Optics Communications 412 (2018) 37–40

Contents lists available at ScienceDirect

Optics Communications

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

Photo-excited multi-frequency terahertz switch based on a composite metamaterial structure

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A R T I C L E I N F O

Keywords:
Terahertz
Metamaterials
Photo-excited
Multi-frequency switch

A B S T R A C T

We propose a photo-excited tunable multi-frequency metamaterial (MM) switch that can be used in the terahertz region. This metamaterial switch is composed of a polyimide substrate and a hybrid metal–semiconductor square split-ring resonator (SRR) with two gaps, with various semiconductors placed in critical regions of the metallic resonator. By changing the incident pump power, we were able to tune the conductivity of the diverse semiconductors filling the gaps of the SRR, and by using an external exciting beam, we were able to modulate the resonant absorption properties of the composite metamaterial structure. We demonstrated the tunable multi-frequency metamaterial switch by irradiating the composite metamaterial structure with a pump laser. In addition, we proposed a tunable metamaterial switch based on a circular metallic split-ring resonator.

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1. Introduction

Terahertz (THz) electromagnetic radiation, which lies between the microwave and far-infrared regions, has attracted more and more attention due to its potential for use in communications, imaging, biology, medicine, and safety applications [1,2]. Electromagnetic metamaterials are constructed subwavelength-period structures, and they have been researched widely for use as terahertz functional devices, including filters, perfect absorbers, polarization converters, modulators, and switches [3–18]. For example, Cong et al. demonstrated a split-ring resonator whose resonance strength depended on the resistance of its silicon gaps [19]. By reducing the gap resistance by adjusting its geometry, the required photoconductivity and thus pump power can be substantially reduced without deteriorating the resonance tuning effect. However, once the structure is made and the gaps of the split ring are filled with semiconductor, the position of the resonant dip is fixed. Thus, it is urgent to produce a photo-excited resonator operating in multiple frequencies.

In this work, we propose a photo-excited tunable multi-frequency metamaterial switch that can be used in the terahertz region. Our metamaterial switch is composed of a polyimide substrate and a hybrid metal–semiconductor square split-ring resonator (SRR) with two gaps. The conductivity of the diverse semiconductors filling the gaps of the SRR can be tuned by changing the incident pump power, and the resonant absorption properties of the composite metamaterial can be modulated by exciting it with a laser beam. We demonstrate the tunable multi-frequency metamaterial switch by irradiating its structure with a pump laser. In addition, we propose a tunable metamaterial switch based on a circular metallic SRR.

2. Material structure and design

Fig. 1 shows a unit cell of the proposed composite metamaterial structure, composed of a polyimide substrate and a hybrid metal–semiconductor square split ring with two gaps [17]. As shown in the front view, the metamaterial switch has the following dimensions: $p_x = p_y = 140$ μm, $l = 100$ μm, $w = 10$ μm, and $g = 4$ μm. The metallic rings are made from Al with a conductivity of $\sigma_{Al} = 4 \times 10^7$ S/m, and the substrate is made from polyimide with a conductivity of $\sigma = 0.0898$ S/m. The Al layer has a thickness t_1 of 0.5 μm, while the polyimide layer has a thickness t_2 of 2 μm and a dielectric constant of $\varepsilon_{spacer} = 3.5$. The silicon and germanium filling the split gaps were simulated using the parameters $\varepsilon_{Si} = 11.7$ and $\varepsilon_{Ge} = 16.3$.

3. Results and discussion

Fig. 2 shows the simulated transmission spectra for structures with various conductivities of silicon and germanium, corresponding to different pump powers. Transmission is achieved at 1.425 THz, where

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https://doi.org/10.1016/j.optcom.2017.11.080
Received 3 November 2017; Accepted 28 November 2017
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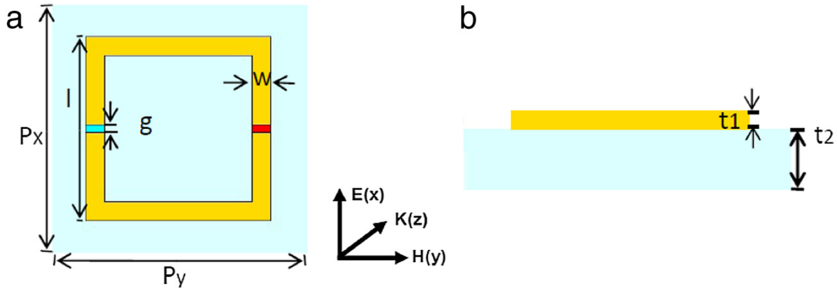

Fig. 1. (a) Unit cell of the metamaterial switch. (b) Cross-section of the proposed metamaterial switch.

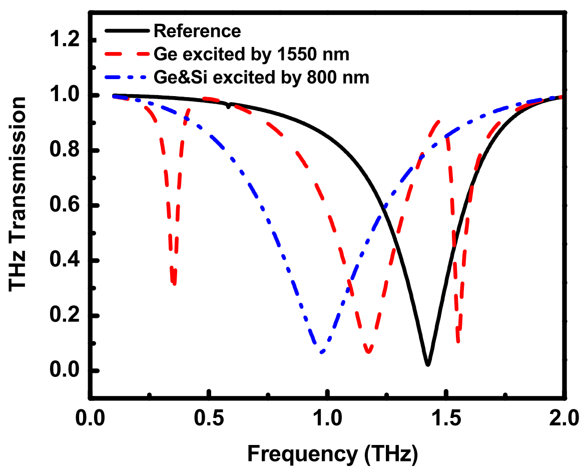

Fig. 2. Transmission spectra of the composite metamaterial structure at various conductivities of silicon and germanium.

$\sigma_{Si} = \sigma_{Ge} = 0$ S/m. The germanium is excited by a laser beam with a wavelength of 1560 nm. The conductivity of the germanium is tuned by changing the incident pump power, which modulates the frequency of the resonant dip. The germanium and silicon are excited simultaneously by a laser beam with a wavelength of 800 nm. The conductivity of silicon and germanium changing in consistency was supposed. A resonant dip occurs at 0.975 THz, where silicon and germanium have the same conductivity of $1{\times}10^4$ S/m.

As shown in Fig. 3(a), a resonant dip appears at 1.425 THz, where silicon and germanium have the same conductivity of 0 S/m. Silicon seems have equal conductivity to germanium when irradiating the structure with a laser beam at 800 nm. As the matched conductivity of germanium and silicon increases, the transmission intensity at the dip decreases and the resonant frequency gradually disappears. The resonant dip appears at 0.975 THz when the matched conductivity of silicon and germanium increases to 20,000 S/m, as shown in Fig. 3(b) [16]. The resonance frequency varies from 1.425 to 0.975 THz as the matched conductivity of silicon and germanium increases from 0 to 200,000 S/m. As the matched conductivity of silicon and germanium increases, the change of transmission intensity could be considered a dynamic switching action at 1.425 THz or 0.975 THz, as shown in Fig. 3(c). Fig. 3(d) shows the simulated transmission spectra of the composite metamaterial structure for various germanium conductivities. As the conductivity of germanium increases, the resonance frequency shifts from 1.425 to 1.1725 THz, and the change in transmission intensity could be considered a dynamic switching action at 1.425 THz or 1.1725 THz. These results demonstrate that we produced a photo-excited tunable metamaterial multi-frequency switch.

To further understand the resonance absorption mechanism, we simulated the electric and magnetic field distributions of the structure at various resonant frequencies, as shown in Fig. 4. As shown in Fig. 4(a) and (d), the ring is split with gaps and four disconnected currents are distributed around the ring perimeter when $\sigma_{Si} = \sigma_{Ge} = 0$ S/m. Thus, those four dipole resonances produce the absorption at 1.425 THz. When $\sigma_{Ge} = 1 \times 10^4$ S/m, $\sigma_{Si} = 0$ S/m, the ring is split with a gap and three disconnected currents appear, so the resonance at 1.1725 THz is induced by the coupling of these three dipole resonances, as shown in Fig. 4(b) and (e). When $\sigma_{Si} = \sigma_{Ge} = 1 \times 10^4$ S/m, the ring becomes a closed loop, so the resonant frequencies at 0.975 THz are caused by dipole resonance along the two sides of the ring parallel to the electric field [18,20–24].

4. Other structures

The above multi-frequency switch can also be applied by building a circular metallic SRR whose gaps are filled with silicon, germanium, and indium oxide (In_2O_3). Fig. 5(a) shows a unit cell of this proposed composite metamaterial structure, whose dimensions are $p_x = p_y =$ 140 μm, R = 45 μm, w = 5 μm, and g = 4 μm. The conductivity of the metal, and the thickness and dielectric constant of the dielectric, are the same as those of the square-ring structure. Fig. 5(b) shows transmission spectra for structures with various conductivities of silicon, germanium, and In_2O_3, where the materials are excited by lasers with various wavelengths of 1560 nm, 800 nm, and 355 nm. The cyan line in Fig. 5(b) shows the transmission spectra when the structure is irradiated by a laser beam with a wavelength of 355 nm; the silicon, germanium, and In_2O_3 are excited and have an equal conductivity of 1×10^4 S/m. Fig. 5(c) shows transmission spectra of the composite metamaterial structure for various equal conductivities of silicon and germanium. The conductivity changes by changing the power of the exciting laser beam, whose wavelength is 800 nm. As the conductivity of germanium increases, the resonance frequency shifts from 1.73 THz to 1.33 THz. Fig. 5(d) shows transmission spectra of the structure for various conductivities of silicon, germanium, and In_2O_3. As the conductivity of germanium and silicon increase, the resonance frequency shifts from 1.73 to 1.035 THz. Clearly, by irradiating the structure with a laser beam at various pump powers, we demonstrate a photo-excited tunable multi-frequency metamaterial switch.

5. Conclusions

We have demonstrated a photo-excited tunable multi-frequency terahertz switch based on a composite metamaterial structure. We were able to tune the resonance frequency and transmission intensity of the resonant dip by varying the conductivity of the gap materials. Our results show that we produced a photo-excited tunable multi-frequency terahertz switch, as we were able to change the conductivity of the various semiconductors filling the gaps of the composite metamaterial and we were able to irradiate the structure with a laser with varying wavelength and power.

Acknowledgment

This research was supported by the National Natural Science Foundation of China (Grant No. 61505125) and the National Instrumentation

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