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Tunable multi-resonance of terahertz metamaterial using split-disk resonators

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ABSTRACT
We present three tunable multi-resonance of terahertz (THz) metamaterials. They are composed of single-, dual-, and triple-split-disk resonators (SDRs) on Si substrates, which are denoted as SDR-1, SDR-2, and SDR-3, respectively. They exhibit extraordinary electromagnetic characteristics. SDR-1 exhibits polarization-dependence owing to the asymmetrical SDR structure. To increase the flexibility and applicability of SDR configuration, SDR-2 and SDR-3 are presented to modify the distances between the SDR layers. By moving the top SDR layer of SDR-2, a controllable resonance with a 0.32 THz shifting and tunable free spectrum range (FSR) of 0.15 THz at transverse magnetic mode is achieved, while an electromagnetically induced transparency-like effect appears at the transverse electric mode. The spectral bandwidth of SDR-3 can be tuned to 0.10 THz, and the resonant intensity becomes controllable by moving the middle SDR layer of SDR-3. Furthermore, by moving the top SDR layer of SDR-3, the tuning ranges of resonance, FSR, and bandwidth of SDR-3 are 0.23 THz, 0.20 THz, and 0.08 THz, respectively. Such designs of SDR configurations provide a high-efficient THz resonator in the THz-wave applications such as filters, switches, polarizers, sensors, imaging, and so on.

I. INTRODUCTION

Terahertz (THz) wave is the electromagnetic spectrum between the microwave and infrared wavelength range. It is a hot technique topic and is hopefully to be widely employed in various applications including but not limited to semi-conductor lasers, imaging, detectors, sensors, and radars.1–9 The major drawback of the THz wave is the lack of high-efficient interaction coupling with the device because the THz wave has high transmission in common plastics, insulation materials, woods, and rubbers, and high reflection for metals.10–19 These traditional materials cannot be interacted well with the THz wave, which will impede the practical applications of the THz wave technique.

Recently, metamaterials are artificially made materials, which exhibit extraordinary electromagnetic characteristics that cannot be found in natural materials, such as negative refraction index,10,11 perfect absorption,12,13 Fano resonance,14 and so on. The emergence of metamaterials provides the potential possibilities to develop the THz optoelectronic applications. According to the theory of the Drude–Lorentz model, the characteristics of the incident electromagnetic wave could be interacted and then controlled by the metamaterial configurations.15,16 Many literature studies have been reported for diversified metamaterials based on the configuration of the split-ring resonator (SRR).17–23 The variations of SRR configurations include V-shaped SRR,17,18 C-shaped SRR,19 U-shaped SRR,20–22 and three-dimensional (3D) SRR.23,24 Moreover, they can also combine with two-dimensional materials (such as graphene),25–27 phase change materials,28 super conductors,29,30 and semiconductors.18,31

To increase the flexibility and applicability of the metamaterial in the THz frequency range, many tuning methods have been presented to control the resonant frequency, phase, amplitude, and
polarization of the incident light by using thermal control, \textsuperscript{31,35–37} optical pumping, \textsuperscript{3} liquid crystal, \textsuperscript{39,40} micro-electro-mechanical systems (MEMS) control, \textsuperscript{39–41} and so on. These control methods possess huge potential in practical application fields such as perfect absorption, switches, antennae, filters, sensors, superlenses, cloaking devices, and programmable devices spanning the visible, infrared, and THz spectral ranges. \textsuperscript{37,43–50} These controllable methods are always limited by the small tuning range and nonlinear characteristics. Therefore, the high-efficient tuning methods and configuration designs of the metamaterial without extra implanted materials, e.g., liquid crystal, are crucial to improve the electromagnetic performances of metamaterial devices.

In this study, we present a high-efficient design of tunable THz metamaterial with multi-bandwidth by using multiple split-disk resonators (SDRs). The proposed tunable SDRs are, respectively, composed of single-, dual-, and triple-SDR layers on Si substrates. To investigate the electromagnetic responses of tunable SDRs, three-dimensional finite difference time-domain (FDTD) solutions are employed to simulate the optical properties of SDRs in the full-field plane electromagnetic wave. The propagation direction of the incident light is set to be perpendicular to the \( x \)-\( y \) plane in the numerical simulations, and periodic boundary conditions are adopted along the \( x \)- and \( y \)-axis, while perfectly matched layer boundaries are assumed along the \( z \)-direction. The spectrum monitor is set on the bottom side of the proposed device to calculate the transmission spectra. Three SDR devices exhibit the characteristics of polarization-dependence, tunable resonance, tunable bandwidth, and large controllable free spectrum range (FSR).

II. MATERIALS AND METHODS

Figure 1(a) shows the schematic drawing of the proposed SDRs, including the incident transverse electric (TE) and transverse magnetic (TM) waves, while \( E, H \), and \( k \) are the electrical field, magnetic field, and wave vector, respectively. The configurations of SDRs are composed of single-, dual-, and triple-SDR layers to form the SDR-1, SDR-2, and SDR-3, respectively. The SDRs are tailored Au layers on Si substrates. The permittivities of Au and Si materials are simulated as constant in this study. They are \( 10^\text{7} \) for the Au layer and 10 for the Si substrate. The materials and thicknesses of SDR layers are tailored to be Au thin films in 300 nm thickness. The geometrical parameters of SDRs are illustrated in Fig. 1(b), where \( D, W \), and \( L_s \) are the disk diameter (\( D = 60 \) \( \mu \)m), split width (\( W = 4 \) \( \mu \)m), and split length (\( L_s = 30 \) \( \mu \)m) of the SDR structure, respectively. The period of SDRs are kept constant as \( 80 \) \( \mu \)m \( \times \) \( 100 \) \( \mu \)m. Figures 1(c) and 1(d) show the cross-sectional views of SDR-2 and SDR-3 along the red dashed-squares in Fig. 1(a), respectively. There is a height (\( h_1 \)) between bottom and top SDRs for SDR-2, while there are heights from bottom to middle SDRs (\( h_i \)) and from bottom to top SDRs (\( h_2 \)) for SDR-3. By changing these \( h_1 \) and \( h_2 \) values, the resonances of SDR-2 and SDR-3 could be tuned owing to the guide-mode theory to generate the multi-resonances. According to the Drude–Lorentz model, \textsuperscript{39,40} the resonant frequency is a function of the refraction index of electromagnetic radiation. This resonant frequency of an external frequency-dependent perturbation can be expressed as:

\[
n_{\text{EM}} = \left(1 - \frac{f^2 - f_p^2}{f^2 - f_{\text{LC}}^2}\right) \left(1 - \frac{f^2 - f_{\text{LC}}^2}{f^2 - f_{\text{CE}}^2}\right) \left(1 - \frac{f^2 - f_{\text{CE}}^2}{f^2 - f_{\text{CM}}^2}\right),
\]

where \( f \) is the frequency, \( f_p \) is the plasma frequency, \( f_{\text{LC}} \) is the resonant frequency, and \( F \) is a dimensionless quantity, as the subscripts \( e \) and \( m \) refer to electric and magnetic response, respectively. Here, \( L_{\text{eq}} \) and \( C_{\text{eq}} \) are the equivalent capacitance and inductance in the SDR configuration. \( f_{\text{LC}} \) is derived to be a function of geometrical parameters. In the designs of SDR-2 and SDR-3, \( C_1 \) and \( C_2 \) are two types of capacitances formed within the gaps of SDRs and vertical spaces between two SDRs, which can be represented as:

\[
C_i = \frac{\epsilon_0 \epsilon_s \ell_i S}{W}, \quad C_{\text{eq}} = \frac{\epsilon_0 \epsilon_s S}{h_i},
\]

where \( \epsilon_0 \) is the free space permittivity, \( \epsilon_s \) is the relative permittivity of the materials within the gap, \( i \) is the thickness of the SDR layer, and \( S \) is the area along the \( x \)-\( y \) plane of the tailored Au thin film of the SDR structure. \( i \) is one or two, the capacitance between the bottom and second SDRs or the top and middle SDRs. Therefore, the resonant frequency can be tuned by changing the distances between two SDR layers, i.e., \( h_1 \) and \( h_2 \) values along the \( z \)-axis direction.

III. RESULTS AND DISCUSSIONS

Figure 2(a) shows the transmission spectra of SDR-1 at TE and TM modes. At TE mode, there are five resonances at \( 0.28 \) THz, \( 0.58 \) THz, \( 0.77 \) THz, \( 0.88 \) THz, and \( 0.94 \) THz. These resonances are generated within the split of SDR-1 as the electric (E) and magnetic (H) field distributions shown in Figs. 2(b) and 2(c), respectively. The monitors of field distributions are installed at \( 0.58 \) THz at TE mode. It can be seen that the E-field and H-field energies are focused...
on the contour of split. It means that the resonance of SDR-1 at the TE mode is generated by LC resonance. At TM mode, there is single-resonance at 0.52 THz, as shown in Fig. 2(a), which is generated by one inductive element (the frames or the loops) within SDR-1 as the E- and H-field distributions shown in Figs. 2(b) and 2(c), respectively. The monitors of field distributions are installed at 0.52 THz at TM mode. The E-field distributions are focused on the contour of disk rather than constraining in the split of SDR-1. It indicates the resonance of SDR-1 at TM mode generated by dipole resonance. As the above-mentioned results, SDR-1 exhibits polarization-dependent characteristics.

Figures 3(a) and 3(b) show the transmission spectra of SDR-2 with different $h_1$ values changing from 6 $\mu$m to 1 $\mu$m at TM and TE modes, respectively. The electromagnetic responses of SDR-2 are distinctly different at TM and TE modes due to the asymmetrical SDR-2 structure. In Fig. 3(a), two resonances are red shifted from 0.53 THz to 0.42 THz and 1.10 THz to 0.78 THz for first and second resonances, respectively. The tuning ranges of resonances are 0.11 THz (first resonance) and 0.32 THz (second resonance) for SDR-2 changing $h_1$ values from 6 $\mu$m to 1 $\mu$m. The corresponding FSR of the first resonance is modified from 0.52 THz to 0.37 THz with a tuning range of 0.15 THz. The corresponding E- and H-field distributions monitored along the x–z plane at TM mode are illustrated in Figs. 4(a) and 4(b), respectively. The E-field is distributed in the space between two SDRs, while the H-field is distributed around the SDRs except the split region. In Fig. 3(b), there are multi-resonances of SDR-2 by changing $h_1$ values at TE mode. Four resonances are red shifted from 0.27 THz to 0.22 THz, 0.56 THz to 0.42 THz, 0.60 THz to 0.49 THz, and 0.76 THz to 0.66 THz. Their tuning ranges are 0.05 THz, 0.14 THz, 0.11 THz, and 0.1 THz, respectively. It is worth noting that the second resonance of $h_1 = 4$ $\mu$m is Fano resonance. When the $h_1$ value is changed to 3 $\mu$m, this Fano resonance vanishes. It is because two resonant states of SDR-2 are exactly destructive interference under the condition of $h_1 = 3$ $\mu$m, and then, the Fano resonance...
FIG. 4. (a) and (c) E-field and (b) and (d) H-field distributions of SDR-2 with $h_1 = 1 \mu m$ to $h_1 = 5 \mu m$ monitored along the $x$–$z$ plane at (a) and (b) TM and (c) and (d) TE modes.

overlaps with another resonance at 0.57 THz. The E- and H-field distributions at TE mode are illustrated in Figs. 4(c) and 4(d), respectively. The E-field energy around two SDRs is coupled strongly in the space of SDRs. On the contrary, the H-field energy is focused on the top split region of SDRs. This electromagnetic characteristic of SDR-2 exhibits the potential uses in polarization switch and optical switch applications.

For the design of SDR-3, there are two tuning mechanisms to modify the middle and top SDRs along the $z$-axis direction while other SDR parameters are fixed. It is because the bottom SDR layer is in contact with the Si substrate surface and the other two SDRs are floating. First, the top SDR layer is fixed and the $h_2$ value is kept constant as 10 $\mu m$. By changing the $h_1$ value from 5 $\mu m$ to 1 $\mu m$, the transmission spectra of SDR-3 at TM and TE modes are shown in Figs. 5(a) and 5(b), respectively. There are three resonances at 0.54 THz, 0.81 THz, and 1.26 THz for the condition of $h_1 = 5 \mu m$ at TM mode, as shown in Fig. 5(a). By changing the $h_1$ value from 5 $\mu m$ to 1 $\mu m$, the first resonance is red shifted from 0.54 THz to 0.41 THz with a tuning range of 0.13 THz. The corresponding bandwidth of the first resonance becomes narrower from 0.12 THz to 0.02 THz.

On the contrary, the bandwidth of the second resonance becomes broader from 0.02 THz to 0.12 THz. The corresponding E-field distributions are shown in Fig. 6(a). The E-field energy is constrained in the split region, and the coupling intensity between the top and middle SDR layers is weaker. The H-field energy is strongly coupled in the space between the top and middle SDR layers and gradually weakened by decreasing the $h_1$ value, as shown in Fig. 6(b). Furthermore, there is a Fano resonance at 1.27 THz at TM mode. This Fano resonance is red shifted from 1.27 THz to 1.10 THz by changing the $h_1$ value from 5 $\mu m$ to 1 $\mu m$. The corresponding resonant intensity is gradually decreased and then vanishes under the condition of $h_1 = 1 \mu m$ because the fields coupling between the top and middle SDR layers become weaker with the decrease in the $h_1$ value. At TE mode, five resonances are red shifted from 0.27 THz to 0.12 THz, 0.48 THz to 0.41 THz, 0.57 THz to 0.48 THz, 0.70 THz to 0.64 THz, and 0.76 THz to 0.66 THz, respectively, by changing $h_1$ values, as shown in Fig. 6(b). The second resonance is the Fano resonance generated from the stronger capacitance coupling within the SDRs. It is enhanced by the change from $h_1 = 5 \mu m$ to $h_1 = 1 \mu m$ due to the inference coming from the bottom SDR layer, and its bandwidth becomes

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FIG. 5. Transmission spectra of SDR-3 by changing the $h_1$ value from 5 $\mu$m to 1 $\mu$m, while the $h_2$ value is kept constant as 10 $\mu$m at (a) TM and (b) TE modes.

FIG. 6. (a) and (c) E-field and (b) and (d) H-field distributions of SDR-3 with $h_1 = 1$ $\mu$m to $h_1 = 5$ $\mu$m monitored along the x–z plane at (a) and (b) TM and (c) and (d) TE modes.
FIG. 7. Transmission spectra of SDR-3 by changing the $h_2$ value from 6 $\mu$m to 2 $\mu$m, while the $h_1$ value is kept constant as 1 $\mu$m at (a) TM and (b) TE modes.

FIG. 8. (a) and (c) E-field and (b) and (d) H-field distributions of SDR-3 with $h_2 = 2$ $\mu$m to $h_2 = 6$ $\mu$m monitored along the x–z plane at (a) and (b) TM and (c) and (d) TE modes.
broader as 0.01 THz. The corresponding E- and H-field distributions are shown in Figs. 6(c) and 6(d), respectively. The coupling intensity of the E-field energy is gradually enhanced when two SDR layers are closer. Meanwhile, the H-field energy is confined within the split region of the top SDR layer and then gradually gets transferred to the bottom SDR layer caused from the coupling efficiency, which is enhanced between the middle and bottom SDR layers by decreasing the $h_1$ value.

Figures 7(a) and 7(b) show the transmission spectra of SDR-3 by changing the $h_2$ value at TM and TE modes, respectively, and keeping the $h_1$ value constant as 1 $\mu$m. In Fig. 7(a), the first and third resonances of SDR-3 are almost kept constant around 0.40 THz and 1.10 THz by changing the $h_2$ value from 6 $\mu$m to 3 $\mu$m at TM mode. The variations are within 0.01 THz. Apparently, the second resonance is red shifted from 0.74 THz to 0.50 THz by changing the $h_2$ value from 6 $\mu$m to 2 $\mu$m. The tuning range of resonance is 0.23 THz. The corresponding bandwidth becomes narrower from 0.13 THz to 0.05 THz with a tuning range of 0.08 THz. Furthermore, the FSR between the first and second resonances can be tuned from 0.32 THz to 0.12 THz with a range of 0.2 THz. The E-field distributions are concentrated around the contour of SDRs, as shown in Fig. 8(a). The H-field distributions are confined between the top and middle SDR layers, as shown in Fig. 8(b). The third resonance is Fano resonance, which becomes gradually weaker by decreasing the $h_2$ value. At TE mode, there are four resonances at 0.22 THz, 0.39 THz, 0.48 THz, and 0.61 THz. The first and third resonances are almost kept constant with a little variation of 0.02 THz. The second resonance is red shifted from 0.39 THz to 0.28 THz by changing the $h_2$ value from 6 $\mu$m to 2 $\mu$m. The tuning range of resonance is 0.11 THz. Furthermore, the FSR between the first and second resonances can be tuned from 0.17 THz to 0.07 THz with a tuning range of 0.10 THz while the FSR between the second and third resonances can be inversely broadened from 0.09 THz to 0.18 THz with a tuning range of 0.09 THz by changing the $h_2$ value from 6 $\mu$m to 2 $\mu$m. Owing to the change of interaction between SDR layers, the corresponding E- and H-field distributions of the second resonance are presented in Figs. 8(c) and 8(d), respectively. The E-field energy is distributed in the space between the top and middle SDR layers. On the contrary, the H-field energy is confined in the split region. The fourth resonance is red shifted from 0.61 THz ($h_2 = 6 \mu$m) to 0.55 THz ($h_2 = 2 \mu$m) with a tuning range of 0.06 THz. The FSR between the third and fourth resonances is narrowed from 0.13 THz to 0.09 THz with a tuning range of 0.04 THz. These results indicate that the SDR-3 device is multi-functional, which can be used in the tunable filter, tunable FSR, and tunable optoelectronic THz-wave applications.

IV. CONCLUSIONS

In conclusion, we present a high-efficiency design of tunable THz metamaterial to tune the resonance, FSR, and bandwidth by using SDR layers. These results show that these are single-, dual-, and triple-resonances depending on polarization and the specific design of SDRs at TM mode. By changing the $h_1$ value of SDR-2, the tuning ranges of resonance and FSR are 0.32 THz and 0.15 THz at TM mode, respectively. At TE mode, the resonance could abruptly generate or vanish by moving the SDR layer, which provides a potential application in the future THz switches. For SDR-3, moving the top SDR layer or the middle SDR layer leads to different results. By fixing the top SDR layer and moving the middle one, the resonant bandwidth could be tuned in the range of 0.10 THz and the resonance is gradually enhanced or weakened at TE and TM modes, respectively. Moreover, by fixing the middle SDR layer and moving the top one, the resonant bandwidth could be controlled with a range of 0.08 THz and the tuning range of FSR is up to 0.20 THz at TM mode, while two FSRs can be tuned in the ranges of 0.10 THz and 0.09 THz at TE mode. These characteristics indicate the SDR designs potentially to be realized as a tunable filter by using the MEMS technique to modify the electromagnetic response of SDR with reconfigurable geometrical dimensions. Moreover, the proposed device can be a polarization switch by manipulating the geometrical dimensions of SDR and changing the incident angle of light. Such an SDR design provides a high-efficient resonator in THz-wave applications, which opens up an avenue for the real-world applications in THz filters, THz polarizers, THz switches, THz sensors, THz imaging, and so on.

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