A Broadband Terahertz Metamaterial Absorber Based on Square Ring Resonators

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Abstract— A simple design of broadband metamaterial absorber (MA) is numerically investigated at terahertz frequencies in this paper. The unit cell of this absorber consists of two square rings with different geometric dimensions, a dielectric substrate and continuous metal film. A wide frequency band ranging from 2.95 THz to 3.71 THz with absorption rate of over 90% is obtained. Distributions of surface current density on the front and back metallic layers are illustrated. Finally, the loss contributions of metallic structures and dielectric substrate are also discussed. The proposed absorber is an ideal candidate as absorbing elements in many applications, such as thermal detectors, terahertz imaging, and stealth technology.

1. INTRODUCTION

Electromagnetic metamaterials (MM) have been attracting considerable attention during the past decade due to their ability to exhibit exceptional physical properties, which are not available in naturally occurring materials, such as negative refractive index [1, 2] superlensing [3], cloaking [4], and optical transformation [5]. Most of these proposed structures were mainly implemented at the microwave frequencies due to the simplicity in design and characterization. By adjusting proportionally geometric parameters of resonant components in MM unit, the response frequency can achieve the most part of the electromagnetic spectrum ranging from radio to the near optical regimes [6–9]. MMs can be widely used in many applications, including invisibility cloaks [4], perfect lens [3], and bandpass filters [10].

Recently, MMs are fashioned to create subwavelength resonant absorbers. In 2008, Landy et al. proposed the first configuration of MA. The MA is composed of electric resonator on the front side of FR-4 substrate and cut wire on the bottom and has an experimental absorption rate of 88% at 11.5 GHz [11]. Later, many novel MA designs were investigated to achieve polarization-insensitive absorption [12] or wide-angle absorption [13] at gigahertz and terahertz frequencies. The idea is to tune electric and magnetic response of absorber independently to make the effective impedance match to free space and to attain a large imaginary part of refraction index, the reflectance and transmission of the incident wave energy will be minimized simultaneously, the MA can completely absorb the incident electromagnetic wave. However, most of these designs are based on strong electromagnetic resonances to effectively absorb the incident wave. Consequently, the working bandwidth of these MAs is relatively narrow, typically no more than 10% with respect to the center frequency. At present, much attention has been paid to the design of multiband [14, 15] and broadband MAs [16], which are generally composed of multilayer metallic and dielectric components. These multilayer absorbers are usually difficult to design and fabricate. These above-mentioned defects impose many restrictions on future applications in the scientific and technological areas.

In this paper, we design a simple broadband terahertz MA using rectangular ring, dielectric substrate and continuous metal film. A wide frequency band ranging from 2.95 THz to 3.71 THz with absorption rate of over 90% is obtained. Simulated results show that the MA can achieve polarization-insensitive and wide-angle absorption for both TE and TM waves in this band.

2. DESIGN AND SIMULATION

The schematic diagram and geometric parameters of the proposed MA unit cell are depicted in Fig. 1. The outer and inner rings on the front side are shown in Figs. 1(a) and 1(b). The length and width of the outer and inner rings are equal to $b_1 = 11.2\,\mu\text{m}$, $w_1 = 0.2\,\mu\text{m}$ and $b_2 = 10.6\,\mu\text{m}$, $w_2 = 2.5\,\mu\text{m}$, respectively. Fig. 1(c) is the perspective view of the MA unit cell, the axes indicate that the polarization and propagation direction of the incident wave. The thickness of dielectric substrate is $t = 5\,\mu\text{m}$. The lattice constants along the and directions are both $p = 14\,\mu\text{m}$. The rectangular ring strongly couples to the electric component of the incident wave to provide an electric response. The incident magnetic field couples to two metallic conducting layers on both sides of dielectric substrate, which exhibits a magnetic response. We can tune the geometric parameters of the unit cell to acquire tailored electric and magnetic response and achieve a perfect absorption.

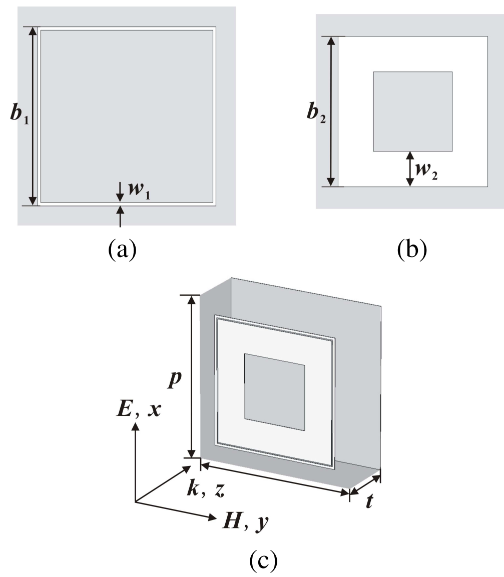

Figure 1: Schematic diagram and geometric parameters of the proposed MA unit cell. (a) The outer and (b) inner ring on the front side. (c) The perspective view with axes indicating the polarization and propagation direction of the incident wave.

The absorption rate is calculated by $A(w) = 1 - R(w) - T(w)$, where $R(w) = |S_{11}|^2$ and $T(w) = |S_{21}|^2$ are the reflectance and transmission, respectively. As the thickness of metal film in this paper is much larger than the penetration depth in the terahertz regime, the transmission is equal to zero in the whole frequencies of interest and the reflectance is the only factor determining the absorption. The absorption formula is simplified to $A(w) = 1 - R(w)$. To attain a perfect absorption, we can only minimize the reflectance.

The proposed MA is designed and optimized by the commercial finite difference time domain solver (CST Microwave Studio 2009). Unit cell boundary conditions are set along the lateral directions of the MA and open boundary condition is set along the direction. The substrate is modeled as FR-4 with relative dielectric constant = 4.9 and loss tangent tan = 0.025. The simulated absorption spectra of the MA are shown in Fig. 2 (solid line). There is a wide frequency band ranging from 2.95 THz to 3.71 THz with absorption rate of over 90%. Therefore, the bandwidth of strong absorption is about 0.76 THz.

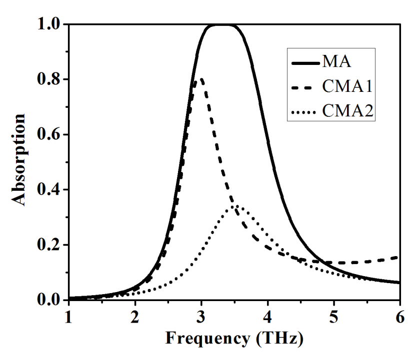

Figure 2: Simulated absorption spectra of the MA, CMA1 and CMA2 as a function of frequency.

For comparison, two designs of absorber (CMA1 and CMA2) are proposed. The only difference between CMA1 (or CMA2) and original MA is the front structure. The front structure of CMA1 and CMA2 are only composed of outer and inner ring, respectively, as shown in Figs. 1(a) and 1(b). The simulated absorption spectra of CMA1 (short dash line) and CMA2 (short dot line) are illustrated in Fig. 2. When the front structure is only composed of outer ring (CMA1), a distinct peak with absorption rate of 80.8% at 2.97 THz is obtained and the working bandwidth (more than 50%) is 0.56 THz. When the front structure is only composed of inner ring (CMA2), there is an absorption peak of only 34% at 3.53 THz. These results indicate that a wide absorption band is obtained by overlapping different resonances and a broadband MA could be achieved by integrating different resonant elements into a unit cell.

To get an insight into the intrinsic mechanism of high absorption, the distribution of surface current density on the front and back metallic layers at 3.33 THz is illustrated in Fig. 3. From Fig. 3(a), we can see that opposite current flows between the outer and inner rings are formed on the front structure of the MA. However, there are comparatively small opposite currents on the front and the back metallic layers as shown in Fig. 3(b). It is concluded that the rectangular rings can supply both electric and magnetic response.

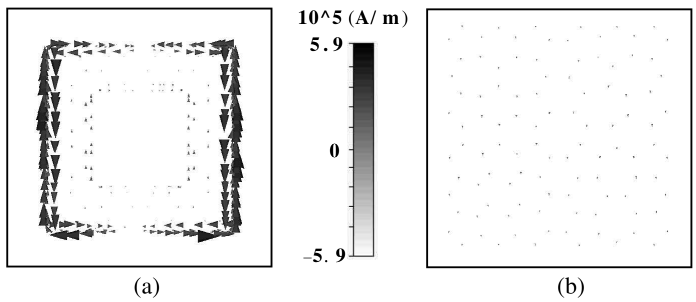

Figure 3: Distribution of surface current density on the (a) front and (b) back metallic layers at 3.33 THz.

3. POLARIZATION-INSENSITIVE AND WIDE-ANGLE ABSORPTION

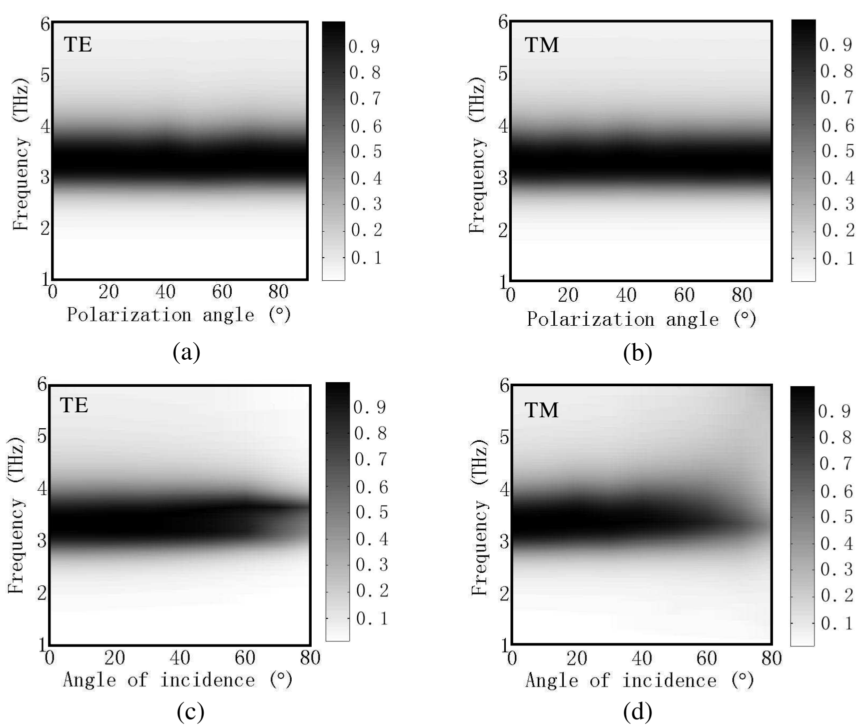

Figure 4: Absorption spectra as a function of frequency and polarization angle for (a) TE and (b) TM waves. Absorption spectra as a function of frequency and angle of incidence for (c) TE and (d) TM waves.

Figures 4(a) and 4(b) show the absorption spectra as a function of frequency and polarization angle for TE and TM waves, respectively. As the polarization angle increases from 0 to 90, the absorption spectra for TE and TM waves almost remain the same. The absorption spectra as a function of frequency and angle of incidence for TE and TM waves are illustrated in Figs. 4(c) and 4(d), respectively. For the case of TE wave, the absorption spectra of the MA keep unchanged as the incident angle varies from 0 to 60. Beyond 60, the amplitude of the absorption peak decreases quickly and the absorption band becomes very narrow. For the TM wave, the absorption spectra are almost the same as the incident angle increases from 0 to 55. As the incident angle continues to increase, the amplitude of the absorption peak begins to decrease and the absorption band becomes narrower and narrower. These simulated results validate that the absorber can work at wide polarization angles and wide angles of incidence for both TE and TM waves.

4. THE LOSS CONTRIBUTIONS OF EACH PART OF THE MA

To understand how and where the absorption happens, the absorption spectra of the MA with different components are illustrated in Fig. 5. It is easily found that the front two absorption spectra are almost the same. There is a wide frequency band ranging from 2.95 THz to 3.71 THz with absorption rate of over 90% and the absorption bandwidth is 0.76 THz. When the metal is perfect electric conductor (PEC) and the substrate is lossy, there are two distinct peaks at 3.15 THz and 4.2 THz with corresponding absorption rate of 30.7% and 81.8%. These absorption spectra of different components suggest that high absorption of the MA mainly originates from the metallic absorption (Ohmic loss). This is different from the studies in previous works where Ohmic loss is minor compared with dielectric loss of the substrate. The MA has a great potential application in some fields where energy is needed to be absorbed by the metal structure.

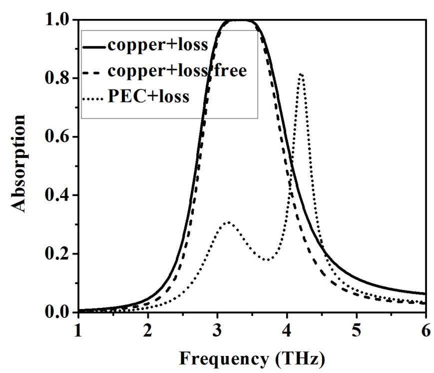

Figure 5: Absorption spectra as a function of frequency and polarization angle for (a) TE and (b) TM waves. Absorption spectra as a function of frequency and angle of incidence for (c) TE and (d) TM waves.

5. CONCLUSION

In summary, we have presented a polarization-insensitive and wide-angle broadband MA, which is composed of two rectangular rings with different geometric dimensions, dielectric substrate and continuous metal film. A wide frequency band ranging from 2.95 THz to 3.71 THz with absorption rate of over 90% is obtained. Distribution of surface current density is illustrated to indicate that the rectangular rings can supply both electric and magnetic response. Absorption spectra of the MA at different polarization angles and different angles of incidence validate that the MA can achieve polarization-insensitive and wide-angle absorption for both TE and TM waves. Absorption spectra of different components suggest that high absorption of the MA mainly originates from Ohmic loss and the dielectric loss of the substrate is minor compared with Ohmic loss. Importantly, the proposed MA is also geometrically scalable. Therefore, our results are not limited to terahertz frequencies and may be used in other parts of the electromagnetic spectrum. The MA has great promise for many applications ranging from the active element in a thermal detector to stealth technology.

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