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The investigation of electromagnetic properties of E-shape metamaterials

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Abstract

The modification of the electromagnetic properties of terahertz metamaterials is important to overcome the short of natural terahertz materials. In this paper, the toroidal dipole phenomenon is realized in the terahertz band by means of a double E-shaped metamaterial. Data simulation analysis is performed by CST software, and it is observed that the transmission spectrum has two distinct resonance points at low and high frequencies, and the electric and magnetic field distributions at the corresponding frequencies are also given. By changing different parameters of the structure, it is found that the transmittance is almost constant at low frequencies and changes significantly at high frequencies, and the corresponding quality factor also changes. The analysis based on the LC resonant theory shows that the decrease in resonant frequency was caused by the increase in the equivalent capacitance. The proposed metamaterial structure can greatly improve the quality factor of the device and has important application prospects for important fields such as sensor and perfect absorption.

Keywords

Terahertz; Metamaterials; Toroidal dipole; Quality factor Q.

1. Introduction

The frequency range of 0.1-10 THz is usually referred to as terahertz waves (THz), which are electromagnetic waves with wavelengths in the range of 0.03-3 mm [1]. Terahertz waves have physical properties such as low loss, fast propagation speed, and high penetration ability [2]. Its position is located between microwaves and infrared light, and because of the specificity of its position makes terahertz have the unique physical properties, in 1964 Crocker et al. observed far-infrared waves excited in water [3-4], then terahertz has been studied by numerous researchers. So far, terahertz-related applications have gradually emerged, such as space communication [5], security detection [6], and biomedicine [7]. Currently, the strong absorption of terahertz by water hinder the widely use of terahertz technology.

A toroidal dipole (TD) is the lowest order member of a toroidal multipole. A TD can be understood as a large magnetic dipole that forms a closed circle when the heads and tails of magnetic dipoles are connected. The electric dipole is produced by the oscillating charge and the magnetic dipole is produced by the transverse component of the oscillating current. In 1958 Zel'dovich analyzed TD experimentally when explaining the phenomenon of cosmic non-conservation in atomic nuclei [8], Then the existence of the TD was also confirmed in subsequent studies of nuclear physics [9] and classical electrodynamics [10-11]. The electromagnetic response of the TD is relatively weak and therefore difficult to be detected and studied [24].

The TD can be realized via metamaterials. A metamaterial is a new type of periodic material made by artificial compounding, which is generally a subwavelength size metallic structure fabricated on a semiconductor or dielectric substrate by a photolithographic process to form the basic structure of a metamaterial [14]. Metamaterials possess physical properties that are not found in natural materials, such as negative magnetic permeability, anomalous transmission, negative refractive index and superabsorption [15-16], and metamaterials are used to compensate for the defects of natural materials.

The design of a suitable metamaterials unit structure can enhance the electromagnetic response of the TD and suppress the electric and magnetic multipole resonance [25]. Xiao-Qiang Jiang et al. proposed a simple all-dielectric hypersurface with symmetric structure and obtained strong TD resonance and ultra-high quality factor [17]. Wang Dongxu et al. designed a dual-frequency terahertz absorber with a square metal ring structure and obtained absorbers at two absorption peaks with good absorption performance and high quality factor [18]. Therefore, metamaterials are widely used in the terahertz band, such as slow light devices [20], polarization converters [21], sensors [22] and medical detection [23].

In this paper, we focus on the electromagnetic properties of double-E metamaterials by changing the parameters ,such as the length of the metallic structure, Via CST simulation ,and the quality factor was also investigated. the TD was observed, where the TD with its unique electromagnetic properties combined with terahertz waves, is widely used in terahertz transparent materials, absorbers, filters and other functional devices. The proposed planar terahertz TD metamaterial provides an theoretical basis for the subsequent study of the TD, and offers a new idea for the study of flexible TD metamaterials.

2. Design of the structure of the double-E metamaterial

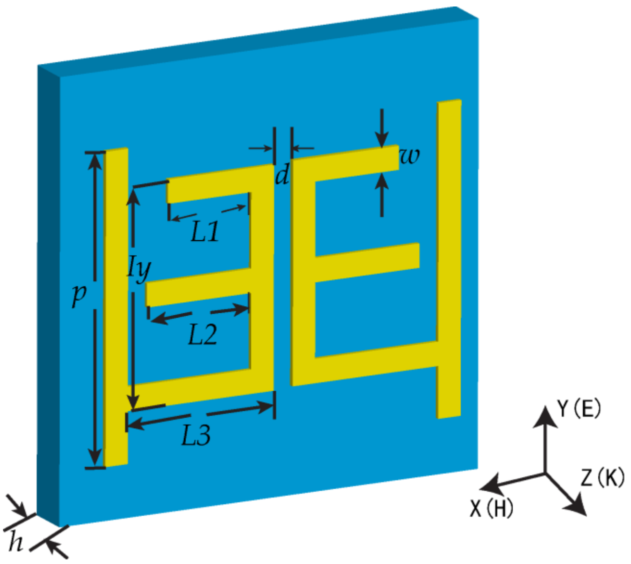

Figure 1 Metamaterial structural unit

The metamaterial structural unit consists of E-type and metallic aluminum strips, which are then mirror-symmetric along the Y-axis, as shown in Figure 1. The dielectric substrate of the metamaterial has a dielectric constant ε=2.65, external dimensions of 61.2㎛×61.2㎛, and thickness h=3.4㎛. The mirror ESRR uses metallic aluminum rods with structural parameters of L1=13.3㎛,L2=15.3㎛,L3=17.3㎛,P=51㎛,Iy=20.6㎛,w=1.4 ㎛ and the thickness of the metal aluminum bar t=0.119㎛.

In the metamaterial structural unit, three parallel nonresonant aluminum rods L1, L2, and L3 lead to structural asymmetry and play an important role in the response of the circular dipole moment. From Figure 1, we can clearly see that the resonator unit structure is formed by mirroring between the left and right sides of the mirror structure ESRR, and then by introducing a spacing distance of d = 0.2㎛ to allow sufficient space between the mirror E-shaped structures. Periodic boundary conditions are used in the X and Y directions. Terahertz waves are incident vertically along the metamaterial Z direction and the electric field is incident along the X direction. In the analysis of the metamaterial properties simulations, CST, a commercial simulation software, is used in the time domain solver to obtain the transmission spectrum of the metamaterial structural unit and to perform the field strength analysis at the resonance point.

3. The analysis of simulation results of double-E structured metamaterials

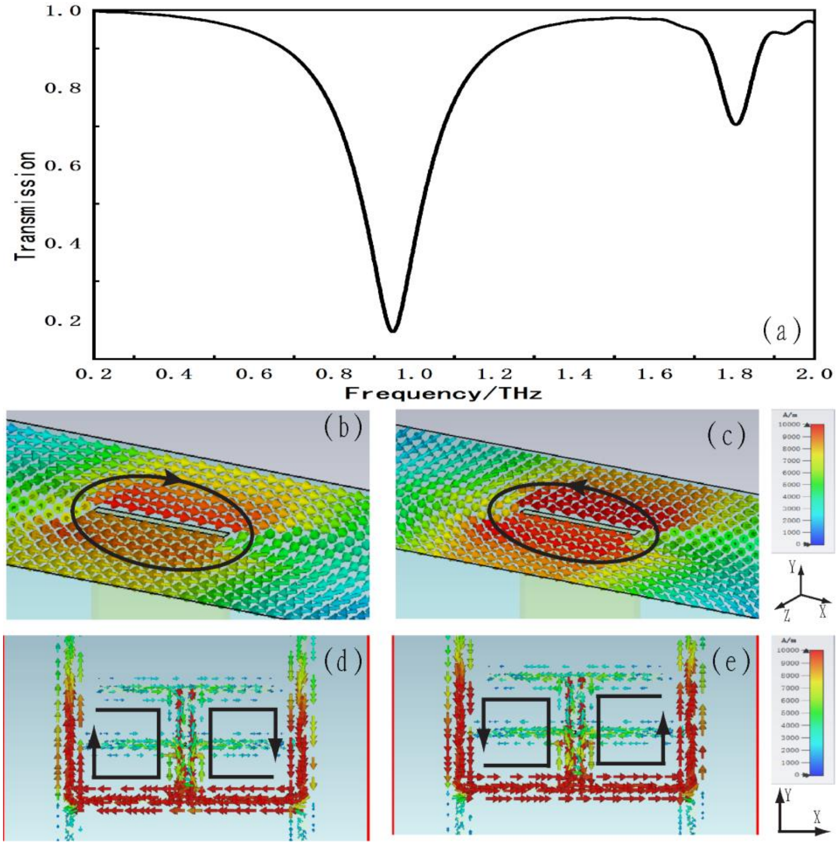

Fig. 2 (a) Transmission spectrum of the double-E structure.(b) Low frequency resonant magnetic field distribution of metamaterials.(c) High frequency resonant magnetic field distribution of metamaterials. (d) Low frequency resonant surface electric field distribution of metamaterials. (e) High-frequency resonant surface electric field distribution of metamaterials.

Through electromagnetic simulation, the transmittance curve of the double E ring resonator is obtained, as shown in Figure 1(a), from the transmittance curve can be clearly observed in two resonance points, one resonance point is located around 0.947 THz, this resonance point is called the low frequency resonance point, a resonance point is located around 1.80 THz, this resonance point is called the high frequency resonance point. From Fig. 2(b) and Fig. 2(c), the magnetic field distribution diagrams of the first and the last can be seen, when it is obvious to observe the ring dipole along the clockwise direction at low frequency and along the counterclockwise direction at high frequency, and the intensity of the magnetic field gradually decreases from the center to the surrounding. Figure 2(d) and Figure 2(e) show the surface electric field distribution at low and high frequencies, respectively. At low frequencies, the current in the E structure of the metal aluminum rod is in the clockwise direction, and at high frequencies, the current in the metal aluminum rod is in the counterclockwise direction. From Fig. 2(d) and Fig. 2(e), it can be observed that the current intensity is mainly concentrated with the metal aluminum bar P and the metal aluminum bar L3.

The quality factor Q at the two resonance points is calculated by equation 1. The Q factor at the low frequency resonance point is about 4.97 and the Q factor at the high frequency resonance point is 21.80. It is obvious from the Q value that the resonance characteristics are stronger at the high frequency than the Q value at the low frequency .

$$Q = \frac{f_0}{f_2 - f_1} \tag{1}$$

where f1 and f2 are the frequency values corresponding to the half-width height of the transmission spectrum; f0 is the frequency value at the resonant frequency of the transmission spectrum curve.

3.1. Effect of Iy parameter on electromagnetic properties

The structural parameters of the double-E metamaterial were set to be consistent with the model above, and the Iy parameters were 20.6μm, 23.6μm, 26.6μm, and 29.6μm,while the other parameters are constant. The transmission spectra of metallic aluminum structure Iy at different lengths was shown in Fig. 3(a). And Q values at low and high frequency resonances with different Iy were obtained via Eq. 1, as shown in Fig. 3(b).

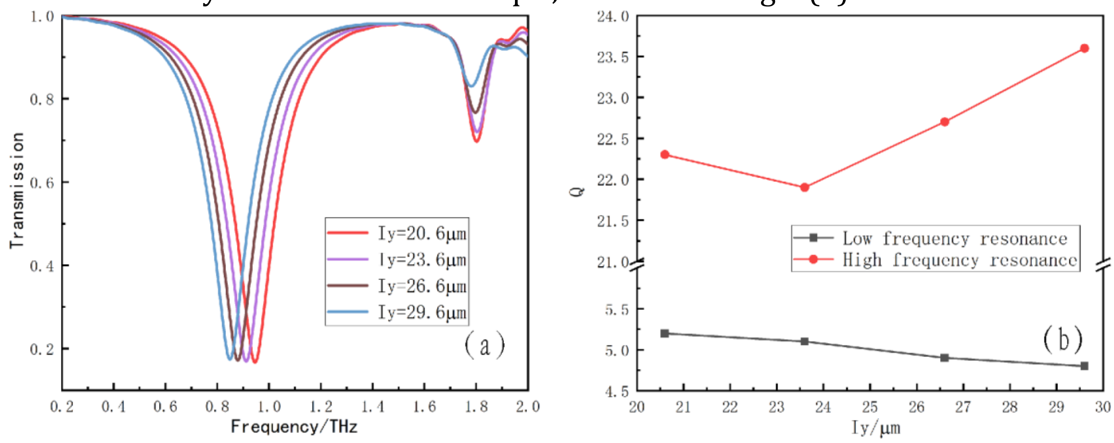

Fig. 3 (a) Transmission spectrum of metallic aluminum structure Iy at different lengths. (b) Q of the metallic aluminum structure Iy at different lengths.

It is obvious from Fig. 3(a) that with the gradual increase of metallic aluminum Iy, the transmission spectrum is red-shifted at low-frequency resonance. At high frequency resonance, the transmittance increases along with the gradual increase of Iy. Fig. 3(b) In the accompanying increase of the metal structure Iy, the Q value gradually decreases at low frequency, the low frequency resonance gradually weakens, and the Q value at high frequency decreases gradually from Iy=20.6μm to Iy=23.6μm, and Iy=23.6μm, with the increase of the metal structure Iy its corresponding Q gradually increases and the high frequency resonance is enhanced.

3.2. Effect of P parameter on electromagnetic properties

The structural parameters of the double-E metamaterial were set to be consistent with the model above, and only the metallic aluminum rod P were changed,whose parameters were 46 μm, 51μm, 56μm, and 61μm. The transmission spectra and Q values at low and high frequency resonances with different lengths of metal aluminum bar P were shown in Fig. 4.

It is obvious from Fig. 4(a) that the transmission spectrum as a whole is red shift as the metal aluminum P gradually increases. At low frequency resonance, the resonant frequency gradually decreases with the gradual increase of the metal structure P and the transmittance remains unchanged, and at high frequency resonance, the resonant frequency gradually decreases with the gradual increase of the metal aluminum P and the transmittance gradually decreases. Figure 4(b) As the metal structure P increases from 46μm to 56μm, the Q value gradually decreases and the low-frequency resonance weakens. As the metal structure P increases from 56μm to 61μm, the Q value gradually increases and the low-frequency resonance is enhanced. At high frequencies, as the metal structure P increases from 46㎛ to 56㎛, the Q value gradually increases and the high frequency resonance is enhanced. When the metal structure P increases from 56㎛ to 61㎛, the Q value gradually decreases and the high frequency resonance gradually weakens.

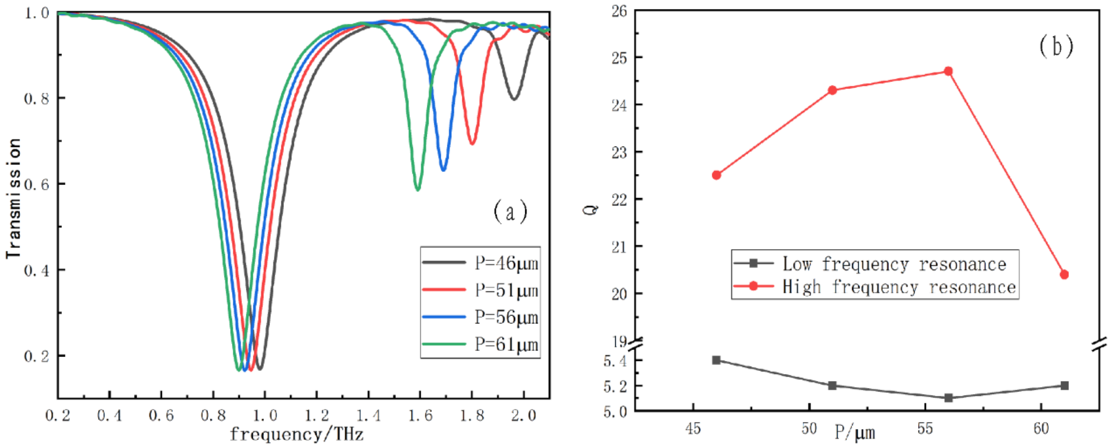

Fig. 4 (a) Transmission spectrum of metallic aluminum structure P at different lengths. (b) Q of metallic aluminum structure P at different lengths.

3.3. Analysis

In order to better analyze the resonance characteristics of the double-E resonator, it can be analyzed via the the LC resonant circuit. The double-E resonator can be calculated via the resonant frequency equation:

$$\omega^2=1/LC \quad (2)$$

In Eq. 2, ω is the resonant frequency, the equivalent capacitance C is the corresponding open gap, and the equivalent inductance L is the corresponding metal structure.

The equivalent capacitance C is determined by the distance of the opening gap, the cross-sectional area of the opening and the dielectric constant of the metal ring. The equivalent inductance L is determined by the circumference and width of the metal strip. In a double-E resonator, as the metal structure Iy and P gradually increase, the cross-sectional area of the opening gradually increases, and the equivalent capacitance C then increases, leading to a decrease in resonant frequency and thus a red shift.

4. Conclusion

In this paper, we theoretically design a double-E-based TD metamaterial, and use the electromagnetic simulation software CST to simulate and analyze the electromagnetic properties.It was investigated the transmission curve of the metamaterial, and further analyze the surface electric and magnetic field distribution of the metamaterial. The TD response of this metamaterial in the terahertz frequency band is obtained by simulation. Under the action of the applied electromagnetic radiation, the magnetic dipoles on the left and right sides with opposite directions are connected and coupled to each other to realize the electromagnetic response of the TD. Two resonance appear in the transmission curve, which are located at low frequency and high frequency, respectively. When the metal structure P or Iy are increased, the red-shift phenomenon is produced at both the low-frequency resonance and the high-frequency resonance. And the electromagnetic transmission performance at high frequency is gradually enhanced when changing the metal structure P.

At the same time, metamaterials are an important way to realize the electromagnetic response of TD, and the study of TD metamaterials at terahertz wavelengths is of great significance. In addition, the high Q value is a reflection of the high performance of metamaterials. In this paper, the designed metamaterial structure unit has a red-shift in the transmission spectrum with increasing parameters P and Iy at low frequencies, which has a small effect on the Q value. At high frequencies, the transmission spectrum redshifts and the transmittance decreases as the parameter P increases, and the transmission spectrum redshifts and the transmittance increases as the parameter Iy increases, where the Q value reaches a maximum of 23.6 for the metallic structure Iy = 29.6㎛ and 24.7 for the metallic structure P = 56㎛.Because of its unique electromagnetic properties, terahertz wave has a wide range of applications in the fields of nondestructive inspection, image recognition and other technologies.

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