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Photo-excited terahertz switch based on composite metamaterial structure

Guocui Wang, Jianna Zhang, Bo Zhang*, Ting He, Yanan He, Jingling Shen*

Beijing Key Laboratory for Terahertz Spectroscopy and Imaging, Key Laboratory of Terahertz Optoelectronics, Ministry of Education, Department of Physics, Capital Normal University, Beijing 100048, China

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ABSTRACT

A photo-excited terahertz switch based on a composite metamaterial structure was designed by integration of photoconductive silicon into the gaps of split-ring resonators. The conductivity of the silicon that was used to fill the gaps in the split-ring resonators was tuned dynamically as a function of the incident pump power using laser excitation, leading to a change in the composite metamaterial structure's properties. We studied the transmission characteristics of the composite metamaterial structure for various silicon conductivities, and the results indicated that this type of composite metamaterial structure could be used as a resonance frequency tunable terahertz metamaterial switch. We also designed other structures by filling different gaps with silicon, and proved that these structures could be used as terahertz metamaterial switches can change the working mode from a single frequency to multiple frequencies.

1. Introduction

Metamaterials are artificial subwavelength periodic structures that can achieve certain exotic electromagnetic properties that are not found in nature, including a negative refractive index [1,2], electromagnetically based invisibility cloaking properties [3,4], and perfect absorber properties [5,6]. In recent years, multiple metamaterial structures have been designed and investigated, and the results have shown that they have broad application prospects, including absorbers, modulators, and filters [7–12]. Because most of these metamaterial structures were metallic resonant structures, their electromagnetic properties were determined by the size and the permittivity of the individual split ring. When the size or the permittivity of the individual split ring is fixed, the resonance frequency and the absorption intensity of the material cannot be tuned.

In contrast, the tunable composite metamaterials controlled by external stimulus including photo-excitation [13–15], electrics bias [16–19], temperature [20–22], are increasingly attracting attention for use in the terahertz field, as they are capable of dynamic and active manipulation of terahertz wave. In particular, the tunable composite structure of metamaterial incorporated with photoconductive semiconductors, which has advantage of ultrafast response, is a promising candidate to be used as switch, and the resonance frequency and intensity is modulated by an external pump laser [23,24]. Recently, some tunable metamaterial terahertz switches based on a split-ring resonator (SRR) embedded with photoconductive silicon have been investigated [25–27]. For example, Shen et al. demonstrated an optically implemented absorption modulation and redshift switch of metamaterial absorber at terahertz frequencies [25], Shen et al. designed a broadband blueshift tunable metamaterials and dual-band switches, then they also presented an improved device based on a photo-induced mode-switching effect [26,27]. However, the number of functional devices, especially available switches for use in the terahertz band is relatively small, and tunable metamaterial modulators, switches and absorbers in particular are highly desirable for use in the development of THz technology. Therefore, it is necessary to design actively controlled composite metamaterial structures to produce better device performance levels.

In this work, we have designed a tunable composite metamaterial structure with a photoconductive silicon incorporated into the gaps of the SRRs to achieve a better performance tunable terahertz metamaterial switch with photo-excitation. Compared to previous reports [26,27], we designed a composite metamaterial structure and achieved a broadband tunable terahertz switch of the resonant peak frequency shift greater than 1 THz. We also designed other new structures by filling different gaps with the

* Corresponding authors.
E-mail addresses: bzhang@cnu.edu.cn (B. Zhang), sjl-phy@cnu.edu.cn (J. Shen).

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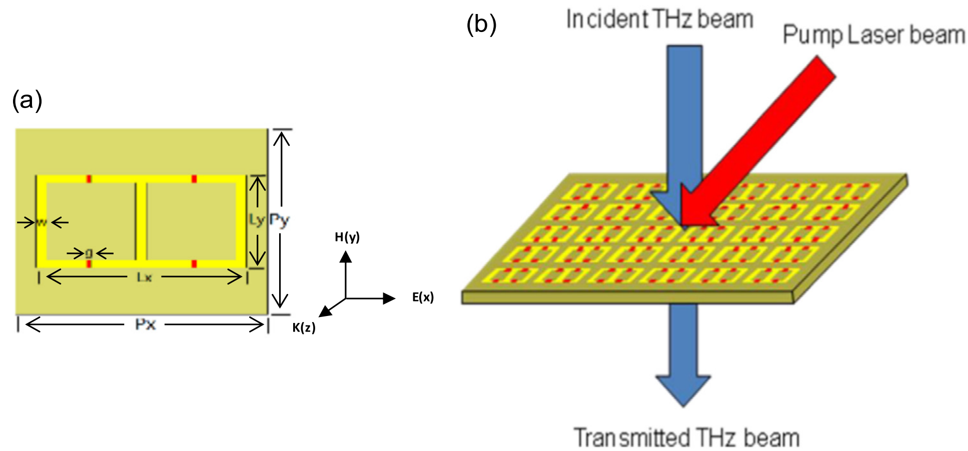

Fig. 1. (a) Unit cell of optically tunable metamaterial structure. (b) The schematic drawing of the testing configuration.

photoconductive silicon, and realized that the terahertz metamaterial switches that can change the working mode from a single frequency to multiple frequencies, which are more flexible in applications of metamaterial functional devices.

2. Sample material structure and design

A unit cell of the proposed composite metamaterial structure is shown in Fig. 1(a). A planar array of SRRs was simulated using 2-μm-thick copper on a 2-μm-thick polyimide substrate. The dimensions of an individual SRR are $w=5$ μm, $L_x=100$ μm, and $L_y=60$ μm, the gap $g=2$ μm, and the cell period $P_x=P_y=120$ μm. The silicon used to fill in the gaps of the SRRs is photoconductive semiconductor. The structure is illuminated with a normally incident THz beam whose electric field is perpendicular to the split gaps. Meanwhile an external pump laser irradiates the SRR array to generate the photo carriers in the silicon region, as shown in Fig. 1(b). Based on our previous studies, the conductivity of silicon could be varied by changing the power of the laser used to excite the material [28]. Also, if an organic polymer is spin-coated onto the silicon, the conductivity of the silicon can be greatly increased while using smaller optical powers [29–32]. Here, we fill the four gaps of the SRRs with photosensitive silicon, and when the silicon conductivity is gradually increased, the metallic properties of the silicon are then enhanced. When the optical power is very high, the silicon conductivity can reach the order of 10^5 S/m, which is close to metallic conductivity [33]. In this case, the silicon could then be treated as a metal, and the gaps of the SRRs could be considered to be closed, resulting in changes in the resonance frequency and the transmission intensity of the structure. Therefore, we can fabricate a resonance frequency tunable terahertz metamaterial switch based on the proposed composite metamaterial structure.

3. Results and discussion

We used the finite integration technique to simulate the transmission spectra of the proposed composite metamaterial structures, where the metamaterial structures are illustrated using a normally incident plane THz wave along the *z*-axis, with the electric field parallel to the *x*-axis and the magnetic field parallel to the *y*-axis, as shown in Fig. 1. The polarization of the incident THz wave is perpendicular to the split gaps. Fig. 2. shows the transmission properties of the composite metamaterial structure for the different silicon conductivities.

As shown in Fig. 2(a), a resonant dip was obtained at 2.128 THz when the silicon conductivity was 0 S/m. With increasing silicon conductivity, the transmission intensity at the dip increased and the resonant frequency gradually shifted. The resonant dip at 2.128 THz disappeared when the silicon conductivity increased to 300,000 S/m. At the same time, a new resonant dip appeared at 1.091 THz shown as the black line in Fig. 2(a). The resonance frequency varied from 2.128 to 1.091 THz when the silicon conductivity increased from 0 to 300,000 S/m, as shown in Fig. 2(b). In addition, the transmission spectrum of the structure was changed dynamically with increasing silicon conductivity. As shown in Fig. 2(c), the change in the transmission intensity could be considered as a dynamic switching action at 2.128 THz or 1.091 THz. The simulation results above showed that we can achieve a resonance frequency tunable terahertz metamaterial switch based on the proposed composite metamaterial structure, and that we can actively control both the resonant frequency and the transmission intensity of the switch using an external laser.

The metallic properties of silicon are enhanced as its conductivity increases. When the silicon conductivity reached 3×10^5 S/m, the gap was closed, leading to a change in the electromagnetic properties of the structure. Based on this fact, we also designed other types of frequency switches by using the silicon to fill different gaps in the structure, and simulated the transmission spectra of these new structures for various silicon conductivities, as shown in Fig. 3.

When silicon was used to fill in the diagonal gaps of the SRRs, a strong resonant dip was achieved at 2.146 THz when the silicon conductivity was 0 S/m, which is equivalent to that with no silicon filling. With increasing silicon conductivity, the gaps in the SRRs were short-circuited, resulting in a decrease in the resonant dip. When the conductivity increased to 300,000 S/m, the resonant dip disappeared at 2.146 THz, and two new dips appeared at 0.418 THz and 1.685 THz. Similarly, we used silicon to fill in gaps on the same side of the SRRs and obtained a