Dynamical Electric and Magnetic Metamaterial Response at Terahertz Frequencies

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Utilizing terahertz time domain spectroscopy, we have characterized the electromagnetic response of a planar array of split ring resonators (SRRs) fabricated upon a high resistivity GaAs substrate. The measured frequency dependent magnetic and electric resonances are in excellent agreement with theory and simulation. For two polarizations, the SRRs yield a negative electric response ($\epsilon < 0$). We demonstrate, for the first time, dynamical control of the electrical response of the SRRs through photoexcitation of free carriers in the substrate. An excited carrier density of $\sim 4 \times 10^{16}$ cm^{-3} is sufficient to short the gap of the SRRs, thereby turning off the electric resonance, demonstrating the potential of such structures as terahertz switches. Because of the universality of metamaterial response over many decades of frequency, these results have implications for other regions of the electromagnetic spectrum.

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Artificial materials which exhibit a designed electromagnetic (EM) response have recently generated great interest [1]. This is due in part from the ability of these materials to exhibit an EM response not readily available in naturally occurring materials such as: negative refractive index [2], artificial magnetism [3], super focusing [4,5], and reduced lens aberrations [6]. Another advantageous and distinguishing property of EM metamaterials is that resonant structures can be designed over a large portion of the electromagnetic spectrum ranging from rf [7] through the terahertz [8] and near infrared regimes [9]. Thus, regions devoid of natural material response, such as the so-called terahertz gap, can be targeted for metamaterial applications. Further, the majority of metamaterials use elements (typically highly conducting metals such as Cu, Ag, or Au) that are common in conventional microfabrication techniques, offering considerable flexibility in the design of new structures or in the incorporation of additional functionality into existing devices.

For many potential applications, it would be desirable to create metamaterials that exhibit a controlled active, dynamical, and/or tunable response. For example, the dynamic control of metamaterial properties has been demonstrated at microwave frequencies [10]. However, while resonant metamaterials have been fabricated which operate at terahertz [8] and higher frequencies, dynamic control has yet to be demonstrated. Specifically, a dynamic metamaterial response has yet to be demonstrated at terahertz frequencies.

An issue regarding the practicality of metamaterials as devices involves their potentially complicated EM response. Many metamaterial structures (though geometrically simple) exhibit a bianisotropic response, making a full electromagnetic characterization difficult and complicating their utilization as devices. For example, the split ring resonator (SRR) was originally designed for its unique magnetic response. However, great care must be taken in characterizing or utilizing this magnetic response since, as symmetry arguments reveal, the magnetic $\mu(\omega)$ and electric $\epsilon(\omega)$ resonances occur at the same frequency [11]. Additionally, a coupling exists between the frequency dependent electric and magnetic responses. This is characterized by off diagonal terms in the magneto-optical permittivity, and, thus, the SRR is bianisotropic [11,12]. Nonetheless, with careful characterization, such complications can be avoided or even taken advantage of, as new unique EM properties emerge for bianisotropic materials [13]. Although much work has been completed on investigation of the magnetic SRR response, the electric and magneto-optical response has yet to be fully characterized or utilized.

In this Letter, we utilize terahertz time domain spectroscopy [14] to characterize the electromagnetic response of a planar array of SRRs fabricated upon semi-insulating gallium arsenide. In addition to characterizing both the $\epsilon(\omega)$ and $\mu(\omega)$ responses, we demonstrate for the first time the potential for creating dynamic SRR structures. This is accomplished through photoexcitation of free carriers in the GaAs substrate, which short out the SRR gap, thereby turning off the electric resonance, demonstrating the potential of SRR-based artificial materials as terahertz switches. As mentioned, EM metamaterials have been demonstrated over many decades of frequency. Thus, our results are not limited only to terahertz frequencies but may be used over much of the electromagnetic spectrum.

A planar array of SRRs are fabricated from 3 μm thick copper on a 670 μm thick high resistivity gallium arsenide (GaAs) substrate. The outer dimension of an individual SRR is 36 μm and the unit cell is 50 μm [15]. We characterized the frequency dependent electric and magnetic response using terahertz time domain spectroscopy (THz-TDS) where the transmitted electric field is measured for the SRR sample and a suitable reference, which in this case is a bare GaAs substrate. Dividing the Fourier transformed sample and reference waveforms yields the complex transmissivity $\tilde{t}(\omega) = \sqrt{T(\omega)}e^{i\phi(\omega)}$ of the sample under investigation. This phase sensitive characterization further permits determination of the frequency dependent optical constants, e.g., $\tilde{\epsilon}(\omega) = \epsilon_1(\omega) + i\epsilon_2(\omega)$, through inversion of the Fresnel equations without model assumptions. Utilization of GaAs as a substrate provides the opportunity to dope the substrate by optical excitation. This is accomplished using optical-pump terahertz probe spectroscopy [16], whereby a ~50 fs, 800 nm pulse excites carriers across the 1.42 eV band gap in GaAs. The lifetime of the photodoped carriers is ~1 ns, thus allowing for characterization of the quasisteady state response of the SRRs as a function of the carrier density by simply changing the excitation fluence.

In the following, we first consider the SRR response without photoexcitation. In Fig. 1(a), we show the transmission spectra and, in Fig. 1(b), the corresponding phase.

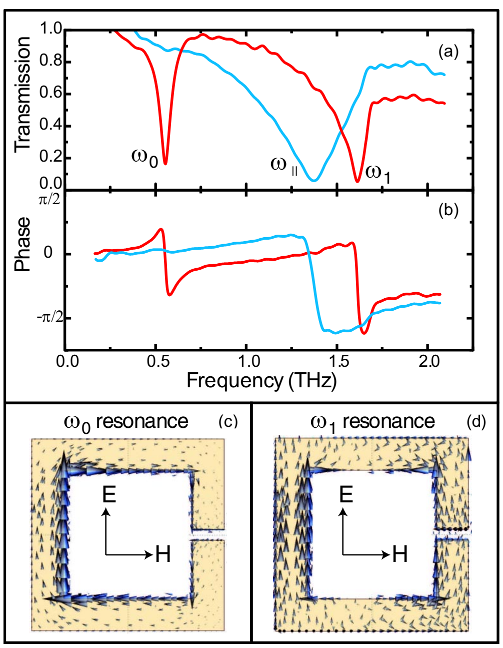

FIG. 1 (color online). The frequency dependent transmission spectra $T(\omega)$ of the SRR sample is shown in (a), and in (b) the corresponding phase of the transmission is shown. In (a) and (b), the electric field is perpendicular to the SRR gap [red (dark) curves] and parallel to the SRR gap [blue (light) curves] at normal incidence. (c) and (d) are the surface current densities for the ω_0 (0.5 THz) and ω_1 (1.6 THz) resonances, respectively, as calculated by simulation. See the text for details.

Since the measurements are obtained at normal incidence and the magnetic field lies completely in the SRR plane, the measurements focus solely on the electric resonant response. The red (dark) curves are the response with the electric field (**E**) polarized perpendicular to the SRR gap [depicted in Fig. 1(c)], while the blue (light) curves are with the electric field oriented parallel to the SRR gap. On the low frequency side, the transmission is high and approaches 95% for both polarizations. With the electric field perpendicular to the SRR gap, a pronounced resonance $\omega_0 = 0.5$ THz is observed where the transmission decreases to ~15%. In addition, there is a second absorption resonance near $\omega_1 = 1.6$ THz. In order to understand the origin of the ω_0 and ω_1 resonances, we have performed numerical simulations of the SRR response using commercial code. Figures 1(c) and 1(d) show the results of the calculated surface currents at ω_0 and ω_1, respectively. The low energy ω_0 terahertz absorption, due to an electric response $\epsilon(\omega)$ of the SRRs, occurs at the same frequency as the magnetic $\mu(\omega)$ resonance [11]. This is evidenced by the observation of the circulating currents shown in Fig. 1(c) produced from the incident time varying electric field which generates a magnetic field polarized parallel to the surface normal of the SRR. This is not surprising since, as mentioned, SRRs are bianisotropic, meaning that the electric and magnetic responses of the SRR are coupled $\epsilon(\omega) \Longleftrightarrow \mu(\omega)$. In contrast, the higher energy ω_1 resonance at 1.6 THz is from the half wave resonance due to the side length $L = 36$ μm of the SRR, consistent with the calculated surface currents shown in Fig. 1(d) [17].

Upon rotating the SRR sample by 90° such that **E** is parallel to the SRR gap, a different electrical resonant behavior is observed [blue (light) curves in Figs. 1(a) and 1(b)]. In particular, there is only a single broad absorption at $\omega_{\|} = 1.38$ THz. We have verified through simulation (not shown) that this resonance is analogous to the ω_1 half wave resonance. The redshift and broadening of the $\omega_{\|}$ resonance in comparison to the ω_1 is consistent with the fact that there are now two $L = 36$ μm side lengths per unit cell resulting in enhanced dipolar coupling [18]. Importantly, there is no electric resonance that is analogous to the ω_0 resonance for this orientation; i.e., there is no response with **E** producing circulating currents with an associated magnetic field directed perpendicular to the GaAs substrate. This is expected as a detailed group theoretical analysis has revealed [11].

To further investigate the nature of the ω_0 resonance, the SRR response was measured at various angles of incidence. Measurements were performed with **E** parallel to the SRR gap so that there is no electrically active ω_0 resonance to complicate determination of the $\mu(\omega)$ response. In particular, the SRR is rotated about an axis parallel to the split gap of the SRR. This permits characterization of the magnetic response of the SRR since $\mu(\omega)$ increases for increasing angles with a maximum occurring for $\Theta = 90°$. The results for angles of incidence $\Theta = 0$, 23, and 45 are shown in Fig. 2. The normal incidence data for **E** perpendicular to the SRR gap [from Fig. 1(a)] is replotted as a dashed red line as a reference. For normal incidence [blue (light) curve], there is no discernible feature at 0.5 THz. However, at the incident angle $\Theta = 23°$ (black curve), a slight dip begins to develop at ω_0. The magnetic coupling to this mode can be further strengthened by increasing the incident angle, and this is apparent and for 45° [green (lightest) curve], where there is a well developed absorption obvious in transmission at ~0.5 THz. This behavior is consistent with the development of a resonant $\mu(\omega)$ response since, with an increasing angle of incidence, a correspondingly larger component of the incident THz magnetic field is projected normal to the plane in of the SRRs (i.e., perpendicular to the GaAs substrate). In addition, as the black dashed vertical line in Fig. 2 reveals, the $\mu(\omega)$ and $\epsilon(\omega)$ responses both occur at ω_0 as discussed above. The combined results of Figs. 1 and 2 provide a fairly complete description of the electromagnetic response of the SRRs in the absence of photoexcitation.

In the remainder of this Letter, we focus on induced changes in the electric resonant response (i.e., ω_0 and ω_1) following photoexcitation. Since the ω_0 resonance shown in Fig. 1(a) has been shown to focus strong electric fields within the split gap of the SRR [13], it is expected that the resonance at ω_0 should strongly depend upon materials placed in or near the gap. Our approach to study the change in resonant response of the SRR is to change the background dielectric of the substrate material as a function of photodoping. The dielectric function of GaAs is changed dynamically with a ~50 fs optical pulse that creates free carriers in the conduction band. The resulting effect on the resonant SRR response is studied as a function of pump power. The pump pulse is timed to arrive 5 ps before the peak of the THz waveform, ensuring that a long-lived carrier density has been established. Since the lifetime of carriers in GaAs is significantly longer than the THz waveform, this allows us to characterize the quasisteady state response of the SRRs as a function of incident power (i.e., carrier density in the GaAs substrate).

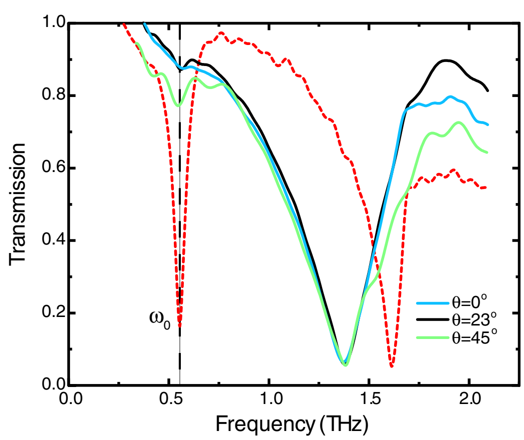

FIG. 2 (color online). Transmission spectra of the magnetic response of the SRRs. The dashed red curve is the electric response (i.e., **E** perpendicular to the SRR gap, normal incidence) replotted from Fig. 1. As the SRR is rotated about an axis parallel to the electric field, an absorption dip due to the magnetic response $\mu(\omega)$ of the SRRs is observed at ω_0.

In Fig. 3(a), we show the dependence of both electric resonances ω_0 and ω_1 on pump power in transmission. The solid red (dark) curve in Fig. 3 is the response of the SRRs replotted from Fig. 1(a), i.e., the electric response of the SRRs at zero pump power. At a pump power of 0.5 mW [green (lightest) curve in Fig. 3], the overall transmission decreases and the strength of the ω_0 resonance significantly weakens. In our experiment, 0.5 mW corresponds to a fluence of 1 $\mu J/cm^2$ resulting in a photoexcited carrier density $n \sim 2 \times 10^{16}$ cm^{-3}. Although ω_0 is strongly affected by pump powers as small as 0.5 mW, it is interesting to note that ω_1 is not significantly altered. When the pump power is increased to 1 mW ($n \sim 4 \times 10^{16}$ cm^{-3}), the low energy resonance ω_0 associated with circulating currents in the SRRs is nearly entirely quenched. In this case, the transmission at ω_0 increases from ~15% to over 70%. Further, $T(\omega)$ continues to decrease over all frequencies

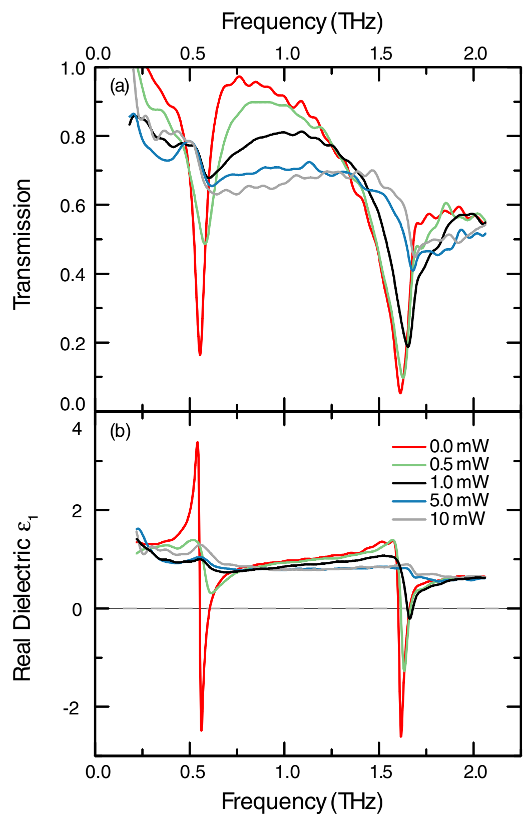

FIG. 3 (color online). (a) Transmission spectra as a function of photodoping fluence for the electric resonance of the SRRs. The polarization of the incident EM wave is as shown in Fig. 1(c). As the power is increased, the first mode is shorted out and the overall transmission decreases. At higher powers, the second mode can also be seen to die off. (b) Corresponding change of the real dielectric constant $\epsilon_1(\omega)$ of the SRRs as a function of power.

characterized which is due, in part, to the free carrier response of the photoexcited GaAs. Notice that, although ω_0 has been short-circuited, there is still little change in ω_1. At 5 mW of pump power, $T(\omega)$ further decreases and finally ω_1 begins to weaken.

The dependence of ω_0 and ω_1 on pump power can be understood by considering the different nature of these two resonances. As mentioned, the lower energy resonance is attributed to circulating currents within the SRR. Thus, by providing free charges within the substrate, it becomes possible to short-circuit the response and, as the gap in the SRR is relatively small ($\sim$2 μm), only low pump powers are required. However, ω_1 is due to the side length of the SRR, and, therefore, more charges (and thus more power) are required to effectively screen this resonance.

We now discuss the real part of the dielectric function $\epsilon_1(\omega)$, displayed in Fig. 3(b). This further highlights that, for low excitation densities, the ω_0 resonance completely disappears, while the ω_1 survives to slightly higher fluences. Notice, for zero pump power, the SRR metamaterials obtain a region of negative $\epsilon(\omega)$ for both the ω_0 and ω_1 resonances. The region of negative ϵ for ω_0 spans from 550 to 600 GHz and reaches a maximum negative value of $\epsilon = -2.5$ at $\omega = 560$ GHz, while ω_1 spans from 1.6 to 1.66 THz and obtains a slightly greater value of $\epsilon = -2.6$. For a pump power of 0.5 mW, the ω_0 resonance is reduced greatly and the $\epsilon < 0$ response destroyed. Thus, one scenario permitting these metamaterials to be used as dynamical devices involves a photoinduced bandpass response. For example, if used at $\omega = 560$ GHz, where the transmission has a minimum, a 1 mW pump pulse increases $T(\omega)$ by $\sim$60% and, consequently, changes the SRR metamaterial medium from absorbing to transparent.

The results of Fig. 3 were obtained for SRRs fabricated on intrinsic GaAs substrates. In this case, the recombination time of the carriers in GaAs is greater than 1 ns, meaning that the switched state of the SRR structure (i.e., the photoinduced increase in transmission) is long-lived. However, it would be possible to fabricate identical SRR structures on low temperature grown gallium arsenide or GaAs:ErAs semiconductor heterostructures [19], the latter of which allows for engineered picosecond (1 to 10 ps) carrier recombination times. This would enable picosecond on/off switching times of the SRR electric response, enabling optically controlled high frequency modulation of narrow band THz sources. Furthermore, with electrical carrier injection, another possibility would be to create all-electrical THz modulators.

In conclusion, we have demonstrated dynamical control of the SRR metamaterial at THz frequencies. The full characterization of the biaxial electric response of the SRRs has been given and all expected absorption dips in the spectra identified. To the best of our knowledge, these are the first results characterizing SRRs using THz-TDS which take full advantage of the ability to measure the electric field amplitude and phase. In addition, through photoexcitation of carriers in the GaAs substrate, control of the main ω_0 resonance associated with both an electric $\epsilon(\omega)$ and magnetic $\mu(\omega)$ response has been shown. These results indicate the possibility of using SRRs as an active narrowband THz switch.

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