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# Influence of structural symmetry on resonant property and optical sensitivity in terahertz metamaterials

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## ABSTRACT

By utilizing optical pump terahertz probe spectroscopy we have investigated four samples with terahertz subwavelength structures, which derived from split ring resonators. The experimental results show that adding the same length bar in the middle of the symmetric samples has less influence on resonant properties. However, asymmetric samples could present coupling and splitting effect in transmission spectra. Additionally, compared with the symmetric structures the asymmetry structures are more sensitive to pump excitation. Under pump excitation for different resonant mechanisms, we find the LC resonance has higher sensitivity than dipole resonance to the pump excitation. Our obtained results indicate that the photogenerated carriers in the substrate play a very important role in optical modulation properties.

## 1. Introduction

In recent years, metamaterial attracts much attention because of its novel properties, such as negative refractive index [1,2], subdiffraction imaging [3], and electromagnetic cloaking [4,5]. Split ring resonators (SRRs) are the basic building block for many metamaterials [6,7]. Terahertz metamaterial is such kind of man-made material with subwavelength structural array. Researchers have shown that the higher sensitivity of an asymmetric structure has been probed before in a passive scheme. Singh et al. [8] studied the asymmetric structure to achieve ultra-sensitive refractive index label-free sensors. Yang et al. [9] modulated the fundamental inductive–capacitive resonance in asymmetric double-split ring terahertz metamaterials. For practical applications, terahertz metamaterials can be used as modulators and filters [10–15]. The modulation could be achieved by changing the property of substrate and metallic structure under external perturbation, such as thermal, optical and electric excitations. Chen et al. [16,17] reported the response of metamaterials to external optical excitation on the substrate. They also studied the modulation properties of the metamaterial under the bias voltage. Singh et al. [18] reported thermally active substrate of a bulk single-crystal strontium titanate ($SrTiO_3$) allows switching of LC resonance (LC resonance is consisting of inductance L from metallic arm and capacitance C from gap, resulting in a circular transient current in SRR). Furthermore, many researchers investigated the response to changes of the unit cell under external stimulation. For instance, Gu et al. [19] studied active control of terahertz waves in metamaterials by integrating photoactive silicon islands into functional unit cells. Chowdhury et al. [20] demonstrated reconfigurable terahertz metamaterial in which constituent resonators can be switched from SRRs to closed-ring resonators via optical excitation of silicon islands strategically placed in the split gap. Based on the same method, they realized ultrafast switching of dark LC resonance [21] and controlled the LC resonance actively on a scale of 16–20 ps [22]. Cao et al. [23] demonstrated that a thermally active superconductor–metal coupled resonator based hybrid terahertz metamaterial could show the tuning of the coupling between LC and the dipole resonance.

In our work, we designed a series of metamaterials that are based on SRRs and obtained some unexpected results, which are confirmed by the simulation of the surface current [24,25]. Besides the metamaterial resonance properties can be controlled by the geometry and dimension of the metamaterial, the substrate as part of the sample can enable the dynamical control [26]. For better understanding of the intrinsic mechanism of this process, we utilized the optical excitation on the substrate to investigate the influence of structural symmetry on resonant property and optical sensitivity in terahertz metamaterials. We find the asymmetry samples are more sensitive to pump excitation compared with the symmetric. And LC resonance has higher sensitivity to optical excitation than dipole resonance.

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## 2. Experimental results and discussions

The planar array of metamaterial based on SRR is made up of gold with the thickness of 0.2 μm. The gold is fabricated on a 670 μm thick high resistivity gallium arsenide (GaAs) using the photolithography method. In our previous studies, we found when the lattice constant *p* is the subwavelength scale around 60 μm, the experimental results are within measurement capability of our terahertz time domain spectroscopy system. Therefore the lattice constant what we take is 60 μm. Each structure unit has an envelope size of 36 μm × 36 μm. Optical pump terahertz probe spectroscopy used in our experiment has a plethora of advantages to provide the ability to temporally resolve phenomena with subpicosecond resolution. The measurement is performed using a Ti:sapphire regenerative amplifier delivering ultrashort optical pulses with duration of 100 fs and a central wavelength of 800 nm at a repetition rate of 1 kHz. The output of the laser is divided by beam splitters into three portions (terahertz generation, terahertz probe, and optical pump). The generation pulse is incident on a $\beta$-$BaB_2O_4$ crystal to generate the terahertz pulse [26]. The transmitted terahertz signal is detected by free-space electro-optic sampling in a 1 mm-thick ⟨110⟩ ZnTe crystal with a probe pulse [27]. The terahertz beam from generation to detection is in nitrogen in order to prevent absorption of water vapor. The experiment is carried out in room temperature, and we can get both one-dimensional and two-dimensional pump probe schemes [28]. The pump beam energy is about 66 μJ/cm$^2$.

Firstly, we simplify the SRR and make the gap open to a U-shape, as shown in Fig. 1(a). In our measurement, the terahertz electric field is parallel to the bottom bar. In one-dimensional scan, we fix the probe time delay at the peak of the terahertz pulse, and scan the optical pump delay to obtain the dynamics of carriers, as shown in the inset of Fig. 1(b). We can find the value of $|\Delta T(t)/T_0|_{\max}$ is about 0.075, where $\Delta T(t) = T(t) - T_0$, $T(t)$ is the time-dependent transmission of terahertz peak value with pump, and $T_0$ is the terahertz peak transmission without pump. $|\Delta T(t)/T_0|_{\max}$ indicate the maximum pump-injected carrier density, corresponding to the time when terahertz wave encounters with pump pulse. It can be seen that if terahertz signal is ahead of pump pulse, the pump pulse has no effect on terahertz signal. However, as the pump delay time increases, the terahertz signal and pump pulse encounter to induce the significant decrease of transmitted signal because of the photo-generated carriers in the GaAs. As pump delay time further increases, the curve is gradually to the initial state due to the process of carrier recombination. To further study the optical modulation, we present the transmission spectra at different pump delay times, as shown in Fig. 1(b). If the sample has not been excited by the pump, we find that there are two dips around 0.65 THz and 1.5 THz. The simulated surface currents show that the low frequency originates from LC resonance, and the high frequency is dipole resonance, as shown in Fig. 1(c). However when the pump delay time is ~133 ps, the curve shows a smooth trend almost without dips, indicating the moment that lots of photo-generated carriers are in the substrate. As the pump delay time reaches ~666.7 ps, the curve is gradually to the initial state because of part of the carrier recombination. With further recombination of the photo-generated carriers (~813 ps), all transmission dips almost tend to recover. Furthermore, we find the LC resonance has a bigger effect compared to dipole resonance. The reason is that LC resonance is greatly related to the gap in golden structure on the top of the substrate and conductivity of photoexcited layer in the substrate [28], but dipole resonance comes from the impact of structure. In our previous studies [25], we found that under high photogenerated carrier density, the simulated circular transient current of LC resonance in the SRR is no longer obvious, indicating that a large part of the current flows into the photoexctied layer in the substrate. When the recombination time is long, circular transient current emerges again. But for the dipole resonance, the transient current mainly flows along the terahertz field in two arms. Therefore the LC resonance is more sensitive to the pump excitation.

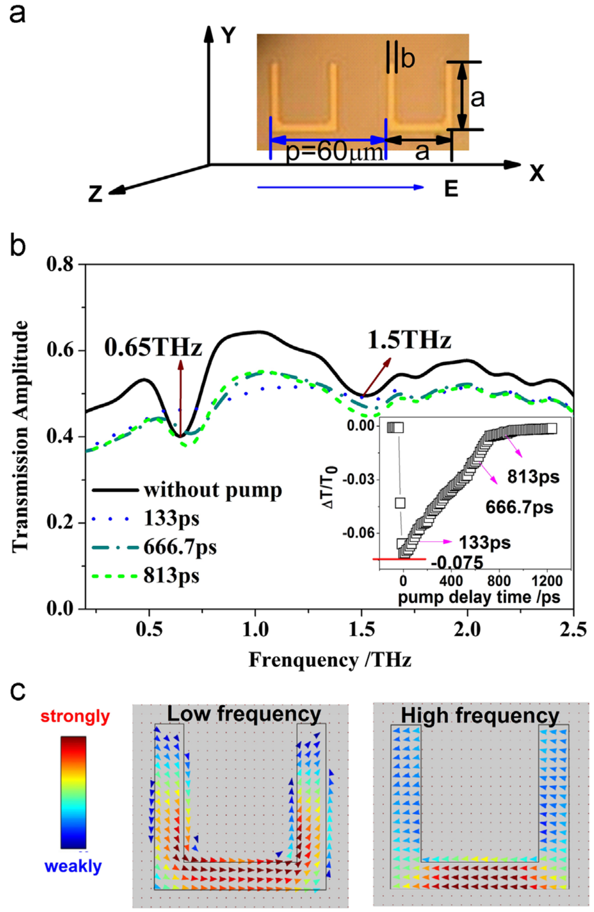

**Fig. 1.** (a) Optical photo and the parameters of U-shaped structure, $a = 36$ μm, $b = 6$ μm and $p = 60$ μm, (b) the transmission spectra of U-shape at different pump delay times when terahertz electric vector is along bottom bar. Inset is the relative changes in the transmission of the terahertz peak value, $\Delta T(t)/T_0$, obtained by a one-dimensional scan scheme, (c) current distributions for low frequency and high frequency resonances.

Then we added the same length bar in the middle of the symmetric U-shape, as shown in Fig. 2(a). We think there are two possible results. The first one is that the low frequency is much deeper because of superposition of two LC resonances which can modulate the depth. The second one is that the distance of each two bars becomes small, so the resonance may show a shift in frequency. In order to verify our assumption, we give the transmission spectra, as shown in Fig. 2(b).

To our surprise, we did not observe our expected phenomena. The dips' locations around 0.65 THz and 1.5 THz are the same as those in U-shape. In order to find the reason we have simulated the surface current. The simulated results indicate the middle bar does not work in such structure, as shown in Fig. 2(c). Through the comparison of the two samples, we could conclude that the design of such kind of samples needs to avoid the same length in the middle, which will lead to the invalid design. Furthermore, under pump excitation, it is easy to find that the value of $|\Delta T(t)/T_0|_{\max}$ is about 0.09, as shown in the inset of Fig. 2(b) bigger than that in the inset of Fig. 1(b). When the pump delay time is ~133 ps, the optical beam also quenches the resonances. And when the pump delay times are ~666.7 ps and 813 ps, the curves are gradually to