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Investigation of Electromagnetic Characteristics of Toroidal Dipole based on Metamaterial under Terahertz Frequencies

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Abstract: ***Toroidal dipole response was observed by four U-SHAPE Metamaterial at terahertz frequencies, this shows that the toroidal dipole can be produced through the arrangement of four double U- SHAPE metamaterial as meta-atoms by manipulating the form properly meta-atoms. The experiment shows that the toroidal resonance gives subwavelength-scale electromagnetic, the electromagnetic field distribution and the surface current distribution were observed through the simulation of the electromagnetic field, and the toroidal dipole is observed from the magnetic field distribution map. The structure consists of the most advantage S-parameters:a=168µm,b=104µm,w=18µm,lx=152µm,ly=60µm,thm=0.4µm,g=15µm,t= 22µm, s=5µm. The transmission curve of the Metamaterial is observed in the (0.2 to 1.0) THz band. The transmission curve shows two main resonant valleys, respectively at the Low-frequency F=0.416THz and the High-frequency F=0.865THz.In the frequency F=0.865THz The toroidal geometry together with the Fano resonance of four U-SHAPE metamaterial induced strong toroidal dipole response will have enormous potential applications such as invisibility cloaks, superlenses, and devices with negative indices of refraction.***

Keywords: Metamaterial, Toroidal dipole, Blueshift, U-shape.

1. Introduction

Metamaterials are artificial materials which can manipulate electromagnetic (EM) waves at will. These periodic lattices give engineers and researchers a large atmosphere of control over EM radiation and can be used to create exciting and novel applications such as invisibility cloaks, superlenses, and devices with a negative index of refraction. The geometrical design of the structure is a large challenge in creating them. These structures are periodic lattices with magnetodielectric, metallic, or plasmonic inclusions. Their size, which scales on the order of the wavelength of interest, and their geometry uniquely determine the effect on EM waves as well as the frequency bands in which they operate. As the third kind of radiation source, the toroidal dipole has distinctive characteristics, which is produced by the coherent action of an electric multipole or a magnetic multipole and has the characteristics of activity, high-quality factor and so on. The concept of the toroidal dipole was first proposed in the Study of Nuclear physics 1957 years ago by Soviet scientist Zel ' Dovich, also known as "Anapole" [1]. A toroidal dipole can be equivalent to a circular structure formed by the end to end of a plurality of magnetic dipoles [2]. In nature, the response ratio of the toroidal dipole is weaker, and it is usually obscured by other responses, so it has not been proved that the existence of the toroidal dipole directly. Until recently, the development of metamaterials has provided a new method for observing and exploring the toroidal dipole.

2007, Marinov K [3] and others, for the first time, a molecule with a toroidal dipole was theoretically designed, and the characteristics of unidirectional transmission and negative refractive index of the metamaterial were studied. 2010, Kaelberer T [4] and other people with four open resonant ring (SRRs), in the microwave band design and preparation of the toroidal dipole supramolecular material molecules and obtain a higher Q value, this is the first time in the experiment to detect the toroidal dipole. After the research group on the study of the toroidal dipole and its properties based on the metamaterial, many achievements have been made, and the research group of Professor Cai Dingping of the National Taiwan University has designed and implemented the toroidal dipole response of the terahertz band (112.3thz~120thz) [5] N.i.zheludev Research Group, University of Southampton, UK design and implementation of the toroidal dipole response of the mid-infrared band Optical hypermedia [6]; D.timbrell Research Group of University College London The toroidal dipole response in near infrared band is achieved by nonlinear plasma hyper-media [7] Zhang and others [8] The asymmetric bimetal magnetic resonance device is combined into a ring structure, and a feasible nanostructured metamaterial is designed, which realizes the response of the toroidal dipole in the optical frequency. 2012, Dong Z G Wait for a man. In theory, a kind of toroidal dipole supramolecular molecule with rotational symmetry is designed, and a high Q value is obtained [9];Huang Y W etc in the realization of the toroidal dipole, which can be used to design lasers. In recent years, Basharin [10] and other people have first proposed the use of LiTaO3 with high dielectric constants, and designed and implemented a toroidal dipole supramolecular molecule working in terahertz frequency band. Guo Linyan of Huazhong Normal University, in the medium structure of nanometer cylinder, the design of the M-resonance based on the displacement current and proves that the toroidal dipole can also be realized in the medium super medium. The resonant frequency is located at 411.5THz, and a simplified form of spiral ring hypermedia is also designed, and the.

Mechanism of the magnetic toroidal dipole is studied, and the chiral characteristics of the super medium, including activity and roundness [11] Li Jianjian, Nanjing University of

Aeronautics and Astronautics, designed a kind of double atom molecule (dumbbell-shaped structure) metamaterial, using the electromagnetic field numerical simulation method, realizes the microwave frequency band double frequency band high Q value toroidal dipole [2]. Thereafter, more and more experiments have been carried out to study the toroidal dipole with the material of metamaterials, and the research of the toroidal dipole has been studied in the microwave band, the terahertz band, the infrared band and the visible band, but the research in the terahertz band is relatively few.

Terahertz (THz) wave is the frequency of 0.1THz to 10THz, is located between the microwave and far-infrared electromagnetic waves (wavelength 3mm to 30μm), has not been widely developed in the electromagnetic frequency band. In the 90's, terahertz emission sources and detectors made a series of breakthroughs, triggering the rapid development of terahertz science and technology, and terahertz is now widely used in the fields of biomedicine, safety monitoring, spectroscopy and imaging technology, and information science [12].

This paper shows a planar scheme for toroidal metamaterial, with the unit cell comprised of four asymmetric U-SHAPE.I demonstrated that toroidal magnetic properties can be constructed through the arrangement of planar 4U as meta-atoms via manipulating structural symmetry among the meta-atoms. Field maps clearly indicate that the toroidal resonance paves fantastical electromagnetic field confinement in dielectric substrates within a subwavelength-sized volume of toroidal geometry. The electromagnetic simulation is carried out by using CST software to study the resonant point frequency and transmission amplitude of different structural parameters metal bar width **W** and cycle **a, b.** Q value and its effect on the toroidal dipole. The four **U-shaped** structures can observe the phenomenon of the toroidal dipole, the model provides a theoretical basis for the study of the toroidal dipole, which has great application value can also be used to design lasers, Polarizer, FM, optical meter and so on.

2. Theoretical Discussion and Simulation Results

The electromagnetic response of an infinite two-dimensional array of metamaterial was observed. **Fig**.1 shows the schematic diagram of a unit cell of metamaterial with its design parameters. **Fig**.1 shows the image of the four U-SHAPE fabricated from 0.4μm thick aluminum (Al) on 22μm thick Mylar substrate. **Fig**. 1 is a schematic diagram of the unit structure of the four double 4U-structure super medium. The unit structure has a total of four layers, including the U-ring A and B in the first layer, the intermediate medium Mylar and the second layer U-ring A* and B*. The material of the U-shaped metal strip in the structure is made of metal aluminum because the metal aluminum can be regarded as an ideal conductor, and its joule loss is very little negligible in the terahertz band [2]. Polyimide materials are used for both intermediate and substrate materials. Because the polyimide material is a high-performance macromolecule material, has the good dielectric property, the dielectric constant is about 3.4, moreover has the high transmission rate, the low loss in the terahertz frequency band characteristic.

Figure 1: Schematic diagram of two-u structure material Element

The four metal ring A, A*, B and B* in the four U-SHAPE structure are of the same structure and size respectively: thickness thm=0.4μm, spacing of the left and right two U g=15μm, the length of U is lx=152μm and high ly=80μm, and the thickness of the polyimide material in the intermediate medium and the basement medium are t= 22μm and s=5μm respectively, at the same time, I set the metal bar width W and the cell structure cycle a, b of different size parameters, they are: w=28μm,20μm,14μm, 10μm;a=168μm, b=104μm,a=210μm, b=130μm,a=252μm, b=156μm. The element structure of the metamaterial is formed by the optimization design of the structural parameters. The structure of the same plane (A and B, A * and B*) is a rotational symmetry with 180° for the z-axis, and the U-ring structure at the first layer is translated to obtain the second layer U-ring structure. The structure presents a periodic distribution on the XY plane, which forms a planar metamaterial. All simulations were carried out using time-based solver CST microwave studio. Toroidal resonance can be excited by the incident field (Ex) polarized perpendicular to the arm of the U-structure High-frequency **F=0.865THz.**In the frequency **F=0.865THz**, the electromagnetic field distribution and the surface current distribution are obtained through the simulation of the electromagnetic field, and the toroidal dipole is observed from the magnetic field distribution map. **Fig**. 2 is the curve of transmission rate obtained by simulation.

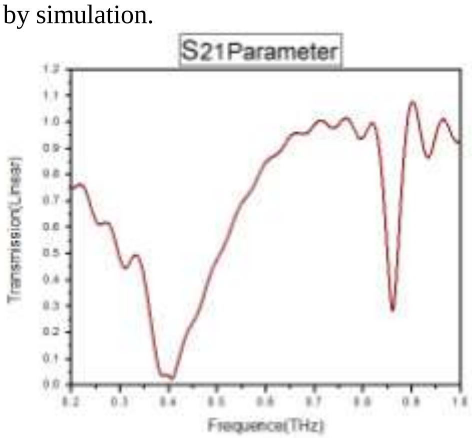

Figure 2: Transmission curve

Fig. 3 is the surface current distribution of the four U-SHAPEd structure. The U-shaped metal ring produces an annular current along the metal ring under the action of electromagnetic radiation. From **FIG**. 3, we can see that the current direction of A, A * and B， B* ring is the same; A, A * producing a magnetic dipole moment opposite to B， B*. The four magnetic dipoles are connected at the end to form a **toroidal dipole** along the y-axis.

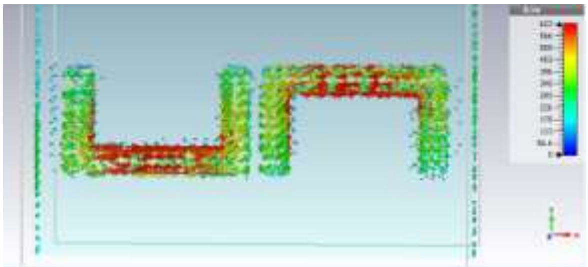

Figure 3: Surface current distribution of four U-SHAPE Structure

Fig. 4 is the distribution of the magnetic field of the four U-shaped structures. As can be seen from **Fig**. 4, the four U-shaped structural metamaterial produces a toroidal dipole, this is because in the cell structure of the left and right sides of the U-ring forming the annular magnetic field along the y-axis of the toroidal dipole moment

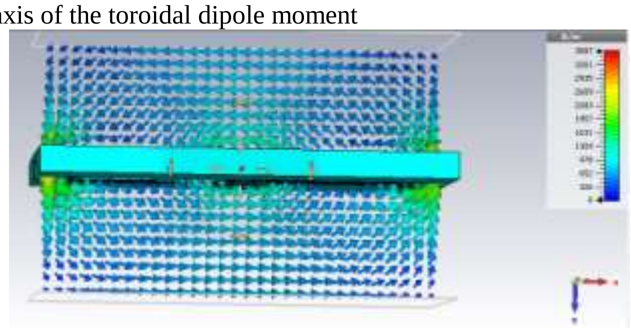

Figure 4: Magnetic field distribution of four U-SHAPE structure

3. Structure parameters of metamaterial

3.1 The influence of the structure with width W of the metamaterial

The influence of W on the transmission rate (transmission) at a certain frequency can be found only when the W (U-shaped metal width) is changed without any other factors. As shown in **Fig**ure 5(a), with the increase of U-shaped metal width w (from 10μm, 14μm, 18μm,24 μm to 28μm), the transmission waveform will have a significant blue shift, low frequency resonant varied from **0.3535THz to 0.4495THz**, the corresponding Q value from 9.5 to 13.6 (as shown in Figure 5(b). For the amplitude of the waveform, it can be seen from the graph that the W increase has little influence on the harmonic amplitude of the 0.3THz, but the value of the harmonic amplitude around 0.8THz decreases with the increase of W. With the increase of U-shaped metal bar width, the side width of two U-shaped structures increases, and the coupling of U-shaped metal rings also increases, which makes the frequency move to the high frequency

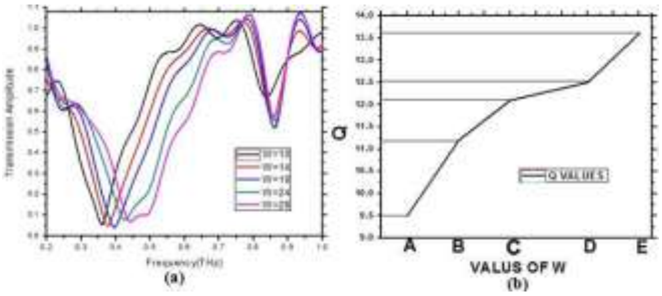

Figure 5: Transmission and Q curve under different width W

The structure of the metamaterial is mainly composed of four U-shaped metal rings. Each U-shaped structure can be regarded as an open resonant ring, and the frequency of the open resonant ring is defined according to ω= (1/2LC). The L is inductance, which is represented by the U-shaped metal in the model and can be replaced by the direct conductor inductance model. C is a capacitor, which can be represented by openings of a U-shaped metal ring. Because the L∝l/s, s is a metal cross-sectional area, l is the metal length, the C∝s/d, s is the area of the metal strips on both sides of the U-shaped metal, and d is the distance between the two metal strips. The frequency response formula of the open resonant ring shows the product of the frequency inversely proportional to the inductance (L) and the capacitance (C).When W increases in the four U-SHAPE structures, the metal section area (S) increases but the length (l) does not change, so the inductance (l) decreases. As the metal bars widen, the metal bars on both sides of the U-shaped metal are reduced (d), but the length of the metal bar (S) does not change, so the capacitance (C) increases. It can be known that with the increase of W, inductance decreases capacitance increase, but the inductance decreases the amplitude is greater than the capacitance increase amplitude, then the total frequency increases. Conversely, because the metal section area is proportional to length and width, and with the reduction of the product of the reduced amplitude will be less and less, that is, at this time the impact of the change of the inductance can be neglected, and capacitance changes are very small, so further reduce the W, resonant frequency is not affected by the width)".

3.2 The influence of the structure parameter period a and b of metamaterial

The other parameters of the material element structure are not changed, and the cycle parameters **a** and **b** of the material element structure are changed, and the different periodic dimensions are simulated and analyzed. From the simulation transmission curve of **Fig.6**, which corresponds to **A:a=294μm, b=182μm,B:a=252μm, b=156μm,C:a=210μm and b=130μm, D:a=168μm, b=104μm,** the cell structures of different periodic sizes can be found in the second resonant frequency. Toroidal dipole resonant response is generated at 0.354THz, 0.479THz and 0.492THz. With the increase of the structure period of the U-shaped cell, the resonant trough is blue shifted, the resonant frequency increases from 0.354THz to 0.492THz and the amplitude of resonance is increased from 0.02 to 0.04, and the resonant response of the toroidal dipole is gradually weakened. From **Fig** 6(b), shows that the Q value decreases significantly with the increase of the cycle size (from 17.7 to 2.7). Because the higher the quality factor (q value) indicates the less loss of the incident electromagnetic wave, the higher Q value is very advantageous to the normal work of most electromagnetic wave devices [15 16]. It can be considered that the periodic dimension of **D (a=168μm and b=104μm)** is relatively good, and the toroidal dipole response is stronger, the transmission rate is small and the Q value is larger. The blue shift of resonant response frequency (from f= 0.749THz increased to 0.892THz because as the cycle size decreases (A to D), the distance between the left and right parts of the two-U-shaped Metamaterial cell structure decreases correspondingly, the coupling action of the near-field dipole of two parts of a single metal ring is enhanced, while the radiation damping of the material structure section decreases, the radiation loss decreases, and the response of the toroidal dipole is gradually increased.

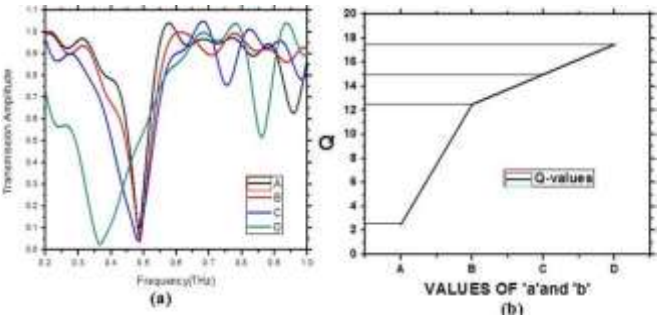

Figure 6: Transmission curve under different values of a and b

4. Summary and Conclusion

This paper mainly introduces the development process of the toroidal dipole based on the metamaterial, uses the CST software to carry on the electromagnetic simulation, analyzes the surface current distribution and the magnetic field distribution, and realizes the toroidal dipole phenomenon in the terahertz band. Then, the variation of the toroidal dipole, the resonant frequency, the transmission amplitude and the Q value of different width W and cycle a and b are analyzed. As the W increases, the toroidal dipole response is enhanced, the resonance frequency is blue shift, the transmission amplitude value decreases, the Q value increases. With the increase of **a** and **b**, the toroidal dipole response weakens, the resonant point frequency redshift, the transmission amplitude value increases, Q value decreases. The unique characteristics of terahertz wave and toroidal dipole electromagnetic response characteristics of the combination will produce new electromagnetic characteristics and new physical phenomena [1], therefore, it is of great value to study the toroidal dipole in Terahertz band. The four U-shaped metamaterial structures just realize the toroidal dipole of terahertz bands; the model has important research value. Because of the good performance of the toroidal dipole and the advantages of low cost, it can be applied to the circularly polarized deflector, polarizer and optical device.

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