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A photoexcited switchable perfect metamaterial absorber/reflector with polarization-independent and wide-angle for terahertz waves

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ABSTRACT

We present a photoexcited switchable perfect metamaterial absorber/reflector for terahertz waves. The switchable absorber/reflector is based on a cross-shaped structure (CSS) integrated semiconductor photoconductive silicon (Si). The electric response property of the photoconductive Si can be easily modified through a pump optical beam. The conductivity of Si pads filled in the gap of CSS is tuned efficiently through the incident pump optical beam with different power, resulting in the modulation of absorption magnitude from 0 to 100% at the fixed operation frequency. Thus, the switch ability of the perfect absorber/reflector can be easily realized. Furthermore, the proposed design is polarization insensitive and operated well at wide incidence angles for both TE and TM waves.

1. Introduction

Development of terahertz (THz) spectroscopy has ushered a new field of science and technology research [1], where new devices and materials are on demand. In the past twenty years, many research efforts have been focused in the areas of THz generation and detection [2], while high-performance THz devices are still lacking. Electromagnetic (EM) metamaterials (MMs) as artificially sub-wavelength periodic structures have provided an effective platform for the creation of artificial material properties unavailable in nature [3–5]. Thus, MMs could be desirable candidates for creating exotic THz devices owing to the possibility of tailoring the response of the structure with great flexibility. Currently, MMs-based THz devices, such as detectors, switchers, modulators and absorbers have being proposed [6–10], which have opened a bright perspective in filling the THz gap.

THz MMs-based reflectors/absorbers could clearly be potentially used in many areas of security, imaging systems, stealth, and detectors etc [10–12]. Since then, THz MMs-based perfect absorbers have received considerable attention, and many MMs structures have been proposed and investigated intensively [13–18]. Unfortunately, most of these MM absorbers operated in a fixed frequency and absorption level, which greatly hampers their practical applications. Dynamic modulation of THz MMs has enabled signal modulators and switchers [6–8,19,20]. They are usually designed to work in a variable resonance response strength and frequency range by external stimulus, including electrical [6], thermal [19] or optical [8,20]. The efficient design for tuning the magnitude and phase of the reflected waves dynamically is also important, which could achieve perfect absorption or reflection. Generally, the electrically and optically active semiconductors materials integrated into MMs structures could be a promising candidate. Many electrically and optically tunable design schemes have been proposed and demonstrated to control both the strength and resonance frequency of the MMs absorbers for THz waves [21–27]. However, near all these tunable THz MM absorber is polarization sensitivity for normal incident waves. In addition, the perfect MMs reflectors have some potential application in bioimaging and sensing, and would be useful to protect surfaces against high power irradiation [28,29]. Thus, the MM switchable absorber/reflector with polarization-independence and wide-angle is highly desirable for practical application.

In this work, we propose a switchable perfect MM absorber/reflector based on the cross-shaped structure (CSS) incorporated photoconductive Si, whose absorbance can be tuned through photoexcited carrier injection. Contrast to the earlier proposed

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structures, the switchable perfect reflection/absorption for all polarization can be controlled continuously by tuning the pump optical beam power. This switchable MM reflector/absorber structure for THz waves is simple and easy in design and manufacture.

2. Structure design, theory and simulations

The proposed MM structure for switchable reflector/absorber is based on previous design of a polarization independent absorber [30–32]. The unit cell of the switchable reflector/absorber is schematically illustrated in Fig. 1(a). Our design consists of two functional layers: CSS on the top layer of a dielectric substrate and metallic film on the bottom layer, which can form a sandwiched structure as shown in Fig. 1(a,c). The CSS is a typical electric ring resonator (ERR) which can couple strongly to uniform electric fields, but negligibly to a magnetic field [32–34]. The electric response is determined by the ERR structure while the magnetic response is determined by the dielectric type and thickness between the ERR structure and the ground plane [30–32]. The electric and magnetic responses can be tuned independently through adjusting the ERR dimensions and dielectric substrate thickness. They allow for specification of effective permittivity and permeability providing impedance matching to that of free space approximately at resonance [23]. The designed sandwiched structure can be equivalent a *LC* resonance circuit model, while the change of the wire inductance *L* and the plate capacitance *C* can shift the magnetic resonance frequency $\left(f_m = \frac{1}{2\pi\cdot\sqrt{L_m C_m}} \propto \frac{1}{l}\right)$ [15].

The metallic part of the MM structure is modeled as lossy gold film with a frequency-independent conductivity $\sigma = 4.5 \times 10^7$ S/m and a thickness of 600 nm, which is much larger than the typical skin depth in the THz regime. The PDMS with dielectric constant 2.35 and loss tangent 0.06 was used as isolation spacer layer between two metallic layers [35]. The rectangular pad photoconductive Si (grey part) with dimension of $10 \times 2 \times 0.6$ μm^3 is put in the gap of the adjacent CSSs. The photoconductive Si filled in the split gap is simulated as a dielectric with constant permittivity $\varepsilon_{Si} = 11.7$, while the conductivity σ_{Si} is dependent on external pump beam power [8,24]. The thickness t_s of PDMS is 3.5 μm, and the periodic of the unit cell in both *x* and *y* directions are $p_x = p_y = 50$ μm. The cross wire length and width is 48 μm and 10 μm, respectively. As shown in Fig. 1(c), when pump optical beam

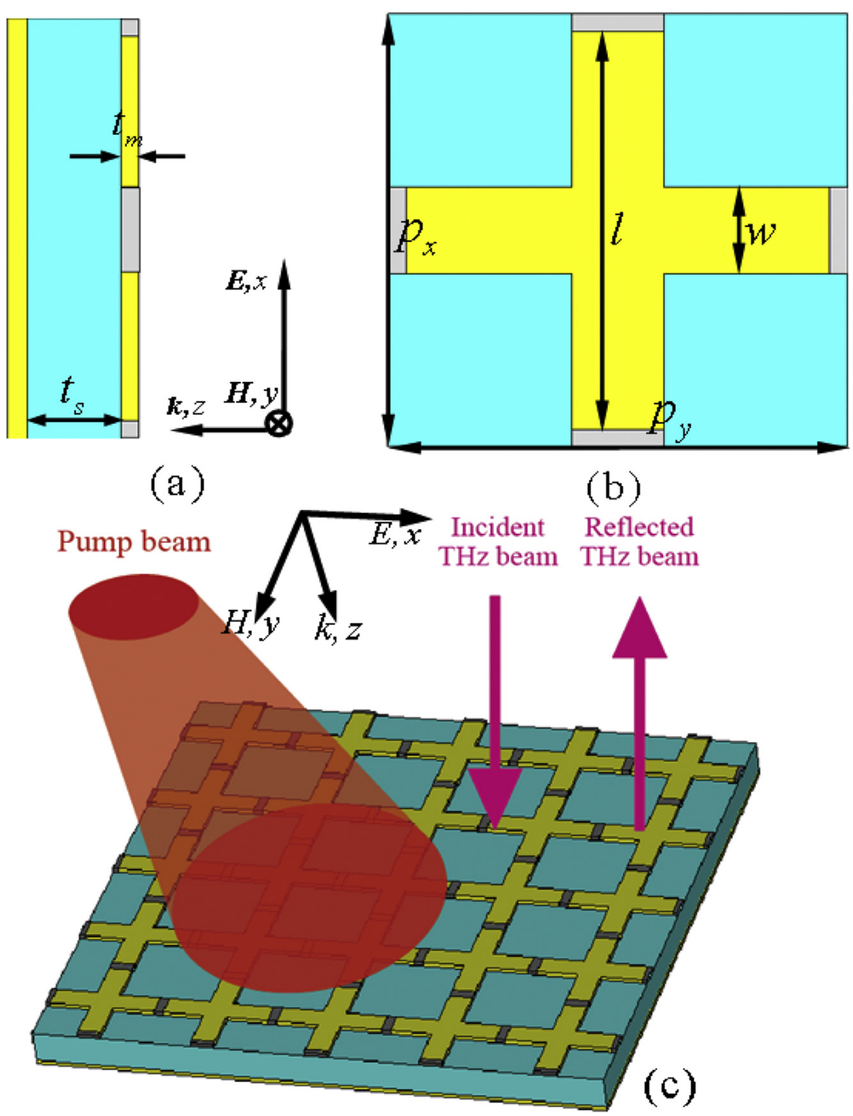

Fig. 1. Schemes of the proposed switchable MM reflector/absorber structure, (a, b) lattice and front views of the unit cell structure, (c) two-dimensional array.