Investigation of wide-angle thin metamaterial absorber at infrared region

HUANG Xiutao (黄修涛)*, ZHANG Chunbo (张春波), CONG Lin (丛琳), FAN Jun (樊君), and YUAN Hang (袁航)

Aerospace Institute of Advanced Materials & Processing Technology, Beijing 100074, China

(Received 13 March 2021; Revised 26 April 2021)

In the practical application, a wide-angle absorption with simple structure is still crucial property of metamaterial absorbers (MAs). A single-band infrared MA is introduced to analyze the angle insensitive mechanism. Numerical simulation reveals that a perfect absorption peak with 99.9% (7.55 μm) is achieved at normal incidence, as well as the absorptivity is respectively 69.7% (7.46 μm) and 93.5% (7.46 μm) for transverse electric (TE) and transverse magnetic (TM) modes at 70° incidence. By changing substrate thickness, the absorption ratio at 70° is increased to 91% (7.46 μm) for TE mode. Our design can also keep the good absorption stability for the geometric parameters. The E_z-field distributions for different incident angles are given to investigate the physical mechanism. The designed MA can realize good wide-angle tolerance. This MA owns great applications, including infrared spectroscopy, solar harvester and plasmonic sensors.

Document code: A **Article ID:** 1673-1905(2021)11-0669-4

DOI https://doi.org/10.1007/s11801-021-1034-1

Metamaterial absorbers (MAs) have been researched widely due to their strong absorption and flexibility since it was proposed in 2008[1]. They have been developed to realize many important application, such as solar energy harvesting[2], sensor[3], thermal emitters[4], and other fields[5]. Based on different application fields, MAs have the development trends as follows: broadband absorption for stealth[6], tunable absorption for intelligence[7], narrowband absorption for sensor[8], strong absorption for energy harvesting[9]. For example, signals can be detected by the variation of the resonant frequency when MAs are used as sensors. Many designed methods have been proposed to construct the MAs with the specific function. Multiband or broadband MAs are obtained by the spatial or horizontal superposition of different metal-dielectric structures[10]. The controlled materials, such as water, graphene, and liquid crystal, ensure the tunable performance of MAs[11].

In many reports, MAs have the good absorption characteristics at normal incidence. Once the incident angle is increased, their absorptivity is usually reduced. Since the absorbers are increasingly used in practical applications, it is observed that they usually work at oblique incidence. So, the wide-angle absorption stability is very crucial. Recently, many researchers draw the attentions to the point in the range from microwave to infrared wavelengths. CUI et al[12] reported a microwave wide-angle triple-band polarization-insensitive absorber by closed-ring resonators, and its absorptivity owns above 90% at 50°. CHEN et al[13] presented an omnidirectional polarization-insensitive absorber, which can achieve 90% absorption below 40°. TAO et al[14] demonstrated a flexible wide-angle MA by split-ring resonators, polyimide and ground metal, as well as the absorptivity is below 90% at 50° for transverse electric (TE) mode. LUO et al[15] designed a polarization-independent broadband wide-angle absorber by non-noble metal in the visible regime, and the absorption decreases to 80% at oblique incident of 60°. GUO et al[16] presented a wide-angle infrared absorber with the high absorption, and the absorptivity was quickly reduced when the oblique angle exceeded 60°. Although some MAs have achieved the wide-angle absorption, the absorptivity is still low at oblique incidence. Moreover, for TE case, the incident-angle stability is worse. Even if few resonators have shown good wide-angle stability for TE and transverse magnetic (TM) mode, it is very complicated for us to manufacture the MAs. Therefore, for TE mode, a wide-angle MA with the simple geometrical structure is very necessary in the infrared range.

A resonator with the simple circular-ring shape is obtained in this work. By numerical optimization, the geometrical structure is determined to realize the wide-angle absorption for TE and TM modes. Especially, the infrared MA remains high absorptivity under TE incident angle of 70°. The electric field distributions with differ-

* E-mail: xiutaoh90@163.com

rent angles are given to investigate the physical mechanism of wide-angle absorption.

A variety of MAs have been designed and investigated. Their structures typically consist of patterned metal, a middle dielectric and ground metal. When the plane wave works into the absorbers, the electric and magnetic resonances are usually excited to achieve the high absorption. In high frequency, such as terahertz (THz) or infrared wavelength, the surface plasmon is also excited at metal-insulator interface. In our design, an MA is made up of circular ring, middle dielectric layer and a continuous metal in Fig.1. The upper metal is Tantalum (Ta), and its conductivity is 7.63×10^6 S/m. The ground metal is aluminum (Al), and its conductivity is 3.56×10^7 S/m. The permittivity of the middle dielectric layer (ZnS) is 5.06. It is observed that the conductivity of upper and bottom metals is different. Based on full-wave simulation, the optimized parameters are as follows: r=0.29 μm, R=0.79 μm, T=0.18 μm and t=0.1 μm. The lattice period of the MA is P=2 μm. The thickness of the tantalum metal is 0.08 μm. S parameters are calculated by CST software. Absorption ($A(\omega)$) is obtained by the equation $A(\omega)=1-R(\omega)-T(\omega)$, where $R(\omega)$ is reflectance and $T(\omega)$ is transmission. Transmission ($T(\omega)$) is zero due to a continuous ground metal.

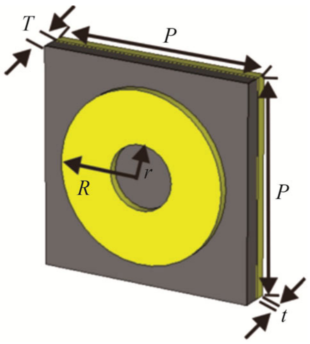

Fig.1 Schematic of the metamaterial unit cell

Based on the above optimization, the simulated value is shown in Fig.2 in the wavelength from 5 μm to 10 μm. It is clear that the perfect absorption is obtained at 7.55 μm when the lossy metal (Ta) is used in MA. The whole thickness is thinner, which is only $\lambda/21$. When the upper metal is perfect electric conductor (PEC), the absorptivity is decreased to 0.69 at 7.23 μm, and the resonance is shifted. Therefore, the simulated results reveal that ohmic loss can enhance the strong absorption of MA.

In the infrared band, the high level of manufacture is required due to the small size of a single cell. By considering fabrication tolerances, it is very important for MA to design the absorption stability with parameters. The main parameters (dielectric thickness (T) and inner radius (r)) are selected, as shown in Fig.3. It is very clear that the resonance and absorptivity change little with the variation of inner radius (r) and dielectric thickness (T). Even if the manufacture has the small tolerance, the MA can keep the good absorption. Simulated results reveal that the designed MA owns the absorption stability with respect to the geometric parameters.

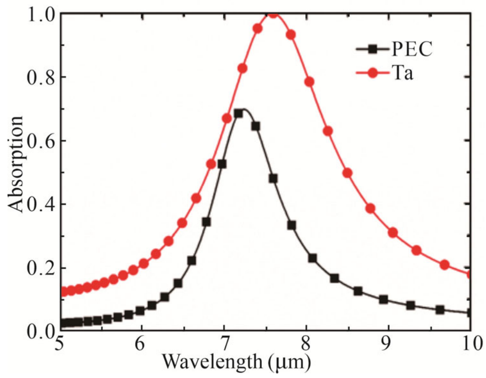

Fig.2 Simulated absorption spectra at normal incidence

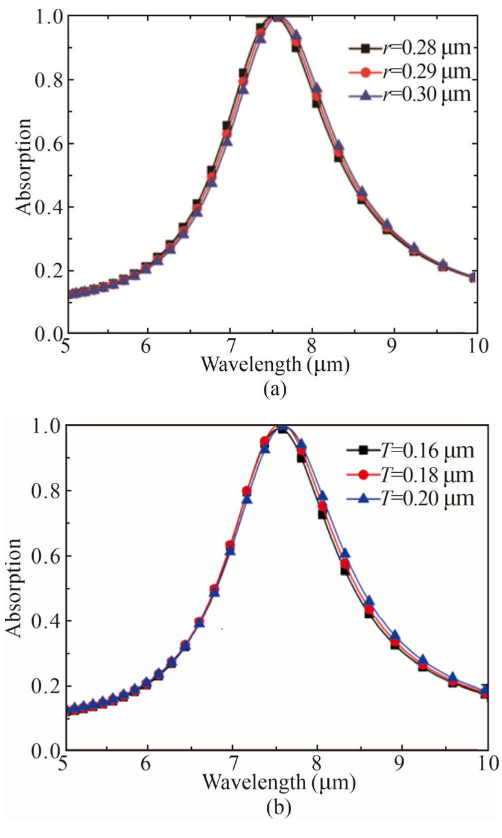

Fig.3 Simulated absorptivity with the variation of (a) inner radius and (b) substrate thickness

In a real situation, electromagnetic waves are emerged in all directions. It requires that the designed MA is insensitive to incident angle for TE and TM modes. The absorptance which is dependent on the incident angle is shown in Fig.4(a) and (b). In Fig.4(a), the resonance is slightly changed with the increase of angles, and the absorptance is reduced. Especially, its absorptance at 7.46 μm is only 0.69 at 70°. In Fig.4(b), the absorptivity is more than 0.9 around 7.50 μm in the TM angles from 0° to 70°. Moreover, the resonance can remain constant for different angles except 70°. Therefore, the absorption performance in TM mode is better than that in TE mode. This is a common phenomenon in the previous reports. The next part will investigate the physical mechanism of wide-angle absorption. By changing dielectric thickness, the high absorptance which depend on the oblique angle of TE mode is obtained.

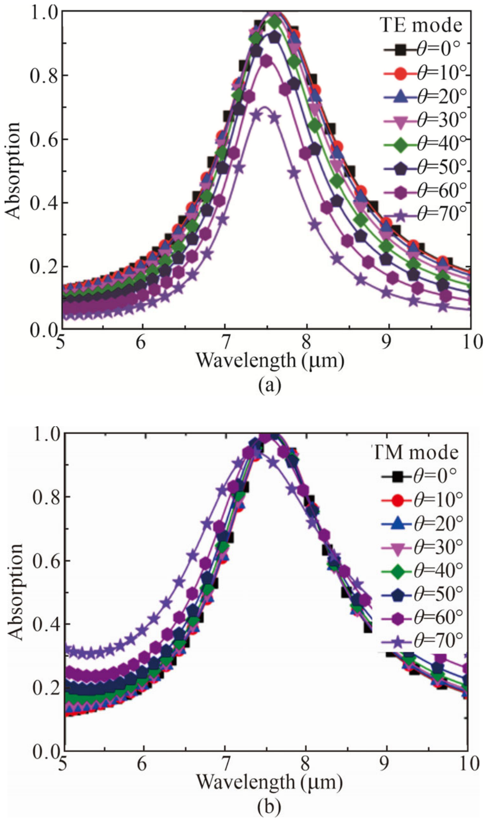

Fig.4 Absorptivity of different incident angles at *T*=0.18 μm: (a) TE mode; (b) TM mode

To better analyze the absorption performance, the E_z-field distributions are depicted in Fig.5. In TE mode, E_z fields are distributed along the upper and lower parts of resonator. In TM mode, the E_z-field distributions are concentrated around the left and right parts of a circular ring. Whether TE mode or TM mode, the electric dipole resonances are generated for different incident angles. Moreover, the surface plasmon resonances become stronger with the increase of angle in the junction between circular ring and dielectric substrate. Hence, the MA offers the high absorptance under different angles. It is carefully observed that the electric and plasmon resonances of TM waves are stronger than that of TE mode at 70°. So, the absorptance in TM mode is higher at 70°.

To enhance the absorbing ability of TE angles, the thickness of dielectric layer in MA is changed to 0.25 μm. Simulated results are shown in Fig.6. Obviously, the absorptance becomes more than 0.9 at 7.46 μm even when TE incidence angle is 70°. And, resonance is almost unchanged under the incident angle from 0° to 70°, as shown in Fig.6(a). Indeed, compared with the absorption in Fig.4, the absorptance is slightly reduced in Fig.6(b). Even so, the absorptivity achieves 0.74 around 7.31 μm at 70°. Hence, dielectric thickness has a strong influence on the stability of wide-angle absorption.

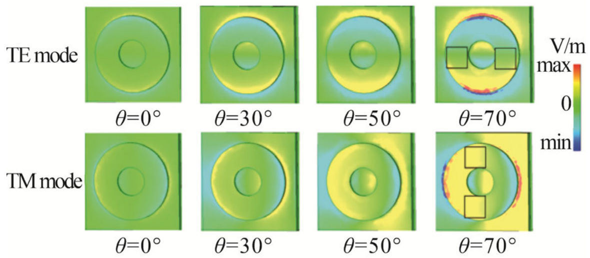

Fig.5 *Z* component of electric filed distribution at *T*=0.18 μm, where square represents the difference

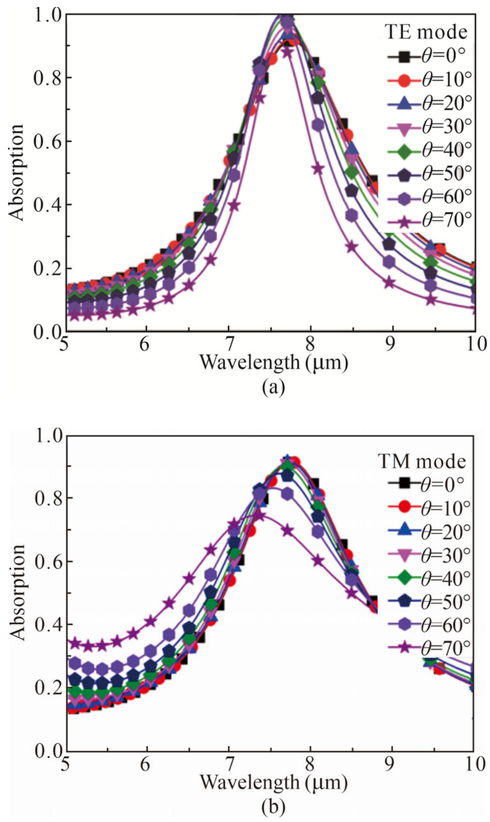

Fig.6 Absorptivity of different incident angles at *T*=0.25 μm: (a) TE mode; (b) TM mode

Fig.7 illustrates the E_z-field distributions at *T*=0.25 μm. Similarly, the electric dipole resonance and surface plasmon are excited at oblique incidence. Obviously, the electric resonance in TE mode is stronger than that in TM mode when the incident angle achieves 70°. Due to the electric field enhancement, the wide-angle absorption under TE angle of oblique incidence is improved.

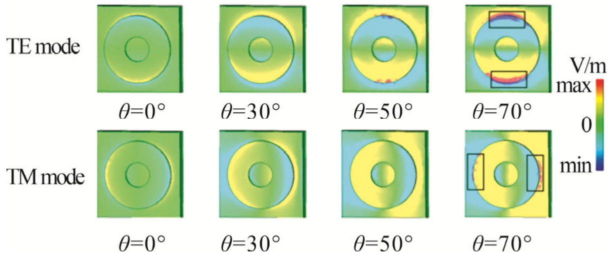

Fig.7 *Z* component of electric filed distribution at *T*=0.25 μm, where square represents the difference

A simple circular-ring MA has been investigated at infrared regions. Simulated results show that the absorptance is insensitive to the incident angle and main parameters. The working mechanism is explained by E_z-field distributions. Compared with the previous MAs, our designed MA with a simple resonator can achieve the high absorption with respect to angle and parameters. Our structure is easily fabricated and applied in a lot of fields such as sensor, frequency selective detector and infrared stealth.

References

[1] LANDY N I, SAJUYIGBE S, MOCK J J, et al. Perfect metamaterial absorber[J]. Physical review letters, 2008, 100(20)：207402.

[2] BAGMANCI M, KARAASLAN M, ÜNAL E, et al. Broad-band polarization-independent metamaterial absorber for solar energy harvesting applications[J]. Physica E：low-dimensional systems and nanostructures, 2017, 90：1-6.

[3] WANG B X, ZHAI X, WANG G Z, et al. A novel dual-band terahertz metamaterial absorber for a sensor application[J]. Journal of applied physics, 2015, 117(1)：014504.

[4] WANG H, YANG Y, WANG L. Switchable wavelength-selective and diffuse metamaterial absorber/emitter with a phase transition spacer layer[J]. Applied physics letters, 2014, 105(7)：071907.

[5] LIU B, SHEN S. Broadband near-field radiative thermal emitter/absorber based on hyperbolic metamaterials：direct numerical simulation by the Wiener chaos expansion method[J]. Physical review B, 2013, 87(11)：115403.

[6] SHEN Y, ZHANG J, PANG Y, et al. Transparent broadband metamaterial absorber enhanced by water-substrate incorporation[J]. Optics express, 2018, 26(12)：15665-15674.

[7] YUAN H, ZHU B O, FENG Y. A frequency and bandwidth tunable metamaterial absorber in X-band[J]. Journal of applied physics, 2015, 117(17)：173103.

[8] LUO S, ZHAO J, ZUO D, et al. Perfect narrow band absorber for sensing applications[J]. Optics express, 2016, 24(9)：9288-9294.

[9] RUFANGURA P, SABAH C. Design and characterization of a dual-band perfect metamaterial absorber for solar cell applications[J]. Journal of alloys and compounds, 2016, 671：43-50.

[10] XIONG H, HONG J S, LUO C M, et al. An ultrathin and broadband metamaterial absorber using multi-layer structures[J]. Journal of applied physics, 2013, 114(6)：064109.

[11] SHREKENHAMER D, CHEN W C, PADILLA W J. Liquid crystal tunable metamaterial absorber[J]. Physical review letters, 2013, 110(17)：177403.

[12] SHEN X, CUI T J, ZHAO J, et al. Polarization-independent wide-angle triple-band metamaterial absorber[J]. Optics express, 2011, 19(10)：9401-9407.

[13] CHEN S, CHENG H, YANG H, et al. Polarization insensitive and omnidirectional broadband near perfect planar metamaterial absorber in the near infrared regime[J]. Applied physics letters, 2011, 99(25)：253104.

[14] TAO H, BINGHAM C M, STRIKWERDA A C, et al. Highly flexible wide angle of incidence terahertz metamaterial absorber：design, fabrication, and characterization[J]. Physical review B, 2008, 78(24)：241103.

[15] LUO M, SHEN S, ZHOU L, et al. Broadband, wide-angle, and polarization-independent metamaterial absorber for the visible regime[J]. Optics express, 2017, 25(14)：16715-16724.

[16] GUO L, MA X, ZOU Y, et al. Wide-angle infrared metamaterial absorber with near-unity absorbance[J]. Optics & laser technology, 2018, 98：247-251.