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 VO$_2$ 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.

**Keywords:** ultra-wideband, metamaterial absorber, wide incident angle, THz band, switchable

**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
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 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 VO₂ disk, polyimide dielectric substrate, and gold ground plane. The periodicities of the unit cell are \( a = b = 12 \mu m \). The geometrical parameter of the VO₂ disk is \( r = 5 \mu m \). During the simulation process, the VO₂ disk is set as a thermally tunable resistance film material with the conductivity \( \sigma = 2 \times 10^5 S/m \) when the temperature \( T = 300 K \) and \( \sigma = 2 \times 10^6 S/m \) when temperature \( T = 350 K \) according to the reference (Dao et al., 2019), the thickness of VO₂ disk is 3 \( \mu m \). The polyimide dielectric substrate selected has a relative dielectric constant of \( \varepsilon_r = 2.35 \), a loss of \( \tan \delta = 2.35 \) and its thickness is 7 \( \mu m \). The thickness of the gold ground plane \( (\sigma = 4.56 \times 10^7 S/m) \) is 0.1 \( \mu m \). The difficulty of the realization of our proposed metamaterial absorber in practice is the preparation of VO₂ disk.

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

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 \( T = 300 K \) and \( T = 350 K \) 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 7 | The absorption of the metamaterial absorber at different incident angles ($T = 300$ K). (A) TE mode, (B) TM mode.

FIGURE 8 | The absorption of the metamaterial absorber with different thickness of VO$_2$ disk ($T = 300$ K).
substance, and gold ground plane. The simulation results show that the absorber provides a strong wideband absorption for incident 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 analysising the model. The contribution of DX, YW and XD is data processing.

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