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Optically controllable terahertz modulator based on electromagnetically-induced-transparency-like effect

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ABSTRACT

An optically controllable terahertz wave modulator based on the electromagnetically induced transparency-like effect (EIT-like) of the metamaterial structures is proposed and demonstrated. A modulation depth of 63% was measured at 0.33 THz in our study. The modulation action arises from the destructive interference between the resonators composed of high-resistivity silicon and gold resonators. Utilizing terahertz time domain spectrometer (THz-TDS), we show that the transmission properties of the structures can be tuned by an externally applied pump beam. By comparing the modulation depth with and without the structures producing EIT-like behavior, and the bare silicon's modulation depth, it is found that the modulation performance can be significantly improved with employment of EIT effect. Our study provides an alternative route to facilitate potential applications in terahertz range.

1. Introduction

Over the past several decades, the terahertz (THz) technology has attracted tremendous attentions worldwide for various exotic and extraordinary electromagnetic properties of the THz radiation and transmission. THz ray was found to hold great potentials in diverse domains of application, including security, chemistry, medical sensing, imaging and communications [1–5].

In the process of developing THz technology, one of the greatest challenges in THz technology is how to precisely control and manipulate terahertz waves. Therefore, there has been an increasing demand for functional terahertz components in practical applications [6], such as filters, absorbers, sensors and modulators, etc. In particular, modulators are essential for THz imaging systems and high-speed communication with THz rays [7–9]. Previous studies in the area of active modulators have shown various modulation schemes to control the properties of electromagnetic waves, including by applying an external electrical field [10,11], or an optical pump [12–14] to the modulator, or via thermal heating [15,16]. In particular, optical tuning of modulator has attracted growing interest in the terahertz regime due to its ultrafast modulation speed and on-to-off switching capability [12–14]. However, how to increase the modulation depth is one of the hot spots in this field.

Recently, the electromagnetically induced transparency (EIT) behaviors in the metamaterial have been employed to design terahertz functional devices [17]. EIT is an appealing phenomenon in atomic physics, which results from the destructive interference between two different excitation paths and gives rise to a sharp transparency window in spectrum [18–21] with a variety of applications [19,20]. Such transparency window is very sensitive to the environment. This kind of property can be adopted to optimize electromagnetic wave (from microwave to infrared light) modulator, especially for its modulation depth. Many attempts to mimic EIT (or EIT-like) behaviors in terahertz range have been reported [17–19]. The metamaterial is a type of novel artificial and periodical structures, possessing of fascinating electromagnetic properties absented in natural material, such as negative refractive index [22,23], invisible cloaking [24–27], perfect lens [28], etc. Nevertheless, so far the EIT-like properties in metamaterial only can be controlled by varying geometric variables of the metamaterial and the excitation conditions [17,29]. In 2012, a novel method for active THz modulation has been first reported by Gu et al., who demonstrated active control of terahertz waves in classical EIT metamaterials at room temperature through active tuning of the dark mode by integrating photoactive silicon (Si) islands into functional unit cells [30]. At the same time, the optical control of the group delay in the EIT metamaterial was observed in the experiment. But only the silicon islands can be modulated under pump power excitation, additional, the complex fabrication process and low modulation performance limit the development. Miyamaru further demonstrated control over the group delay of

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narrow-band THz pulses with constant amplitude based on optical switching of a metasurface characteristic [31]. But, those studies indicate that the THz modulation methods utilizing EIT metamaterial have limitations in fulfilling high modulation performance and process simplicity together. A convenient and effective way of employing the EIT metamaterial to achieve modulation and fabrication process simplicity for cost reduction should be more widely explored.

Different from the previous works [11,12], we presented an optically controllable terahertz wave modulator based on EIT-like effect using metamaterial structures in our experiments. When a high-resistivity silicon wafer is excited by external pump beam with photon energy higher than its band-gap energy, the conductivity of silicon wafer is increased with the photon-generated carriers. Then, the transmittance of THz wave, which is inversely proportional to the conductivity of substrate material, is decreased by the increased conductivity of silicon wafer [32]. Hence it is possible to modulate the transmission of THz wave by changing the power of the external pump beam. For those metamaterial structures with EIT-like effect are more sensitive to the changing of the conductivity of their substrate material. Therefore, we tried to optimize our modulator by introducing such sensitive metamaterial structures into our device design. And the surface of the device is illuminated by the pump beam, the EIT phenomenon always exists. Additionally, we measured and calculated the modulation depths of bare silicon and without employment of EIT effect. Further, by comparing the modulation depths of the three cases, we have found that the modulation performance can be significantly improved with employment of EIT effect with specially designed structures with EIT-like effect. Experimental result reveals we obtain a modulation depth about 63% at 0.33 THz for our modulator, comparing to modulation depth of ~30% without EIT-like effect.

2. Structure and fabrication

The experiment samples studied in the work were fabricated on a 500-μm-thick high-resistivity silicon substrate. Followed by conventional photolithography techniques, like that for terahertz antenna [33], a 50-nm-thick titanium adhesion layer and a 200-nm-thick gold layer were deposited by magnetron sputtering coating, and a lift-off process was conducted, then the sample device was obtained, as shown in Fig. 1(c). The geometry dimensions of the device unit are as follows: $l1=205$ μm, $l2=195$ μm, $l3=143$ μm, $l4=18$ μm, $g1=40$ μm, $g2=22$ μm, $g3=20$ μm, $d=6$ μm, the lattice constant is 205 μm and linewidth is 8 μm (as shown in Fig. 1(a) and (b)). The device sample is comprised of top and bottom resonators and middle resonator (as shown in Fig. 1 (a)).

3. Simulation and experiment

For the device, the EIT-like effect can be realized by coupling a bright mode with a dark mode, where the bright mode is intensely coupled to the incident electromagnetic field, while the dark mode is not directly coupled to the field [28,29–34]. In order to clarify the coupling frequencies, firstly, we utilized the CST Microwave Studio® based on the finite element method to simulate the bright mode and the dark mode, respectively, as illustrated from Fig. 2 (a) to (d). The substrate silicon was modeled as a lossless dielectric $\varepsilon=11.9$ and Au was simulated with a conductivity of $\sigma=4.56\times10^{7}$ S/m. In Fig. 2(a), when the incident wave is polarized along the x axis, the top and the bottom resonators exhibit a typical dipole localized surface plasmons (DLSPs) [35] resonance at 0.29 THz, while the middle resonators display an inductive-capacitive (LC) resonance at the same frequency when the E polarization parallels to the y axis, like in Fig. 2(c). LC resonance mode arise from electric currents oscillating around the full circumference of the split ring resonator (SRR) loop [34], and the position of the anticipated LC resonance frequency can usually be described via a simple expression, $\omega_L = 1/\sqrt{LC}$, where L means effective inductance while C means effective capacitance of individual SRR [34]. However, the middle resonators would also show a dipolar resonance within the E polarization along the x axis, and the resonance frequency would be at 0.7 THz, as shown in Fig. 2(b). When two parts are combined into a completed presented device, as shown in Fig. 1, the incident wave is polarized along the x axis, the interaction between these two parts leads to the formation of two new modes (two dips in the spectrum) and thus opens up a sharp transparency window around 0.33 THz, as illustrated in Fig. 2(d). Since the top and bottom resonators are strongly coupled to the incident electromagnetic field, whereas the middle resonators need to be excited by the near-field excitation of the top and bottom resonators, namely, they cannot directly couple to the incident field. Thus, the top resonator and the bottom resonator generate a bright mode while the middle resonators generate a dark mode.

The above-mentioned simulated data from Fig. 2(a) to (d) are supported by the experimental results via our THz-TDS. The valid range of our THz-TDS [36] is from 0.2 THz to 2.2 THz. The amplitude transmittance of sample $\left|\tilde{t}(\omega)\right| = \left|\tilde{E}_S(\omega)\right| / \left|\tilde{E}_r(\omega)\right|$ was measured under normal incidence with the E polarization along the x

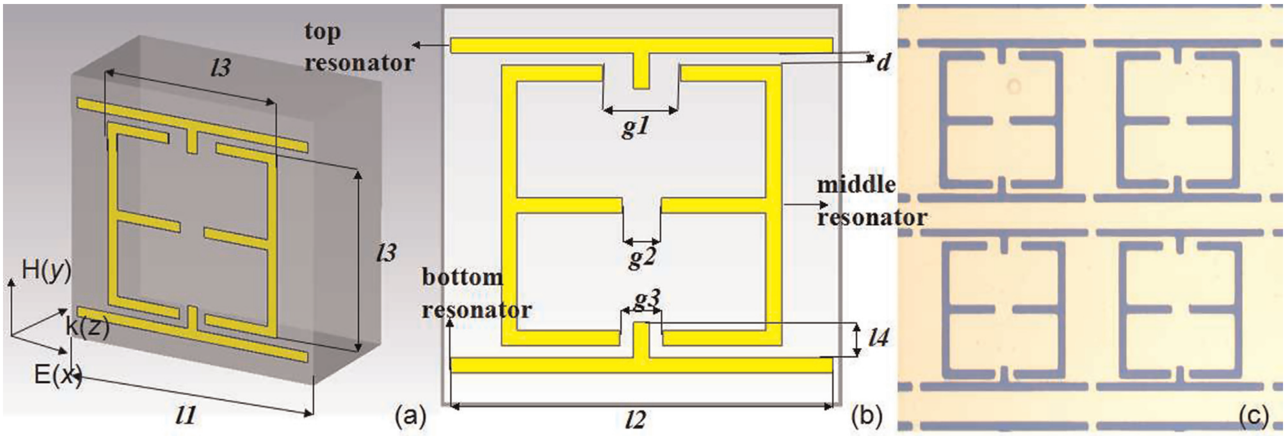

Fig. 1. (a) and (b) depict the schematic of the presented metamaterial structures, (c) is the microscope image of the metamaterial.