# Transient optical modulation properties in the terahertz metamaterial of split ring resonators*

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The ultrafast optical modulation properties of split ring resonators are characterized by utilizing optical pump–terahertz probe spectroscopy. The experimental results show that when the terahertz electric vector is perpendicular to the gap of the split ring resonator, resonant absorption can be quenched significantly under high pump excitation. However, when the terahertz electric vector is parallel to the gap, the resonant absorption is less sensitive to pump excitation due to the structural properties of the metamaterial. Our numerical simulations also demonstrate that the pump pulse significantly influences the split ring resonator current by generating carriers in the substrate.

**Keywords:** terahertz, carrier dynamics, ultrafast spectra

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## 1. Introduction

Terahertz spectra contain rich physical information about the materials.[1−4] The investigations of metamaterials have demonstrated a variety of novel phenomena, such as subdiffraction-limited imaging[5] and electromagnetic cloaking.[6] In recent years, terahertz metamaterials have attracted much attention due to their unique electromagnetic responses and potential applications in many fields.[7−11] Considerable advances have led to the development of various metamaterial components to control the terahertz radiation properties. The spectral responses of split ring resonators (SRRs), which are the basic building blocks for many metamaterials,[12,13] usually show resonant features with the details depending strongly on their structural geometries and constituent materials.[14] In our previous study, we theoretically investigated the resonant absorptions of SRRs with different structures and obtained some interesting results.[15] Moreover, the active control of their properties can further facilitate and open up new applications in terms of modulation and switching. It is therefore important to know the response of metamaterials to external perturbation and understand the underlying physical mechanism.[16−18]

Here we report on the spectral and dynamic behaviors of optical modulation in a terahertz metamaterial with the SRR structure at high pump power using optical pump–terahertz probe (OPTP) spectroscopy. We observe that the modulation strengths of the resonance absorptions are different when the terahertz electric vector is pointing in different directions (perpendicular or parallel to the gap), showing that the structure-related resonance is less sensitive to pump excitation. The calculated surface currents using finite-difference time-domain (FDTD) simulation are presented to characterize the optical modulation of the resonance absorption when the terahertz electric vector is parallel to the gap.

## 2. Experimental results and analysis

A planar array of SRRs is fabricated with 1.6 μm thick gold on a 670 μm thick high resistivity gallium arsenide (GaAs) substrate. An individual SRR has

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an envelope size of 37 μm × 37 μm ($a = 37$ μm ) with a $b = 6$ μm linewidth, and the unit cell is 50 μm. The width of the gap opening on one arm of each ring is $w = 4$ μm. The measurement is performed using a Ti:sapphire regenerative amplifier delivering ultrashort optical pulses with a duration of 100 fs each 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, optical probe, and optical pump). The generation pulse is incident on a 2 mm-thick (110) ZnTe crystal to generate the terahertz pulse via optical rectification.[19] In our experiment, the terahertz wave is normally incident on the SRR sample plane ($X$–$Y$ plane), the wave vector $\boldsymbol{k}$ is along the $Z$ axis, and the electric vector $\boldsymbol{E}$ is in the $X$–$Y$ plane (inset in Fig. 1). The transmitted terahertz signal is detected by free-space electro-optic sampling in a 1 mm-thick ⟨110⟩ ZnTe crystal with a probe pulse.[20,21] The terahertz beam path from the transmitter to the receiver is purged by nitrogen to prevent absorption by the atmospheric humidity. The spot size is at least two times larger than that of the terahertz beam to ensure uniform pump-beam illumination. All the experiments are performed at room temperature, and the system can operate in both one- and two-dimensional pump–probe schemes.[22,23] In the one-dimensional scheme, the optical pump delay is scanned to map out the dynamics, while the probe delay line is fixed at the peak of the terahertz pulse. In the two-dimensional scheme, we typically need to obtain the terahertz waveforms by scanning the probe delay line, while the optical pump delay line is set at a fixed time delay $t$ (relative to the arrival of the terahertz pulse at the sample).

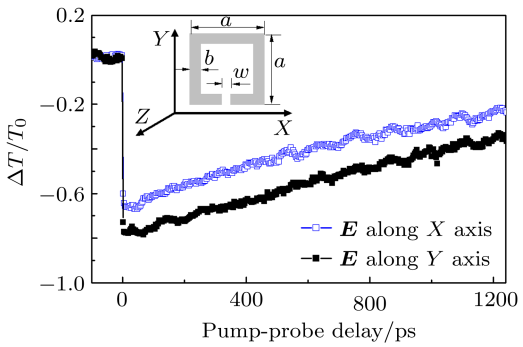



**Fig. 1.** (colour online) Relative changes in the transmission of the terahertz peak value, $\Delta T(t)/T_0$, obtained in a one-dimensional scan scheme when electric vector $\boldsymbol{E}$ is along the $X$ axis ($\boldsymbol{E}$ is perpendicular to the gap) and $Y$ axis ($\boldsymbol{E}$ is parallel to the gap), respectively. The pump power is 14 mW.

The relative change in the transmission of the terahertz peak value, $\Delta T(t)/T_0$, is monitored as a function of the pump time delay under 800 nm photoexcitation, as shown in Fig. 1, where $\Delta T(t) = T(t) - T_0$, with $T(t)$ being the time-dependent transmission of the terahertz peak value with the pump, and $T_0$ the terahertz peak transmission without the pump. Here, we present the measured results when electric vector $\boldsymbol{E}$ is along the $X$ direction ($\boldsymbol{E}$ is perpendicular to the gap) and $Y$ axis ($\boldsymbol{E}$ is parallel to the gap), respectively. If the terahertz signal is ahead of the pump pulse, i.e., the delay time is negative, then the optical pump beam has no effect on the terahertz signal, resulting in zero value in $\Delta T(t)/T_0$. When the terahertz pulse encounters the pump pulse, $\Delta T(t)/T_0$ changes remarkably due to the photogenerated carriers in the GaAs substrate. As the pump delay time further increases, the curves show recovery as a result of carrier recombination. Furthermore, it is obvious that when $\boldsymbol{E}$ is along the $X$ axis, the $\Delta T(t)/T_0$ is smaller than that of $\boldsymbol{E}$ along the $Y$ axis, suggesting different optical pump effects on the characteristic absorptions in these two directions.

By rotating the sample, we also measure the angle-dependent terahertz peak value, as shown in Fig. 2. Even without pump excitation, the curve of the terahertz peak value still shows a change in cosine function, indicating different electromagnetic properties at different angles. If the sample is excited by setting the pump time delay at 0 ps, the terahertz amplitude decreases dramatically and shows the same change feature with the rotating angle.

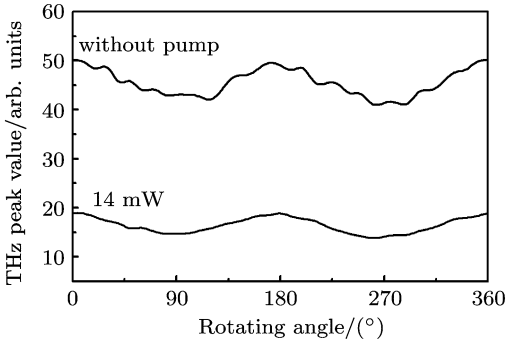



**Fig. 2.** Angle-dependences of terahertz peak value with and without pump power. The pump delay time is set at 0 ps, corresponding to the time when lots of carriers are photo-generated in the substrate.

In order to further investigate the optical modulation in the SRRs, we give the evolution of the transmission spectrum with the pump delay time, as shown

in Fig. 3. It is clear that when $\boldsymbol{E}$ is along the $X$ axis without the pump, two transmission minima are located at ∼0.57 THz ($EX1$ resonance) and ∼1.55 THz ($EX2$ resonance), respectively, in Fig. 3(a). When $\boldsymbol{E}$ is along the $Y$ axis without the pump, the resonant absorption of $EY$ is located at ∼1.37 THz, as shown in Fig. 3(b). Under a pump power of 14 mW, there is no characteristic absorption in the $X$ direction even when the pump delay time is at the order of a nanosecond. However, with a long delay time, the characteristic absorption has a recovery trend in the $Y$ direction. This suggests that the modulation in the $X$ direction is more sensitive to the pump power and is suitable for low power modulation, whereas in the $Y$ direction, an optical modulation with a larger range of pump power can be obtained. In order to see this evolution clearly, we also present the transmission spectra for different pump delay times, with $\boldsymbol{E}$ being along the $X$ axis and the $Y$ axis, respectively, as shown in Figs. 3(c) and 3(d). We find that when the pump delay time is 0 ps, $EX$ and $EY$ resonances all disappear, and similar frequency-dependent curves present, indicating that the substrate absorption, not the influence of SRRs, dominates the characteristics of the sample. At a long delay time of 1200 ps, with the recovery of the resonance absorption in the SRRs, the spectrum in the $Y$ direction also shows a slight blue shift in frequency.

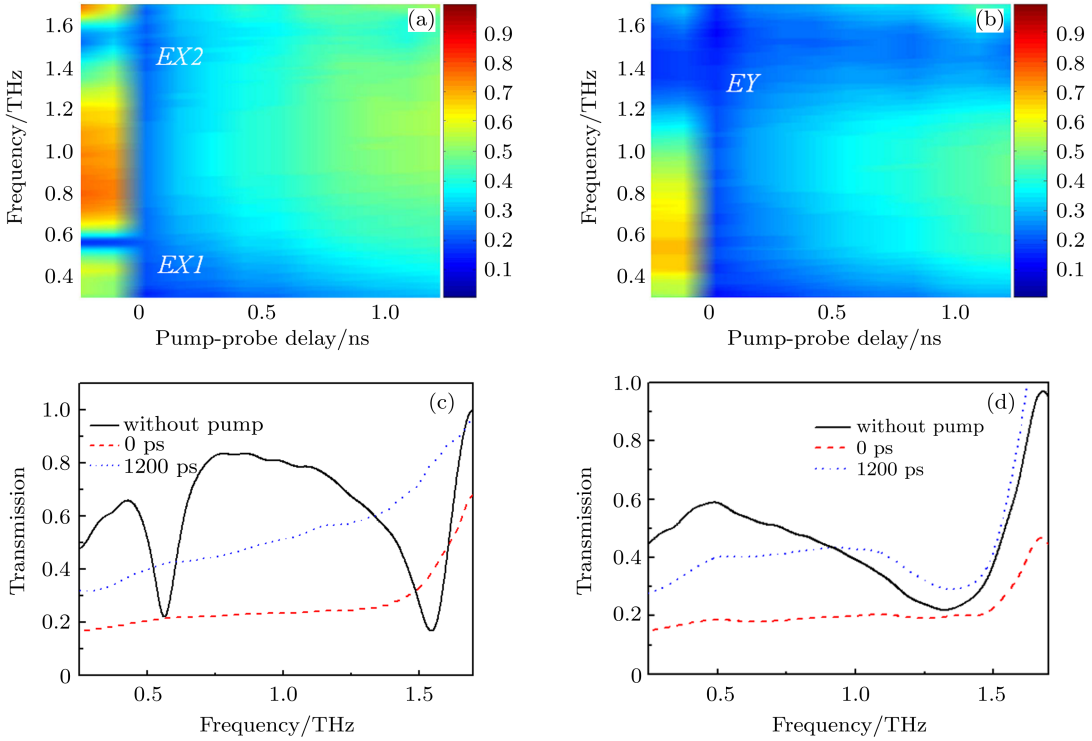



**Fig. 3.** (colour online) Evolutions of the transmission spectra with pump delay time when $\boldsymbol{E}$ is along (a) the $X$ axis and (b) the $Y$ axis. Panels (c) and (d) show the transmission spectra at three different pump delay times when $\boldsymbol{E}$ is along the $X$ axis and the $Y$ axis, respectively.

## 3. Theoretical simulation and discussion

It is known that the $EX1$ resonance results from the circular transient current induced by the incident terahertz field, and it is sensitive to the gap of the SRR. When the pump beam irradiates the sample, the photogenerated carriers will have a great influence on the transient current in the vicinity of the gap. With a high carrier density generated in the substrate, the gap will be short-circuited, leading to less and even quenched resonant absorption of the SRR. On the other hand, the $EX2$ and $EY$ resonances are related to the side length of the SRR,[10] so the optical pump has a small influence on them. However, a comparison between the above experimental results shown in Figs. 3(c) and 3(d) at 1200 ps shows that $EX2$ is more difficult to recover than $EY$, because the structure in the $X$ direction has one arm with a gap, which is sensitive to the optical pump, while the structure in

the $Y$ direction has no gap. We discussed the the $EX$ resonances in our previous studies under a low pump power. Here, we only plot the calculated surface currents of the $EY$ resonance in the SRRs at different pump delay times, as shown in Fig. 4. For the $EY$ resonance, the surface current flows mainly along two arms of the $Y$ axis. With the high photogenerated carrier density ($\sim$ 0 ps), the circular transient current of the $EY$ resonance in the SRRs is more obvious than that in the case without the pump, indicating that part of the current coming from the photogenerated carriers in the substrate flows through the SRRs. When the recombination time is long ($\sim$ 1200 ps), the circular transient current recovers again.

As carriers are created under photoexcitation within the substrate (1 μm depth at 800 nm for the GaAs substrate),[22] the refractive index is expected to change as well as the increased conductivity. In our simulation, we find that the blue shift of the resonant absorption frequency in our experiment is probably dominated by the effect of the decreased refractive index in the substrate due to the photoexcitation-induced dynamic response of the GaAs substrate beneath the SRRs. In fact, this response is not so simple. The photoexcited GaAs substrate and its Au-deposited SRRs interact strongly with each other. More investigations are needed to fully understand the underlying physical mechanism of the terahertz metamaterials.

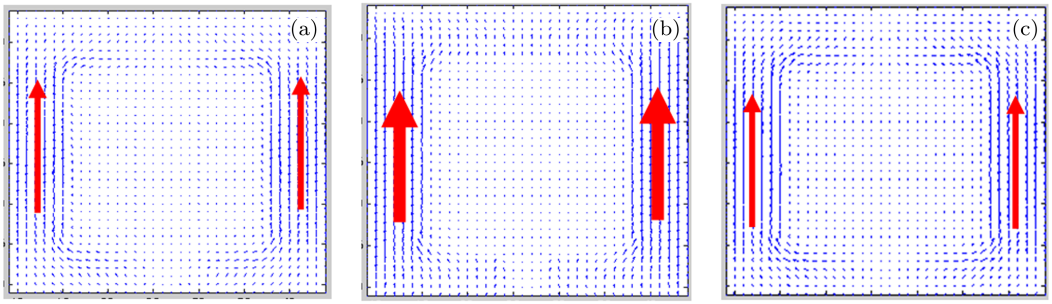



**Fig. 4.** (colour online) Surface current densities in the SRR obtained in the FDTD simulation for the $EY$ resonance under zero pump (a), and with a pump delay time of (b) 0 ps and (c) 1200 ps.

## 4. Conclusion

In this paper, we demonstrate optical pump-induced modulation dynamics in a terahertz metamaterial. It is shown that the photo-excited metamaterial exhibits angle-dependent characteristics. Furthermore, the $EX$ resonant absorptions can be quenched significantly under pump excitation, while the $EY$ resonant absorption shows less sensitivity to the pump excitation due to its structural properties. Our studies indicate that the modulation is governed by the properties of the photoexcited substrate, in which the photogenerated carriers play an important role in the characteristics of the photo-excited terahertz metamaterials.

## References

[1] Wang G Q, Wang J G, Tong C J, Li X Z and Wang X F 2011 *Acta Phys. Sin.* **60** 030702 (in Chinese)

[2] Guo Z, Fan F, Bai J J, Niu C and Chang S J 2011 *Acta Phys. Sin.* **60** 074218 (in Chinese)

[3] Hu H F, Cai L K, Bai W L, Zhang J, Wang L N and Song G F 2011 *Acta Phys. Sin.* **60** 014220 (in Chinese)

[4] Yang Y P, Feng H, Pan X C, Wang Y Q and Wang W Z 2011 *Acta Phys. Sin.* **60** 027802 (in Chinese)

[5] Fang N, Lee H, Sun C and Zhang X 2005 *Science* **308** 534

[6] Pendry J B, Schurig D and Smith D R 2006 *Science* **312** 1780

[7] Padilla W J, Aronsson M T, Highstrete C, Lee M, Taylor A J and Averitt R D 2007 *Phys. Rev.* B **75** 041102

[8] Linden S, Enkrich C, Wegener M, Zhou J F, Koschny T and Soukoulis C M 2004 *Science* **306** 1351

[9] Ferguson B and Zhang X C 2002 *Nat. Mater.* **1** 26

[10] Padilla W J, Taylor A J, Highstrete C, Lee M and Averitt R D 2006 *Phys. Rev. Lett.* **96** 107401

[11] Schurig D, Mock J J and Smith D R 2006 *Appl. Phys. Lett.* **88** 041109

[12] Shelby R A, Smith D R and Schultz S 2001 *Science* **292** 77

[13] Yen T J, Padilla W J, Fang N, Vier D C, Smith D R, Pendry J B, Basov D N and Zhang X 2004 *Science* **303** 1494

[14] Moser H O, Casse B D F, Wilhelmi O and Saw B T 2005 *Phys. Rev. Lett.* **94** 063901

[15] Li L, Zhou Q L, Shi Y L, Zhao D M, Zhang C L, Zhao K, Tian L, Zhao H, Bao R M and Zhao S Q 2011 *Acta. Phys. Sin.* **60** 019503 (in Chinese)

[16] Chen H T, Padilla W J, Cich M J, Azad A K, Averitt R D and Taylor A J 2009 *Nature Photon.* **3** 148

[17] Paul O, Imhof C, Lägel B, Wolff S, Heinrich J, Höfling S, Forchel A, Zengerle R, Beigang R and Rahm M 2009 *Opt. Express* **17** 819

[18] Manceau J M, Shen N H, Kafesaki M, Soukoulis C M and Tzortzakis S 2010 *Appl. Phys. Lett.* **96** 021111

[19] Rice A, Jin Y, Ma X F, Zhang X C, Bliss D, Larkin J and Alexander M 1994 *Appl. Phys. Lett.* **64** 1324

[20] Wu Q, Litz M and Zhang X C 1996 *Appl. Phys. Lett.* **68** 2924

[21] Pearce J, Jian Z and Mittleman D M 2008 *Opt. Lett.* **29** 2926

[22] Zhou Q L, Shi Y, Jin B and Zhang C 2008 *Appl. Phys. Lett.* **93** 102103

[23] Beard M C, Turner G M and Schmuttenmaer C A 2000 *Phys. Rev.* B **62** 15764