Effects of oblique incidence on terahertz responses of planar split-ring resonators*

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Effects of oblique incidence of terahertz waves on the response of planar split-ring resonators are investigated, both experimentally and by simulation. It is found that the incident angle dependent phase delay and coupling conditions of neighboring split-ring resonator (SRR) units play important roles and greatly change both the transmission and reflection spectra for the resonant feature of linear charge oscillations. Our results show that the SRR structure-supported magnetoelectric couplings at oblique excitation are trivial and can be ignored. A highly symmetric response is found in the cross-polarization effects, which may manifest the bianisotropic properties of the SRR system but this needs further study.

Keywords: terahertz, split-ring resonators, polarization

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1. Introduction

Metamaterials have been attracting more and more attention, especially between the microwave and optical frequencies,[1–4] because of their exotic electromagnetic properties, which mainly depend on artificial subwavelength geometric structures. The split-ring resonator (SRR) is the most popular building block in the design and implementation of different metamaterials.[5–8] Planar SRRs are generally characterized for normal incidence with the magnetic field in the plane of the SRRs. Under this configuration, a so-called LC resonance can be excited by an electric component, inducing transient circular currents in SRRs. Oblique incidence is another way to excite LC resonance, with magnetic components directly penetrating the SRRs.[9–12] Because of the bianisotropic property of SRRs, oblique incidence can also cause cross-polarization effects,[13–15] producing a perpendicular electric field component relative to the incident linear polarization. Although all the material constituents consisting of SRRs could be nonmagnetic, macroscopic magnetoelectric couplings exist in SRRs under electromagnetic excitation, and the effects can be attributed to induced electric dipoles in the plane of the SRRs and to magnetic dipoles normal to the SRRs' plane, which together create scattered electromagnetic waves with orthogonal polarizations.[16,17] The contribution of electric dipoles to the cross-polarization effect decreases with increasing incident angle, while that of the magnetic dipole component increases. The cross-polarization effects are highly associated with the symmetry of the geometric structures and could be studied in a frame of optical activities resulting from the extrinsic 3D chirality.[17,18] While further study, both in theory and experiment, is still needed to understand the physics in these observations, the fact that metamaterials based on SRRs can be used to manipulate the propagation of electromagnetic waves is very promising for various functional device applications.

In this paper, we report our study of the effects of oblique incidence on the resonant responses of terahertz (THz) planar SRRs with both experiment and simulation under different configurations. In contrast to normal incidence,[19] three additional effects arise from the SRRs' responses to obliquely incident linearly polarized THz waves: (i) the magnetic component in the incident field directly induces electric polarization in each SRR unit, (ii) the out of phase excitation of SRR units by an obliquely incident wave front sweeps cross the SRR array and influences the coupling efficiency between neighboring units and, (iii) the projection of incident THz field onto the SRR plane changes at different incident angles. Specifically, we checked the angle-dependent transmission properties of incident terahertz waves with the electric component parallel to the gap-bearing sides of SRRs at both p and s polarization. We also investigated the incident angle dependent cross-polarization effects with the projection of incident wave vectors parallel to the gap-bearing sides of SRRs for both p and s polarization. Our results show that the direct magnetic excitation plays only a minor role and the coupling between excited neighboring units can be very important but is also orientation dependent. The cross-polarization effects are symmetric for both p and s polarization incidence, in both transmission and reflection measurements, but show strong incident angle-dependence.

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2. Method

The SRR unit is comprised of structured gold film coating on high resistivity silicon substrate of 500 μm thickness. As shown in Fig. 1(a), the SRR cells are arranged on a square lattice with period $P = 60$ μm, the side length L is 44 μm, the width w of the metal lines is 5 μm, and the gap G in the split ring is 3 μm.

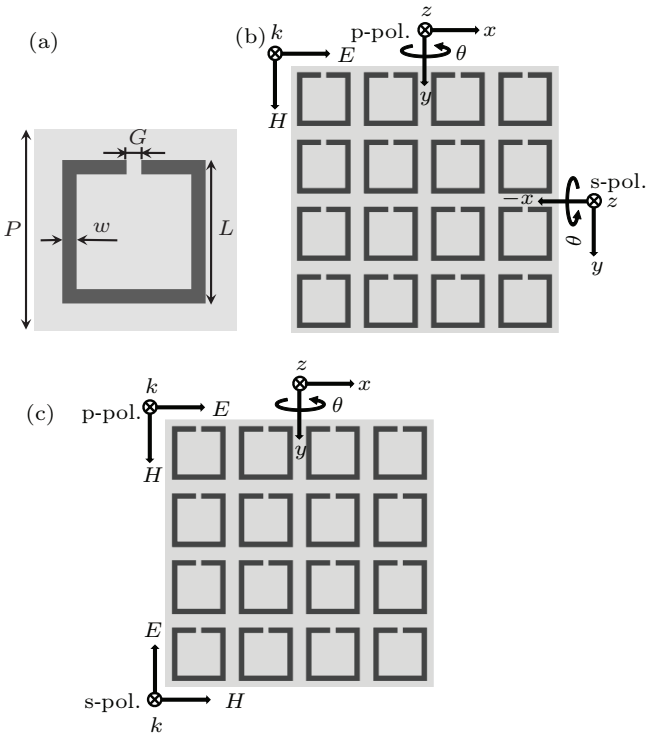


Fig. 1. (a) Unit cell of the SRR array. (b) Configurations for transmission measurements with p- and s-polarized incidence and rotation axes, respectively. (c) Arrangement for investigation of cross-polarization effects.

Terahertz time-domain spectroscopy (THz-TDS) was employed to characterize the electromagnetic response as a function of incident angle θ when the incident terahertz electric field was parallel to the gap-bearing sides of SRRs for p and s polarization, as shown in Fig. 1(b). The p or s polarization means that incident electric field lies in or is perpendicular to the incident plane, respectively. The linearly polarized terahertz wave was generated by a photoconductive antenna, and the incident polarization could be changed by rotating the antenna. Planar SRRs were put on a rotation stage to manipulate the incident angle. The transmitted terahertz electric fields in the same polarization state as the incident ones were detected, and each transmission spectrum was normalized by the transmission spectrum of the silicon substrate at the same incident angle. The experimental spectra were compared with simulation results by the split field finite difference time domain algorithm (SFM-FDTD).[20,21] In the simulation, the substrate was characterized with permittivity of 11.7, and the gold was treated as a perfect metal.

Since the simulation results were quite consistent with those of experiments, we used the SFM-FDTD to study the cross-polarization effects. As shown in Fig. 1(c), when the projections of incident wave vectors are nonzero and parallel to the gap-bearing sides of the SRRs, the polarization states of both the transmitted and reflected terahertz electric field changes and perpendicular components are produced with polarization orthogonal to the incident ones. We characterize the electromagnetic responses by transmission matrix $\boldsymbol{t}$ and reflection matrix $\boldsymbol{r}$, which is defined as follows:

$$t = \begin{pmatrix} t_{\rm pp} & t_{\rm ps} \\ t_{\rm sp} & t_{\rm ss} \end{pmatrix}, \quad r = \begin{pmatrix} r_{\rm pp} & r_{\rm ps} \\ r_{\rm sp} & r_{\rm ss} \end{pmatrix}, \tag{1}$$

$$E^{\rm t}_{\rm mn} = t_{\rm mn} E^{\rm i}_{\rm n}, \quad E^{\rm r}_{\rm mn} = r_{\rm mn} E^{\rm i}_{\rm n}, \tag{2}$$

where m and n correspond to p and/or s polarization, E denotes electric field, and the superscript i, t and r denote incidence, transmission and reflection, respectively. Diagonal elements characterize electric field components parallel to the incident ones, and nondiagonal elements characterize perpendicular electric field components.

3. Results and discussion

3.1. Effects of oblique incidence on transmission spectra

Figure 2(a) shows the experimentally measured transmission spectra normalized by the transmission of the Si substrate for p polarization, defined in Fig. 1(b), at several incident angles. Figure 2(b) is the simulation results. The experimental measurements agree very well with the simulation results. The projection of incident terahertz electric field E_x in the SRRs plane is parallel to the gap-bearing sides of the SRRs, and two resonances are observed. The LC resonance is at around 0.41 THz, and basically independent on the incident angle, while the high frequency resonance, usually attributed to the linear charge oscillations in the side arms of SRRs, red shifts from 1.22 THz to 1.16 THz when the incident angle increases from 0° to 60°, which indicates that the inter-SRR interaction is more important for resonance induced by the linear charge oscillations.[12,22] Oblique incidence causes phase delay between the excitation of SRRs along the x direction. For an incident angle of 60°, the phase difference of the induced charge oscillations at the resonant frequency 1.2 THz between the neighboring SRR unit is about 74.8°, calculated by $360P \sin\theta / \lambda_{\rm THz}$. This phase retardation effect reduces both the resonant strength and frequency, and comes from the coupling of charge oscillations between neighboring units along the x direction, which was further confirmed by measurements of the SRR array samples with the same unit size but different periods and found that this effect, due to asynchronous excitation, was smaller for larger periods. For the LC resonance at 0.41 THz, a minor reduction of the resonant strength was observed and the resonance frequency remained the same, which

indicates that the intrinsic resonant property is dominated by each SRR unit's structure rather than the array's geometry. This fact also suggests that the magnetic coupling between neighboring units is small in our planar SRR arrays.

For the excitation by the s-polarization (see Fig. 1(b)), the oblique incidence produces little influence on the transmission fields, as shown in Figs. 2(c) and 2(d), and less significant changes occur at both resonance at 0.41 and 1.2 THz. In this case, the magnetic field component of the incident fields can directly drive the LC resonance, but the electric vector is still parallel to the SRRs plane, regardless of the incident angle. Closely inspecting the resonant peak at 0.41 THz and comparing to the results of p polarization, it can be concluded that the electric response driven directly by the incident magnetic fields is quite weak and produces negligible effects. For the resonance at 1.2 THz, the excitation condition for charge oscillations along the x direction is unchanged by the incident angles, and therefore, the resonant peaks remain almost the same except for a slight blue shift in simulation data, which may come from the superposition with a resonance of higher frequency. The slight differences between the measured and simulated data are probably from the imperfections in the fine structure of our samples.

Our SFM-FDTD simulation results are very consistent with experimental measurements. Therefore, we used simulation to further investigate the cross-polarization effects.

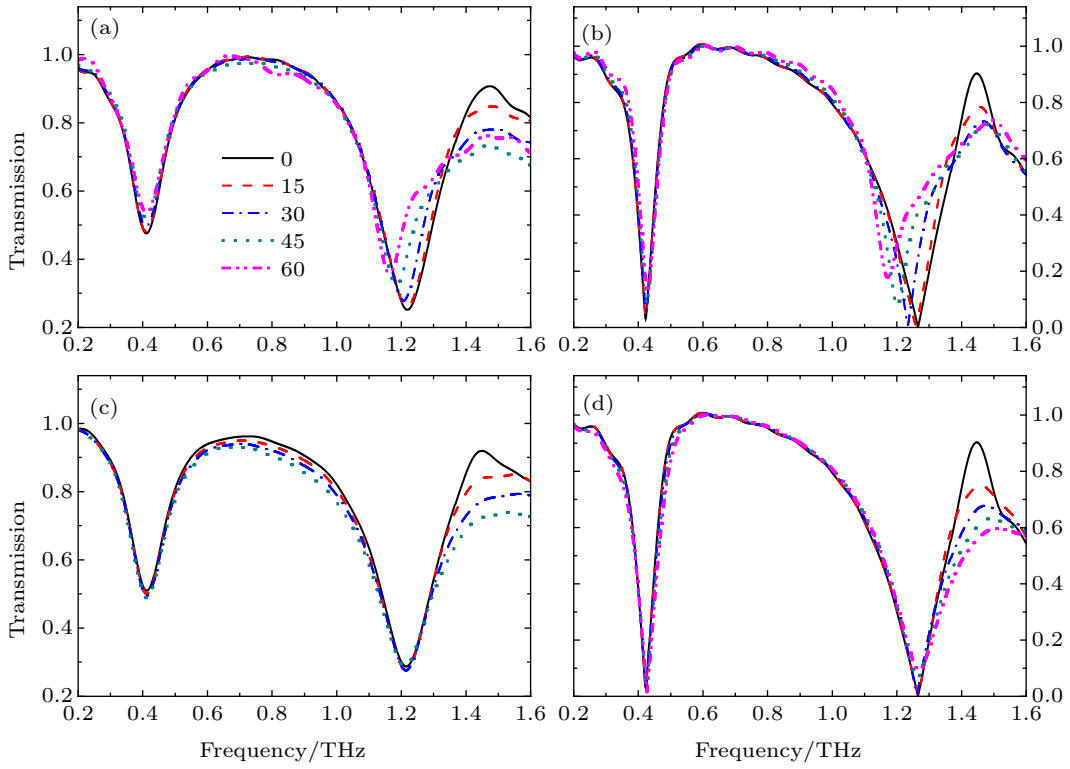


Fig. 2. (color online) Measured and simulated transmission spectra normalized by the transmission of the bare substrate for p- and s-polarized incidence at several angles. (a) Experiment results for p polarization; (b) simulation for p polarization; (c) experiment for s polarization; and (d) simulation for s polarization.

3.2. Cross-polarization effects

The measurement configuration shown in Fig. 1(c) was used to check the cross-polarization effects for p- and s-polarization incidence at oblique angles. The simulated amplitudes of the transmission and reflection matrix elements in Eq. (1) are shown in Figs. 3 and 4, respectively, at several incident angles. In these calculations, we extended the frequency range to 2.0 THz and normalized the spectra to the incident spectrum; that is, the substrate effect was included.

The data in Fig. 3(a) are virtually the same as those in Fig. 2(b) except for the different normalization conditions. Figure 3(b) shows the co-polarization transmission spectra of the s-polarization incidence at different angles. A major resonance at about 1.07 THz comes from the well known linear charge oscillation along the y direction, and its resonant frequency is not incident angle dependent, but there is a noticeable broadening due to changed couplings in the x direction. It is clear that a minimum dip at 0.41 THz gradually develops as the incident angle increases, induced by the magnetic flux from incident fields penetrating through SRRs.

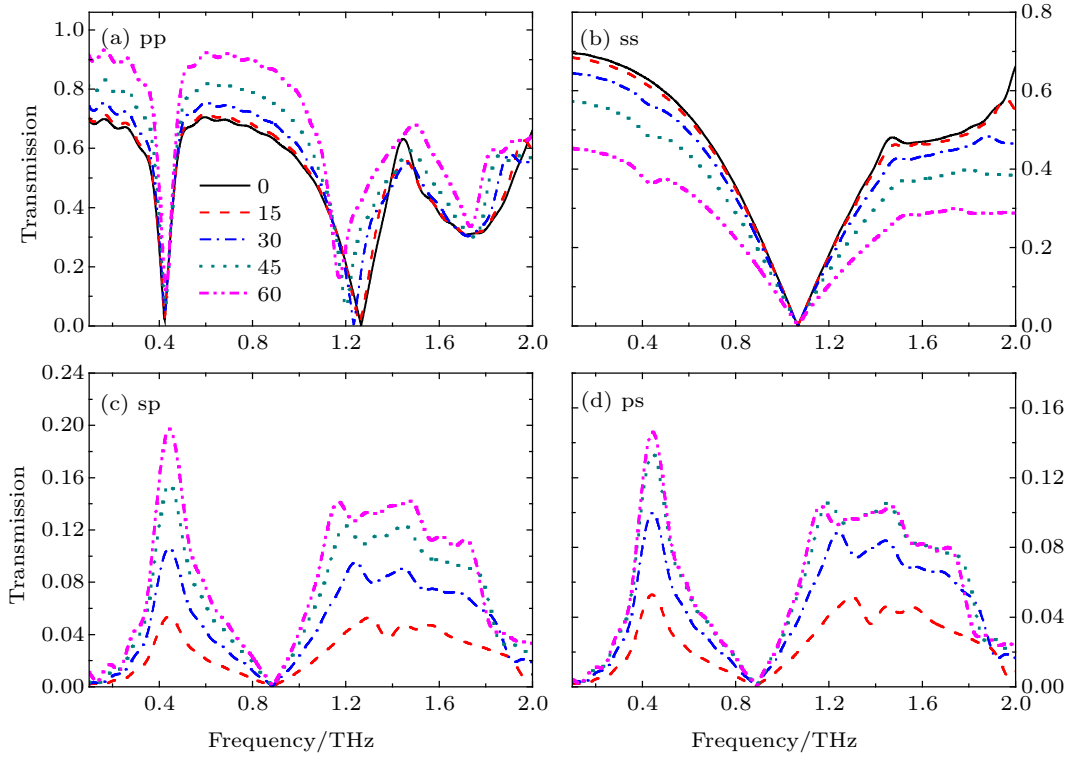


Fig. 3. (color online) Simulated amplitudes of the transmission matrix elements at several incident angles. All data are normalized by the incident spectrum.

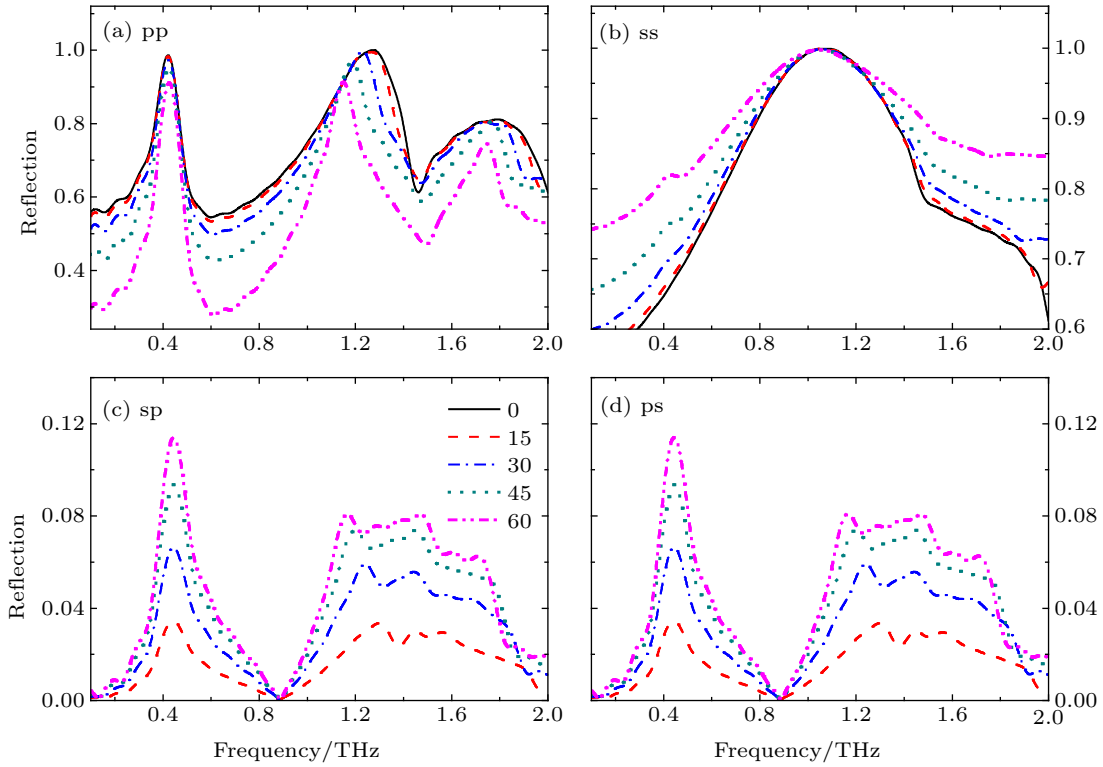


Fig. 4. (color online) Simulated amplitudes of the reflection matrix elements at several incident angles. All data are normalized by the incident spectrum.

The interesting results are the cross-polarization responses: in Fig. 3(c), the s-polarized transmission is produced by the incidence of p polarization, and in Fig. 3(d), the p-polarized transmission results from the incidence of s polarization. Both spectra are surprisingly similar except for a scalar proportional factor, although we have known that the excitation mechanisms in the two cases are quite different. For p-polarized excitation, the circular transient current excited in each SRR unit oscillating at 0.41 THz also contributes to the polarized radiation in the y direction; the antisymmetry of the

current oscillations in the side arms of the SRRs for the resonance at 1.2 THz can also form a magnetic dipole[19] and induce a perpendicular electric field component. For s-polarized excitation, the electric dipoles excited directly by the incident magnetic field result in the LC resonance; the phase delay along the x direction of the charge oscillations in the side arms generates an asymmetric charge distribution, leading to not only LC resonance but also high frequency resonance.[23] Further understanding of the symmetry in the cross-polarization responses will require detailed analysis of the bianisotropic properties of the SRR arrays.

In Figs. 4(a) and 4(b), we show the co-polarization reflection spectra of the p- and s-polarization incidence at different angles. The resonant dips in the transmission correspond to the reflection peaks, indicating that the induced charge oscillations in SRRs at these resonant frequencies re-irradiate the THz fields with a phase shift from the incident waves. The nondiagonal elements, r_{sp} and r_{ps}, are identical and have the nearly same profiles as the transmission counterparts, t_{sp} and t_{ps}. This is not strange, because for all the induced cross-polarized signals, whether they appear in the forward or backward fields, the ones with the same polarization state must originate from the same oscillation source located in the SRRs. The reason why the two components r_{sp} and r_{ps} are so highly symmetric needs further study.

4. Conclusion

In conclusion, the terahertz responses of a planar SRR array excited by oblique incidence in a few special configurations are investigated, both experimentally and by simulation. For transmission of co-polarized components, it is found that the phase delay due to the tilted wave fronts on the SRRs plane play a significant role, and so do the couplings between the excited neighboring SRR units, but the magnetoelectric coupling resulting from the direct excitation of the magnetic component of incident fields is less important. The cross-polarization effects show a very interesting symmetry, which could result from the bianisotropic properties of the SRR systems, which needs further study.

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