A metamaterial terahertz modulator based on complementary planar double-split-ring resonator*

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A metamaterial based on complementary planar double-split-ring resonator (DSRR) structure is presented and demonstrated, which can optically tune the transmission of the terahertz (THz) wave. Unlike the traditional DSRR metamaterials, the DSRR discussed in this paper consists of two split rings connected by two bridges. Numerical simulations with the finite-difference time-domain (FDTD) method reveal that the transmission spectra of the original and the complementary metamaterials are both in good agreement with Babinet's principle. Then by increasing the carrier density of the intrinsic GaAs substrate, the magnetic response of the complementary special DSRR metamaterial can be weakened or even turned off. This metamaterial structure is promised to be a narrow-band THz modulator with response time of several nanoseconds.

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Terahertz (THz) wave has received considerable attention during the past years[1,2]. Short-range indoor communication systems may be designed for the sub-THz or THz range in the future. A growing research emphasis is put on the manipulation of both guided and freely propagating THz beams by means of agile switches, modulators, and optical or electronic phase shifters.

A new type of artificial electromagnetic metamaterials have been developed since Pendry's research in 1996[3]. The metamaterials exhibit extraordinary electromagnetic properties including electric response and magnetic response which are not available in natural materials, and play a particularly important role in the implementation of THz devices, such as absorbers, sensors, filters and modulators[4-6]. Metamaterials formed by periodic array of sub-wavelength scale (~λ_0/10) split-ring resonators (SRRs) have been demonstrated[7] and used to achieve magnetic resonances at THz frequencies with the inductor-capacitor (LC) resonance.

In this paper, we present the results of computation on a planar THz double-split-ring resonator (DSRR) metamaterial and its corresponding inverse structure, where the metallic patterns are replaced with open areas, and open areas are replaced with metallic conducting regions. We adopt the terminology "original" to refer to the DSRR metamaterial structure and "complementary" to refer to its corresponding inverse metamaterial structure. Both metamaterials are fabricated upon intrinsic GaAs substrate. The two rings of the DSRR elements of the original metamaterial are connected by two metallic bridges. The simulation results show that this metamaterial exhibits the stronger magnetic response than the standard DSRR metamaterial without the metallic connecting bridges, and the transmissive spectra of the complementary and the original DSRR metamaterials are consistent with Babinet's principle. Then by optically controlling the free electron density of the GaAs substrate, the THz transmission of complementary DSRR metamaterial can be tuned.

The unit cell geometries of the metamaterial structures are depicted in Fig.1. As shown in Fig.1(a), the DSRR element of the original metamaterial is constructed with two gold split rings, and the conductivity of gold is $\sigma=4.09\times10^7$ S/m, and they are connected by two gold bridges. Both the original and the complementary DSRR metamaterials have an outer dimension R of 15 μm, the lattice parameter $l_x=l_y$=34 μm, the line width w of 3 μm, and a gap width g of 4 μm. And both two DSRR structures are fabricated as square planar arrays on intrinsic GaAs substrates with dielectric constant of ε=12.9[8] and thickness of 670 μm. The thicknesses of gold elements of these two metamaterials are both 200 nm.

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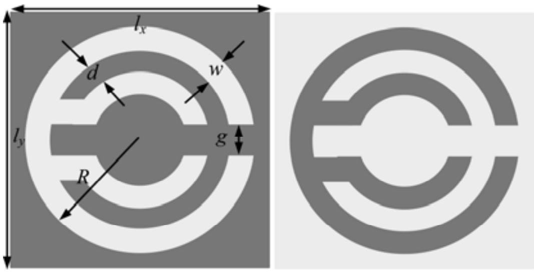


(a) (b)

Fig.1 Schematic diagrams of (a) original planar DSRR metamaterial unit cell and (b) its complementary metamaterial unit cell

The THz transmissions of the original and complementary DSRR metamaterials are numerically simulated by finite-difference time domain (FDTD) method. With normally incident THz radiation, i.e., the electric and magnetic fields are in-plane with the metamaterial structure, the polarization is configured in accordance with the dual sources in Barbinet's principle[9]. If the original metamaterial is illuminated by the incident electromagnetic field of $\boldsymbol{E}_0$ and $\boldsymbol{H}_0$, the complementary fields of $\boldsymbol{E}_0^c$ and $\boldsymbol{H}_0^c$ are defined as

$$\boldsymbol{E}_0 = Z_0\boldsymbol{H}_0^c,\ \boldsymbol{H}_0 = -\boldsymbol{E}_0^c / Z_0\ , \tag{1}$$

where $Z_0=(\mu_0/\varepsilon_0)^{1/2}$. This amounts to a 90° rotation of the field around the propagation axis, as shown in Fig.1(a) and (b).

In order to make a comparison, the spectra of the traditional DSRR metamaterial without connecting bridges and our DSRR metamaterial with connecting bridges are shown in Fig.2(a). The results reveal that the DSRR metamaterial with connecting bridges presents the stronger resonance than the traditional DSRR metamaterial in the low frequency region. This resonance is the LC resonance, which originates from circulating current in the ring structures as shown in Fig.3 and results in a pure magnetic response, as magnetic dipole moment is normal to the interface of the metamaterial. In Fig.3(a), four circular current distributions at 0.636 THz can be discovered with the same flow direction, which are the inner ring circular current, the outer ring circular current, and two circular currents between the two rings connected by the bridges. At the same time, there are only two circular current distributions, including the inner ring circular current and the outer ring circular current, at the resonant frequency of 0.582 THz for the DSRR metamaterial without connecting bridge. It can be explained that our novel DSRR with the connecting bridges has stronger magnetic response than the traditional DSRR. Magnetic response of traditional DSRR metamaterials is widely used at THz frequencies. By tuning the LC resonances of the DSRR, THz wave transmission is controllable[10,11]. With the enhancement of the LC resonance of our novel DSRR metamaterial with the connecting bridges, we can expect that the tunable activity of THz waves can be obviously improved.

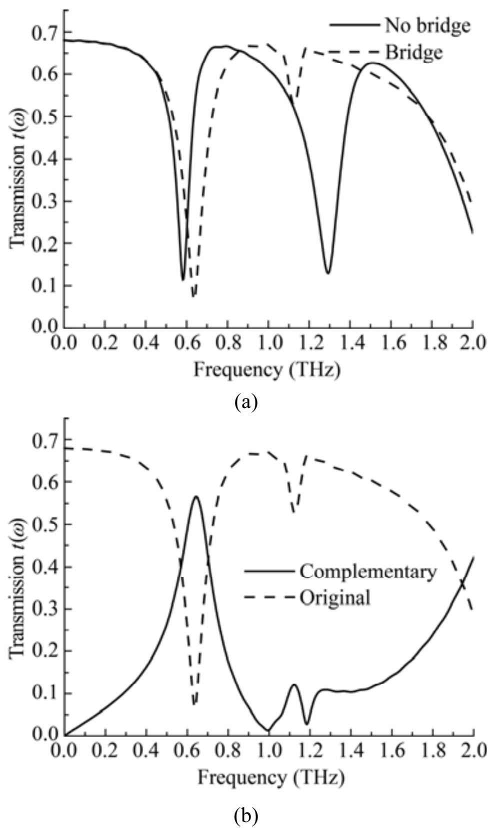
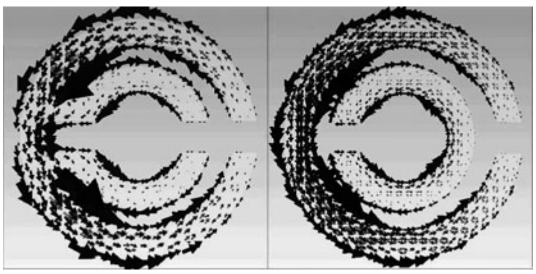


Fig.2 Frequency dependent THz electric transmission coefficients of (a) the original DSRR metamaterial with and without connecting bridges and (b) the original DSRR metamaterial with connecting bridges and the complementary DSRR metamaterial



(a) (b)

Fig.3 Numerical simulations of surface current distributions (a) in the original DSRR metamaterial with connecting bridges at the resonant frequency of 0.636 THz and (b) in the original DSRR metamaterial without connecting bridge at the resonant frequency of 0.582 THz

The frequency dependent THz electric field transmission coefficients of the original DSRR metamaterial with connecting bridges and its complementary metamaterial are displayed in Fig.2(b). The original metamaterial shows a resonant transmission decrease at frequencies between 0.1 THz and 1 THz with the transmission coefficient as low as 6.4%. On the other hand, the complementary metamaterial shows an enhanced resonant transmission as high as 56.4% at the same frequency.

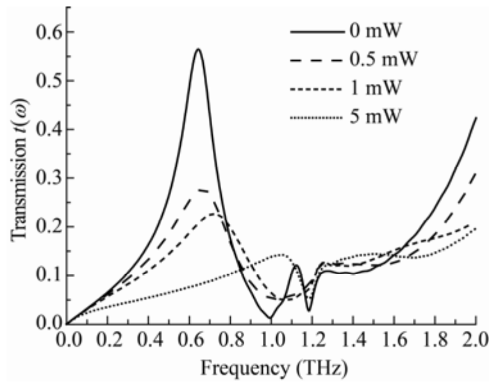
In addition to the LC resonance, there is a second minimum transmission (in the original metamaterial) or a second maximum transmission (in the complementary metamaterial), which originates from the excitation of the electric dipoles. In the remainder of this paper, we mainly focus on inducing changes of the LC resonances. The normal incidence of the THz radiation ensures that the electric and magnetic fields are configured to be completely in-plane, which indicates that there is no component of the magnetic field capable of causing a magnetic response by driving circulating currents. Therefore, this magnetic response is obtained by the electric resonance. It is expected that this resonance should strongly depend on the strong electric field focusing within the split gap of the DSRR. And we can expect that the magnetic resonance at the lower frequency should strongly depend on materials placed in or near the gap.

GaAs is an ideal semiconductor with the tunable carrier density. Free carriers can be produced when it is optically excited with the pumping photon power greater than the electron band gap of 1.424 eV of GaAs. The laser with a pulse width of 80 fs and the wavelength of 780 nm is the perfect choice for tuning the carrier density. 0.5 mW corresponds to a fluence of 1 μJ/cm^2 resulting in a photo-excited carrier density of N≈2×10^{16} cm^{-3}[12]. According to the Drude model, the permittivity can be changed with different carrier densities as

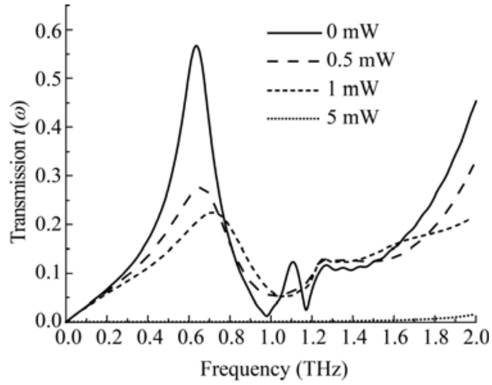
$$\varepsilon(\omega)=\varepsilon_\infty-\frac{\omega_p^2}{\omega^2+i\gamma\omega}, \qquad (2)$$

where ε_∞=12.9 for GaAs represents the high-frequency permittivity, ω represents the angular frequency, and γ represents the damping constant. The plasma frequency ω_p is given by $\omega_p=\sqrt{Ne^2/\varepsilon_0 m^*}$, where N, e, ε_0 and m^* represent the carrier density, the electronic charge, the vacuum permittivity and the effective mass of free carriers, respectively.

With the above Drude model, we calculate the transmission spectra of our complementary DSRR metamaterial on the substrate of GaAs when the metamaterial is illuminated with different pumping power values, and the results are depicted in Fig.4. Obviously, the magnetic resonance is degraded when the carrier density is increased with the optical power increasing to 5 mW. The overall transmission is decreased, and the intensity of the magnetic resonance is significantly weakened. As shown in Fig.4(a), the electric transmission of the magnetic resonance at 0.636 THz decreases from 56.4% to about 8.1%, which means that the amplitude modulation depth can approach 85.6%. If the thickness of gold layer in the complementary DSRR metamaterial decreases to 20 nm, the modulation depth can reach as high as 99.85%. It is because if the pump laser power can be better coupled into the GaAs gap of complementary DSRR, the transimission can be better modulated.



(a)



(b)

Fig.4 Transmission spectra as a function of photodoping fluence for the magnetic resonance of our complementary DSRR metamaterial with the gold thicknesses of (a) 200 nm and (b) 20 nm

Since the recombination time of the free carriers of intrinsic GaAs is about 1 ns, our DSRRs can be used as a high-frequency modulator with the modulation frequency about 1 GHz. If using the GaAs growing at low temperature as the substrate, the modulation frequency can approach terahertz level, because the combination time of carrier can be several picoseconds[13].

In conclusion, we demonstrate an optically controllable THz complementary DSRR metamaterial modulator. The inner and outer rings of the DSRR are connected by two bridges. Numerical simulations indicate that our DSRR exhibits a stronger magnetic response at THz frequencies than the traditional DSRR without the connecting bridges. In addition, through the photo-excitation of carriers in the GaAs substrate, THz wave transmission can be tuned by controlling the magnetic resonance. This metamaterial structure is promised to be a narrow-band THz modulator with response time of several nanoseconds.

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Retraction

I am SUN Li-ping, who is the first and corresponding author of "A new method to characterize the metallic-oxide films for grayscale lithography". This paper has been published by Optoelectronics Letters from Pg.0034 to Pg.0037 on Vol. 9 No.1 in 2013. This work was accomplished by both Nankai University and National Center for Nanoscience and Technology of China. The whole intellectual property right belongs to Nankai University and National Center for Nanoscience and Technology. I just did some experimental and data processing work indirectly, so I should not report this paper. Now, I apply for a retraction of this paper from the journal.

I sincerely feel sorry for the relevant organizations. I am sorry to mislead the readers and the journal.

In addition, this is my own mistake and the other authors of this paper did not know this mistake. If this mistake makes problems on the other authors, I feel sorry, too.

SUN Li-ping
School of Science, Tianjin University of Technology
June 2013