Characterizations of Tunable Terahertz Metamaterial by Using Asymmetrical Double Split-Ring Resonators (ADSRRs)

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***Abstract*-Four types of tunable terahertz (THz) metamaterials by using asymmetrical double split-ring resonators (ADSRRs) are presented, which are composed of Al material on Si substrate. These ADSRRs have different optical characterizations in THz frequency range. They exhibit TE polarization-dependent and TM polarization-independent by changing resonant gaps. The resonant shift of LC mode is 0.19 THz at TE polarization and invariant at TM polarization.**

Keywords—metamaterials, asymmetrical double SRRs, high switching ratio, multi-functionalities

I. INTRODUCTION

Tunable terahertz (THz) metamaterial is a candidate material of electro-optics devices, such as filter, polarizer, resonator, switch and so on, owing to it has extraordinary electromagnetic properties [1-3]. Recently, there are many literatures reported about THz metamaterial designs deriving from split-ring resonators (SRRs). Among of these SRRs, the tunable methods include thermal change [3], diverse voltage [1], and structural reconfiguration [1, 2] to realize tunable THz metamaterial for widespread applications. The traditional SRR designs are symmetrical or asymmetrical configurations to perform THz filters, THz polarizers, and THz switches [1-3]. However, these SRRs are either polarization-dependent nor polarization-independent caused from the symmetric structure or asymmetric structure with periodic configurations, respectively. It does not have applicability for one single chip with multi-functionalities.

In this study, we proposed four types of tunable THz metamaterials by using asymmetrical double split-ring resonators (ADSRRs). ADSRRs are composited of Al materials on Si substrate. These designs exhibit multi-functional characterizations, such as TE polarization-dependent and TM polarization-independent by changing their geometrical gaps. Therefore, such designs could be used for filters, polarizers, switches, and so on in THz frequency range.

II. MATERIALS AND METHODS

Fig. 1 shows the schematic drawings of four ADSRRs designs. They are configured of inverse SRRs (Design_1), connected square SRRs with slits at inner edge (Design_2), at outer edge (Design)_3), and at middle SRRs (Design_4) as shown in Fig. 1(a-d), respectively. The geometrical dimensions of all metamaterial designs are kept as Al material with 300 nm in thickness, 5 μm in line width (w = 5 μm), 40 μm in unit cell width (a = 40 μm), and 120 × 100 μm^2 in period, respectively. In Fig. 1(a), the periodic structure is 120 × 100 μm^2 modified at equal proportion with increasing gap of SRR (g_1) from 30 μm to 60 μm to monitor electromagnetic behaviors at TE and TM polarizations.

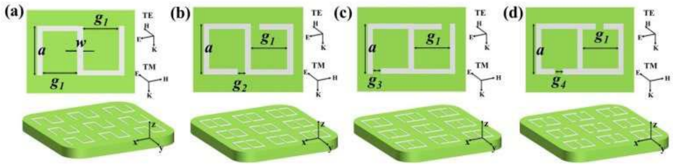

Fig. 1. Schematic drawings of ADSRRs for (a) Design_1, (b) Design_2, (c) Design_3, and (d) Design_4, respectively. All geometrical dimensions of ADSRRs are kept at 300 nm in thickness, a = 40 μm, and w = 5 μm on Si substrate.

Fig. 1(b-d) exhibit the derivatives of Design_1 by adding extra bars with different locations within g_1, i.e. three connected square SRRs with slits at inner (Design_2), outer (Design_3), and middle (Design_4) locations, respectively. Fig .1(b) shows Design_2 with two extra bars parallel to x-axis to form two gaps (g_2) which are adjunct to the central vertical bars. The parameters of a, g_1 and period are kept as 40 μm, 30 μm, and 120 × 100 μm^2, respectively. Similarly, the gap (g_3) of Design_3 was located at two outer vertical wires, while the gap (g_4) of Design_4 was located at the middle of square SRRs as shown in Fig. 1(c) and (d), respectively. To investigate the influence of changing g_1, g_2, g_3, g_4 to four individual designs, the gaps were modified from 0 μm to 10 μm to realize the modulation of metamaterial filtering characterizations because of the resonant frequency of ADSRR is $f = 1/2\pi\sqrt{LC}$, where L and C are inductance and capacitance of ADSRR, respectively.

III. RESULTS AND DISCUSSIONS

Fig. 2 shows the transmission spectra of four designs which exhibit resonance shift by changing gaps operated at TE polarization. Fig. 2(a) shows the resonance shift by increasing g_1, it presents a linear red shift of 0.1 THz as shown in the insert figure of Fig. 2(a). Owing to the g_1 is large, which is insufficient to generate LC resonance. Therefore, LC mode is almost negligible in Design_1, while the main resonance is

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caused from dipole resonance by changing g_1. The corresponding electric (E) and magnetic (H) fields are shown in the insert images of Fig. 2(a), respectively. In Design_2, Design_3, and Design_4, there are two resonances caused from dipole and LC modes [2]. It is clear to be observed that dipole resonance shifts in the vicinity of 0.3 THz are identical for Design_2, 3, and 4 when gaps changing. It is linear blue shift of 0.036 THz for Design_2, 3, and 4 as shown in Fig. 3(a). The second resonances of Design_2, 3, and 4 are LC resonances. They exhibit blue shift under decreasing L and C by increasing the gap width (g_2, g_3, g_4) as shown in Fig. 2(b-d), respectively. These relationships of gaps changing to LC resonances of Design_2, 3, and 4 are shown in Fig. 3(b). They are linear blue shifts of Design_2, 3, and 4 (0.19 THz for Design_2, 0.08 THz for Design_3, 0.19 THz for Design_4), respectively under gap change from 2 μm to 10 μm, which are obvious shift compared to dipolar resonances. The relevant E-field and H-field distributions are shown in the insert images of Fig. 2(b-d) for Design_2, 3, and 4, respectively. The resonant intensity of dipole mode is higher than that of LC mode when gap width is large, while the resonant intensity of dipole mode is lower than that of LC mode when gap width is small. Meanwhile, it can be observed that there is no LC resonance under the condition of gap is zero (g_2, g_3, g_4 = 0 μm) as the black curves shown in Fig. 2(b-d). Furthermore, Design_3 and Design_4 exhibit THz switch function at 0.6 THz, the resonant intensity could be switched from 0.03 to 0.68 compared without and with gap width of ADSRR. The switching ratio is 22.67, which value is higher than those reported in literatures [1-3] and attractive to use in THz optics applications.

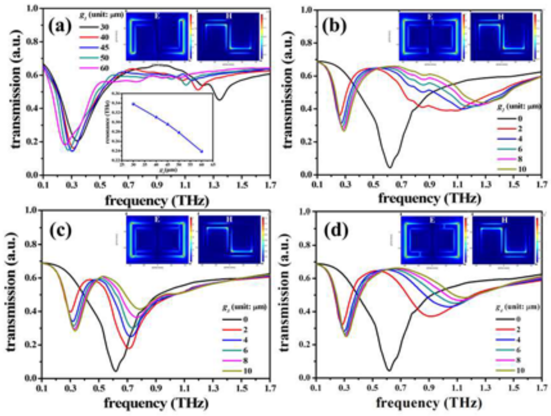

Fig. 2. Transmission spectra of (a) Design_1, (b) Design_2 , (c) Design_3 and (d) Design_4 at TE polarization, respectively.

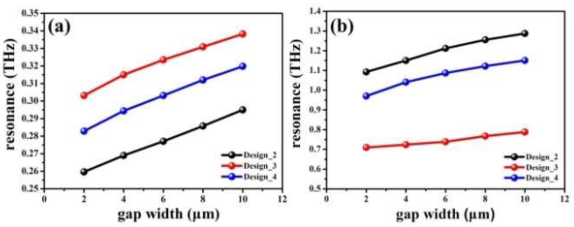

Fig. 3. The relationships of (a) dipolar resonance and (b) LC resonance to gap width for Design_2 (g_2), Design_3 (g_3), and Design_4 (g_4) at TE polarization, respectively.

To further study the electromagnetic characterizations of our ADSRRs designs, we also investigated four ADSRRs operated at TM polarization. As shown in Fig. 4(a), the resonance of Design_1 is 0.96 THz and shows the linear red shift of 0.18 THz by increasing g_1 width from 30 μm to 60 μm. However, the electromagnetic behaviors of Design_2, 3, and 4 are different to Design_1 which are almost identical electromagnetic characterizations by increasing the gap width as shown in Fig. 4(b-d) for Design_2, 3, and 4, respectively. The reasons are E-field at TM polarization is parallel to the capacitance polar electrode width that LC resonance hardly impacts on Design_2, 3, and 4. That can be seen the same E-field distributions at TM polarization as shown in the insert images of Fig. 4(b-d). The resonances are generated by dipole mode and show the same resonant frequencies. It means the proposed Design_2, 3, and 4 are TM polarization-independent. To compare the proposed ADSRRs operated at TE and TM polarizations, ADSRRs are TE polarization-dependence and TM polarization-independent. Therefore, such designs are suitable used in THz filter, THz polarizer, and THz switch applications.

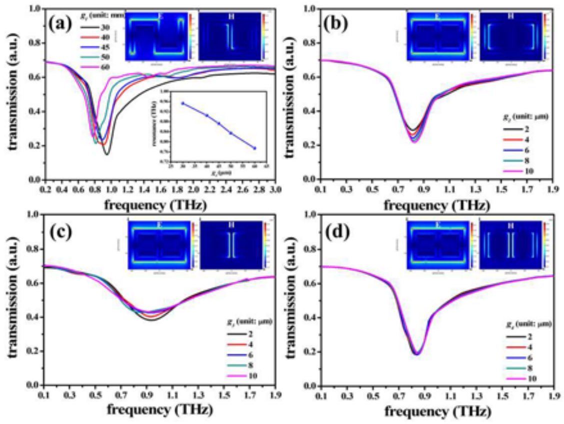

Fig. 4. Transmission spectra of (a) Design_1, (b) Design_2 , (c) Design_3 and (d) Design_4 at TM polarization, respectively.

IV. Conclusion

In conclusion, we developed four types of ADSRRs for tunable THz metamaterials and investigated their electromagnetic characterizations. The maximum tuning range could be reached 0.19 THz and could present different adjustment characterizations by changing gap width within ADSRRs. These designs could make ADSRRs possessing multi-functionalities in THz frequency range. Such methods might reduce chip area and enhance applicability in THz filters, polarizers, and switches applications. In the future, we will utilize ADSRRs to realize environmental sensors and biosensors, etc.

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