



A Switchable Ultra-Wideband Metamaterial Absorber with Polarization-Insensitivity and Wide-incident Angle at THz Band

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In this paper, we report a switchable ultra-wideband metamaterial absorber with polarization-insensitivity and wide-incident angle at THz band which is composed of VO₂ disk, polyimide dielectric substrate, and gold ground plane. The results show that the absorption is greater than 90% from 3.5–8 THz for a temperature of 300 K and this absorption band disappears when the temperature rises to 350 K. The absorption property of our proposed metamaterial absorber is insensitive to polarization states and angles and it can withhold high absorption of more than 80% for wide-incident angles, up to 60° for TE mode and TM mode. The wideband absorption mechanism is elucidated using an effective medium and surface current analysis.

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INTRODUCTION

Absorbing materials refer to natural materials or metamaterials constructed by electromagnetic structures that can absorb electromagnetic waves in free space. Traditional absorbing material is a kind of absorbing material coated on the target surface, which is usually made of ferrite, carbon powder, and other absorbents mixed with some non-metallic substrates such as thermoplastic or epoxy resin. The traditional absorbing material usually has the disadvantage of having a narrow absorption band, small absorption angle and being bulky. In 2008, Landy et al. (Landy et al., 2008) firstly proposed the concept of metamaterial absorber. Since then, metamaterial absorber has attracted wide attention. Many researchers have achieved excellent results on wideband absorption, polarization-insensitivity, tunable absorption, and so on from microwave to the visible light band (Chen, 2012; Wang et al., 2014a; Hao et al., 2014; Chen et al., 2015; Lin et al., 2016; Chen et al., 2019; Xie et al., 2019; Zhang et al., 2019; Zheng et al., 2019; Quader et al., 2020; Zhang et al., 2021). At present, the researches of metamaterial absorber are flourishing to achieve wideband absorption, polarization-insensitive absorption, tunable absorption, and multi-band absorption (Aydin et al., 2011; Li et al., 2011; Ding et al., 2012; Xu et al., 2012; Argyropoulos et al., 2013). However, the narrow-incident angle of metamaterial absorbers limit their applications in practice. Consequently, it is necessary to design metamaterial absorbers with polarization-insensitivity and wide-incident angle.

Many methods have been devoted to widen the incident angle of metamaterial absorbers. In 2017, Fan J X et al. proposed a wide-angle wideband terahertz metamaterial absorber with a multilayered heterostructure (Fan et al., 2017). In 2018, Huang X T et al. designed a wide-angle perfect metamaterial absorber based on cave-rings and the complementary patterns (Huang et al., 2018a), its absorption is

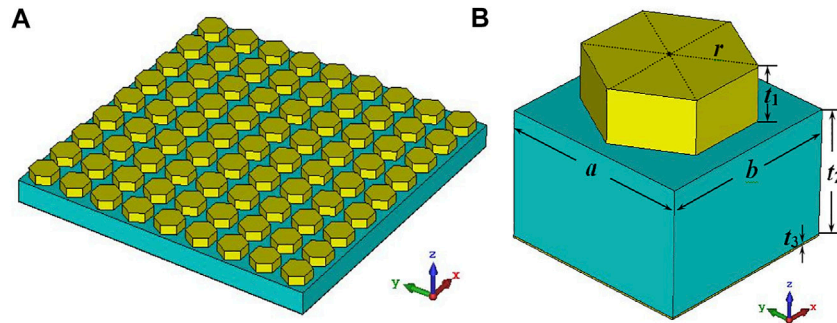


FIGURE 1 | Schematic diagram of the metamaterial absorber unit cell, **(A)** 9×9 array of the unit cell, **(B)** perspective view of the unit cell.

over 92% at around 6.53 THz when the incident angle for the TE mode is up to 80° , and at TM mode, its absorption at 7.64 THz is greater than 92% even for an incident angle of up to 70° . In the same year, Huang X T designed multiband ultrathin polarization-insensitive terahertz perfect absorber (Huang et al., 2018b), it presented the ability to maintain high absorption of more than 80% for a large incident angle up to 60° for both TE and TM modes.

However, the absorption band of the above mentioned wide-angle terahertz metamaterial absorber is narrow, this limits their application in practice. In this work, we propose a switchable ultra-wideband metamaterial absorber with polarization-insensitivity and wide-incident angle at the THz band. Its absorption is over 90% from 3.5–8 THz for a temperature of 300 K and the absorption band fades away when the temperature rises to 350 K. It remains highly absorptive with over 80% absorption for a wide-incident angle up to at 60° for both TE mode and TM mode. Compared with the reported wide-angle terahertz wideband metamaterial absorber (He et al., 2011; Wang et al., 2014b; Li et al., 2015; Huang et al., 2018c; Dinh et al., 2021), our designed metamaterial absorber has the advantages of wider absorption bandwidth and incident angle.

MODEL DESIGN

As illustrated in **Figure 1**, the unit cell of our proposed metamaterial absorber consists of VO_2 disk, polyimide dielectric substrate, and gold ground plane. The periodicities of the unit cell are $a = b = 12 \mu\text{m}$. The geometrical parameter of the VO_2 disk is $r = 5 \mu\text{m}$. During the simulation process, the VO_2 disk is set as a thermally tunable resistance film material with the conductivity $\sigma = 2 \times 10^2 \text{ S/m}$ when the temperature $T = 300 \text{ K}$ and $\sigma = 2 \times 10^5 \text{ S/m}$ when temperature $T = 350 \text{ K}$ according to the reference (Dao et al., 2019), the thickness of VO_2 disk is $3 \mu\text{m}$. The polyimide dielectric substrate selected has a relative dielectric constant of $\epsilon_r = 2.35$, a loss of $\tan \delta = 2.35$ and its thickness is $7 \mu\text{m}$. The thickness of the gold ground plane ($\sigma = 4.56 \times 10^7 \text{ S/m}$) is $0.1 \mu\text{m}$. The difficulty of the realization of our proposed metamaterial absorber in practice is the preparation of VO_2 disk.

The full-wave electromagnetic simulation of our proposed metamaterial absorber is performed with CST Microwave Studio.

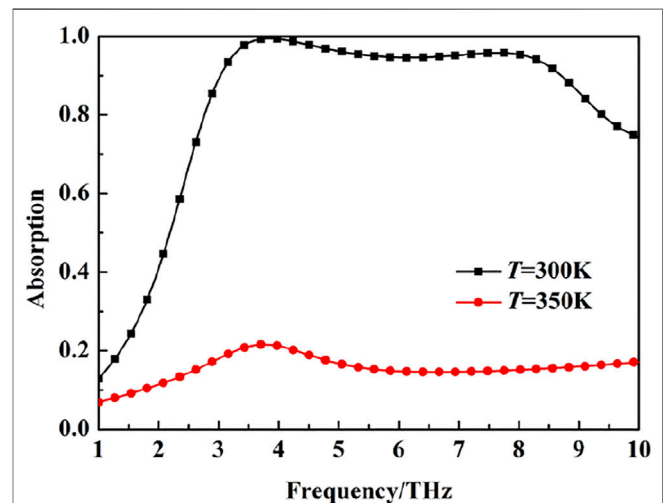


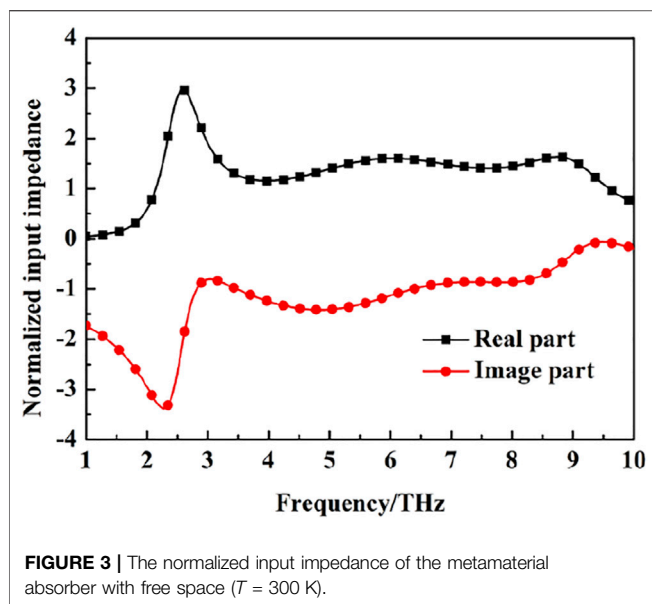
FIGURE 2 | The absorption of the metamaterial absorber under the temperatures $T = 300 \text{ K}$ and $T = 350 \text{ K}$

Throughout the simulation process, the boundary conditions of x and y directions are set as unit cell, the z -direction is set as open. All + Floquet ports are used to simulate the incoming and outgoing waves. The electromagnetic parameters are calculated using a frequency-domain electromagnetic solver.

RESULTS AND DISCUSSION

For the metamaterial absorber, the absorption can be calculated by $A(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2$ (S_{11} and S_{21} are the reflection and transmission). For our designed metamaterial absorber, there is no transmission due to the gold ground plane. Thus, the expression of absorption can be simplified as $A(\omega) = 1 - |S_{11}|^2$. The simulated absorptions of the metamaterial absorber with the temperature $T = 300 \text{ K}$ and $T = 350 \text{ K}$ are shown in **Figure 2**. The absorption is more than 90% from 3.5–8 THz for a temperature of 300 K and the absorption band disappears when the temperature rises to 350 K.

To understand the absorption mechanism, the normalized input impedance of the metamaterial absorber with the free space



for normal incidence ($T = 300$ K) is retrieved from the simulated S_{11} and S_{21} parameters by using the scattering parameter method (Smith and Schultz, 2002), as shown in **Figure 3**. The real part of the normalized input impedance of the metamaterial absorber with free space is nearly unity from 3.5–8 THz, which indicates that our proposed metamaterial absorber acquires an impedance match with free space from 3.5–8 THz, which means that the reflection is nearly zero. As an outcome, the absorption will be very high.

The wideband absorption mechanism of the proposed metamaterial absorber is further clarified in **Figure 4**. **Figure 4** shows the surface current of the metamaterial absorber on the VO_2 disk and gold ground plane at 6 THz ($T = 300$ K). It can be seen that the induced anti-parallel currents on these two layers prove that magnetic resonance is formed at 6 THz. Therefore, the absorption of the metamaterial absorber at 6 THz originates from the magnetic resonance (Son et al., 2014). The reason for

wideband absorption is that the circuit resonant structure formed by VO_2 disk, polyimide dielectric substrate, and a gold ground plane can realize the impedance match between the metamaterial absorber and free space over a wide frequency range near the resonant frequency, and can then broaden the absorption band (Costa et al., 2010; Zhang et al., 2013).

The power loss density distributions at different frequencies are monitored at $T = 300$ K, as shown in **Figure 5**. It can be observed that there are similar power loss density distributions at different frequencies at 4 and 6 THz, the power losses all concentrate on the front part of polyimide dielectric substrates.

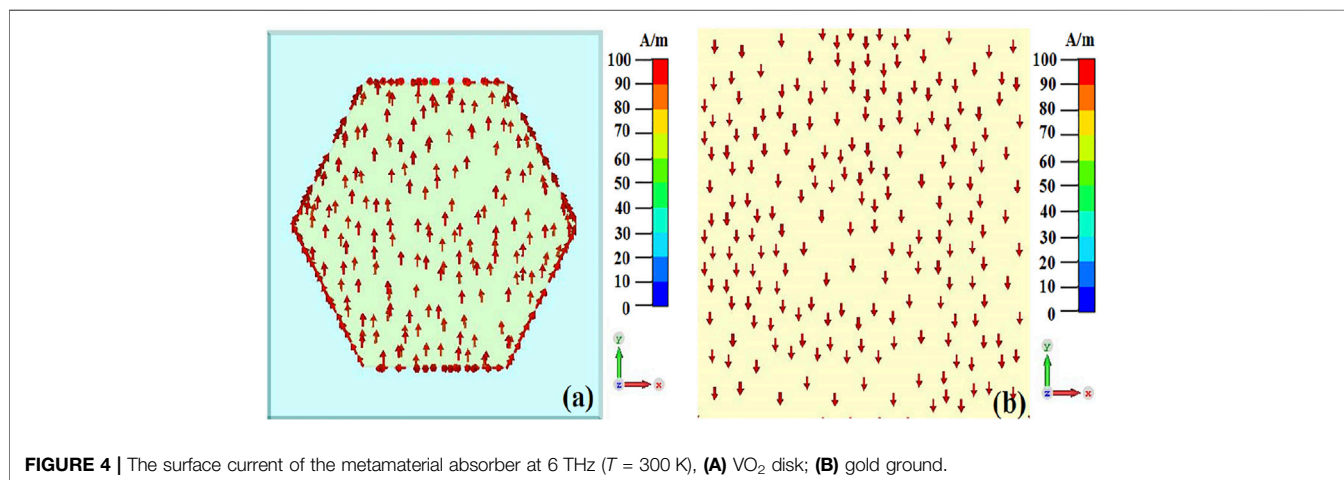
Figure 6 shows the absorption of the metamaterial absorber at different polarization angles ($T = 300$ K). Owing to the rotational symmetry of the unit cell, the absorption under different polarization angles is the same.

The waves are usually incident on to metamaterial absorber with different incident angles. **Figure 7** shows the absorption of the metamaterial absorber with different incident angles at TE and TM mode ($T = 300$ K). For TE and TM mode, the absorption is over 80% for incident angles below 60° from 3.5–8 THz. However, the absorption decreases noticeably for incident angles beyond 60° . This indicates that the absorption property of the metamaterial absorber has the advantage of being responsive towards wide-incident angle.

Figure 8 and **Figure 9** shows the absorption of the metamaterial absorber for different thickness of VO_2 disk and polyimide dielectric substrate ($T = 300$ K). The absorption band of the metamaterial absorber gradually shifts to a higher frequency with the increase of thickness of VO_2 disk. The absorption of the metamaterial absorber gradually decreases with the increase of the thickness of the polyimide dielectric substrate.

CONCLUSION

In conclusion, we propose a switchable ultra-wideband terahertz metamaterial absorber with polarization-insensitivity and wide-incident angle. It is composed of a VO_2 disk, polyimide dielectric



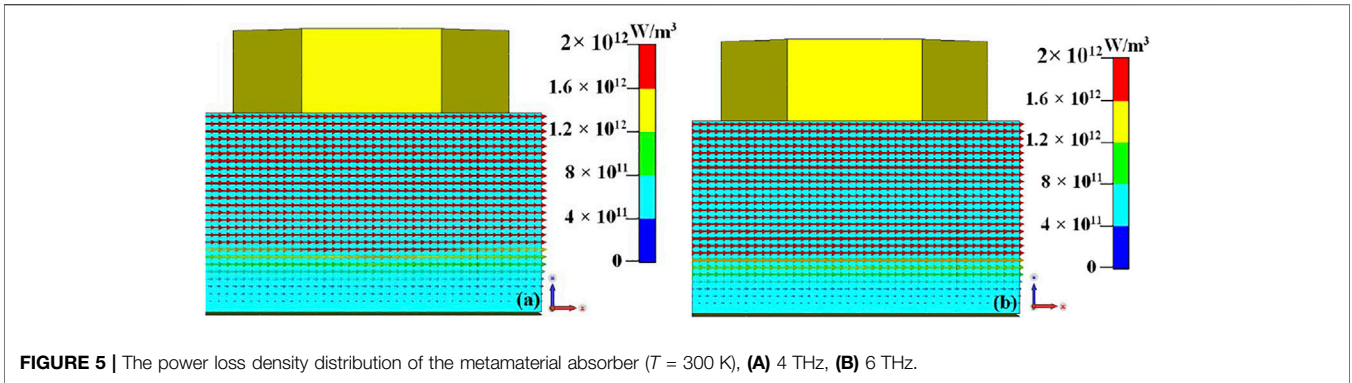


FIGURE 5 | The power loss density distribution of the metamaterial absorber ($T = 300$ K), **(A)** 4 THz, **(B)** 6 THz.

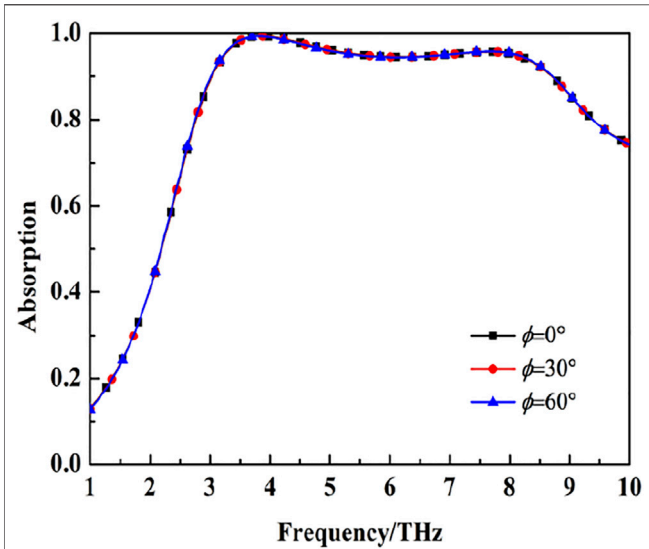


FIGURE 6 | The absorption of the metamaterial absorber at different polarization angles ($T = 300$ K).

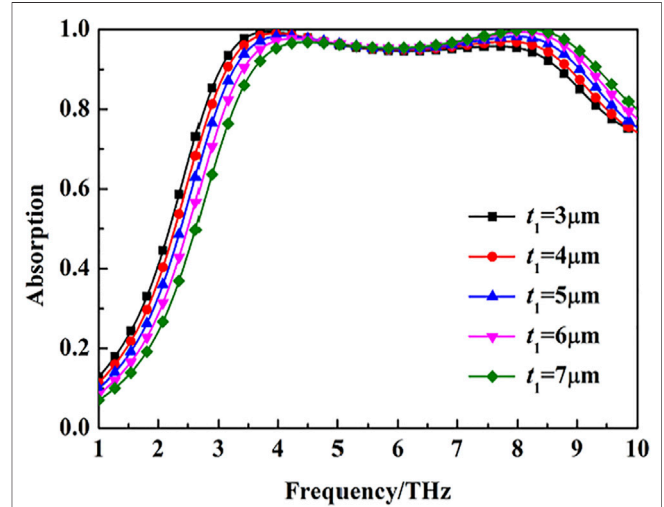


FIGURE 8 | The absorption of the metamaterial absorber with different thickness of VO₂ disk ($T = 300$ K).

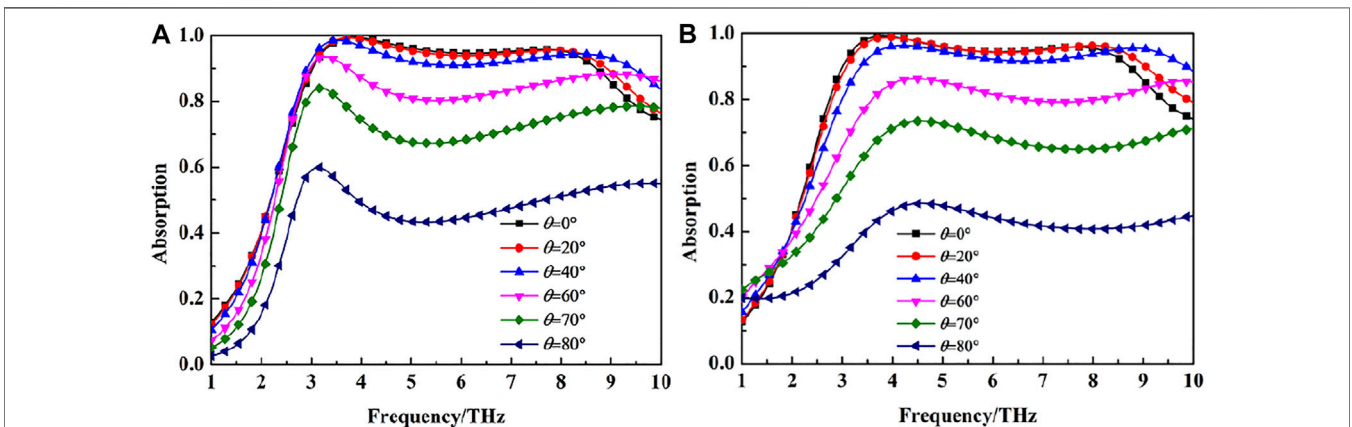
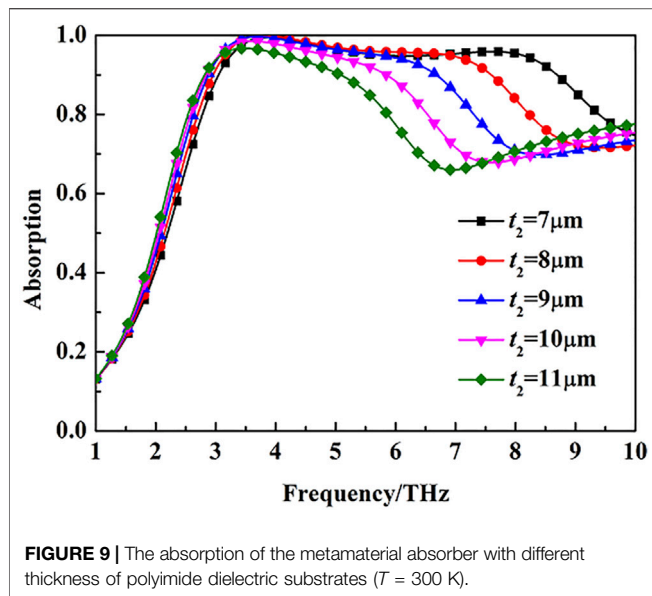


FIGURE 7 | The absorption of the metamaterial absorber at different incident angles ($T = 300$ K), **(A)** TE mode, **(B)** TM mode.



substrate, and gold ground plane. The simulation results show that the absorber provides a strong wideband absorption for incident

REFERENCES

- Argyropoulos, C., Le, K. Q., and Mattiucci, N. (2013). Broadband absorbers and selective emitters based on plasmonic Brewster metasurfaces. *Phys. Rev. B* 87, 205112. doi:10.1103/physrevb.87.205112
- Aydin, K., Ferry, V. E., Briggs, R. M., and Atwater, H. A. (2011). Broadband polarization-independent resonant light absorption using ultrathin plasmonic super absorbers. *Nat. Commun.* 2, 517. doi:10.1038/ncomms1528
- Chen, H. T. (2012). Interference theory of metamaterial perfect absorbers. *Opt. Express* 20, 7165–7172. doi:10.1364/oe.20.007165
- Chen, K., Jia, N., Sima, B., Zhu, B., Zhao, J., and Feng, Y. (2015). Microwave absorber based on permeability-near-zero metamaterial made of Swiss roll structures. *J. Phys. D: Appl. Phys.* 48, 455304. doi:10.1088/0022-3727/48/45/455304
- Chen, K., Luo, X., Ding, G., Zhao, J., Feng, Y., and Jiang, T. (2019). Broadband microwave metamaterial absorber with lumped resistor loading. *EPJ Appl. Metamat.* 6, 1. doi:10.1051/epjam/2018011
- Costa, F., Monorchio, A., and Manara, G. (2010). Analysis and design of ultra-thin electromagnetic absorbers comprising resistively loaded high impedance surfaces. *IEEE Trans. Antennas Propag.* 58 (5), 1551–1558. doi:10.1109/tap.2010.2044329
- Dao, R. N., Kong, X. R., Zhang, H. F., and Su, X. R. (2019). A tunable broadband terahertz metamaterial absorber based on the vanadium dioxide. *Optik* 180, 619–625. doi:10.1016/j.ijleo.2018.12.004
- Ding, F., Cui, Y. X., Ge, X. C., Jin, Y., and He, S. L. (2012). Ultra-broadband microwave metamaterial absorber. *Appl. Phys. Lett.* 100, 103506. doi:10.1063/1.3692178
- Dinh, M. Q., Huynh, T. V., Khuyen, B. X., Tung, B. S., Lam, V. D., Ngo, S. T., et al. (2021). Graphene-integrated hybridized metamaterials for wide-angle tunable THz absorbers. *Photonic. nanostruct.* 45, 100924. doi:10.1016/j.photonics.2021.100924
- Fan, J., Xiao, D., Wang, Q., Liu, Q., and Ouyang, Z. (2017). Wide-angle broadband terahertz metamaterial absorber with a multilayered heterostructure. *Appl. Opt.* 56, 4388–4391. doi:10.1364/ao.56.004388
- Hao, J., Lheurette, É., Burgnies, L., Okada, E., and Lippens, D. (2014). Bandwidth enhancement in disordered metamaterial absorbers. *Appl. Phys. Lett.* 105, 081102. doi:10.1063/1.4894181

waves from 3.5–8 THz for a temperature of 300 K and this strong absorption band diminishes when the temperature rises to 350 K. We also show that the absorption property of our proposed metamaterial absorber is insensitive to polarization states and angles and it responds well under wide-incident angles as well.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

The contribution of QF is analysing the model. The contribution of DX, YW and XD is data processing.

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- He, X. J., Wang, Y., Wang, J. M., Gui, T. L., and Wu, Q. (2011). Dual-band terahertz metamaterial absorber with polarization insensitivity and wide incident angle. *Prog. electromagn. res.* 115, 381–397. doi:10.2528/pier11022307
- Huang, M. L., Cheng, Y. Z., Cheng, Z. Z., Chen, H. R., Mao, X. S., and Gong, R. Z. (2018). Based on graphene tunable dual-band terahertz metamaterial absorber with wide-angle. *Opt. commun.* 415 (1), 194–201. doi:10.1016/j.optcom.2018.01.051
- Huang, X., Lu, C., Rong, C., and Liu, M. (2018). Wide-angle perfect metamaterial absorbers based on cave-rings and the complementary patterns. *Opt. Mater. Express* 8, 2520–2531. doi:10.1364/ome.8.002520
- Huang, X. T., Lu, C. H., Rong, C. C., Hu, Z. Y., and Liu, M. H. (2018). Multiband ultrathin polarization-insensitive terahertz perfect absorbers with complementary metamaterial and resonator based on high-order electric and magnetic resonances. *IEEE Photonics. J.* 10 (6), 4600811. doi:10.1109/jphot.2018.2878455
- Landy, N. I., Sajuyigbe, S., Mock, J. J., Smith, D. R., and Padilla, W. J. (2008). Perfect metamaterial absorber. *Phys. Rev. Lett.* 100, 207402. doi:10.1103/physrevlett.100.207402
- Li, L., Yang, Y., and Liang, C. H. (2011). A wide-angle polarization-insensitive ultra-thin metamaterial absorber with three resonant modes. *J. Appl. Phys.* 110, 063702. doi:10.1063/1.3638118
- Li, X. W., Liu, H. J., Sun, Q. B., and Huang, N. (2015). Ultra-broadband and polarization-insensitive wide-angle terahertz metamaterial absorber. *Photonic. nanostruct.* 15, 81–88. doi:10.1016/j.photonics.2015.04.002
- Lin, X. Q., Mei, P., Zhang, P. C., Chen, Z. Z. D., and Fan, Y. (2016). Development of a resistor-loaded ultrawideband absorber with antenna reciprocity. *IEEE Trans. Antennas Propagat.* 64, 4910–4913. doi:10.1109/tap.2016.2598202
- Quader, S., Akram, M. R., Xiao, F. J., and Zhu, W. R. (2020). Graphene based ultra-broadband terahertz metamaterial absorber with dual-band tunability. *J. Opt.* 22, 095104. doi:10.1088/2040-8986/aba814
- Smith, D. R., and Schultz, S. (2002). Determination of negative permittivity and permeability of metamaterials from reflection and transmission coefficients. *Phys. Rev. B* 65, 195104. doi:10.1103/physrevb.65.195104
- Son, T. B., Van, K. B., Van, D. N., Young, J. Y., Ki, W. K., Dinh, L. V., et al. (2014). Small-size metamaterial perfect absorber operating at low frequency. *Adv. Nat. Sci. Nanotechnol.* 5, 045008. doi:10.1088/2043-6262/5/4/045008
- Wang, B.-X., Wang, L.-L., Wang, G.-Z., Huang, W.-Q., Li, X.-F., and Zhai, X. (2014). Theoretical investigation of broadband and wide-angle terahertz

- metamaterial absorber. *IEEE Photon. Technol. Lett.* 26 (2), 111–114. doi:10.1109/lpt.2013.2289299
- Wang, B. X., Wang, L. L., Wang, G. Z., Huang, W. Q., and Zhai, X. (2014). Broadband, polarization-insensitive and wide-angle terahertz metamaterial absorber. *Phys. Scripta* 89 (11), 115501. doi:10.1088/0031-8949/89/11/115501
- Xie, J. W., Quader, S., Xiao, F. J., He, C., Liang, X. L., Zhu, R. W., et al. (2019). Truly all-dielectric ultra-broadband metamaterial absorber: Water-based and ground-free. *IEEE Trans. Antennas Propag.* 18 (3), 536–540. doi:10.1109/lawp.2019.2896166
- Xu, H. X., Wang, G. M., Qi, M. Q., Liang, J. G., Gong, J. Q., and Xu, Z. M. (2012). Triple-band polarization-insensitive wide-angle ultra-miniature metamaterial transmission line absorber. *Phys. Rev. B* 86, 205104. doi:10.1103/physrevb.86.205104
- Zhang, H. B., Zhou, P. H., Lu, H. P., Xu, Y. Q., Liang, D. F., and Deng, L. J. (2013). Resistance selection of high impedance surface absorbers for perfect and broadband absorption. *IEEE Trans. Antennas Propag.* 61 (2), 976–979. doi:10.1109/tap.2012.2226225
- Zhang, J., Wei, X. Z., Premaratne, M., and Zhu, W. R. (2019). Experimental demonstration of electrically tunable broadband coherent perfect absorber based on graphene-electrolyte-graphene sandwich structure. *Photon. Res.* 7 (8), 868–874. doi:10.1364/prj.7.000868
- Zhang, J. Z., Li, Z. F., Shao, L. D., and Zhu, W. R. (2021). Dynamical absorption manipulation in a graphene-based optically transparent and flexible metasurface. *Carbon* 176, 374–382. doi:10.1016/j.carbon.2021.01.137
- Zheng, Y., Chen, K., Jiang, T., Zhao, J., and Feng, Y. (2019). Multi-octave microwave absorption via conformal metamaterial absorber with optical transparency. *J. Phys. D: Appl. Phys.* 52, 335101. doi:10.1088/1361-6463/ab2365
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