Optics Communications 361 (2016) 41–46

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

A photoexcited broadband switchable metamaterial absorber with polarization-insensitive and wide-angle absorption for terahertz waves

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ARTICLE INFO

Article history:
Received 18 July 2015
Received in revised form
25 September 2015
Accepted 8 October 2015
Available online 23 October 2015

Keywords:
Switchable metamaterial absorber
Impedance-matched
Polarization insensitive
Terahertz waves

ABSTRACT

We present a design and numerical study of a polarization-insensitive and wide-angle photoexcited broadband switchable metamaterial absorber (MMA) in the terahertz (THz) regime. The switchable MMA comprises a periodic array of dielectric substrate sandwiched with metallic four-splits-ring resonator (FSRR) structure and continuous metallic film. Filling the gap between the SRRs with a photoconductive semiconductor (silicon, Si), leading to easy modification of its electromagnetic (EM) response through a pump beam. The conductivity of photoconductive Si pads filled in the gap of SRRs can be tuned efficiently by external pump power. This results in the modulation of absorption magnitude with a modulation depth of 62.2%, and a broadband switch of absorption peak frequencies varying from 0.82 to 0.51 THz. Further numerical simulations demonstrate that the switchable MMA has the merit of polarization-insensitive and wide-angle absorption. The realization of broadband redshift tunable MMA offers opportunities to mature semiconductor technologies and potential applications in active THz modulator and switcher.

1. Introduction

Electromagnetic (EM) metamaterials (MMs) as artificially subwavelength periodic structures have attracted a great deal of research attentions due to their possibilities to engineer EM properties not available in nature [1–3]. Over past decades, a variety of functional MMs, such as cloak [4], negative index MMs [5–7], EM wave absorber [8–10] have been demonstrated to manipulate EM waves across the whole spectrum from microwave to visible regime. This is especially important in terahertz (THz) frequency range due to the lack of the natural material to response the THz waves, making it hard to construct THz devices [11]. MMs are one potential solution to construct high performance THz devices; some efforts have been made to construct the MMs detectors, modulators, switches and absorber within the THz region [12–16], which have opened a bright perspective in filling the THz gap. In particularly, perfect MM absorber (MMA) for THz waves is a very important device due to its potential applications in security detection, sensing, biomedical imaging, and so on [17,18].

Currently, the realization of high performance THz MMAs has become a hot research topic due to the above mentioned potential applications. Several groups have reported the fabrication and theoretical analysis of MMAs operating in THz spectral band using a variety of designed configurations [16–31]. The first THz MMA using split ring resonators (SRRs) was proposed and investigated by Tao et al., which operated over a wide range of incident angles for both transverse electric (TE) and transverse magnetic (TM) radiation [19]. Then, dual-band/multi-band and broad band THz MMAs were proposed and investigated intensively [20–26]. However, most designs for THz MMAs only work at a fixed frequency, and the absorption cannot be modulated as desired. Actually, dynamic modulation of MMAs is also required for practical applications. Many tuning mechanisms have been proposed and applied to control the absorption strength or resonance frequency of THz MMAs including thermal [27], electrical [28], mechanical [29], and optical excitation [30–32]. Although many design schemes of tunable MMAs have been demonstrated experimentally lately that utilized the aforementioned methods, which only operated well in a particular polarization. Hence, there is still a need to design high performance tunable THz MMAs with polarization-insensitive and wide-angle absorption.

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http://dx.doi.org/10.1016/j.optcom.2015.10.031
0030-4018/

In this work, we present a demonstration of optically tunable MMA operating in the THz regime by incorporating semiconductors in gaps of FSRRs. The operation frequency and absorption strength of the designed MMA can be tuned by external pump power. We demonstrate numerically that a redshift switch of the operation frequency can be dynamically shifted from 0.82 to 0.51 THz, with a broadband tuning range of 62.2%. The novelty brought by our investigated structure is its simplicity in manufacturing, thus focusing on the use of single-sized resonators. In contrast to the earlier proposed structures, our design exhibits the characteristic of polarization-insensitive and wide-angle absorption. Our results are not limited only to THz frequencies but also may be used over the other frequencies region.

2. Theory, structure design and simulations

Generally, MMA consists of three or more layers coupling structures of the electric resonator combined metal wire or sheet layer [25]. The electric response can be obtained from the excitation of the electric resonators by the external electric field, while the magnetic response is provided by the antiparallel currents on the two sides of the substrate [27]. Thus, the perfect absorption mainly originates from the local EM resonance and nearly impedance-matched to the free space in a special frequency range [8,9,25]. It is possible to tune both the strength and resonance frequency of the MMA by controlling metallic resonator structure shape, dielectric thickness, and properties of metallic and dielectric layers. Owing to the sub-wavelength property of the MMs, which can be characterized by a complex permittivity $\tilde{\varepsilon}(\omega)$ and permeability $\tilde{\mu}(\omega)$ based on effective media theory. In practice, the absorbance can be defined as $A(\omega) = 1 - T(\omega) - R(\omega)$, where $R(\omega)$ and $T(\omega)$ represent the reflectance and the transmittance as functions of frequency ω, respectively. The frequency dependent $R(\omega)$ and $T(\omega)$ are mainly determined to the complex index of refraction ($\tilde{n}(\omega) = \sqrt{\tilde{\mu}(\omega)\cdot\tilde{\varepsilon}(\omega)}$) and wave impedance ($\tilde{z}(\omega) = \sqrt{\tilde{\mu}(\omega)/\tilde{\varepsilon}(\omega)}$) [8]. Therefore, it is possible to absorb both the electric and magnetic field of incident EM waves tremendously by properly tuning effective $\tilde{\varepsilon}(\omega)$ and $\tilde{\mu}(\omega)$, and impedance-matched to the free space ($\tilde{z}(\omega) = 1$) [8,25].

Our MMA is composed of a planar FSRRs array above a conductive ground plane layer separated with a dielectric substrate, as shown in Fig. 1. The metallic FSRRs were made of a lossy gold film with a frequency-independent conductivity $\sigma = 4.56 \times 10^7$ S/m and a thickness of $t_1 = 0.2$ μm, which is much larger than the typical skin depth in the THz regime [25]. The effective $\tilde{\varepsilon}(\omega)$ mainly arises from the FSRR's fundamental resonance mode (the *LC* mode) that is due to FSRR's self-inductance and gap capacitance [31,33,34], which responses to the electric field of the incident THz waves. At the same time, the magnetic field of the incident THz waves couple to the MMA through the cavity formed between FSRRs and the ground plane, resulting in an effective $\tilde{\mu}(\omega)$ [31]. The EM response of the FSRR strongly depends on the gaps capacitance. The conductivity of the gaps of the FSRR can be tuned through integration of photoconductive Si via external photo-excitation. Thus, the hybrid metal–semiconductor FSRRs can form an active structure, which can achieve absorption modulation due to the perturbation of matched impedance by applying an external pump beam. Photoconductive silicon (gray part) is put in the split gaps of the FSRRs, which is simulated as a dielectric with constant permittivity of $\varepsilon_{Si} = 11.7$ and pump power dependent conductivity σ_{Si} [30,31].

The resonance absorption mode is tunable easily by incorporating photoconductive Si into the FSRRs. To be realistic, the photoconductive Si is taken to be 2×10^2 S/m and 2×10^5 S/m

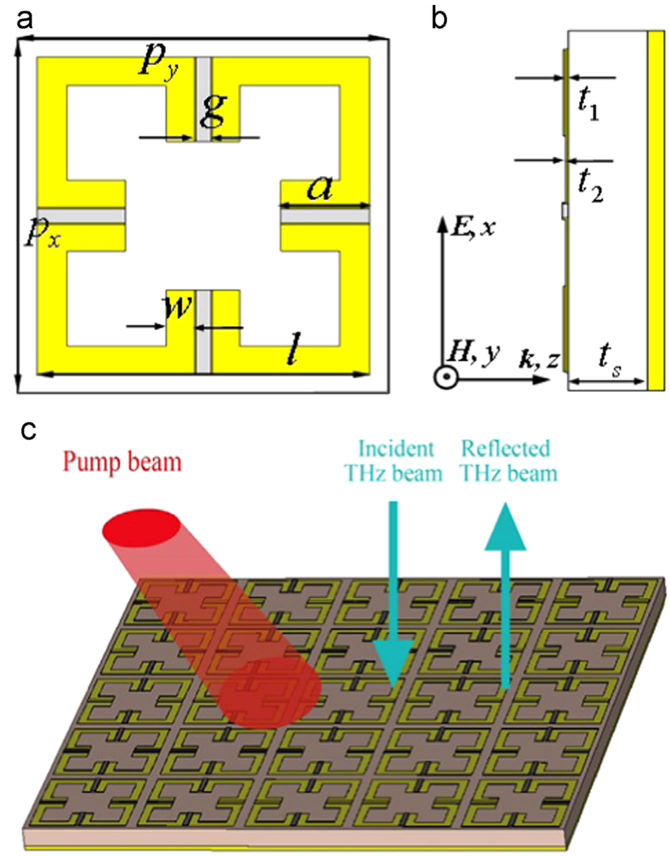

Fig. 1. Scheme of the proposed SMMA, (a and b) the unit cell structure, (c) two-dimensional array.

under the lower and upper limit illumination, which is the same as used for fitting the experimental results in Ref. [12]. The gallium arsenide (GaAs) with a complex dielectric constant of $\varepsilon = 12.9 + 0.0774i$ was etched to $t_s = 7$ μm thickness as the dielectric spacer between such two layers. The MMA unit cell (i.e., the period of the FSRRs array) in both x and y directions are $p_x = p_y = 50$ μm as shown in Fig. 1(a), and the other geometric parameters are as follows: $l = 45$ μm, $a = 12$ μm, $w = 4$ μm, $g = 2$ μm, $t_2 = 0.6$ μm. To predict the spectral response of our design, full wave EM simulations were performed based on the standard finite integration technology (FIT) by CST Microwave Studio software. For the simulations, as shown in Fig. 1(a) and (b), a single unit cell is adopted with appropriate boundary conditions resembling actual conditions in a THz time-domain spectroscopy (THz-TDS) experiment [12,13]. The absorbance could be calculated by using the equation $A(\omega) = 1 - R(\omega) = 1 - |S_{11}|^2$ in our designs due to the presence of the gold ground plane.

3. Results and discussion

Fig. 2 shows the simulated absorbance spectra for different Si conductivities. At first, the corresponding absorbance with nearly unity (99.9%) is achieved at 0.82 THz when the Si conductivity is $\sigma_{Si} = 2 \times 10^2$ S/m with low pump beam power. Then, the absorbance will decrease gradually and accompany by a redshift of the absorption peak frequency with the increase of Si conductivity since the increased photoexcited charge carriers in the gap make the resonance weaker [30–32]. The absorption frequency shifts to 0.62 THz with a minimum absorbance of 37.8% when the Si conductivity increases to $\sigma_{Si} = 5 \times 10^3$ S/m. Then, the absorption strength is enhanced again with the further increase of the Si