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ScienceDirect
Photonics and Nanostructures – Fundamentals and Applications xxx (2015) xxx–xxx
PHOTONICS AND NANOSTRUCTURES
Fundamentals and Applications
www.elsevier.com/locate/photonics

Ultra-broadband and polarization-insensitive wide-angle terahertz metamaterial absorber

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Received 20 November 2014; received in revised form 26 March 2015; accepted 7 April 2015

Abstract

In this paper, an ultra-broadband and polarization insensitive terahertz (THz) metamaterial absorber is presented and investigated. With the optimization of the structural parameters, resonant peaks are merged into a broadband absorption spectrum. The simulation results demonstrate that a wide bandwidth of 3.1 THz is obtained in the range from 2.6 to 5.7 THz, where the absorption is higher than 90% for the normal incident THz waves. The full width at half maximum (FWHM) of absorption spectrum is 95% with respect to central frequency (~4 THz), which is five times greater than the FWHM of a single layer structure. Furthermore, this structure can keep the absorption above 88% over a large frequency range (>2.5 THz) when the incident angle is smaller than 50°. This metamaterial absorber can find potential applications in terahertz imaging and stealth technology.

Keywords: Terahertz; Metamaterials; Subwavelength structures

1. Introduction

Metamaterials (MMs) are artificially designed subwavelength periodic structures which can achieve properties that may not be found in nature. With exotic electromagnetic (EM) properties relying on the structures rather than the compositions, they provide the possibility of creating an effective medium which the permittivity and permeability is controllable. Negative refractive index [1], perfect lens [2], invisible cloaking [3] and some other interesting physical phenomena have been achieved through properly designing the structures of MMs. In recent years, fabrication and optical characterization of metamaterial films designed for THz frequencies are rapidly developing and attracting a lot of attention due to the potential benefit of THz technology in a range of applications, including security, medical determination, and THz imaging. Many studies have been carried out to design all kinds of MMs. A branch of MMs provoking extensive interest currently is metamaterial absorber (MMA). The unit cell of MMA usually consists of three major components. A patterned metallic array works as a frequency selective surface (FSS) spaced a distance above a ground plane by a dielectric layer. The size and thickness of each layer are smaller than the wavelength of interest. The resonant frequency of near-perfect absorption can be obtained by manipulating the effective electrical permittivity ε and

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http://dx.doi.org/10.1016/j.photonics.2015.04.002
1569-4410/© 2015 Published by Elsevier B.V.

Please cite this article in press as: X. L., et al. Ultra-broadband and polarization-insensitive wide-angle terahertz metamaterial absorber, Photon Nanostruct: Fundam Appl (2015), http://dx.doi.org/10.1016/j.photonics.2015.04.002

magnetic permeability μ. However, due to the resonant nature of MMAs based on strong EM resonances, MMAs usually absorb EM waves in a narrow frequency band, which results in narrowband absorption spectra. This limits their performance for broadband applications like solar cells [4]. Therefore, more researches have been done to enhance the bandwidth of metamaterial terahertz absorbers (MMTAs). There are two main design approaches used to realize broadband MMTAs up to date. In the one hand, various resonant frequencies are generated by using different FSSs [5–8]. In the other hand, by properly designing the structure, the adjacent resonant peaks merge together to achieve a broadband absorption spectrum [9–12]. In addition to these two methods, other broadband MMTAs based on destructive interference mechanism have also been proposed [13,14].

In this paper, a vertically cascaded structure is presented to design an ultra-broadband MMTA. Numerical simulations were performed to investigate the absorption properties of the MMTA by using the finite difference time-domain (FDTD) method. In addition, the polarization dependence and incident angle dependence of absorption spectra were analyzed. Simulation results show that the MMTA has a broad absorption bandwidth (~3.1 THz) ranging from 2.6 to 5.7 THz with absorption greater than 90%. This design can find promising applications in THz imaging [15], solar cells [16], sensing [17] and stealth technology [18].

2. Structure and principles

A planar MMA based on standing resonances is exhibited in Fig. 1(a). In the simulation, the thicknesses of the golden ground and the gold layers are both 0.2 μm. The length of the square gold layer is 46 μm and the dielectric layer thickness is 2.0 μm. Additionally, the period is set to 50 μm. The permittivity of dielectric is modeled as $2.8+0.09i$ [19,20]. Simulated absorption spectrum is shown in Fig. 1(b). One can see that there are three narrow absorption peaks distributing across the THz band. The resonant frequencies of three absorption peaks are 1.73, 5.13, and 8.68 THz, respectively. Among these peaks, the first peak reaches near-unity absorption, while the other two peaks, which induced by the high order resonant modes, have the absorptions of 87% and 76% respectively. The resonant frequencies can be simply calculated by $f_{\mathrm{res}} \approx (2j-1)c/2\,nL$ $(j=1, 2, 3,\ldots)$ [6], where c is the light speed in vacuum, and n is the refractive index of the dielectric layer. It is clear that the resonant frequency moves to low frequency with the increase of the rectangle dimension. Thus, some narrow-band peaks with low absorption will shift to the frequency range of interest. Those peaks are not wanted as they have influence on the superstition of the resonant peaks, resulting in the generation of many narrow-band peaks with low absorptions. In this way, we designed a MMTA with the absorption frequency range of 2–6 THz. Some planar MMA structures with different numbers of cascaded gold layers were investigated. Considering the average bandwidth contribution, which we defined as the FWHM divided by the number of the gold layer, the cascaded MMA with six gold layers is better than other planar MMAs with five or seven gold layers.

The unit cell of this MMTA is schematically shown in Fig. 2, where the plane view and side view are both depicted. This unit cell has one gold ground plane and six gold layers separated by the polyimide dielectric layer. It should be noticed that the resonant frequency of absorption peak is mainly determined by the length of the layer. With the optimization of the structural parameters, several resonant peaks closely merge together, obtaining a broadband absorption spectrum. Numerical simulations were performed to investigate the absorption properties of this MMTA. The gold layers are modeled as lossy metal with electric conductivity $\sigma = 4.0\times10^7$ S/m and the dielectric is modeled as polyimide with a frequency independent refractive index of $1.8+0.06i$ [9,21]. In general, the incident THz waves are normal to the surface of gold plane. The lengths of six gold layers from L_1 to L_6 are 27.4 μm, 23 μm, 19.6 μm, 16.6 μm, 14.8 μm, and 14 μm, respectively. Besides, the dielectric thicknesses from h_1 to h_6 are 0.6 μm, 0.7 μm, 1.3 μm, 1.4 μm, 1.8 μm, and 2.8 μm, respectively. As the thickness of gold layer is larger than the typical skin depth, the incident THz waves cannot penetrate the structure. Therefore, the absorption is calculated by $A = 1 - R = 1 - |S_{11}|^2$, where R is the reflectance and S_{11} is the scattering parameter relevant to reflection. Unlike some other cascaded absorbers with many kinds of dielectric materials and complex metal layer structure, this cascaded MMTA is simpler due to the design of the square gold layers and a single dielectric material.

Once the optimum MMTA design has been established, standard metal evaporation, electron-beam deposition, and lithography techniques are used to fabricate the device. Although the square resonator is easy to fabricate, it is no doubt that there are still many fabrication difficulties for the multilayer structures, including lithography, and alignment between neighbored layers. In this way, the real performance of the design is limited by many factors. These include the discrepancy between the real dielectric refractive index and the simulated value [9], a minute disparity of the gold layer lengths

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