

Research Article

Co-Polarization Wideband Terahertz Metamaterial Absorber with a Wavy Split Ring Resonator

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Abstract

A simple design of co-polarization wideband metamaterial absorber (MA) for terahertz devices is proposed, where the wavy split ring resonator has been conceived to broaden the absorption bandwidth of MA. Simulation results ensure that the average absorptivity of proposed MA reaches above 90% ranging from 2.07 THz to 4.80 THz. The relative absorption bandwidth (RAB) of proposed MA is 79.47%. In addition, the proposed MA may also be considered as a wideband polarization converter with high efficiency. The physical mechanism of wideband absorption is analyzed by using the electric field and the surface current distributions. The co-polarization absorption characteristics of proposed MA under oblique incident angle are also investigated. For TE mode, the absorptivity of proposed MA reaches above 81% ranging from 2.07 THz to 4.80 THz for incident angles below 40°. For TM mode, the proposed MA still retains absorptivity above 87% ranging from 2.07 THz to 4.80 THz for incidence angles below 40°. Due to the compact structure and co-polarization wideband absorption with wide incident angle stability, the proposed MA may be widely utilized for medical imaging, material detecting and stealth technology. Moreover, the wavy split ring resonator can be also applied to achieve wideband absorption in various frequency regions from microwave to visible light.

Keywords

Metamaterial Absorber, Wideband, Co-Polarization, Wavy Split Ring Resonator, Dipolar, LC Resonance

1. Introduction

Metamaterial absorbers (MAs) have been extensively studied for potential applications since the perfect MA was presented by Landy et al. [1]. So far, a lot of MAs have been studied in several frequency bands including microwave [2], terahertz (THz) [3], and optical regions [4]. Among those, the MAs operating in THz band are necessarily required for the future THz devices, because there exist few natural materials absorbing the THz waves. However, the early demonstrated THz MAs commonly operate within narrow

frequency band because of the resonance effect at a specific frequency, so their practical applications are severely restricted [5].

To solve this problem, many kinds of THz MAs with multiband/wideband absorption performances have been presented till now [6-11]. In fact, wideband THz MAs are preferred for practical applications including THz sensors, detectors, and stealth technology [12]. There are two common ways to broaden the absorption bandwidth: One way is con-

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structuring the coplanar structure consisted of several resonators with different sizes [13-19], and another way is forming a unit cell by vertically stacking several metal-dielectric layers [20-24]. However, the former requires the large unit cells, so it is not suitable for developing miniaturized absorbers. Meanwhile, the latter faces the technical difficulties in fabrication.

Recent researches on MAs show that the asymmetric MA structures can significantly extend the co-polarization absorption bandwidth by ignoring the cross-polarization reflection, and thus such MAs have been applied in the defense systems including stealth technology, radar cross section (RCS) reduction and electromagnetic interference (EMI) reduction, where achieving the cross-polarization absorption and polarization insensitivity is not essential [25].

Based on the results of Refs [25-30], we propose a co-polarization wideband THz MA based on wavy split ring resonator. It is demonstrated that the proposed MA can attain co-polarization absorptivity above 90% ranging from 2.07 THz to 4.80 THz. Moreover, the absorptivity of proposed MA reaches above 81% at the incident angles below 40°. The electric field and the surface current distributions display that the cooperation of dipolar and LC resonances contributes to the wideband absorption of propose MA. Due to the excellent absorption performance such as simple structure, ultra-thin thickness, wide incidence angle and wide bandwidth, the proposed MA may be effectively used in several THz devices such as detectors, sensors and polarization converters.

2. Design and Simulation

The absorptivity of electromagnetic wave absorber is defined as $A(\omega) = 1 - |S_{11}(\omega)|^2 - |S_{21}(\omega)|^2$, where $|S_{11}(\omega)|^2$ is the reflection and $|S_{21}(\omega)|^2$ is the transmission. Furthermore, the reflection is calculated by $|S_{11}(\omega)|^2 = |S_{TMTE}(\omega)|^2 + |S_{TETE}(\omega)|^2$, where $|S_{TMTE}(\omega)|$ and $|S_{TETE}(\omega)|$ mean the reflection coefficients for the cross-polarization and the co-polarization under TE mode, respectively. For transverse electric (TE) wave, the electric field vector points to the y-axis, while the magnetic field vector points to the x-axis. For transverse magnetic (TM) wave, the electric field vector points to the x-axis, while the magnetic field vector points to the y-axis [31]. In the MA structure, the transmission $|S_{21}(\omega)|^2$ becomes zero because of the underlying metal film. So, we can rewrite the absorptivity as $A(\omega) = 1 - |S_{11}(\omega)|^2$.

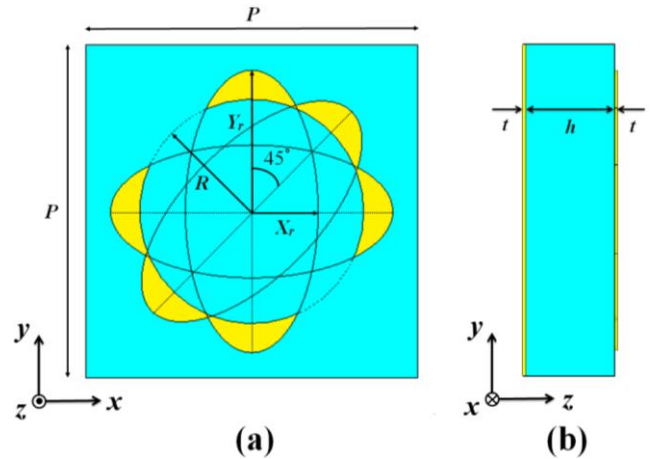


Figure 1. Schematic diagram of the proposed unit cell structure for co-polarization wideband THz MA: (a) front view, (b) side view.

Figure 1 displays the schematic diagram of unit cell for co-polarization wideband THz MA, which has the metal-dielectric-metal configuration. We conceived a wavy split ring resonator as the top metal layer. The middle layer is made of typical lossy polyimide whose dielectric constant is $\epsilon = 3(1+i0.06)$. The underlying layer is a continuous metallic film. The material of metal layers is gold with an electrical conductivity of $\sigma = 4.56 \times 10^7$ S/m and their thicknesses are $t = 0.4 \mu\text{m}$.

We optimize the geometrical dimensions of designed unit cell by utilizing the frequency domain solver imbedded in the simulation software CST Studio Suite 2018. In the simulation setting, the boundary conditions corresponding to the x- and the y- axes are fixed as “unit cell” to mimic an infinite two-dimensional array, and the boundary condition along the z-axis is fixed as “open (add space)”. The aim of iterative optimization processes is to simultaneously achieve the average absorptivity more than 90% and wider absorption bandwidth as shown in Figure 2. Figure 2(a) shows that the proposed MA possesses the broadest bandwidth with absorptivity above 90% when the polyimide layer thickness is $h = 12.4 \mu\text{m}$. Once the thickness value of polyimide layer is fixed, other geometrical dimensions are optimized to further enlarge the working bandwidth with absorptivity more than 90%. Figure 2(b)-2(e) show the absorption characteristics for several values of periodicity of the unit cell (P) in range of 35 – 55 μm , the radius (R) in range of 5.5 - 13.5 μm , the semiminor axis (X_r) in range of 7.7 – 11 μm , and the semimajor axis (Y_r) in range of 16.5 – 20 μm , respectively. Consequently, the final geometrical dimensions are given as $h = 12.4 \mu\text{m}$, $P = 40 \mu\text{m}$, $R = 13.5 \mu\text{m}$, $X_r = 8 \mu\text{m}$, and $Y_r = 17 \mu\text{m}$.

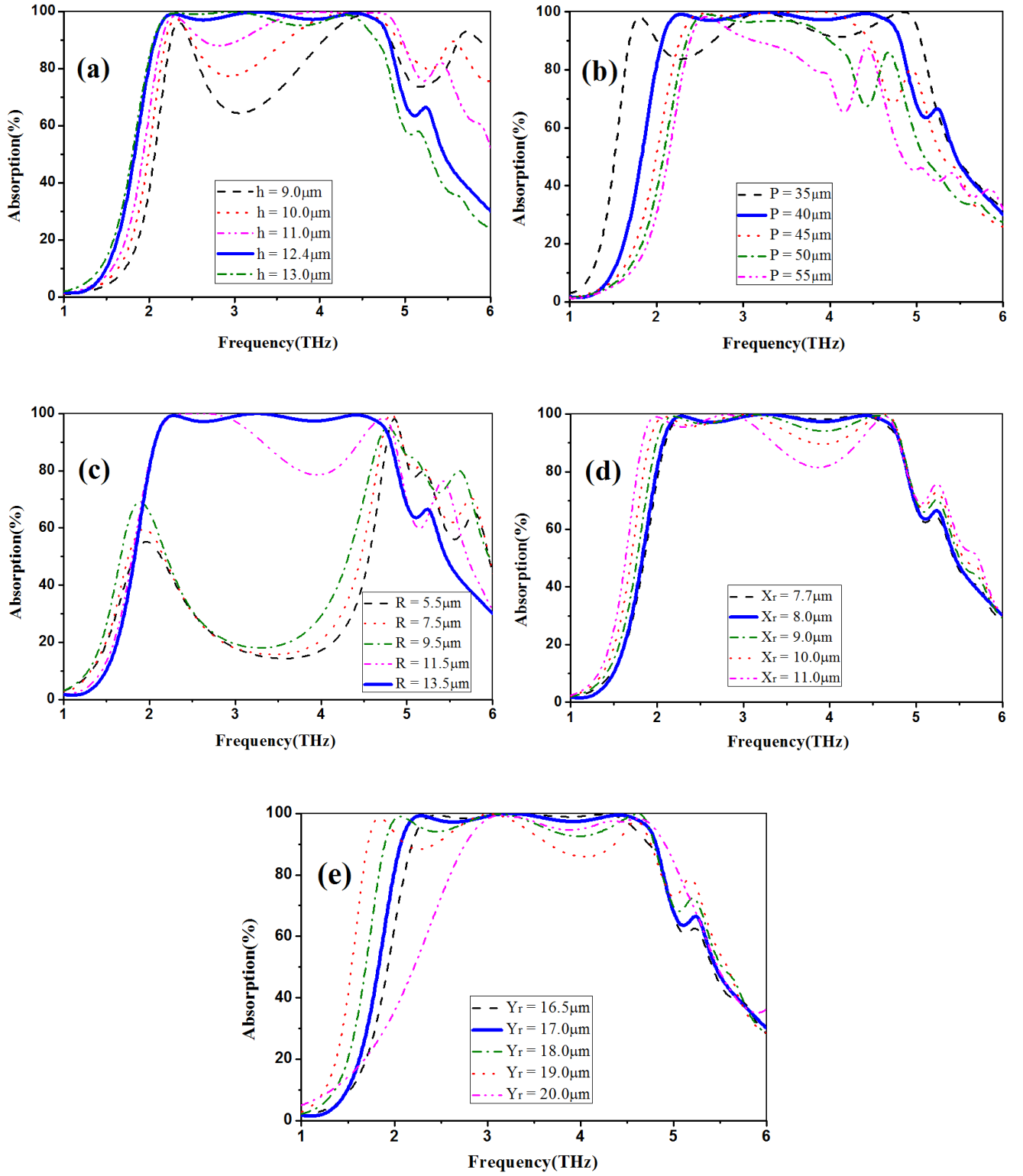


Figure 2. Co-polarization absorption spectra for the wideband MA with different geometrical dimensions: (a) h , (b) P , (c) R , (d) X_r , and (e) Y_r under normal incidence for TE wave.

3. Results and Discussion

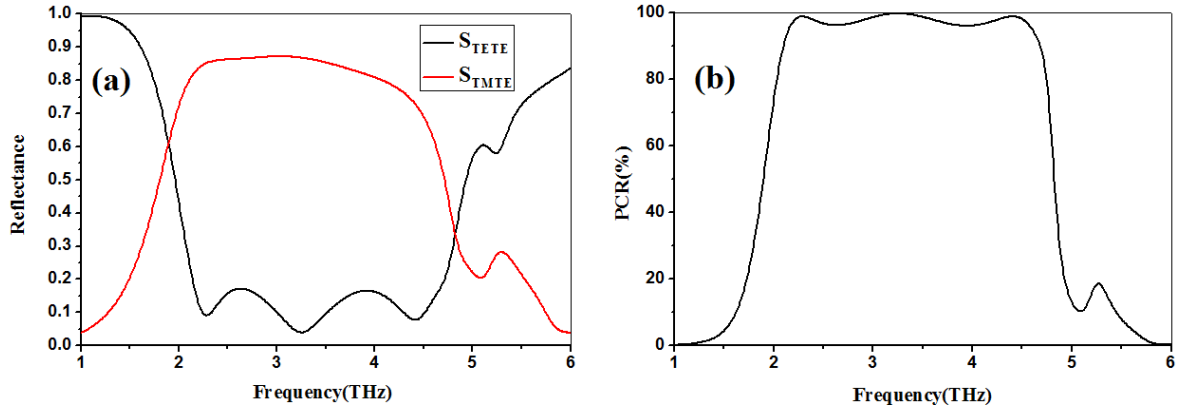


Figure 3. (a) Co-polarization (S_{TETE}) and cross-polarization (S_{TMTE}) reflectance and (b) calculated PCR under normal incidence for TE wave.

When TE wave is incident normally on the proposed MA, the reflection curves of the co- and the cross-polarizations are shown in Figure 3(a). The co-polarization reflectance below 0.3 is observed ranging from 2.07 THz to 4.80 THz, and the cross-polarization reflectance above 0.78 is observed ranging from 2.07 THz to 4.20 THz. If we take account of the cross-polarization reflection in the calculation of absorptivity of the proposed MA, the proposed MA exhibits low absorptivity. Conversely, if we don't consider the cross-polarization reflection, the proposed MA exhibits average absorptivity above 90% ranging from 2.07 THz to 4.80 THz. In fact, the cross-polarization absorption feature is not an essential factor in some applications including stealth technology, RCS reduction and EMI reduction [25]. In other words, only the co-polarization wideband absorption feature becomes an essential factor for the above-mentioned practical applications. In our designed MA structure, the incident THz wave is switched to the cross-polarization mode after reflection. The

polarization conversion ratio (PCR) of the MA with incident TE wave is expressed as Equation (1). As shown in Figure 3(b), the PCR above 86% is observed ranging from 2.07 THz to 4.71 THz. So, the proposed MA may also be considered as a wideband polarization converter with high efficiency.

$$PCR = \frac{|S_{TMTE}|^2}{|S_{TMTE}|^2 + |S_{TETE}|^2} \quad (1)$$

The co-polarization absorption characteristics of proposed MA at normal incidence under TE and TM modes are depicted in Figure 4(a). The co-polarization absorptivity above 90% is observed ranging from 2.07 THz to 4.80 THz. In this case, the resonant frequencies of proposed MA are 2.28 THz, 3.256 THz and 4.408 THz and their absorptivities are 99.18%, 99.85% and 99.40%, respectively.

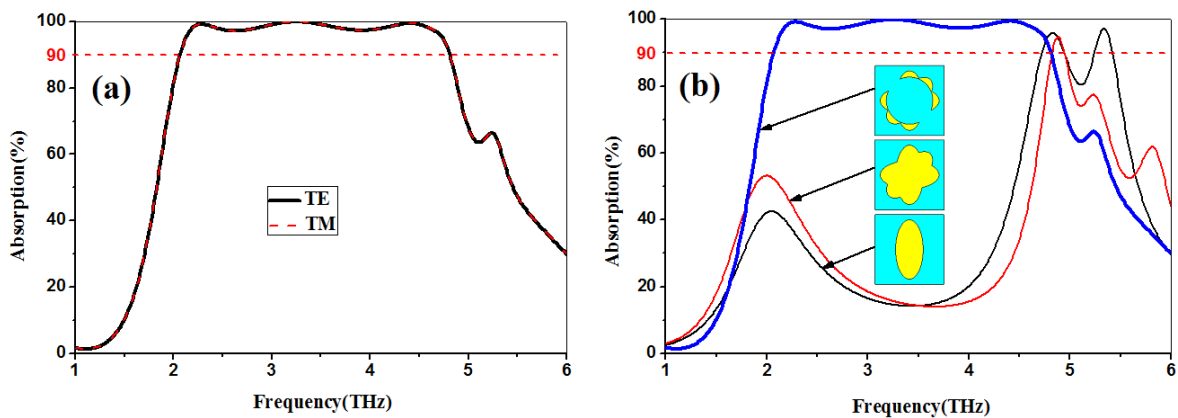


Figure 4. (a) Co-polarization absorption characteristics of proposed MA at normal incidence under TE and TM modes. (b) Co-polarization absorption characteristics for the MAs with different resonators.

Figure 4(b) shows the co-polarization absorption characteristics of the three MAs with different resonator structures. The MA with an elliptical metallic patch resonator has three absorption peaks. Among those, the first absorption peak has low absorptivity of 42.5% at 2.04 THz and other absorption peaks are located close to each other, but they have narrow working bandwidth with absorptivity more than 90%. When the metallic resonator is composed of three elliptical patches, the absorption performance is not significantly improved. So, we cut away a circular patch from the above metal resonator to form a wavy split ring resonator. Consequently, the MA with wavy split ring resonator exhibits high absorptivity more than 90% ranging from 2.07 THz to 4.80 THz. It implies that the MA with wavy split ring resonator can also achieve wideband absorption in various frequency regions from microwaves to optical frequencies [25, 27, 30].

We estimate the performance of proposed MA by calculating relative absorption bandwidth (RAB) defined as Equation (2), where f_U and f_L imply the upper and lower frequencies of working band with absorptivity more than 90%. The proposed MA exhibits the RAB of 79.47%, which is greater than that reported in [10, 16, 18, 21, 24, 25].

$$RAB = 2 \times \frac{f_U - f_L}{f_U + f_L} \quad (2)$$

The geometrical dimensions and RAB of the proposed MA are compared with previous wideband THz MAs as listed in Table 1, where λ notes the wavelength for lower frequency f_L . Our designed MA provides advantages in terms of compact structure, high absorptivity above 90% and wide bandwidth.

Table 1. Comparison of the proposed MA with previous wideband absorbers.

Ref.	Center frequency (THz)	Relative absorption bandwidth (%)	Unit cell size (μm)	Thickness (μm)
[10]	5.165	74.15	20	70.14 (1.0521 λ)
[12]	2.45	108.57	30	100.5 (0.6532 λ)
[16]	4.79	17.12	20	3.4 (0.0514 λ)
[18]	6.64	12.05	38	0.7 (0.0147 λ)
[21]	1.595	53.29	170	22 (0.0924 λ)
[24]	1.96	15.30	85	18 (0.1104 λ)
[25]	1.388	77.52	70	26 (0.078 λ)
[30]	4.705	87.35	43	8 (0.076 λ)
This paper	3.435	79.47	40	12.4 (0.0942 λ)

To realize the perfect absorption response, impedance matching between the MA and free space must be achieved. The relative impedance of the proposed MA structure is calculated from S-parameters.

$$Z(\omega) = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \quad (3)$$

It is observed from Figure 5 that the real and the imaginary values of relative impedance closely reach 1 and 0 ranging from 2.07 THz to 4.80 THz, respectively. In other words, impedance matching between the proposed MA and the free space is occurred. Therefore, the proposed MA exhibits the co-polarization wideband absorption performance.

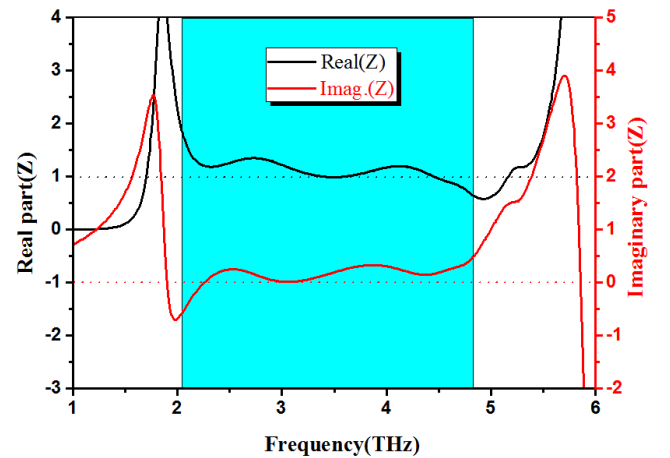


Figure 5. Simulated relative wave impedance for proposed MA.

In order to investigate the mechanism of co-polarization wideband absorption, the electric field ($|E|$) distributions and the surface current distributions are analyzed in detail at three resonant frequencies. At $f_1 = 2.28$ THz, as displayed in Figure 6(a), the electric field intensity strengthens at the corner edges of wavy split ring resonator, thus an electric dipole is induced on the topmost gold resonator. In addition, the electric dipole on top metal layer produces a reverse electric dipole on the bottom metal layer. By these electric dipole resonances, antiparallel surface currents marked with rectangular red lines are generated on top and bottom gold layers as displayed in Figure 7(a, d), thus a vortex current is formed between two metallic layers. The circulating current generates a magnetic field which anti-parallel the incident magnetic field thus, a magnetic resonance is excited. So, the first absorption peak

attributes to the dipolar resonance [32]. At $f_2 = 3.25$ THz, as displayed in Figure 6(b), the electric field intensity strengthens at the end points of wavy split ring resonator, generating another electric dipole resonance on top gold resonator. These electric dipoles also produce antiparallel surface currents marked with rectangular red lines at top and bottom gold layers as displayed in Figure 7(b, e). Therefore, the second absorption peak attributes to the dipolar resonance. At $f_3 = 4.40$ THz, the electric field is distributed as plotted in Figure 6(c), resulting in a LC resonance. This LC resonance induces antiparallel surface currents marked with rectangular red lines at top and bottom gold layers as displayed in Figure 7(c, f). Thus, the LC resonance is responsible for the third absorption peak [33, 34]. As a result, the proposed MA achieves the co-polarization wideband absorption by the dipolar and LC resonances.

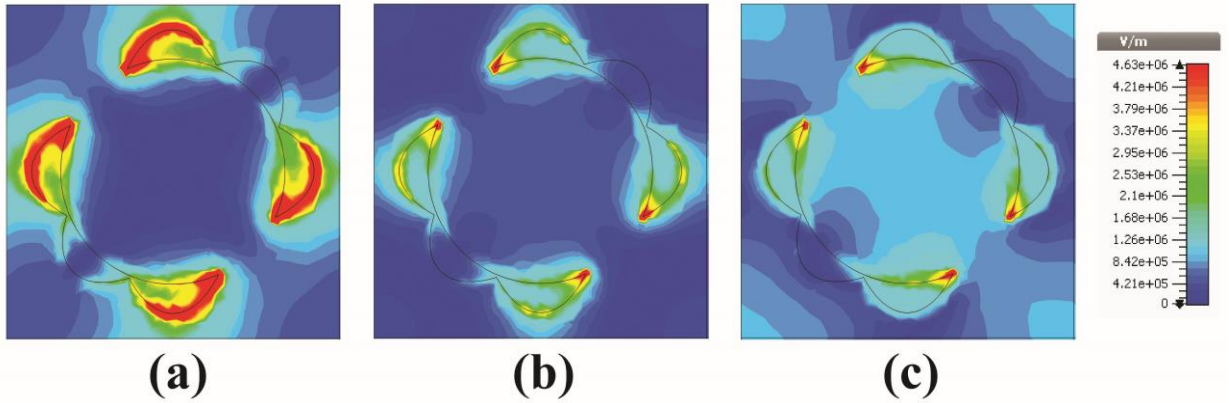


Figure 6. The electric field ($|E|$) distributions on top gold resonator: (a) at 2.28 THz, (b) at 3.25 THz, (c) at 4.40 THz.

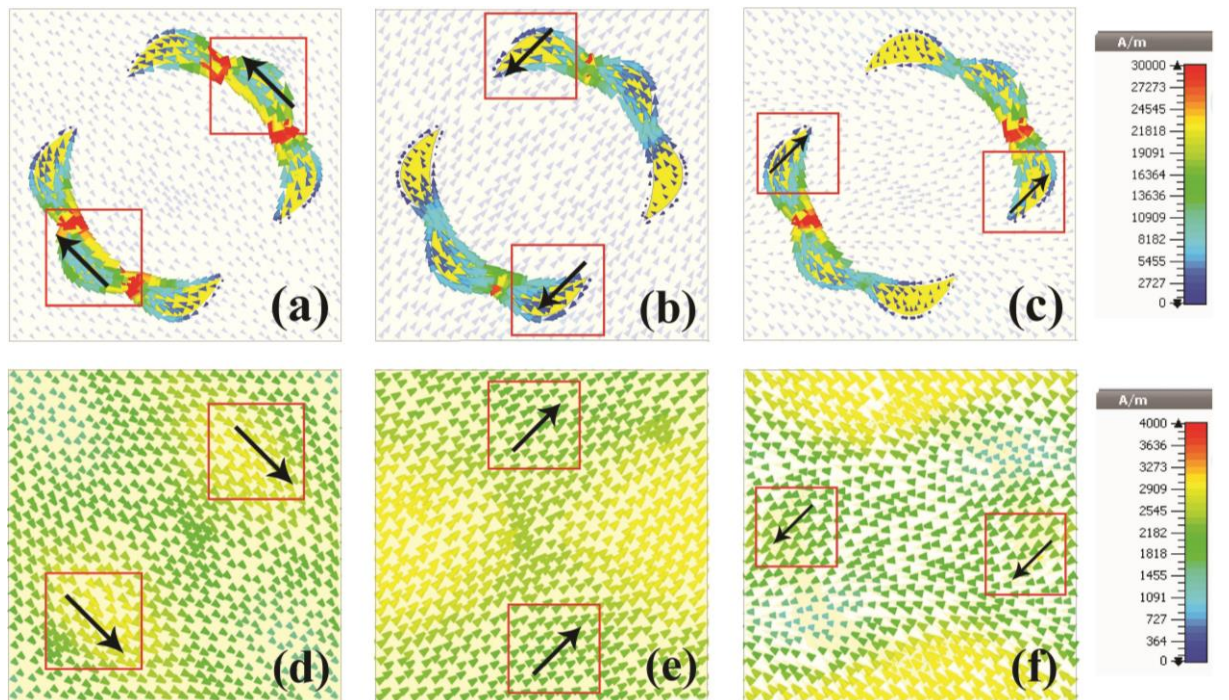


Figure 7. The surface current distributions of (a-c) top and (d-f) bottom metal layers of the proposed MA: (a, d) at 2.28 THz, (b, e) at 3.25 THz, (c, f) at 4.40 THz.

The co-polarization absorption characteristics of proposed MA under oblique incident angle are shown in Figure 8. For TE mode, as shown in Figure 8(a), the absorptivity reaches above 81% ranging from 2.07 THz to 4.80 THz for incident angles below 40° . The rise of incident angle induces the decrease in the absorptivity around 3.25 THz. The cause for these phenomena is that with the growth of incidence angle, the x-oriented magnetic component of incident electromagnetic wave weakens and can no longer excite the strong magnetic

resonance [25]. As shown in Figure 8(b), the proposed MA still retains absorptivity above 87% ranging from 2.07 THz to 4.80 THz for incidence angles below 40° at TM mode. In this case, the absorptivity around 3.25 THz also drops sharply with the growth of incidence angle, because the x-oriented electric component of the incident wave decreases with growth of incidence angle and can't produce the strong electric resonances [26]. That is, the proposed MA holds the high absorption performance for relatively large incidence angles.

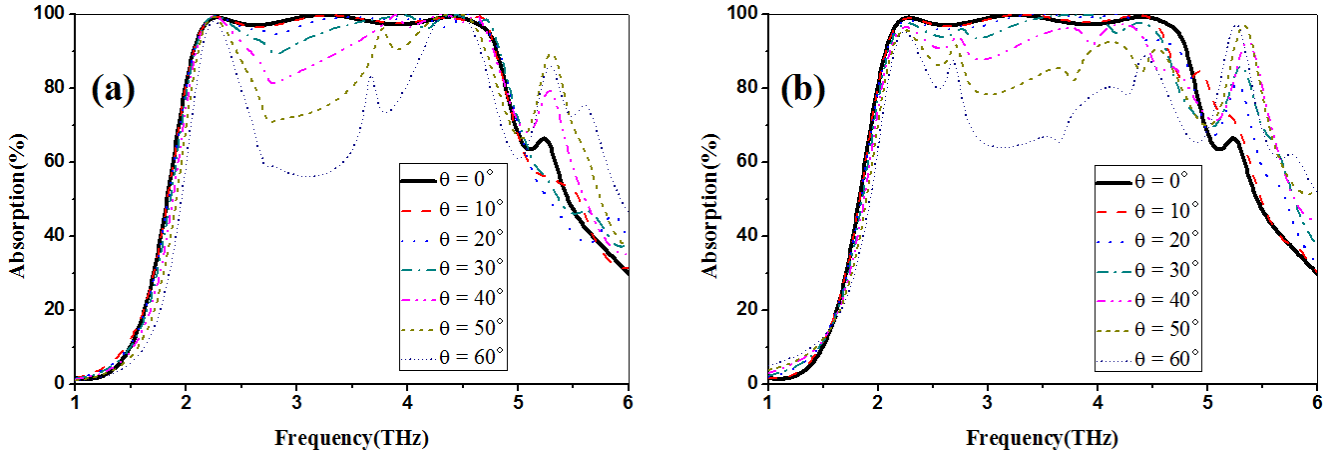


Figure 8. Co-polarization absorption spectra of proposed MA with different incident angles at (a) TE and (b) TM modes.

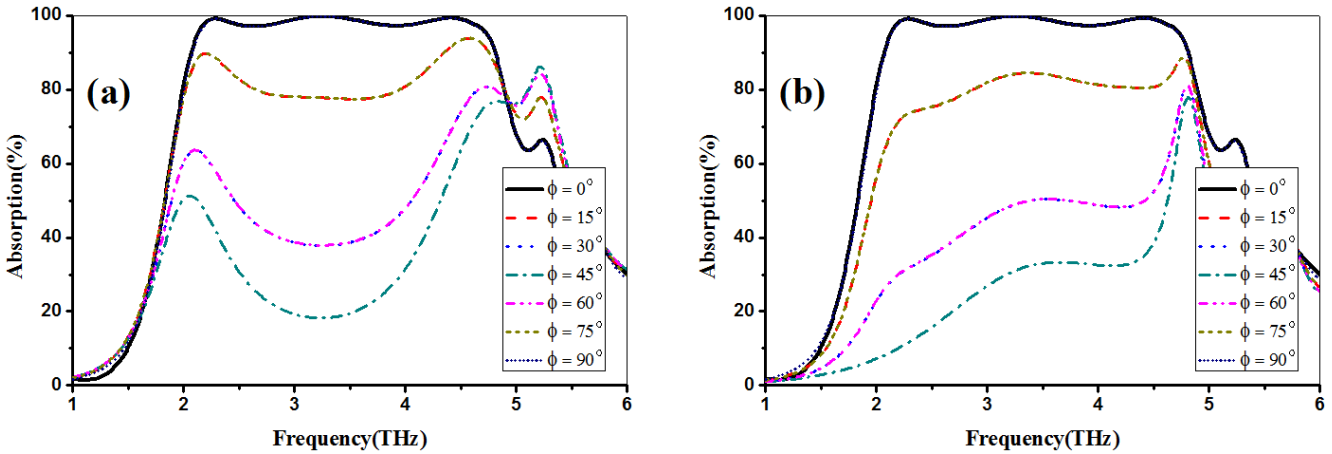


Figure 9. Co-polarization absorption spectra of proposed MA for several polarization angles at (a) TE and (b) TM modes.

The co-polarization absorption characteristics of proposed MA for several polarization angles are investigated under TE and TM modes. As shown in Figure 9, the proposed MA has an asymmetric structure, thus exhibiting the polarization sensitivity. The absorptivity decreases with rising the polarization angle from 0° to 45° and then increases with rising the polarization angle from 45° to 90° . Furthermore, the absorption spectra coincide for 0° and 90° , 15° and 75° , 30° and 60° , respectively. This polarization sensitive MA can be effectively utilized for radar detecting and defense systems [29].

4. Conclusion

In this paper, a co-polarization wideband THz MA with wavy split ring resonator has been proposed. The proposed MA provides good absorption performance with co-polarization absorptivity above 90% ranging from 2.07 THz to 4.80 THz and its RAB is 79.47%. Moreover, the proposed MA exhibits the good incidence angle stability for TE and TM modes. Through the electric field and the surface

current distributions, it is demonstrated that the cooperation of dipolar and LC resonances is responsible for the wideband absorption. The proposed MA may be suitable for many applications in THz technology. Furthermore, the proposed MA structure can be also used to design wideband MAs in microwave, infrared and visible regions.

Abbreviations

MA	Metamaterial Absorber
THz	Terahertz
PCR	Polarization Conversion Ratio
RAB	Relative Absorption Bandwidth
RCS	Radar Cross Section
EMI	Electromagnetic Interference
TE	Transverse Electric
TM	Transverse Magnetic

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, W. J. Padilla, Perfect metamaterial absorber, *Phys. Rev. Lett.* 100(2008): 207402. <https://doi.org/10.1103/PhysRevLett.100.207402>
- [2] K. Muthukrishnan, V. Narasimhan, An Ultra-Thin Triple-Band Polarization-Independent Wide-Angle Microwave Metamaterial Absorber, *Plasmonics* 14(2019): 1983-1991. <https://doi.org/10.1007/s11468-019-00985-y>
- [3] Y. Z. Wen, W. Ma, J. Bailey, G. Matmon, X. M. Yu, G. Aeppli, Planar broadband and high absorption metamaterial using single nested resonator at terahertz frequencies, *Optics Letters* 39(2014): 1589-1592. <https://doi.org/10.1364/OL.39.001589>
- [4] M. J. Hossain, M. R. I. Faruque, M. R. Ahmed, M. J. Alam, M. T. Islam, Polarization-insensitive infrared-visible perfect metamaterial absorber and permittivity sensor, *Results in Physics* 14(2019): 102429. <https://doi.org/10.1016/j.rinp.2019.102429>
- [5] R. T. Sreenath, M. Naveen, K. C. Raghvendra, Design and analysis of an ultrathin triple-band polarization independent metamaterial absorber, *AEU-Int. J. Electron. Commun.* 82(2017): 508-515. <https://doi.org/10.1016/j.aeue.2017.10.024>
- [6] A. Faruk, C. Sabah, Terahertz metamaterial absorber comprised of H-shaped resonator within split-square ring and its sensory application, *Optik-International Journal for Light and Electron Optics* 192(2019): 162976. <https://doi.org/10.1016/j.ijleo.2019.162976>
- [7] B. X. Wang, C. Tang, Q. S. Niu, Y. H. He, T. Chen, Design of Narrow Discrete Distances of Dual-/Triple-Band Terahertz Metamaterial Absorbers, *Nanoscale Research Letters* 14(2019): 64. <https://doi.org/10.1186/s11671-019-2876-3>
- [8] S. J. Guo, C. X. Hu, H. F. Zhang, Unidirectional ultrabroadband and wide-angle absorption in graphene-embedded photonic crystals with the cascading structure comprising the Octonacci sequence, *Journal of the Optical Society of America B*, 37(2020): 2678-2687. <https://doi.org/10.1364/JOSAB.399048>
- [9] M. W. Jiang, Z. Y. Song, Q. H. Liu, Ultra-broadband wide-angle terahertz absorber realized by a doped silicon metamaterial, *Optics Communications* 471(2020): 125835. <https://doi.org/10.1016/j.optcom.2020.125835>
- [10] M. Zhang, Z. Y. Song, Switchable terahertz metamaterial absorber with broadband absorption and multiband absorption, *Optics Express* 29(2021): 21551-21561. <https://doi.org/10.1364/OE.432967>
- [11] R. N. Dao, X. R. Kong, H. F. Zhang, X. R. Su, A tunable broadband terahertz metamaterial absorber based on the vanadium dioxide, *Optik-International Journal for Light and Electron Optics* 180(2019): 619-625. <https://doi.org/10.1016/j.ijleo.2018.12.004>
- [12] L. Liu, W. W. Liu, Z. Y. Song, Ultra-broadband terahertz absorber based on a multilayer graphene metamaterial, *Journal of Applied Physics* 128(2020): 093104. <https://doi.org/10.1063/5.0019902>
- [13] Q. J. Mao, C. Z. Feng, Y. Z. Yang, Design of Tunable Multi-Band Metamaterial Perfect Absorbers Based on Magnetic Polaritons, *Plasmonics* 14(2019): 389-396. <https://doi.org/10.1007/s11468-018-0816-1>
- [14] M. R. Soheilifar, R. A. Sadeghzadeh, H. Gobadi, Design and fabrication of a metamaterial absorber in the microwave range, *Microw. Opt. Technol. Lett.* 56(2014): 1748-1752. <https://doi.org/10.1002/mop>
- [15] Y. H. Liu, S. Gu, C. R. Luo, X. P. Zhao, Ultra-thin broadband metamaterial absorber, *Appl. Phys. A* 108(2012): 19-24. <https://doi.org/10.1007/s00339-012-6936-0>
- [16] Y. Z. Wen, W. Ma, J. Bailey, G. Matmon, X. M. Yu, Broadband Terahertz Metamaterial Absorber Based on Asymmetric Resonators with Perfect Absorption, *IEEE TRANSACTIONS ON TERAHERTZ SCIENCE AND TECHNOLOGY* 5(2015): 406-411. <https://doi.org/10.1109/TTHZ.2015.2401392>
- [17] B. X. Wang, Q. Xie, G. X. Dong, H. X. Zhu, Broadband terahertz metamaterial absorber based on coplanar multi-strip resonators, *Journal of Materials Science: Materials in Electronics* 28(2017): 17215-17220. <https://doi.org/10.1007/s10854-017-7651-6>
- [18] Y. Z. Cheng, Y. Nie, R. Z. Gong, A polarization-insensitive and omnidirectional broadband terahertz metamaterial absorber based on coplanar multi-squares films, *Optics & Laser Technology* 48(2013): 415-421. <https://doi.org/10.1016/j.optlastec.2012.11.016>

- [19] Y. Y. Lu, J. N. Li, S. H. Zhang, J. H. Sun, J. Q. Yao, Polarization-insensitive broadband terahertz metamaterial absorber based on hybrid structures, *Applied Optics* 57(2018): 6269-6275. <https://doi.org/10.1364/AO.57.006269>
- [20] M. R. Soheilifar, R. A. Sadeghzadeh, Design, fabrication and characterisation of scaled and stacked layers planar metamaterial absorber, *IET Microw. Antennas Propag.* 9(2015): 86-93. <https://doi.org/10.1049/iet-map.2014.0350>
- [21] B. X. Wang, L. L. Wang, G. Z. Wang, W. Q. Huang, X. F. Li, X. Zhai, A simple design of ultra-broadband and polarization insensitive terahertz metamaterial absorber, *Appl. Phys. A* 115(2014): 1187-1192. <https://doi.org/10.1007/s00339-013-8158-5>
- [22] X. J. He, S. T. Yan, Q. X. Ma, Q. F. Zhang, P. Jia, F. M. Wu, J. X. Jiang, Broadband and polarization-insensitive terahertz absorber based on multilayer metamaterials, *Optics Communications* 340(2015): 44-49. <https://doi.org/10.1016/j.optcom.2014.11.068>
- [23] J. F. Zhu, Z. F. Ma, W. J. Sun, F. Ding, Q. He, L. Zhou, Y. G. Ma, Ultra-broadband terahertz metamaterial absorber, *APPLIED PHYSICS LETTERS* 105(2014): 021102. <https://doi.org/10.1063/1.4890521>
- [24] B. X. Wang, L. L. Wang, G. Z. Wang, W. Q. Huang, X. F. Li, X. Zhai, Theoretical Investigation of Broadband and Wide-Angle Terahertz Metamaterial Absorber, *IEEE Photon. Technol. Lett.* 26(2014): 111-114. <https://doi.org/10.1109/LPT.2013.2289299>
- [25] W. Pan, X. Yu, J. Zhang, W. Zeng, A Broadband Terahertz Metamaterial Absorber Based on Two Circular Split Rings, *IEEE JOURNAL OF QUANTUM ELECTRONICS* 53(2017): 8500206. <https://doi.org/10.1109/JQE.2016.2643279>
- [26] W. W. Meng, J. Lv, L. W. Zhang, L. C. Que, Y. Zhou, Y. D. Jiang, An ultra-broadband and polarization-independent metamaterial absorber with bandwidth of 3.7THz, *Optics Communications*, 431(2019): 255-260. <https://doi.org/10.1016/j.optcom.2018.08.066>
- [27] T. S. Tuan, N. T. Q. Hoa, Defect induced co-polarization broadband metamaterial absorber, *AIP Advances* 9(2019): 055321. <https://doi.org/10.1063/1.5097198>
- [28] N. T. Q. Hoa, T. S. Tuan, L. T. Hieu, B. L. Giang, Facile design of an ultra-thin broadband metamaterial absorber for C-band applications, *Sci. Rep.* 9(2019): 468. <https://doi.org/10.1038/s41598-018-36453-6>
- [29] D. Sood, C. C. Tripathi, Broadband ultrathin low-profile metamaterial microwave absorber, *Appl. Phys. A* 122(2016): 332. <https://doi.org/10.1007/s00339-016-9884-2>
- [30] K. J. Ri, C. H. Ri, S. Y. Ri, Ultra-broadband terahertz metamaterial absorber using a simple design method, *Optics Communications*, 515(2022): 128191. <https://doi.org/10.1016/j.optcom.2022.128191>
- [31] X. R. Kong, H. F. Zhang, R. N. Dao, G. B. Liu, Comment on "Design of a Quad-Band Wide-Angle Microwave Metamaterial Absorber", *Journal of ELECTRONIC MATERIALS*, 48(2019): 4166-4169. <https://doi.org/10.1007/s11664-019-07194-7>
- [32] F. Bagci, F. Medina, Design of a wide-angle, polarization-insensitive, dual-band metamaterial-inspired absorber with the aid of equivalent circuit model, *J. Comput. Electron.* 16(2017): 913-921. <https://doi.org/10.1007/s10825-017-1009-4>
- [33] D. Hu, H. Y. Wang, Z. J. Tang, X. W. Zhang, Q. F. Zhu, Design of four-band terahertz perfect absorber based on a simple #-shaped metamaterial resonator, *Appl. Phys. A* 122(2016): 826. <https://doi.org/10.1007/s00339-016-0357-4>
- [34] B. X. Wang, G. Z. Wang, New Type Design of the Triple-Band and Five-Band Metamaterial Absorbers at Terahertz Frequency, *Plasmonics* 13(2018): 123-130. <https://doi.org/10.1007/s11468-016-0491-z>