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Broadband and polarization-insensitive terahertz absorber based on multilayer metamaterials

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ABSTRACT

In this paper, a broadband, polarization-insensitive, and wide-angle terahertz metamaterial absorber is constructed by stacking multiple metal–dielectric layers with differently sized saw-shaped annular patch structures in the unit cell. The calculated results show that a broadband absorption above 70% is obtained for the frequency range from 0.76 THz to 0.96 THz, and the full absorption width at half maximum (FWHM) can reach 28%. The magnetic field distributions of the structure are discussed to look into the broadband mechanism. Moreover, the broadband absorption is insensitive to the polarization and incident angle of the TE and TM waves owing to the high-degree symmetry of structure. Importantly, the thickness of the four-layer patches is about 27 times smaller than the central working wavelength. Therefore, the proposed metamaterial provides a promising way to obtain a broadband absorber with a compact dimension, and such design also has potential applications in solar cell, detection, and imaging.

1. Introduction

Metamaterials, which are composed of the sub-wavelength unit-cell structures arranged in periodic arrays, are artificial composite materials. By properly designing the geometry and crystal lattice of the unit-cell structure, metamaterials can exhibit some extraordinary electromagnetic responses unavailable in natural media such as negative index refraction, perfect absorption, backward wave propagation, and reverse Doppler effects [1–5], etc. Due to their exotic properties, metamaterials have attracted considerable attentions during the last decade and been widely investigated from RF to visible optics range [6]. Moreover, different metamaterial-based devices (such as absorbers [2,3] superlenses [7,8], invisibility cloaks [9], antennas [10,11], and filters [12–14]) have been successfully designed and fabricated to realize the correspondingly functional applications. In these devices, more specifically, terahertz metamaterial absorbers have received significant attentions. Currently, many groups and researchers have reported the theoretical analysis, design and fabrication of terahertz metamaterial absorbers [3,15–17]. Unfortunately, these perfect absorbers have common shortcoming of narrow absorption bandwidth, which greatly hampers their practical applications in detecting and imaging.

To expand the frequency response range of terahertz metamaterials, currently, an effective method is to combine planar multi-sized structures or stack multiple metal–dielectric layer structures resonating at the neighboring frequencies [18–21]. For example, Cheng et al. obtains a polarization-insensitive and omnidirectional broadband terahertz metamaterial absorber by using coplanar multi-square patch structures in the unit cell [18]. Grant et al. experimentally demonstrates a polarization-insensitive broadband terahertz metamaterial absorber by stacking three metal–insulator layer structures with closely positioned resonant peaks [19]. Wang et al. theoretically investigates broadband and wide-angle terahertz metamaterial absorber consisting of the multilayer same-size square plate structure [20]. Han et al. achieves a broadband terahertz filter with a bandwidth of 0.38 THz by stacking 2D metamaterial flexible films with different frequency responses [21]. However, the designs of metamaterials mentioned above have some disadvantages such as sensitivity to the polarization direction and incident angle of the incident electromagnetic wave, which limits their potential applications at solar cell, detection, and imaging.

In this paper, we construct a broadband terahertz metamaterial absorber by stacking metal–dielectric layers with differently sized saw-shaped annular patch structures in the unit cell. The designed absorber can achieve a bandwidth response by overlapping and coupling effects of multilayer structures. In addition, the absorption bandwidth is insensitive to the polarization directions and incident angles of the electromagnetic wave due to the high-degree

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symmetry of the unit-cell structure. Therefore, this design has potential applications in solar cell, detection, and imaging.

2. Design and simulation

To broaden the absorption bandwidth, we propose a broadband terahertz metamaterial absorber by stacking multilayer metamaterial structure in the unit cell. Fig. 1 shows the schematic diagram of the single unit-cell structure for the designed terahertz metamaterial absorber, which consists of an alternating stack of four different sizes saw-shaped annular patch structures and dielectric layers on the top of a metal ground plate. Here, the radii of the annular patch structures from top layer to bottom layer are gradually reduced, and the lower layer rotates 90° relative to the upper layer, as shown in Fig. 1(a) and (d). Moreover, the absorber structure is fabricated on a silicon wafer used as the supporting substrate. The polyimide is used as the dielectric layer to separate the two metal layers. The geometric dimensions of the unit-cell structure are indicated in Fig. 1(a) and (b). In this structure, both lattice constants of the unit-cell structure are $p=68$ μm along the x-direction and y-direction. Outer radius r_i ($i=1, 2, 3, 4$) of the annular patch from bottom layer to top layer is 33 μm, 32 μm, 31 μm and 30 μm, respectively. The width of all annular patch is $w=5$ μm, and the width and height of saw structure are $w_1=8$ μm and $h=5$ μm, respectively. The thicknesses of each dielectric layer are $d_1=1.3$ μm, $d_2=7.5$ μm, $d_3=1.5$ μm and $d_4=1.4$ μm respectively, and then the thicknesses of all metal layers are 250 nm, which is much larger than the typical skin depth in terahertz regime.

To investigate the absorption bandwidth and mechanism of the designed absorber, numerical simulations using commercial software CST Microwave Studio are carried out to calculate the reflection spectra and the electromagnetic field distributions corresponding to resonance frequencies [22]. The periodic structure of the metamaterial is simulated on a single unit-cell structure by employing periodic boundary conditions in the x- and y-directions, respectively, where the incident electromagnetic wave with the electric field parallel to the x-direction is normal to the absorber surface (see Fig. 1(c)). In the simulation, all metal layers are made of gold with conductivity of 4.561×10^7 S/m, while the real part of the permittivity ε and the loss tangent of the dielectric layer are set to 3 and 0.05 over the frequency of interest. When the reflection spectra are obtained by CST simulation, the absorption coefficient (A) is extracted by $A=1-T-R$, where T and R are transmission and reflection coefficients, respectively. As the thickness of the ground plane is much larger than the skin depth of the incident wave, the reflection is the only factor determining absorption. As a result, the calculation of the absorption can be simplified to $A=1-R$.

3. Results and discussions

Fig. 2 shows the calculated absorption spectra of the proposed terahertz metamaterial absorber. As expected, only a narrow absorption peak at 0.77 THz is obtained for single layer structure, where the electromagnetic wave energy of 98% is absorbed. In contrast, the absorption bandwidth broadens gradually and becomes flat-top as the number of metal–dielectric layer increases. Moreover, it is observed for four-layer structure device that the corresponding absorption band consists of four resonances at 0.79 THz, 0.81 THz, 0.84 THz, and 0.9 THz with the absorption magnitudes of 95.3%, 91.2%, 97.17%, and 98.3%, respectively (as shown in Fig. 2(a)). Here, four resonances are excited at nearby frequency such that the resonance peaks couple each other and form a broad absorption band. For example, the absorption greater than 70% is achieved for the frequency range from 0.76 to 0.96 THz, and the relative FWHM absorption bandwidth is about 28% with respect to the central frequency. This result is almost six times larger than that of the single layer structure, which indicates that a broad response can be obtained by stacking multilayer structures. Meanwhile, the thickness of the 4-layer structure is still

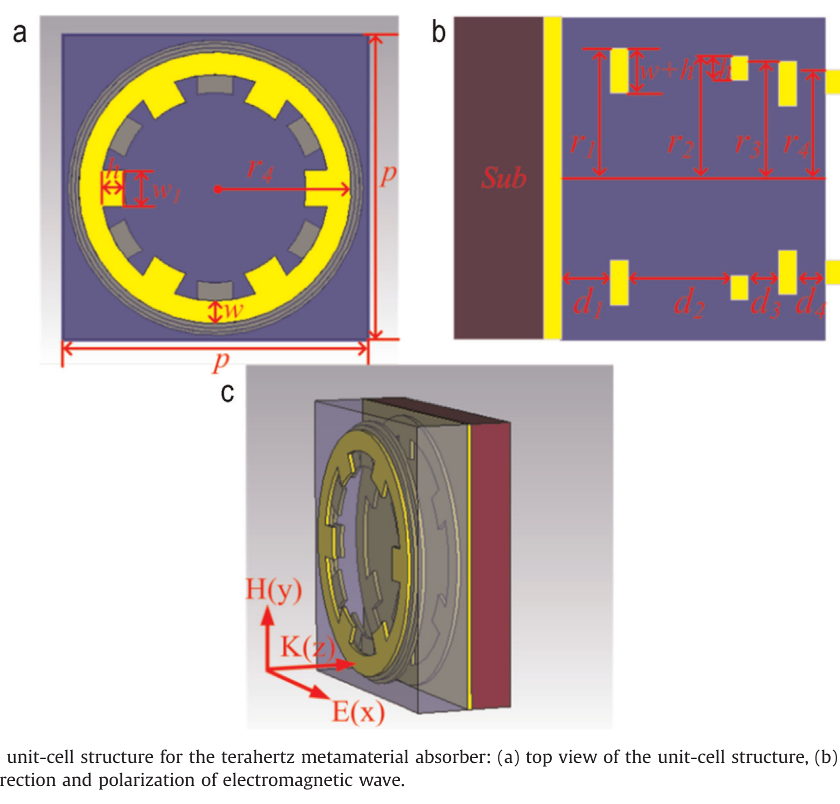

Fig. 1. Schematic diagram of the unit-cell structure for the terahertz metamaterial absorber: (a) top view of the unit-cell structure, (b) cross section view of the unit-cell structure, and (c) propagation direction and polarization of electromagnetic wave.