Terahertz Perfect Absorber Based on Asymmetric Open-Loop Cross-Dipole Structure

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Equipped with multiple and unique features, a terahertz absorber exhibits great potential for use in the development of communication, military, and other fields where achieving perfect broadband absorption has always been a challenge. We present a metamaterial terahertz (THz) absorber comprising a cross-dipole patch, four symmetric square patches and an asymmetric open-loop patch with a good perfect absorption rate for TE and TM polarizations. The average absorption of more than 96% occurs in the frequency range from 2.4 THz to 3.8 THz, in which the absorptance peak can reach 99.9%, as indicated by simulated results. Our design has broad potential applications in THz couplers, as well as in fields like biology and security.

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With a rapid development of photonics and nanotechnology, combined with the advantages of terahertz, research on terahertz has been widely used for applications in information and communication,[1] biomedicine,[2] non-destructive evaluation,[3] national security,[4] quality management of food and other agricultural products,[5] ultra-high-speed computing,[6] and other fields. Terahertz radiation is a general term that describes the frequency range from 0.1 THz to 10 THz and the wavelength range from 30 μm to 3 mm.[7−10]

Metamaterial absorbers are typically configured with a few layers consisting of a metamaterial, a dielectric space and a ground plane,[11−13] or by arraying metal patterns in a period.[14,15] The first experimental work on ultra-thin metamaterial absorbers was presented by Landy *et al.*[16] Since their first presentation, metamaterial-based absorbers have received considerable attention and a lot of absorbers have been proposed in the spectral range from microwave to optical regime.[17−19] In 2016, Wu *et al.* designed a three-layered ring structure which achieved a wideband absorption from 1.5 THz to 2.5 THz.[20] In 2017, Wang *et al.* proposed a new design of the triple-band metamaterial absorber to achieve a multi-band absorption in the 0–3 THz range.[21] In 2018, Janneh *et al.* proposed a novel dual-band terahertz perfect absorber composed of a meta-surface located on top of a flexible polyimide spacer deposited on a silver ground layer[22] used only for transverse electric (TE) polarization. Huang *et al.* proposed a wide-angle tunable dual-band terahertz metamaterial absorber based on a square graphene patch for TE polarization.[23] In 2019, Li *et al.* designed a perfect wideband absorber with an open-loop ring.[24] The perfect metamaterial absorber was widely explored as the frequency range expanded from microwaves to terahertz and visible light. Among these broadband metamaterial absorbers, most of the mentioned THz absorbers operate at frequencies below 2.0 THz. Thus, it is necessary to study absorptance in the 2–4 THz range.

In this Letter, we propose a terahertz absorber comprising a cross-dipole patch, four symmetric square patches and an asymmetric open-loop patch implemented for transverse magnetic wave (TM) and transverse electric wave (TE) polarizations. The terahertz absorber can achieve more than 99% absorption in the 2–4 THz range with polarization insensitivity.

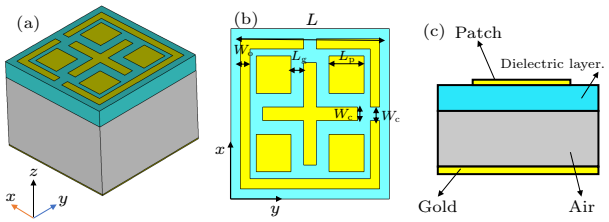

Fig. 1. Schematic of the proposed absorber: (a) the unit cell of the absorber, (b) the top view, and (c) the side view.

The structure of the proposed absorber, with the unit cell consisting of four layers, is shown in Fig. 1. The top patch layer consists of a cross-dipole patch, four symmetric square patches and an asymmetric open-loop patch, which is printed on one side of the substrate layer. The substrate is composed of polyimide ($r = 3.5$, $\tan\delta = 0.0057$) material, where r is the relative permittivity. An air layer is inserted between the gold ground at the bottom and the dielectric layer. The conductivity of gold is 5×10^7 S/m. The period of the unit cell is 12.5 μm. The top Au pattern layer is 0.1 μm thick, while the dielectric layer is 1.4 μm thick. There is a 6-μm-thick air layer between the gold ground and the dielectric layer, and the bottom layer is a continuous Au film with thickness of 0.1 μm.

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The other dimensions of the unit cell are $L_g = 1\,\mu m$; $W_c = 1\,\mu m$; $W_o = 0.75\,\mu m$, $L_p = \frac{L}{2} - W_o - 2 \times L_g$, $L = 11\,\mu m$.

The CST Microwave Studio suite 2018[25–27] is used for analyzing the unit cell and modifying the simulation results. In these simulations, the periodic structures are illuminated by a normally incident EM wave with electric field parallel to the x-axis, perfectly matched layers are applied in the z direction and periodic boundary conditions in the xy-plane. The $\boldsymbol{S}$ parameters (S_{11} and S_{21}) are simulated by a frequency domain solver. The permittivity of gold is described by the Drude model, $\varepsilon_{Au} = 1 - \frac{\omega_p^2}{\omega(\omega + i\Gamma)}$, with the plasma frequency $\omega_p = 1.37 \times 10^{16}$ rad/S and the collision frequency $\Gamma = 1.2 \times 10^{14}$ rad/S.[28–30] The absorptive efficiency of the proposed absorber can be defined as $A = 1 - R - T = 1 - |S_{11}|^2 - |S_{21}|^2$, where A is the absorptance, R is the reflectance, and T is the transmittance.[27] As the thickness of the bottom Au plane is greater than the skin depth of the electromagnetic wave on the gold surface, the transmission (S_{21}) is zero across the entire frequency range. Thus, $A = 1 - |S_{11}|^2$ can be used to calculate the absorptance. Therefore, A can achieve perfect absorption when R is close to zero.[31–33]

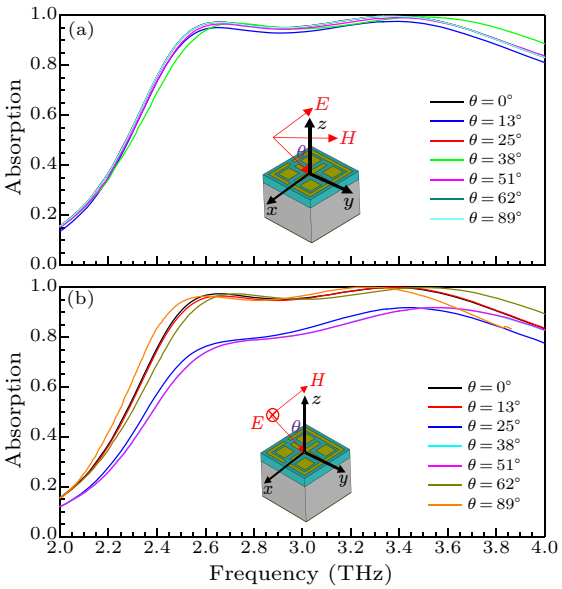

Fig. 2. Simulations of the metamaterial absorber showing the absorptivity as a function of frequency at various angles of incidence for (a) TM and (b) TE incident radiation.

The simulated absorption is presented in Fig. 2 for transverse magnetic (TE) and transverse (TE) polarization electronic at various angles of incidence. Figure 2(a) shows simulated absorptance of absorber under different oblique incidences of TM polarization, the absorption at normal incidence is 99% and remains greater than 90% for all angles of incidence. Since the direction of the TM wave magnetic field is perpendicular to the incident surface, the magnetic surface can always be excited to generate magnetic poles to absorb the electromagnetic wave, the TM wave appears to be insensitive. While for oblique incidence of TE polarization in Fig. 2(b), at normal incidence the absorption of 99.9% is obtained. With the increasing angle of incidence, the absorption decreases to 75%, when the incident angle θ changes from 0° to 51°, the absorption rate changes insignificantly. The result indicates that the average absorption in the frequency range from 2.5 THz to 3.7 THz is more than 96% and the maximum absorption is 99.9% at the frequency of 3.36 THz. There are two peak frequencies at 2.63 THz and 3.36 THz. It is easy to observe that the absorption in the stated range of frequency does not change significantly. This result proves that the asymmetric open-loop cross-dipole terahertz absorber exhibits a good polarization insensitivity and can be applied for wide-angle absorption.[34–36]

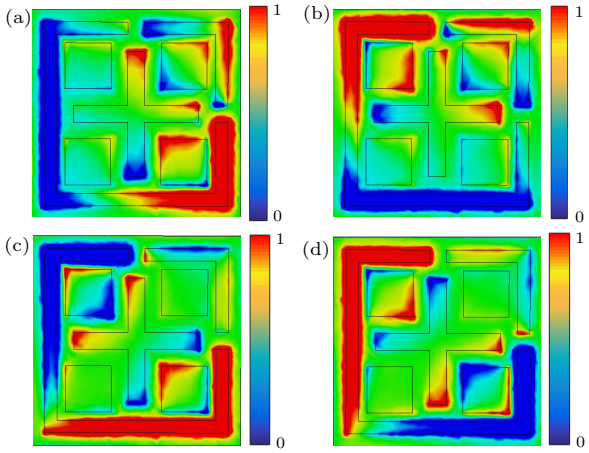

Fig. 3. TE mode of the electric field at 2.63 THz (a) and 3.36 THz(c). TM mode of the electric field at 2.63 THz (b) and 3.36 THz (d).

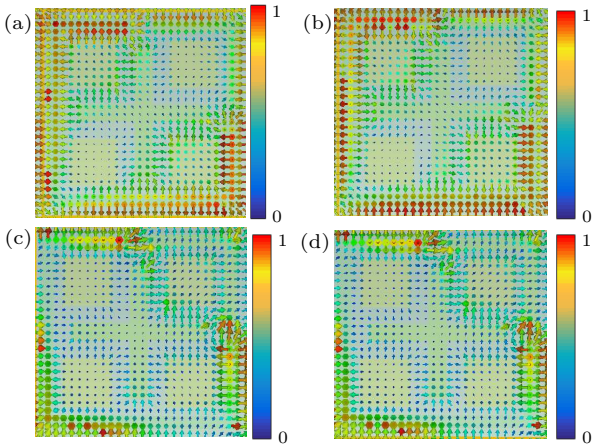

Fig. 4. The TE mode of the current density at 2.63 THz (a) and 3.36 THz (c) and TM mode of the current density at 2.63 THz (b) and 3.36 THz (d) at the surface of the original at $z = 5.6\,\mu m$.

To understand the mechanism of the optimal absorption produced by the absorber,[37–40] the distri-

butions of the electric field and current density modes at 2.63 THz and 3.36 THz are shown in Figs. 3 and 4, respectively. Resonance coupling is an important factor for absorption. Figures 3(a) and 3(b) illustrate the TE and TM electric fields at 2.63 THz, and Figs. 3(b) and 3(c) exhibit the electric field at 3.36 THz. Because of the asymmetry of the open-loop patch, for the TM case, the magnetic field is perpendicular to the incident surface, and a current can always be excited on the metal surface to form a magnetic dipole, which resonates to absorb electromagnetic waves.[41–43] For the TE case, the direction of the incident electric field is perpendicular to the split ring. It can be observed from Fig. 4 that the current density on the loop ring is very strong, which is coupled with the magnetic field generated by the asymmetric thin open-loop patch and the cross-dipole patch, resulting in strong absorption. The surface current distribution is consistent with the structural surface absorption energy density distribution.

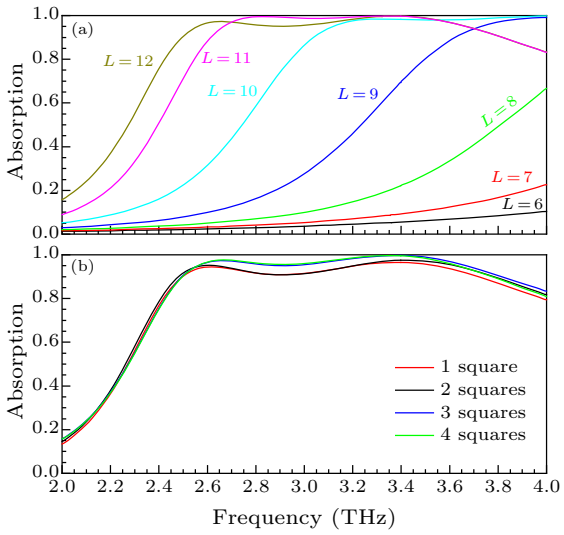

Fig. 5. Absorption for different lengths of loop ring (a) and different numbers of squares (b).

To study the absorption performance of the proposed structure, we simulate absorptance with different lengths of the loop ring and the number of square patches, the corresponding results are shown in Figs. 5(a) and 5(b), respectively. From Fig. 5(a), it can be observed that with other structural parameters of the absorber unchanged, the absorptance fluctuates obviously when the length L changes from 7 µm to 12 µm with steps of 1.0 µm. It also indicates that the length of the open-loop ring could increase Q.[44–46] Figure 5(b) shows the impact of absorptance for different numbers of the square patch, while other geometric parameters are fixed. The absorption declines slightly when the number of square patches increases from 1 to 4, and the absorption band moves to a high frequency. When there are four squares, the absorption of more than 96% occurs in the frequency range from 2.4 THz to 3.8 THz, in which the absorptance peak can reach 99.9%. The above results verify the impact of geometrical structures in improving the performance of the absorber.

In conclusion, we have proposed a perfect terahertz metamaterial absorber based on an asymmetric open-loop ring. To improve the performance of the absorber, we discuss the influence of structural parameters. The numerical simulation results indicate that the proposed absorber achieves broadband absorption with the efficiency more than 96% from 2.5 THz to 3.7 THz, regardless of the angle of incidence, the absorptance peak can reach 99.9% at 3.5 THz. The absorptance average level is very good for TE and TM polarized waves. As an advanced absorber with novel advantages, our design exhibits great potential for broad application prospects in imagers, detectors, sensors, energy harvesting, and tunable sensors.

References

[1] Koenig S, Lopez-Diaz D, Antes J et al 2013 *Nat. Photon.* **7** 977
[2] Kurt H, Citrin D 2005 *Appl. Phys. Lett.* **87** 041108
[3] Watts C M, Liu X, Padilla W J 2012 *Adv. Mater.* **24** OP181
[4] Fan S, Li T, Zhou J et al 2017 *AIP Adv.* **7** 115202
[5] Tao H, Landy N I, Bingham C M et al 2008 *Opt. Express* **16** 7181
[6] Chen H T 2012 *Opt. Express* **20** 7165
[7] Smith D R, Padilla W J, Vier D et al 2000 *Phys. Rev. Lett.* **84** 4184
[8] Zhang B, Lv L, He T et al 2015 *Appl. Phys. Lett.* **107** 093301
[9] Kapoor A, Singh G 2000 *J. Lightwave Technol.* **18** 849
[10] Feng L, Xu Y L, Fegadolli W S et al 2013 *Nat. Mater.* **12** 108
[11] Grady N K, Heyes J E, Chowdhury D R et al 2013 *Science* **340** 1304
[12] Yachmenev A, Lavrukhin D, Glinskiy I et al 2019 *Opt. Eng.* **59** 061608
[13] Li W, Coppens Z J, Besteiro L V et al 2015 *Nat. Commun.* **6** 8379
[14] Cong L, Pitchappa P, Lee C et al 2017 *Adv. Mater.* **29** 1700733
[15] Duan G, Schalch J, Zhao X et al 2018 *Opt. Express* **26** 2242
[16] Landy N I, Sajuyigbe S, Mock J J et al 2008 *Phys. Rev. Lett.* **100** 207402
[17] Liu N, Mesch M, Weiss T et al 2010 *Nano Lett.* **10** 2342
[18] Wang M, Huang S Y, Hu R et al 2019 *Chin. Phys. B* **28** 087804
[19] Low T, Avouris P 2014 *ACS Nano* **8** 1086
[20] Tang X P, Yang Z Q, Shi Z J, Lan F 2016 *Chin. Phys. Lett.* **33** 088401
[21] Wang B X, Wang G Z 2018 *Plasmonics* **13** 123
[22] Islam M R, Kabir M F, Talha K M A et al 2020 *Opt. Eng.* **59** 016113
[23] Paulish A, Gusachenko A, Morozov A et al 2019 *Opt. Eng.* **59** 061612
[24] Fan C Z, Tian Y C, Ren P W et al 2019 *Chin. Phys. B* **28** 076105
[25] Liu M, Yang Q, Rifat A A et al 2019 *Adv. Opt. Mater.* **7** 1900736
[26] Duan G, Schalch J, Zhao X et al 2019 *Sens. Actuators A* **287** 21
[27] Daraei O M, Goudarzi K, Bemani M 2020 *Opt. Laser Technol.* **122** 105853
[28] Zhang H, Ling F, Wang H et al 2020 *Opt. Commun.* **463** 125394

[29] Zhong Q, Wang T, Jiang X et al 2020 *Opt. Commun.* **458** 124637
[30] Yan M Y, Sun Z C, Wu B R et al 2020 *Front. Phys.* **8** 46
[31] Yang P, Qin J, Schalch J, Xu J, Han T C et al 2019 *Acta Phys. Sin.* **68** 087802 (in Chinese)
[32] Soheilifar, M R 2019 *Optik* **182** 702
[33] Hao S B, Zhang L Z, Ma Y Y, Chen M Y et al 2019 *Chin. Phys. Lett.* **36** 124205
[34] Wang D T, Wang X C, Zhang X, Yuan H R et al 2020 *Chin. Phys. Lett.* **37** 045201
[35] Li S H, Li J S 2019 *Chin. Phys. B* **28** 094210
[36] Xie Y M, Liu C Y, Ding Z J et al 2016 *Chin. Phys. Lett.* **33** 094208
[37] Zhao J, Zhang J, Qin C et al 2016 *Chin. Phys. Lett.* **33** 027801
[38] Wang C F, Li Q S, Wang J S et al 2016 *Chin. Phys. Lett.* **33** 076802
[39] Wang L, Song W, Hu W, Li G, Luo X et al 2019 *Chin. Phys. B* **28** 018503
[40] Meng X Q, Chen S L, Fang Y Z, Kou J L 2019 *Chin. Phys. B* **28** 078101
[41] Wang W M, Zhang L L, Li Y T, Sheng Z M, Zhang J 2018 *Acta Phys. Sin.* **67** 124202 (in Chinese)
[42] Liu C, Ooi Y K, Islam S, Xing H, Jena D and Zhang J 2018 *Appl. Phys. Lett.* **112** 011101
[43] Lu X H, Jing C B, Wang L W et al 2019 *Chin. Phys. Lett.* **36** 098501
[44] Cheng X T and Liang X G 2017 *Chin. Phys. B* **26** 120505
[45] Xia G, Kou W, Yang L and Du Y C 2017 *Chin. Phys. B* **26** 104403
[46] Jiang S L, Li X F, Su R F, Jia X Q et al 2017 *Chin. Phys. Lett.* **34** 090701