Terahertz wave polarization rotation in bianisotropic metamaterials*

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Utilizing a polarization sensitive terahertz detection method where the detector is rotated by either 0° or 90° to measure the electric field $\boldsymbol{E}_{\rm p,s}(t)$ of each polarization component, we have characterized the properties of split ring resonators. The strong polarization dependence of the bianisotropic-circular-current-driven and linear-polarization-induced resonances is in excellent agreement with the simulation when the p-polarized terahertz transmission is measured. However, these electromagnetic responses vanish when the s-polarized terahertz transmission is measured. There is only a transmission minimum at 1.64 THz and the terahertz polarization rotation angle of about 90° is observed. The polarized terahertz transmission amplitudes and spectra detected at orthogonal orientations show that these behaviours are probably attributed to the birefringent effect of the sample.

Keywords: terahertz, metamaterials, birefringent effect, bianisotropic effect

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1. Introduction

Metamaterials with subwavelength structural features show unique electromagnetic responses and have stimulated extensive efforts to elucidate their unusual experimental phenomena and to develop potential optoelectronic or plasmonic devices. Split ring resonators (SRRs) are the basic building blocks for many metamaterials.[1−9] The spectral response of SRR arrays usually shows resonant features with details strongly depending on their structural geometry and constituent materials.[10,11] Recently, research of these metamaterials has been pushing forward to the terahertz region because of the potential applications in biological fingerprinting, security imaging, remote sensing and high-frequency magnetic or electric resonant devices in the terahertz region.[11−15] In particular, few natural materials can exhibit a magnetic response in the terahertz region, but the induced current by the terahertz wave in SRRs can lead to an induced magnetic response. Terahertz time domain spectroscopy (TDS) measures the time-resolved electric field of terahertz pulses.[15−18] A typical characteristic of terahertz TDS is that only one polarization component of the electric field vector is measured. However, in the case of birefringent materials, the situation is more complicated and the measurement of only one polarization component is not enough to characterize their optical properties.[16,19]

In this paper, we utilized a polarization-sensitive detection method, which can measure both orthogonal components of the terahertz electric field $\boldsymbol{E}_{\rm p,s}(t)$. As the p-polarized terahertz transmission is detected, we observe a strong polarization dependence of the magnetic and electric resonances of SRRs. A finite-difference time-domain (FDTD) simulation accurately reproduces all of the significant features of the data and the calculated surface currents are presented to characterize these resonances. In contrast, as the s-polarized component is measured, these electromagnetic resonances disappear, only an abnormal terahertz transmission minimum at 1.64 THz exists and a terahertz polarization rotation up to 90° is observed.

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We propose that these phenomena are due to the birefringent response of the sample.

2. Experiment

A planar array of SRRs was fabricated with 1.6-μm-thick gold on a 670-μm-thick high resistivity gallium arsenide (GaAs) substrate (Fig. 1(a)). An individual SRR has an envelope size of 37 μm×37 μm with a 6 μm linewidth and the unit cell is 50 μm. The gap opening of each ring in one arm is 4 μm wide. A standard terahertz TDS system was used in our experiments.[19] The measurement was performed by using a Ti: sapphire regenerative amplifier delivering ultrashort optical pulses with a 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 two portions (generation and probe). The generation pulse is incident on a (110) ZnTe crystal to generate the terahertz pulse via optical rectification.[20] Figure 1(b) shows the terahertz time domain waveform. The radiated terahertz wave has almost pure p-polarization, with only a little residual s-polarized field remaining attributed to the misalignment of the parabolic mirrors. The ratio between the two orthogonal components is about 11:1. All our experiments were performed with the terahertz wave normally incident on the SRR sample plane (X–Y plane), the wave vector $\boldsymbol{k}$ is along the Z axis and the electric vector $\boldsymbol{E}$ of the predominantly p-polarized terahertz is along the X axis (insert of Fig. 1(b)). The transmitted terahertz signal is detected by free-space electro-optic sampling[21] in a 1 mm-thick ⟨110⟩ ZnTe crystal with the probe pulse. The (001) axis of the ZnTe sensor are rotated by either 0° or 90° azimuthally to measure the transmitted terahertz electric field $\boldsymbol{E}_{\mathrm{p,s}}(t)$ of each polarization component separately.[17,22] The terahertz beam path from the transmitter to the receiver is purged by nitrogen to prevent absorption by atmospheric humidity.

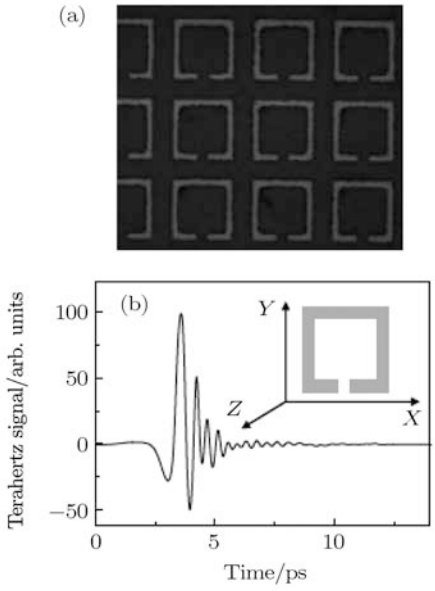


Fig. 1. (a) Photo of the SRR sample on a GaAs substrate. (b) Terahertz time domain waveform, where the insert shows the Cartesian coordinate system (X, Y, Z) chosen in our experiment with the sample located in the X–Y plane and the incident wave along the Z axis. The input p-polarized electric vector is along the X axis.

3. Results and discussion

3.1. Measurement of p-polarized terahertz transmission

Figure 2 (a) shows the evolution of transmission spectra with the angle between the gap-bearing sides of the sample and $\boldsymbol{E}$ (along X axis) varying from 0° to 90° when p-polarized terahertz transmission is measured. Two transmission minima, located at ∼0.57 and ∼1.55 THz, are observed at the angle of 0°. However, the first dip at lower frequency almost vanishes at the angle of 90°, while the one at higher frequency gradually redshifts to ∼1.37 THz. The curve in Fig. 2(b) indicates that an FDTD simulation accurately reproduces all of the significant features of the data. From a fundamental point of view, also based on an effective medium model, the response can be attributed to a bianisotropic response where the total magnetic and electric fields are coupled together in a constitutive relationship.[11,23] The first dip results from the circular transient current induced by the incident terahertz field, the second one is usually regarded as a result of electric coupling of the SRR to the terahertz field,[15] and in some literature is also explained as a diluted plasmon resonance based on the popular theory developed by Pendry *et al.*[24] In order to understand the origin of the bianisotropic behaviour, we have plotted the results of the calculated surface currents at $\omega_{\|0}$ (0.57 THz), $\omega_{\|1}$ (1.55 THz) and $\omega_{\perp}$ (1.37 THz) resonances in Figs. 2(d), 2(e) and 2(f), respectively. Figure 2 (d) shows the circulating currents produced from the incident time varying electric field, which generates a magnetic field polarized parallel to the surface normal of the SRR. The SRRs are bianisotropic, this means that the electric and magnetic responses of the SRR are coupled. The higher energy $\omega_{\|1}$ (1.55 THz) resonance is from the half-wave resonance due to the side length L = 37 μm. The

surface current is concentrated in the upper and lower arms.[15] In contrast, for the case of $\omega_{\perp}$ (1.37 THz) resonance, the current is concentrated in the left and right arms. A birefringent behaviour is also observed (see Fig. 2(c)) in the SRR sample. The refractive index at 0° is approximately 10 percent larger than that at 90°. This might result from the larger effective electron density and carrier mobility experienced by the parallel transmission.

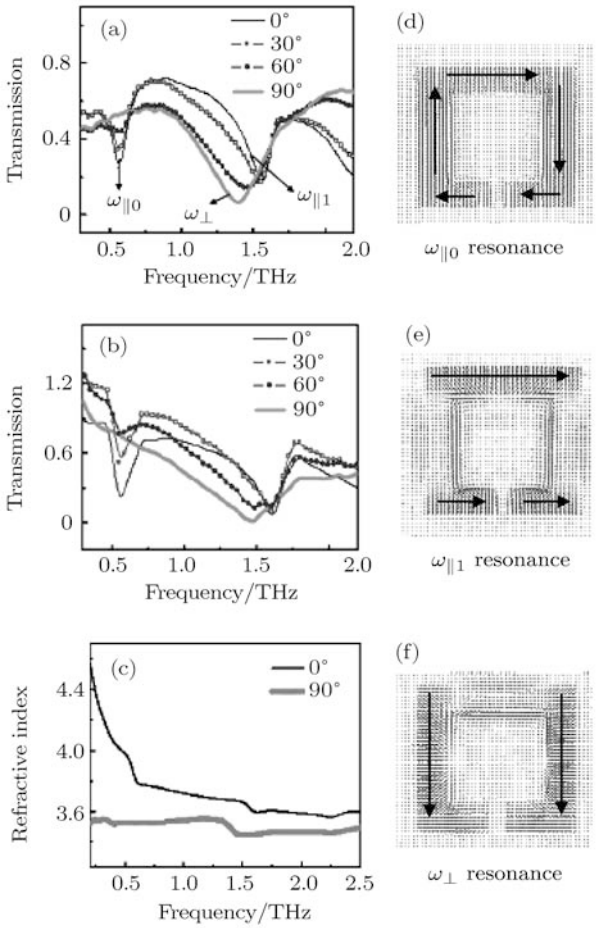


Fig. 2. (a) The frequency-dependent transmission spectra $T(\omega)$ of the SRR sample at different polarization orientations (0°, 30°, 60° and 90°). (b) An FDTD simulation of the transmission. (c) Measured refractive indices of the SRR sample at 0° and 90°. In (a) and (c), the p-polarized terahertz transmission is measured. (d), (e) and (f) are the surface current densities for the $\omega_{\parallel 0}$ (0.57 THz), $\omega_{\parallel 1}$ (1.55 THz), and $\omega_{\perp}$ (1.37 THz) resonances, respectively.

3.2. Measurement of s-polarized terahertz transmission

The azimuthal angle dependence of the transmittance (from 0° to 360° at a step of 10°) for the terahertz wave is presented in Fig. 3 and the vertical axis represents the ratio of the transmitted peak amplitude to the reference signal. In Fig. 3(a), the p-polarized component is detected and the transmittance reaches the minimum as the gap-bearing sides of SRRs are parallel to the terahertz electric field (0°, 180°). This is because that the $\omega_{\parallel 0}$ (0.57 THz) magnetic resonance absorbs the terahertz field effectively. However, when the s-polarized component is measured, there are transmittance values greater than 1, as shown in Fig. 2(b). The fact that the sample signal is bigger than the reference implies that this periodical variation of the transmittance is caused not only by material absorption, but also by the rotation of the terahertz polarization. Moreover, to our knowledge, since the curve for the p-polarized wave has a period of 180° (see Fig. 2(a)), the minima of the s-polarized wave should appear at 90° and 270°. However, it is amazing to see that the minima of the s-polarized wave are located at approximately 45° and 225° positions, a −45° translation occurs during this process.

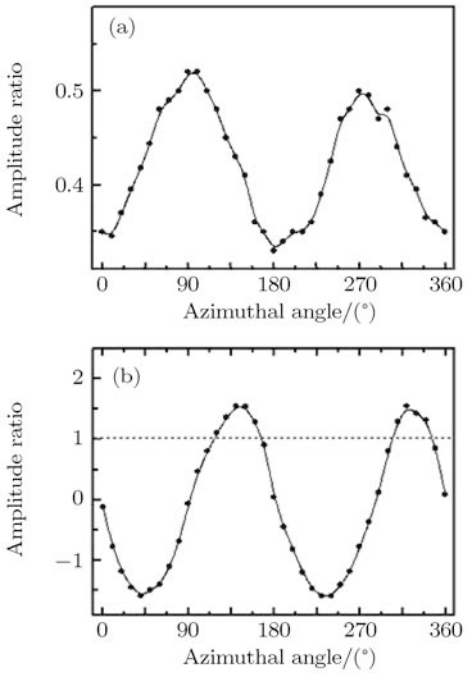


Fig. 3. Azimuthal angle dependence of terahertz transmission of the SRR sample when (a) p- and (b) s-polarized transmitted terahertz waves are detected, respectively.

Figure 4 plots the measured transmissions of the SRRs for different orientations (0°, 40°, 90°, 120°) when s-polarized terahertz transmission is measured. It is surprising to see that both the circular-current-driven and linear-polarization-induced resonances vanish. The transmission for both 0° and 90° are similar and lower than 1, and there is no significant transmission minimum. However, it is noteworthy that for 40° and 120°, transmission even reaches more than 3 and remarkable transmission minima

are shown, especially at 1.64 THz, which could be easily misidentified as a material characteristic absorption. We propose that the birefringence effect might be responsible for the observed transmission minimum.[16,18] The reason is that the SRR sample could rotate the linearly polarized terahertz wave (i.e. when 40° with respect to X axis) for certain frequencies and then the rotated terahertz wave component is fully or partially blocked.[16,18] The phase retardation between 0° and 90° of the SRR sample is also given in the insert of Fig. 4. The dashed line indicates that there is a remarkable phase change at 1.64 THz and the phase retardation is coincidentally about $\pi/2$.

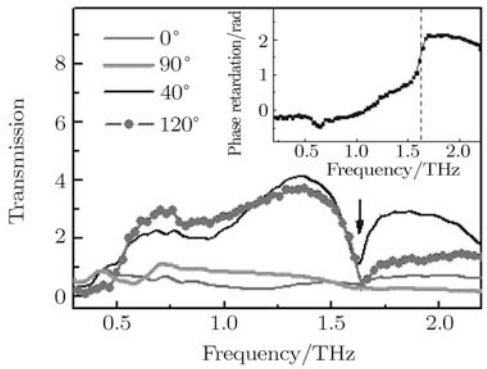


Fig. 4. Measured transmission of the SRR sample when the s-polarized component is measured. The arrow denotes the transmission minimum at 1.64 THz at 40° and 120° orientations. The insert is the difference between the measured phases of the sample at 0° and 90°, respectively, when s-polarized terahertz transmission is measured, and the dashed line indicates the phase retardation of $\pi/2$ at 1.64 THz.

The rotation angle of the terahertz polarization can be extracted from the equation below:[22]

$$\theta = \arctan\left(\frac{E_{\rm s}}{E_{\rm p}}\right), \tag{1}$$

where $E_{\rm p}$ and $E_{\rm s}$ are the p- and s-polarized components of the terahertz electric field when the SRR sample is placed at a certain orientation. The azimuthal angle dependence of the terahertz electric field rotation is shown in Fig. 5. For 0°, 90°, 180°, 270°, rotation angles are close to 0°. Once deviated from these angles, the polarization angle is rotated by almost ± 90°.

We summarize that for the s-polarized component, the terahertz electric field amplitude and spectrum are no longer governed by the magnetic and electric resonances, but by the birefriengent effect. For the parallel and perpendicular orientations of the sample, the transmitted terahertz wave maintains the same p-polarized state as the input beam and the transmission is less than 1. However, once the sample is in-plane rotated, much of the p-polarized component is rotated to the s-direction and, in this way, the sample signal is much larger than the reference. It is demonstrated that s-polarized terahertz transmission is much more sensitive to the birefringent-induced polarization rotation than the p-polarized component because of its dark background.

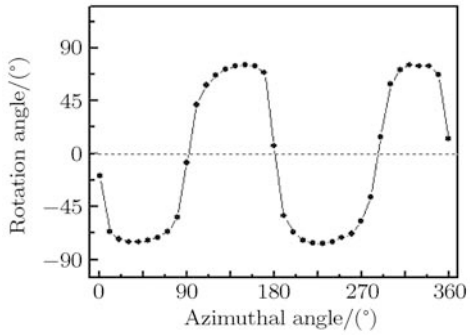


Fig. 5. Azimuthal angle dependence of the terahertz polarization rotation.

4. Conclusions

In conclusion, we have studied the bianisotropic and birefringent effects of an SRR sample by using a polarization sensitive detection method. The measurements provide direct insight into the polarization-dependent properties of the sample. Detailed knowledge of the terahertz polarization dependence of SRR metamaterials is highly relevant to the development, characterization and application of these metamaterials in the terahertz region. This method may be a useful alternative approach to elucidating the polarization properties in SRRs or other similar materials. The results indicate the possibility of controlling terahertz polarization with these artificial structures.

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