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Photoexcited broadband blueshift tunable perfect terahertz metamaterial absorber

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ABSTRACT

We present an demonstration of optically tunable metamaterial absorber at terahertz frequencies. The metamaterials are based on two split ring resonators (SSRs) that can be tuned by integrating photoconductive silicon into the metamaterial unit cell. Filing the gap between the resonator arm with a semiconductor (silicon), leads to easy modification of its optical response through a pump beam which changes conductivity of Si. The conductivity of silicon is a function of incident pump power. Therefore, the conductivity of silicon is tuned effectively by applying an external pump power. We demonstrate that a blueshift of the resonance frequency under illumination can be accomplished and a broadband switch of absorption frequencies varying from 0.68 to 1.41 THz, with a tuning range of 51.8%. The realization of broadband blueshift tunable metamaterial absorber offers opportunities for achieving switchable metamaterial absorber and could be implemented in terahertz devices to achieve additional functionalities.

1. Introduction

A great deal of research into metamaterials (MMs) has used microwave radiation [1–4]. MMs scale to operate at terahertz frequencies have attracted great interest [5–8]. Most MMs rely on geometrically fixed electromagnetic resonances which provide functionality only within a narrow spectral range or a single frequency. Recently, it is interested for researchers in how to adapt a metamaterial (MM) to its environment by tuning its frequency. MMs that exhibit a tunable response have attracted extensive attention due to their great flexibility in many practical applications. So far, a variety of approaches to achieving tunable MM have recently emerged. One of the approach of tunability is integrable with current semiconductor technologies into MMs [9]. Subsequently, another approach of tunability is confirmed using the thermal control which is based on a variation of temperature altering the intrinsic carrier density in a semiconductor [10,11]. In addition, various optically and electrically active semiconductors materials are integrated into MMs as a promising candidate [12,13].

Recently, there has been considerable interest in the design, fabrication, and measurement of MM absorbers from microwave to optical frequencies due to their potential applications in thermal detectors, photovoltaic devices, stealth technology, imaging, and sensing systems [14–18]. Here, we present an demonstration of optically tunable MM absorber operating in the THz regime by incorporating semiconductors in critical regions of metallic split-ring resonators. We demonstrate that a blueshift switch of the absorption peak frequency can be dynamically shifted from 0.68 to 1.41 THz, with a broadband tuning range of 51.8%.

2. Design and simulation

The design of the tunable MM absorber consists of two metallic layers separated by a dielectric space, as depicted schematically in Fig. 1(a), which has been used to achieve highly flexible wide angle of incidence terahertz MM absorber by Hu Tao [19]. The top layer is made of an electric-LC (ELC)resonator which has both inductive (L) and capacitive (C) elements. Then the devices can be equivalent an circuit model, while the change of the ring inductance L and the split gap capacitance C can shift the resonance frequency ($\omega \propto \frac{1}{\sqrt{LC}}$). When the ELC resonator is excited by an external field, the inductive element do not couple to the magnetic field that two antiparallel currents are driven. The metallic part of the resonator which is responsible for determining electric permittivity is modeled as a lossy gold with an electric conductivity $\sigma_{\text{gold}} = 4.09 \times 10^7$ S/m. The top view of the MM absorber shows the dimensions: $b = 43$ μm , $c = 14$ μm, $d = 3$ μm, $g = 4$ μm. The thickness of

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the metallic part and the polyimide dielectric layer is about 0.2 μm and 7.1 μm. The polyimide with dielectric constant $\varepsilon = 2.9$ and loss tangent $\tan(\delta) = 0.02$ was used as the isolation spacer layer between two metallic layers in the simulation. Photoconductive silicon (red part) is put in the center of the gold ELC resonator. The permittivity of photoconductive silicon is simulated with ε_{si} = 11.7. We note that the conductivity of silicon σ_{si} is pump-power dependent. By incorporating photoconductive silicon into the MM absorber, a tunable resonance absorption mode switching is achievable. We performed computer simulations of the MM absorber using the commercial finite difference time domain (FDTD) solver Microwave Studio by CST 2010, in which the perfectly electric conducting (on the *xz*-plane) and perfectly magnetic conducting (on the *yz*-plane) boundaries are applied for a single unit cell. In the simulation, the conductivity of silicon σ_{si} is assumed to be 1 S/m without illumination.

3. Results and discussion

When optical radiation is incident on the silicon as shown in Fig. 1(b), an excess carrier density is generated as long as the energy of light exceed the band gap energy of the semiconductor. The photo-induced carriers can be considered as an electron–hole plasma, it is possible to change the conductivity of the silicon σ_{si} using an external pump beam. The density of the photo-generated carriers can be taken to be proportional to the fluence of incident photons.

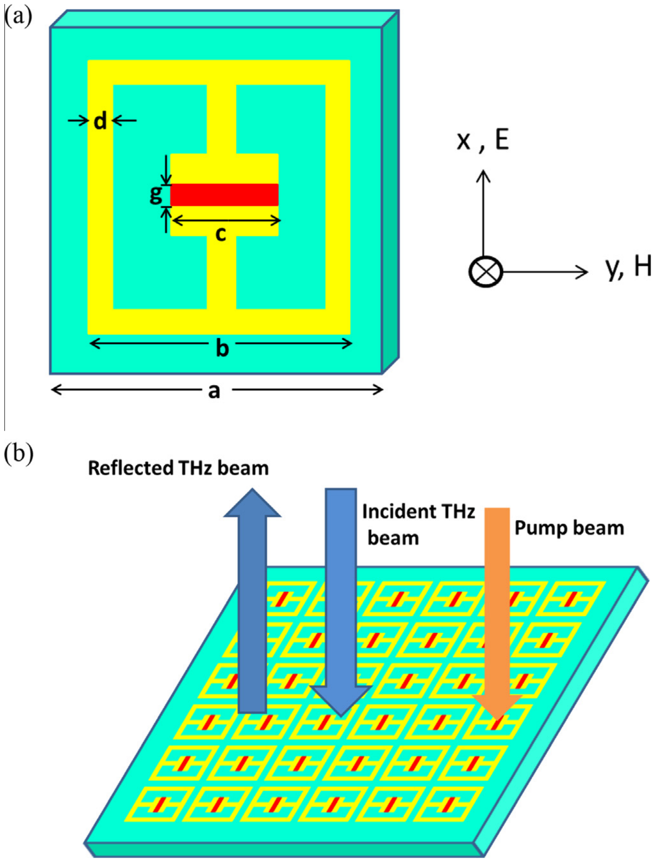

Fig. 1. (a) The unit cell of the MM absorber structure. The yellow regions are gold, the red region is photosensitive semiconductor silicon, and the light green region is the dielectric polyimide. The axes indicate the polarization and propagation direction of the incident THz wave (E, H and K represent electric field, magnetic field, and wave vector, respectively). (b) Perspective of a planar array. The pump power and THz wave are incident normally on the planar array. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

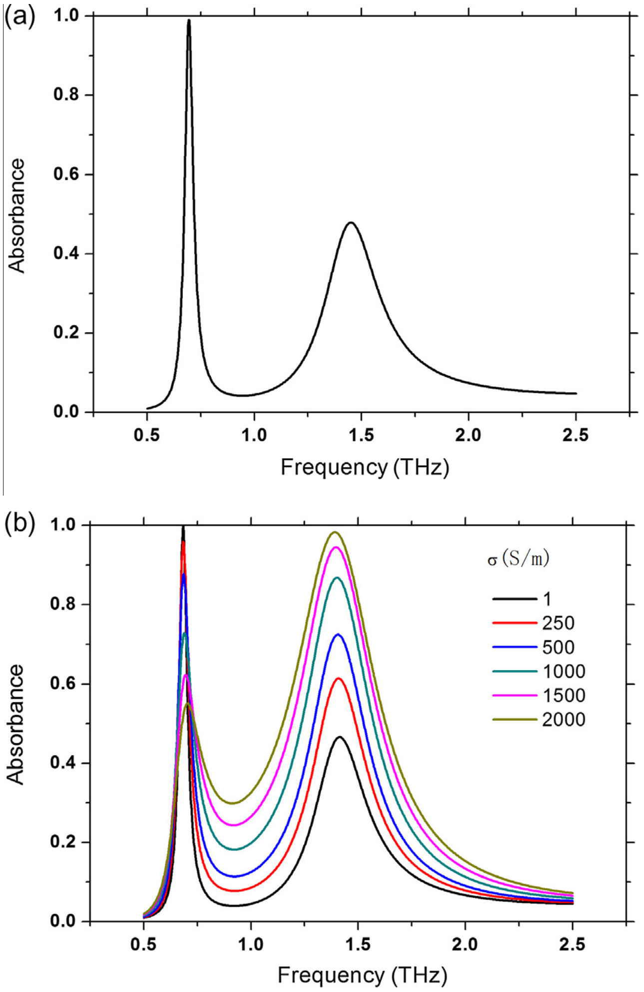

Fig. 2. Simulated absorptive spectrum of the MM absorber (a) without illumination (b) for different values of silicon conductivity.

The simulated absorptive spectrum and the calculated surface current densities in the top resonator structure and the lower ground plane for the 0.68 and 1.41 THz resonances are displayed in Figs. 2 and 3. Fig. 2(a) shows that without illumination, there are two absorptive peaks that occur at 0.68 THz and 1.41 THz, respectively. The first peak has a strong absorption, with the absorption rates of 99.9%. For the 0.68 THz resonance absorption, it is generated by the *LC* resonance of the MM absorber. To better understand the nature of this absorption, the surface current distributions at resonance are simulated and depicted in Fig. 3(a). When the incident light with electric field E is first reflected and transmitted at the air-spacer interface with SRR resonator array, it excites an effective surface current. The transmitted light continues to propagate and is reflected by the ground plane which excites a surface current at the ground plane. Electrons in neighboring SRR resonator move in phase and generate overall a dipole contribution to permittivity, while electrons move in anti-phase between the SRR resonator and ground plane generate magnetodipole responses. The principle of the absorber for 0.68 THz is that the top structure to couple the incident electric field and the magnetic couple between the top SRR resonator and ground plane. The resonance is determined by the electrical and magnetic response.

As the conductivity of silicon increases, the first resonance absorptive strength will weaken; however, with the photoconduc-