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Tailoring terahertz electromagnetic responses of bilayer metamaterials

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ABSTRACT

The electromagnetic (EM) responses of a series of single layer and bilayer terahertz (THz) metamaterials (MMs) were systematically investigated. Bilayer split ring resonators (SRRs) consisting of different SRR units and/or surrounding dielectrics show an excellent capability to tailor and tune EM responses using the combined responses in the SRRs in different layers. By avoiding complex interactions between the layers, easy and quick design for complex multi-responses MMs can be carried out. This tailoring and tuning capability of bilayer MMs shows a great potential for many novel THz applications such as signature control, chem/bio detection, and multi-response sensors.

1. Introduction

In the past decade, metamaterials (MMs) with unique electromagnetic (EM) properties have been the focus of intensive interest in physics and material science. The metamaterials, consisting of metal patterns with sub-wavelength structure, can realize certain EM responses which are impossible to obtain in naturally occurring materials, such as negative refractive index [1], cloaking [2] and "perfect lens" [3]. These new artificial materials have been realized in many regions of the electromagnetic spectrum [4–8] and applied in some novel practical devices, such as modulators [9], absorbers [10,11] and memory [12].

The real advantage of artificial MMs is the fact that it is possible to construct novel materials with precisely engineered EM responses. For most MMs, the designed EM responses depend on the periodical elementary building blocks with sub-wavelength scale ($\lambda/5\sim\lambda/15$). For example, the split ring resonators (SRRs) [13], exhibiting strong magnetic responses across much of the EM spectrum, have become a standard and classic MM structure. The spectral response of SRR arrays can be controlled well by varying their structural geometry and constituent materials. However, the novel EM responses of a certain SRRs are usually limited at a few fixed frequencies. This is a huge limitation for practical applications which always need more flexible and multiple spectral responses, such as the designs which can mimic the responses of chem/bio molecules. Bingham et al. suggested a kind of planar wallpaper group MMs [14], which consisted of three different subunits and responded at three different frequencies. In this way, EM responses in grouped MMs can be designed to coincide with the EM resonances of chem/bio molecules such as biotin. The multi-response can be possibly applied in detecting or sensing technologies by the significant field enhancement for surface enhanced Raman scattering (SERS) [15,16] or by the responses' shifts resulting from changes of the environment index [17–20]. Furthermore, the coupled effects between the combined MMs elements on the same plane were also studied [21–23], which also showed a good tunability for the EM responses.

Even so, the potential application of two-dimensional planar MMs is limited. In planar MMs, the combination with more different units means certainly s reduction of relative function unit densities, and as a consequence, the required EM responses are inevitably weakened. Recently, some researchers have arranged SRRs' MMs layer-by-layer using dielectric spacers to form a quasi-three-dimensional bulk [24–30]. In such bulk MMs, EM responses with unique properties can be purposefully modulated. Most of those researches are focusing on the novel but complex coupling interactions between the elements in different layers [24–26], when the thickness of the spacer layer is much smaller than the wavelength. When the spacer thickness becomes larger, superposition effects are found between different layers, which can be applied in a broadband absorber or filter [27–30], but the intensities of responses in different layers are hardly consistent because of the large spacer thickness. However, if the responses

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of the unit elements remain unchanged after stacking different layers together, the target multi-responses can be "tailored" by simple combination of pre-marked MMs layers. This is very convenient for an easy and quick design for target multi-responses in noticeably underutilized THz sensing, which is a promising technology in many research fields, such as medical and biological applications.

In this letter, we shall focus on tailoring the EM responses of the bi-layer MMs in the THz region. The EM responses in a series of different bi-layer SRRs MMs were systematically investigated by both experiment and simulation. Evident tailoring effects are found in the bi-layer SRRs consisting of different SRR unit groups and/or different surrounding dielectrics. The new bi-layer MMs exhibited good potential for novel THz applications.

2. Experimental section

The samples of bi-layer SRRs MMs were fabricated in a standard microfabrication layer-by-layer process including aligned lithography, metal deposit and lift-off. Wafers coated with S1813 resists were first exposed utilizing a KarlSuess MA6 UV photolithographer. Then a thin Au film was deposited on the samples by thermal evaporation. After lift-off and surface cleaning, a polymeric space layer (SU-8) was spin-coated and baked. On the space layer, another careful alignment exposure, deposit, lift-off process was carried out. Finally, a SU8 cover layer was coated upon the samples as the consistent surrounding dielectric environment. The schematic of a single cell in bi-layer SRRs structure is shown in Fig. 1. In order to investigate the modification effects of the

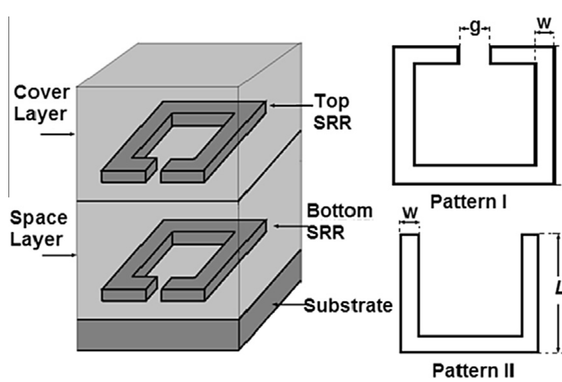

Fig. 1. Schematic of a single cell of bi-layer SRRs structure and geometries of designed SRRs patterns.

surrounding dielectric environment, silicon (thickness of 500 μm) and quartz wafers (thickness of 800 μm) were chosen as substrates separately. The thickness of all Au SRR patterns is 100 nm. Thicknesses of SU8 space layer and cover layer are both 6.9 μm. The area of the aligned arrays on double layers is $6 \times 6\ \text{mm}^2$ with a unit cell size of $55 \times 55\ \mu\text{m}^2$ for all samples. Two groups of SRR patterns were designed as shown in the right part of Fig. 1. Pattern I is a standard SRR pattern, in which the square element size is $L = 43$ μm and the line width w and capacitive gap g are both 4 μm. Pattern II is a U-shape SRR, whose square element size is $L = 38$ μm and line width is $w = 4$ μm. The transmission spectra of bi-layer SRRs MMs were measured by a THz time domain spectroscopy (THz-TDS) system and compared to systematic finite-difference time domain (FDTD) simulations by using a free software package—MEEP [31]. Due to our particular interest in the magnetic responses (the L-C resonance due to circulating current driven by the incident field) of SRRs [32], the polarization of the incident terahertz field was kept parallel to the gap-bearing arm of the SRRs in our experiments and simulations.

3. Results and discussion

3.1. Surrounding dielectric environment

Fig. 2 shows the transmission spectra for the single layer and bilayer MMs with the same SRRs patterns (Pattern I) on different substrates. All the measured results (filled line) match well with simulation results (dashed lines). For the traditional SRRs' L-C resonances, the single layer SRRs' MMs with given dimensions resonate at 0.39 THz on silicon and 0.54 THz on quartz, as seen in Fig. 2(a) and (b), while the resonant peak in the higher frequency side (1.16 THz on silicon and 1.64 THz on quartz) is from linear charge oscillations related to a half-wave oscillation [32]. Compared to the responses in a single layer, there is a new dip at 0.59 THz in the transmission spectrum of bilayer MMs on the silicon substrate (shown in Fig. 2(c)). However, the responses in bilayer MMs on quartz (in Fig. 2(d)) remained unmoved.

For single layer THz MMs, the EM resonance frequencies red shift due to the increase of surrounding dielectric constants, whose influences on THz EM responses have been investigated elsewhere [18,33]. In the terahertz region, the refractive index of SU8 ($n = 1.7$) is much closer to that of quartz ($n = 1.9$) rather than that of silicon ($n = 3.4$). Consequently, the responses of SRRs around SU8 and quartz are much similar than those of SRRs around silicon. This is also the reason why the new 0.59 THz response in bi-layer

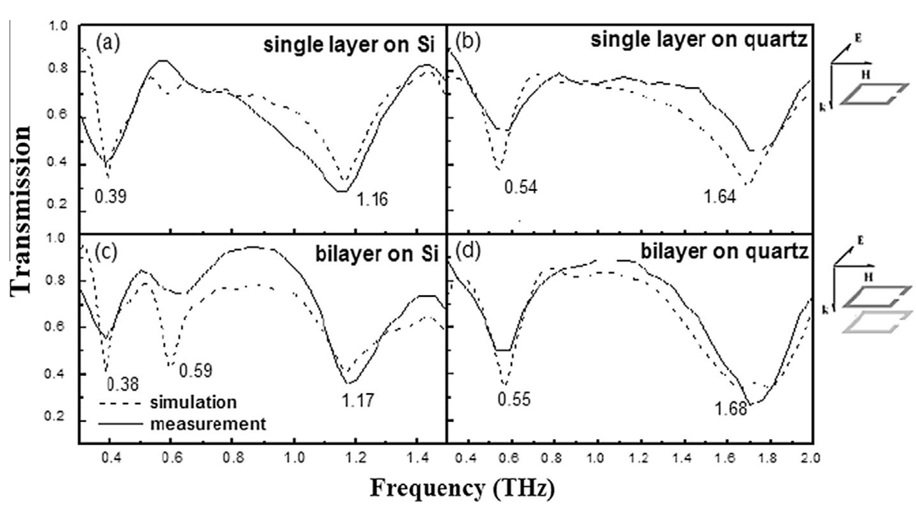

Fig. 2. Transmission spectra for the single layer (a and b) and bi-layers (c and d) MMs with same SRRs (Pattern I) on different substrate (a and c on silicon, b and d on quartz).

MMs on silicon is very close to the L-C response frequency (0.54–0.55 THz) in the MMs on quartz. The resonance behaviors of bi-layer MMs on silicon substrate with SU8 space are just the combined responses of MMs in different dielectric environments. The slight shifts at the eigenfrequencies in bi-layer MMs may be caused by both the interaction between layers and the difference of effective dielectric surrounding. This result indicates that the EM responses in the bi-layer THz MMs with different surrounding dielectric environments exhibit a kind of tailoring effect, which could be applied in THz detection or sensing technologies.

3.2. Combining SRR patterns

Besides controlling the surrounding dielectric environment, combining different SRR patterns is another way to tailor EM responses. We fabricated an aligned bilayer SRR combined with different patterns on quartz substrate and spacer separately (Pattern I as bottom SRR and Pattern II as top SRR), while carefully maintaining a consistent dielectric environment around the single layer MMs for comparison. Fig. 3 shows both measurement (filled line) and simulation (dashed line) results of the EM responses of single layer MMs with Pattern I, Pattern II SRRs and bilayer MMs combined with both patterns respectively. There are two dips in the transmission spectra of single layer MMs with Pattern I SRRs as shown in Fig. 3(a). The lower dip at 0.54 THz indicates the L-C mode magnetic response, and the higher one at 1.64 THz is caused by electric response. The only dip at 0.93 THz in Fig. 3(b) stands for the magnetic response in single layer Pattern II SRRs MMs, whose electric response is much higher and out of our measurement range (2.55 THz in simulation). It exhibits a really excellent EM response tailoring effect in that all three dips in single layer samples appear in the spectra of combined bilayer MMs, as shown in Fig. 3(c). The experimental results are in an excellent consistency with the simulation design. And obviously, all the responses in combined MMs maintain the same profile in transmission spectra as the original responses in single layer MMs. It means the responses in a single layer remain almost unchanged after stacking different layers together, and a target multi-response can be "tailored" by such a simple combination of pre-marked MMs layers.

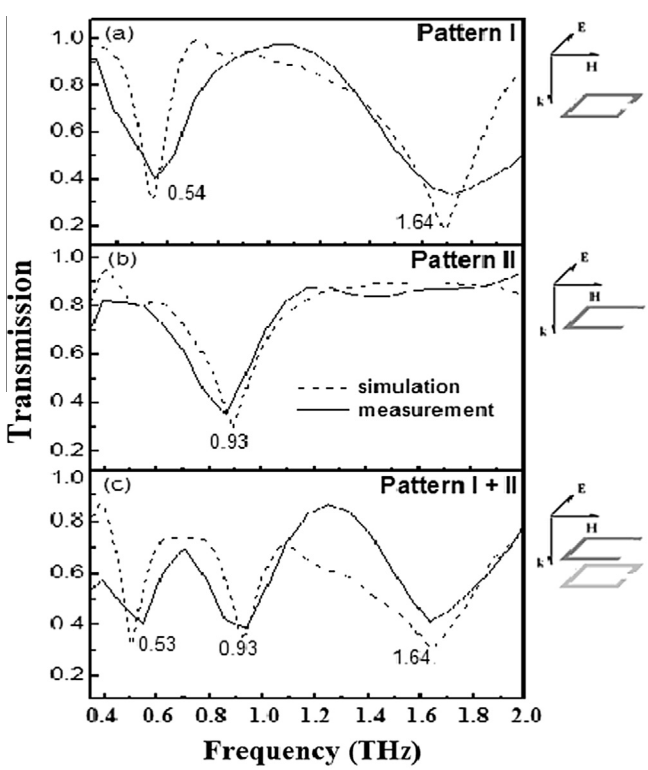

Fig. 3. Transmission spectra for (a) the single layer MMs with Pattern I SRRs, (b) Pattern II SRRs and (c) the bilayer MMs with combined SRRs (Pattern I as bottom layer SRRs and Pattern II as top layer SRRs).

3.3. Interactions between the layers

To clearly identify the interaction mechanism behind these EM responses of combined bilayer MMs, we carried out an ideal simulation by eliminating the effect of the dielectric surrounding, and the results are shown in Fig. 4. By setting the substrate and spacer layer as air, the interaction between layers only depends on the spacing layer thickness (SL) *i.e.*, the distance of layers. In the air, the eigenfrequencies in bare SRRs of Pattern I (Fig. 4(a)) and Pattern II (Fig. 4(b)) are 0.82 THz and 1.22 THz, respectively. For the bilayer structure consisted of only pattern I (Fig. 4(c)), the response shifts obviously due to the well-known resonant coupling, and shows an evident dependence of spacing distance (inset of Fig. 4(c)). However, for the bilayer consisting of both pattern I and pattern II the response are just the superposition of their eigenfrequencies, and there are hardly any differences (inset of Fig. 4(d)). In the mismatched combination of SRR patterns, eigenfrequencies with large differences could weaken the effect of the interactions.

Additionally, in order to modulate the combined responses, we change the surrounding dielectric environment by varying the space layer thicknesses. The response frequencies in bilayer MMs with different space layer thicknesses were measured and simulated as shown in Table 1. Only the target tailored responses (frequencies of ω_1, ω_2 and ω_3) occurred in all results. Both in simulation and measurement, the response at 1.64 THz caused by the electric response of Pattern I SRRs is almost independent of the spacer thickness. When the spacer thickness decreased, both L-C magnetic resonances show a clear red shift, which is in

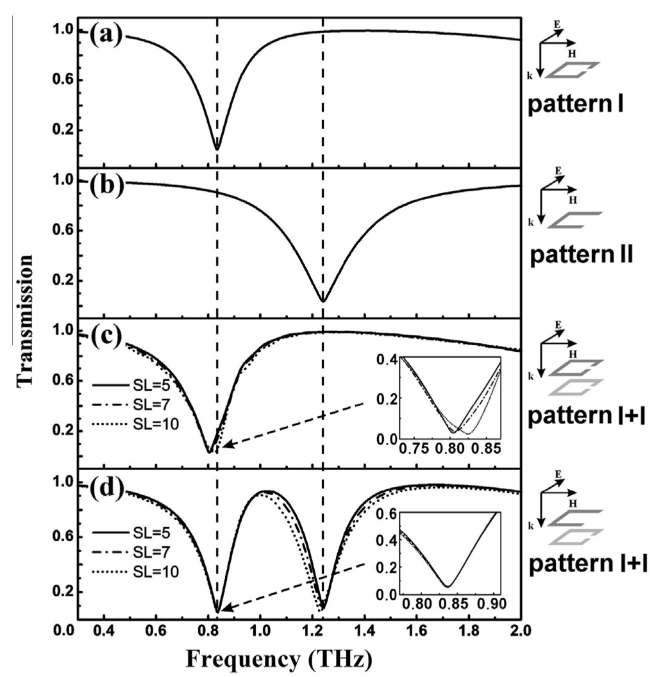

Fig. 4. Transmission spectra for patterns without substrate and space layers (set as air): the single layer MMs with (a) Pattern I SRRs, (b) Pattern II SRRs, the bilayer MMs with combined SRRs (c) Pattern I for both layers and (d) Pattern I as bottom layer SRRs and Pattern II as top layer SRRs.

Table 1
Values in THz determined for the EM resonances of the combined bilayer SRRs samples with different space layer (SL) thickness.

Simulation				Measurement			
SL (μm)	ω_1	ω_2	ω_3	SL (μm)	ω_1	ω_2	ω_3
5	0.49	0.89	1.64	4.7	0.50	0.86	1.63
7	0.50	0.92	1.63	6.9	0.53	0.93	1.64
10	0.51	0.96	1.63				

agreement with the increased effective refraction index of the surrounding dielectric environment [18]. This result shows the possibility to fine tune the response frequencies by controlling the spacer thickness accurately within a certain range.

4. Conclusion

In this paper, we designed, fabricated and measured a series of single layer and bilayer MMs in the THz region. Detailed mechanisms behind their combined EM responses were also analyzed. Our results exhibit very good EM response tailoring and tuning capability in bilayer SRRs consisting of different SRR units and/or surrounding dielectrics. This work proposes an easy way for rapid multi-response designs in THz MMs by avoiding complex coupling interactions, which could be applied in many novel THz applications such as EM signature control, chem/bio detection, and multi-response sensors.

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