ distributions in both sides of parallel to the direction

Fig. 3 Dependence of the absorption spectra of the presented bifunctional MA on the parameter changes of the inside length g (a), outside length l (b), unit period P (c), and dielectric spacing thickness t (d)

of the color bar and in spatial region of the inner of the square metallic ring are clearly stronger than the cases of the second and the third modes. Particularly, because the $|E|$ fields of the last three modes of the MA are different, the real E_z and $|H_y|$ of the three resonance modes are also not the same (see Fig. 2b₂–d₂ and b₃–d₃). We observed that the $|H_y|$ distributions of the second mode in Fig. 2b₃ and the third mode in Fig. 2c₃ are both mostly focused on the left and right edges of the dielectric layer of the MA, while the $|H_y|$ of the fourth mode in Fig. 2d₃ is chiefly gathered in the dielectric layer of MA below the air gap of the square metallic ring resonator. These field distribution features demonstrate that the second mode and the third mode of the MA should be attributed to two different coupling effects of surface propagation resonance and localized response of the Au resonator, while the third mode should be due to the combination of cavity resonance and localized response of the Au resonator.

To estimate the effect of geometric parameter changes on the absorption performance of the device, we next give the dependence of absorption spectra on the parameter changes of the bifunctional MA. As illustrated in Fig. 3a and b, the last three modes of the MA are strongly affected by the geometric parameters (such as inside length g and outside length l) of the square metallic ring resonator itself, while the frequency shift degree of the first mode is different. Because the first mode of the MA is the FMR of the resonator, the length l change can obviously influence its resonance frequency. However, very weak $|E|$ distribution is observed in both sides of the inside (g) of the square metallic ring resonator (see Fig. 2a₁), and therefore, the frequency shift of the first mode with the variation of

the length g should have a slight change, as illustrated in Fig. 3a. Simulation results further prove that the absorption performance of the broadband response of the MA can be controlled by utilizing different sizes of period P and dielectric spacing thickness t , while the change of the single-band resonance response of the MA is nearly unchanged, as shown in Fig. 3c and d. By analyzing the changing trends of the designed bifunctional MA, we can conclude that the broadband absorption performance of the MA can be easily tuned by using the parameter changes of the square metallic ring resonator itself and the unit cell, while only the length l change of the square metallic ring resonator can obviously affect the performance of the first absorption peak.

4 Conclusion

In conclusion, a bifunctional absorption performance of the terahertz MA based on an Au ring resonator and an Au continuous board separated by a dielectric sheet is theoretically investigated and demonstrated. Simulation results demonstrate that the presented device can achieve the bifunctions of single-band and broadband absorption responses. Particularly, the relative resonance bandwidth of the broadband absorption performance of the device in absorption greater than 50% and 80% can, respectively, reach 47.22% and 35.97%, which are superior to previous single function of broadband MAs that integrate several different dimensions of metallic elements into structures of stacked or coplanar. The resonance mechanisms of the single-band and broadband absorption functions of the MA are discussed and obtained by analyzing the field distributions. Results further show that the single-band and broadband absorption functions of the MA can be controlled through reshaping the parameters of the Au ring resonator and the unit cell. The bifunctional MA designed here can provide wider range of applications than single-functional absorber devices of single-band and broadband.

Acknowledgements This research was funded by National Natural Science Foundation of China (21603087, 11647143), Natural Science Foundation of Jiangsu (BK20160178, BK20160189), China Postdoctoral Science Foundation (2019M651692), Jiangsu Postdoctoral Science Foundation (2018K113C), Fundamental Research Funds for Central Universities (JUSRP51721B).

Compliance with ethical standards

Conflicts of interest The authors declare no competing interests to declare.

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