Metamaterials-based terahertz filter

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***Abstract*- We investigate the terahertz (THz) responses of fractal concentric rectangular square resonators (CRS) induced by different mode coupling mechanisms. Near-field coupling results in the resonant mode redshift, while conductive coupling cause the results in the resonant mode blueshift. One can achieve a high Q mode with strong modulation depth by switching the capacitive coupling to conductive coupling in a fractal meta-atom.**

I. INTRODUCTION

The THz responses of metamaterials (MMs) are attributed to the shape, size, orientation, layout, and period of meta-atom (MA), which is a unit cell composed of resonators. Normally, the scale of single MAs needs to be ten times smaller than the operation wavelength, which restricts the miniaturization of device volume. A fractal structure-based MA pattern become a promising approach, which diverge the surface area of MAs within a finite volume[1]. It is found that one can achieve multi-frequency operation or broadband tenability in a MM composed of fractal MAs[1,2]. Actually, a fractal MA is a composite of many resonators at different scales. Therefore, it is significant to understanding the interaction between resonators of different scales in a fractal MA. The earlier works indicate that the interplay of resonating modes leads to unexpected THz response in coupled MAs based on a composite of wires and split-ring resonators, such as plasmon-induced transparency[3,4] and ultrasharp mode coming out[5]. The aforementioned two intrigue effects offer advantages for tunable filter and biosensor application. Therefore, it is significant to explore the THz response and mode coupling effect between the resonators of different fractal levels in one MA. we propose two types of fractal MAs made of concentric rectangular square resonators (CRS).In the first type of MA, each generated CRS is a simple duplication of the initiator CRS with a reduced length of boundary at the square root of 0.5to the adjacent CRS. The shape and orientation of generated CRS is totally the same as the initiator. This type of MA is termed as independent concentric rectangular square (I-CRS). In the second type of MA, the shape and reduction ratio of resonators are the same as I-CRS, however, the orientation of the generated one is rotated $\pi/2$ radius to the initiator. Since the reduction ratio is the square root of 0.5, the 4 vertices of smaller CRS resonators contact exactly the mid-point of the quadrilateral of adjacent larger CRS. This type of MAs is termed as junctional concentric rectangular squares (J-CRS). According to the fractal geometry [1,2], the fractal level refers to the number of generated smaller layer of CRS. As a consequence, the THz response of I-CRS and J-CRS can be compared at the same fractal scale. Due to the centro-symmetry of CRS, the THz polarization sensitive effect is excluded in our experiment. The THz transmittance of above fractal MAs are calibrated using a standard THz time-domain spectroscopy (THz-TDS) setup. The surface currents and electric field strengths of resonance modes are simulated. Finally, the origin of THz response of above two types of fractal MAs is discussed.

II. RESULTS

A. Figures and Tables

The geometric parameters of fractal MAs are described as belows: The patterns of MAs are transferred onto 625 μm-thick <100>-oriented semi-insulating gallium arsenide (SI-GaAs) substrates by photolithography.The incident THz polarization and the pattern direction of I-CRS and J-CRS samples are presented in Fig. 1(a). Owing to the dielectric isotropy of <100>-oriented crystal, the normal line to the metal pattern layer is along with the crystallographic orientation of SI-GaAs. The relation between the surface

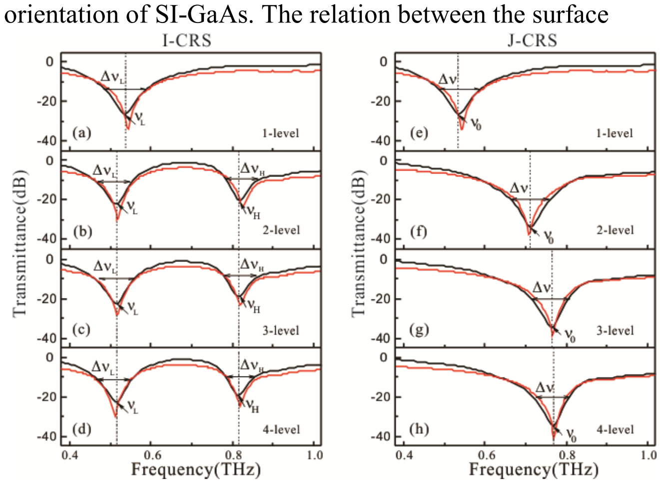

Figure 1. (a) ~ (d) THz transmittance of I-CRS; (e) ~ (h) THz transmittance of J-CRS. Black solid line: Experimental data. Red solid line: Simulation data. Dashed line: the central position of resonance modes

orientation of metal patterns and SI-GaAs substrate is illustrated in Fig.1 (b). The effective area of fractal MAs is 10 mm□10 mm. The MAs are metallized by a layer of 120 nm thick gold (Au) and 5 nm thick titanium (Ti). The lattice period is 100 μm, the quadrilateral-length of the first level CRS resonator is 65 μm, of which the width is 4 μm, respectively.

B. THz Response

The THz transmittance of both types of fractal MAs are presented in Fig 2. There are only two visible resonance modes in I-CRS. The high-order resonance frequencies of I-CRS are invisible even though the fractal is above 2. To J-CRS, however, the multiple resonance modes disappear while a single resonance mode occurs in the transmission spectrum of J-CRS. It is evident that ν_L and ν_H modes of I-CRS occurs redshift behavior with increasing the fractal level. Correspondingly, the ν_0 mode of J-CRS performs an obvious frequency blueshift. Meanwhile, the linewidth of ν_L and ν_H modes become narrower while that of ν_0 become broader. The results indicate that the Q factors of resonance modes of both MAs increase monotonically with the fractal levels. The surface current of resonance modes of both types of MAs are simulated to reveal the origin of variation of THz response.

C. Analysis

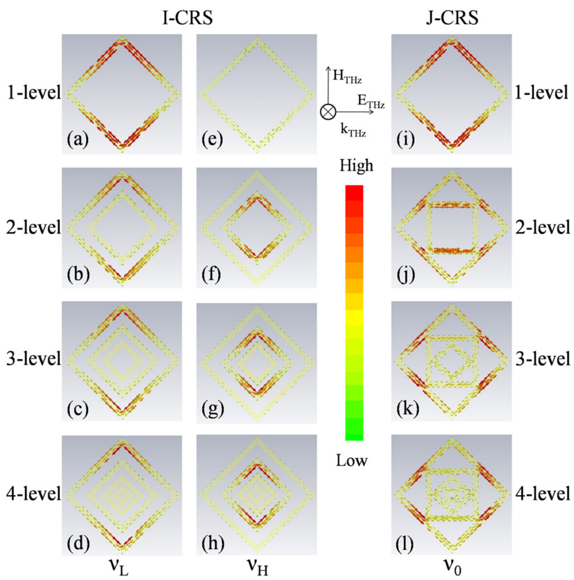

Fig. 2. (a) ~ (d) Surface currents of vL of I-CRS; (e) ~ (h) Surface currents of ν_H of I-CRS. (i) ~ (l); Surface currents of ν_0 of J-CRS. E_{THz}: the electric field of incident THz radiation. H_{THz}: the magnetic field of incident THz radiation. K_{THz}: the wave vector of incident THz radiation. Color bars: the relative strength of surface current.

It is evident that anti-parallel currents are produced in adjacent CRS resonators. The intensity of surface current indicates that single CRS experiences a strong coupling to the incident terahertz wave. When the fractal level increases from 2 to 4, however, the generated smaller CRS is weakly coupled to the incident THz radiation through capacitive interaction between the quadrilaterals of adjacent CRS. Therefore, a destructive interference of the scattered fields between the two adjacent resonators leads to the frequency redshift of ν_L, which is in agreement with the results in Fig.2. The similar phenomena are also observed in simulated surface current at ν_H, as shown in Fig. 3(e)~(h). The earlier works indicate that the capacitive mode coupling between two immediately adjacent resonators is proposed to be the origin of modes redshift. When the fractal levels increase up to 3 or 4, the outermost CRS and the innermost CRS undergoes much weaker coupling to the incident THz radiation field, hence the THz response for I-CRS mainly derives from the mode coupling of the biggest two adjacent resonators. On the other hand, there is no opposite surface current in J-CRS of different fractal levels. At the mode of ν_0, the current is strongly accumulated at the connected vertices of the adjacent CRS. The connected vertices play the role as the divergence points of the surface currents, which induce a current leakage from the outer large CRS to the inner small CRS. Since a single CRS works as a dipole oscillator, the effective length of the oscillator is reduced by the connection between the adjacent of CRS. The smaller the size of dipole oscillator, the higher the resonance frequency[5]. Therefore, the mode blueshift is attributed to the conductive coupling between the adjacent resonators in J-CRS.

III. Summary

In summary, the THz electromagnetic responses in fractal meta-atoms based on two-types of CRS resonators are investigated. In I-CRS, the capacitive coupling induces the redshift of multiple modes and reduces the MD. In J-CRS, the multiple modes are coupled conductively into a single resonance mode. The resonance modes appear to be blueshift in frequency spectra and the resonance strengths are increased when the fractal level increases. One can achieve a high Q mode with strong MD by switching the capacitive coupling to conductive coupling in a fractal MAs.

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