Electric and Magnetic Responses from Metamaterial Unit Cells at Terahertz

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Abstract: Metamaterials are artificial media with novel electromagnetic properties. We study the metamaterial unit cells at terahertz frequencies, investigate their electric and magnetic responses to the incident wave, and retrieve their effective material parameters. Simulation results reveal the origins of the effective permittivity and permeability and prove the predicted responses persuasively. In addition, we prove that symmetric resonant structures exhibit purer resonance properties than the asymmetric ones exhibit purer resonance than the asymmetric ones.

Keywords: Metamaterials, Terahertz, Electric and magnetic responses

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1. Introduction

In our conventional opinion, the range of the electromagnetic responses displayed by natural materials is quite limited. Recently, a kind of artificial material, or metamaterial, has become a subject of great interests for its novel electromagnetic characteristics, including the negative refractive index and the tunable permittivity and permeability [1]. Metamaterial was originally proposed for the microwave domain [2, 3] and then introduced into terahertz frequencies [4]. Simulations and experiments have demonstrated the properties of metamaterials from radio frequencies to THz [5].

Metamaterial is composed of periodically arranged resonant unit cells. Since the dimension of each unit cell is much smaller than the wavelength, this kind of artificial periodic composites could be considered as real materials [6]. The most popular unit cell is split ring resonator (SRR), which has two interleaved metallic rings with two opposite gaps, as shown in Fig. 1. When the incident magnetic field is perpendicular to the SRR plane, electric currents are induced along the rings. Simply, each unit cell acts as an LC oscillator and responses to the external magnetic field at the resonance frequencies. The effective permeability of the SRR-composed metamaterial has been shown to be

$$\mu_{eff}(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\Gamma\omega}, \tag{1}$$

where F is a geometrical factor, ω_0 is the resonance frequency, and Γ is the resistive loss in the resonating SRR. Some alternative magnetic resonant structures have been proposed in recent years [7, 8].

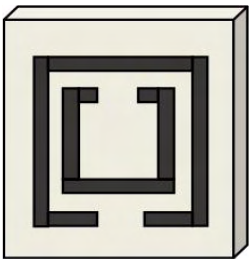


Fig. 1 Split ring resonator (SRR).

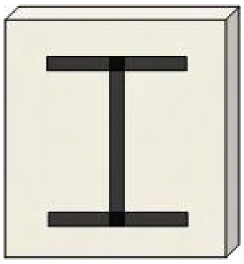


Fig. 2 I-shaped structure.

In contrast, although the electric response was firstly realized by lattices of long metallic wires, these long wires are not appropriate for constructing metamaterials. That is because the metallic wires must be continuous in the direction that parallel to the external electric field. As a result, the length of the wire is comparable to the wavelength. Instead of the long metallic wires, some other electric resonant unit cells have been proposed [9, 10]. Figure 2 shows an I-shaped structure, a promoted structure from long wires [11]. In this case, long wires are cut into short pieces by two horizontal short wires and each I-shaped structure acts as an electric dipole. The effective permittivity of the composed medium is

$$\varepsilon_{eff} = 1 - \frac{\omega_{ep}^2 - \omega_{e0}^2}{\omega^2 - \omega_{e0}^2 + i\gamma\omega}, \tag{2}$$

where ω_{ep} is the plasma frequency of metallic wires, ω_{e0} is the electric resonance frequency, and γ represents the dissipation of plasmon's energy in the metallic wire.

In this paper, we study some kinds of metamaterial unit cells at THz frequencies. These sub-wavelength structures exhibit resonant responses to the electric and magnetic field. Simulation results demonstrate the responses as well as their effective parameters like the negative permittivity and permeability. It is also observed that some structures response to the electric field at normal incidence but response to the magnetic field at parallel incidence. Coupled electromagnetic responses make it complicated to control the properties of metamaterials. This problem is solved for symmetric structures because their electric and magnetic responses happen at different frequencies.

2. Electric response at the normal incidence

To investigate the resonance properties of metamaterial unit cells, we arrange them periodically on an isotropic dielectric substrate, as illustrated in Fig.3. Take the spiral structure as an example. The incident direction is often chosen to be perpendicular or parallel to the structure plane. The perpendicular incident waves could induce electric responses when the electric field polarization is parallel to the long edges of the structures, and the parallel incident waves are easy to inspirit magnetic responses if there is a loop in the structure.

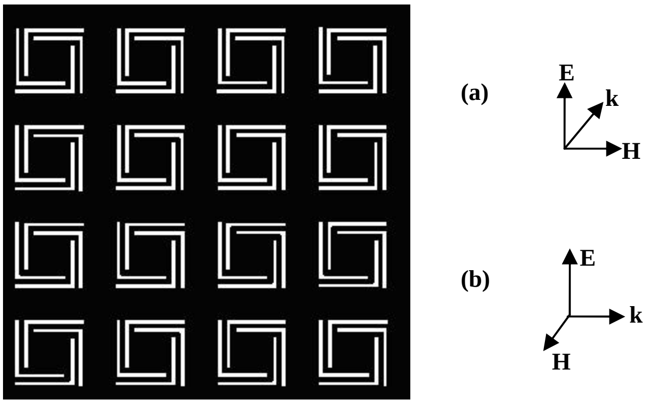


Fig. 3 The periodically arranged structures at (a) perpendicular incidence and (b) parallel incidence.

To study the properties of metamaterials at THz frequencies, we use CST Microwave Studio TM 2006B, a 3D full-wave solver for simulation. In order to mimic the infinite periodically arranged unit cells, PEC and PMC boundary conditions are employed. We assume that the metamaterial structures are made of gold with a thickness of 20*nm*. These structures are printed on a square lattice of period of 100*nm* and the dimension of each structure is 80*nm*. Since a typical isotropic dielectric substrate would only shift the resonance frequencies without affecting the electromagnetic properties, we set the substrate as vacuum with electric tangent. It should be pointed out that if we use substrates with higher permittivity, like quartz or GaAs that has been used in previous successful experiments [12], the unit cell will have smaller unit-to-wavelength ratio.

Figure 4 shows the simulation results of four kinds of electrically resonant structures. In this figure, we list the surface current, the transmission and reflection, and the retrieved permittivity using a retrieval algorithm [13]. The first line shows a typical I-shaped structure and the second line suggests that a meander line could lower the resonance frequency. Spiral and SRR are presented as examples of symmetric and asymmetric resonant structures. In fact, they could also be used as magnetically resonant particles because they have a loop component in the structures. It is observed that at the electric resonance frequencies, the currents flow parallel to the polarization direction, indicating that the structures act like electric dipoles. For example, for the spiral case, the currents on the two edges are in phase with each other because they response to the electric field individually. There is a stop band around the resonance frequencies, where the real part of the effective permittivity varies acutely to the negative value. Whereas the range of permittivity displayed by natural materials is quite limited at THz frequencies, metamaterials have many promising potential applications in this frequency domain.

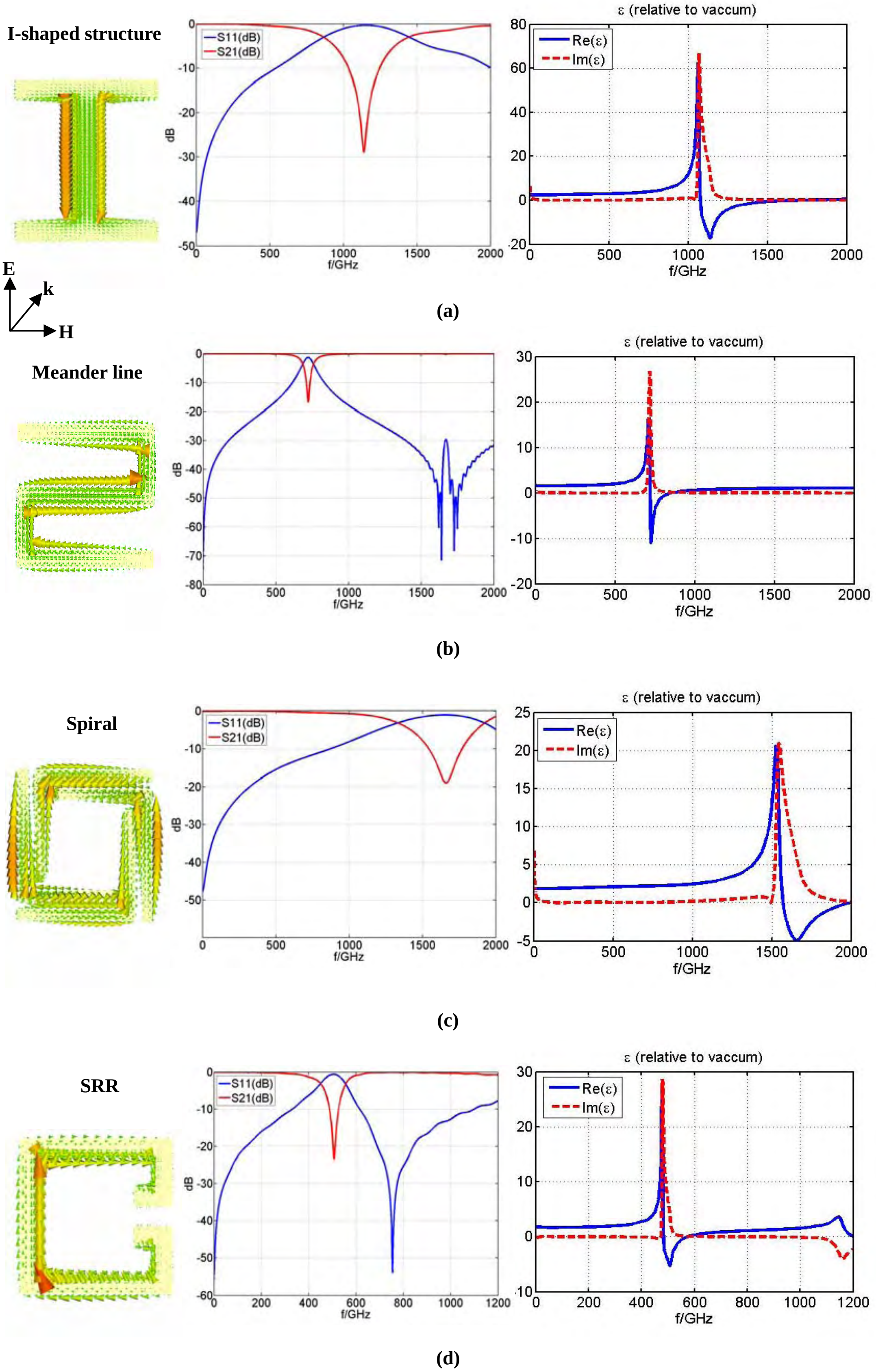
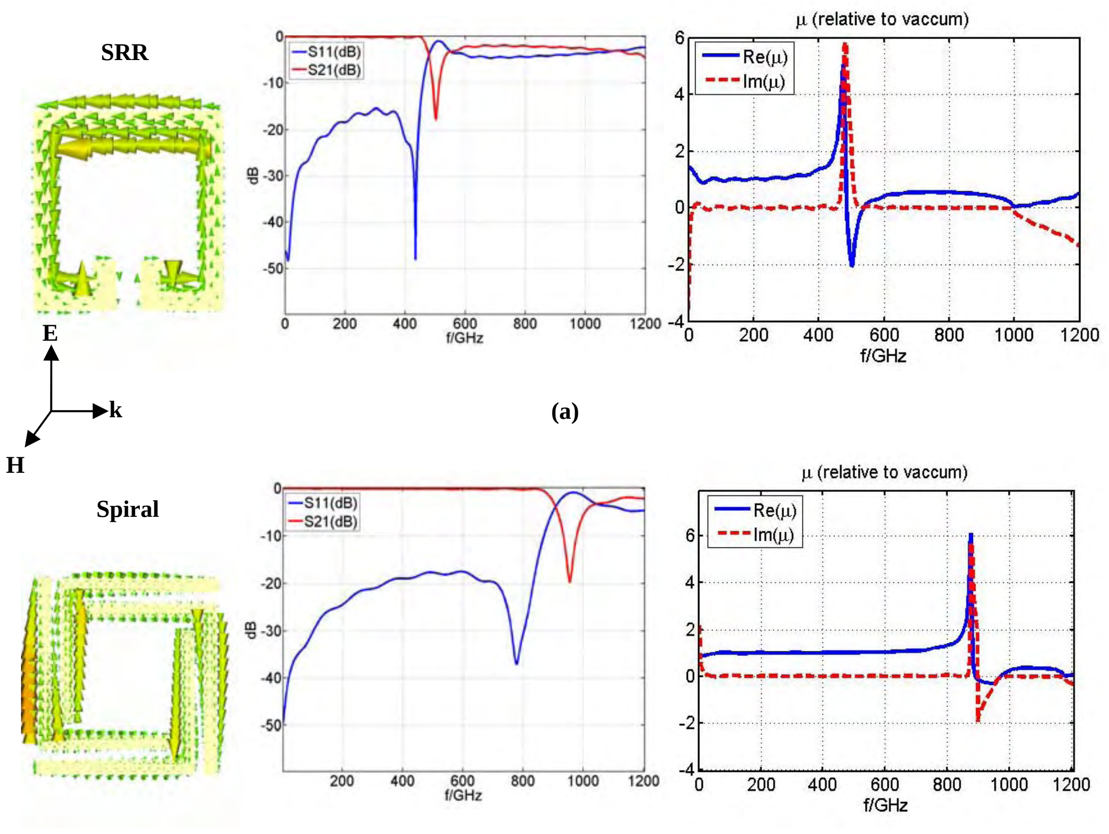


Fig. 4 Simulation results of four kinds of electrically resonant structures. The left column shows the names of the structures and the surface currents at resonance frequencies. The middle column illustrates the S parameters and the right column reveals the retrieved permittivity.

3. Magnetic response at the parallel incidence

In order to obtain strong magnetic responses from metamaterial unit cells, the incident direction should be parallel to the structure plane. The electric field polarization is chosen to be parallel to the plane and the magnetic field is polarized perpendicularly.

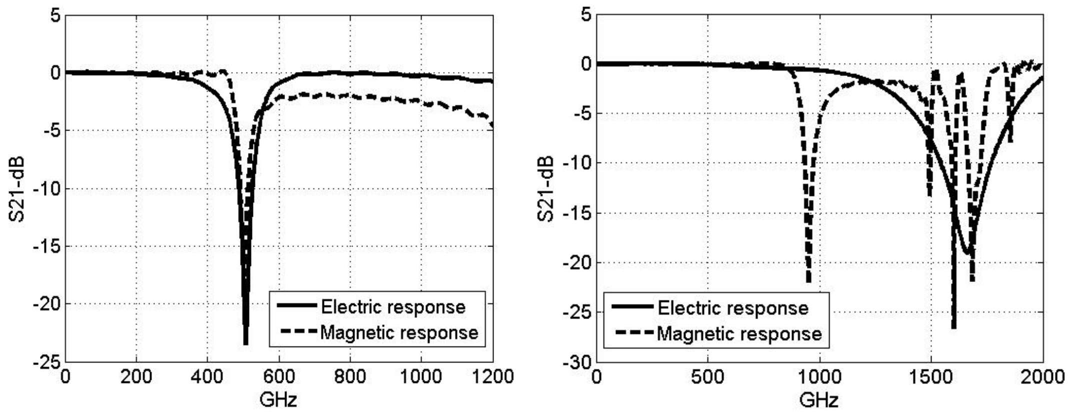
Fig.5 shows the simulation results of two kinds of magnetically resonant unit cells, the SRR and the spiral structure. Obviously, at the resonance frequencies, the induced surface currents flow in a circular path, generating a magnetic field opposite to the external field. The figure also illustrates the transmission and reflection, and the retrieved permeability. The real part of the permeability becomes negative around the resonance frequencies. Compared with the electric response, the magnetic response is fairly weak, although the retrieved permeability exhibits a similar shape to the permittivity.



(b)

Fig. 5 Simulation results of two kinds of magnetic resonant structures. The left column shows the names of the structures and the surface currents at resonance frequencies. The middle column illustrates the S parameters and the right column reveals the retrieved permeability.

Furthermore, we investigate into the SRR and the spiral structure. According to the surface current on the SRR at an electric resonance, although the energy is mainly focused on the long edge parallel to the electric field, there also exists a circulating current. Such circulating current generates a magnetic field polarized perpendicular to the SRR plane so as to induce a magnetic resonance. In other words, the electric response and magnetic response are coupled together, making it complicated to control the electromagnetic properties of metamaterials. Such coupling is strengthened at oblique incidence, which is often applied to realize negative refractive index at THz frequencies. The transmission could indicate this character, as shown in Fig. 6(a). When the incident wave comes normally to the SRR plane, the electric response is the dominant response (illustrated by the solid line), and when the incident wave is parallel to the plane, the magnetic response becomes the dominant one at the same frequency (illustrated by the dashed line). However, it is another story for the spiral structure because the symmetric particle can suppress the magnetic response [14]. As we mentioned before, at the electric resonance frequencies, the currents on the two edges are in phase with each other. So there is no circulating current to induce the magnetic response on the spiral. Fig. 6(b) indicates that the electric response and magnetic response are isolated at different frequencies. Generally, the spiral structure, or the symmetric one, is better to provide pure electric response and magnetic response at THz frequencies.



(a) **(b)**

Fig. 6 The comparison of the transmittances between electric response and magnetic response for (a) SRR and (b) spiral structure.

4. Conclusions

In conclusion, we investigate the resonance properties of metamaterials at THz frequencies. The simulation results demonstrate that metamaterial unit cells could response to the incident electromagnetic waves and extend the range of permittivity and permeability that exist in nature. This novel material has many promising potential applications. Once we have the technology to fabricate um-dimensional and nm-dimensional metamaterial structures efficiently and economically, THz metamaterials will attract more and more interests.

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References

[1] V. G. Veselago, "The Electrodynamics of Substances with Simultaneously Negative Values of Epsilon and Mu", *Sov. Phys. Usp*, 10(4), 509~514, (1968).

[2] J. B. Pendry, A. J. Holden, W.J. Stewart, et al., "Extremely Low Frequency Plasmons in Metallic Mesostructures", *Phys. Rev. L*, 76(25), 4773~4776, (1996).

[3] J. B. Pendry, A. J. Holden, D. J. Robbins, et al., "Magnetism from Conductors and Enhanced Nonlinear Phenomena", *IEEE Tran Microwave Theory Tech*, 47(11), 2075~2084, (1999).

[4] T. J. Yen, W. J. Padilla, N. Fang, et al., "Terahertz Magnetic Response from Artificial Materials", *Science*, 303(5663), 1494~1496, (2004).

[5] R. A. Shelby, D. R. Smith, S. Schultz, "Experimental Verification of a Negative Index of Refraction," *Science*, 292(5514), 77~79, (2001).

[6] R. P. Liu, T. J. Cui, D. Huang, et al., "Description and Explanation of Electromagnetic Behaviors in Artificial Metamaterials Based on Effective Medium Theory", *Phys. Rev. E*, 76(2), 026606-1~8, (2007).

[7] H. Chen, L. Ran, J. Huangfu, et al., "Left-handed Materials Composed of Only S-shaped Resonators", *Phys Rev E*, 51(7), 1516~1519, (2003).

[8] H. Zhao, T. J. Cui, "A Double-spiral Resonator Structure to Realize Left-handed Material with Lower Resonant Frequency", *Microwave and Optical Technology Letters*, 48(5), 923~926, (2006).

[9] D. Schurig, J. J. Mock, D. R. Smith, "Electric-field-coupled Resonators for Negative Permittivity Metamaterials", *Appl. Phys. Lett.*, 88(4), 041109-1~3, (2006).

[10] W. X. Tang, H. Zhao, X. Y. Zhou, et al., "Negative Index Material Composed of Meander Lines and SRRs", *PIER B*, 8, 103~114, (2008).

[11] H. S. Chen, L. X. Ran, J. T. Huangfu, et al., "Magnetic Properties of S-shaped Split-ring Resonators", *P. I. E. R.*, 51, 231~247, (2005).

[12] W. J. Padilla, M. T. Aronsson, C. Highstrete, et al., “Electrically Resonant Terahertz Metamaterials: Theoretical and Experimental Investigations”, *Phys Rev B*, 75, 041102-1~4, (2007).

[13] D. R. Smith, D. C. Vier, Th. Koschny, et al., “Electromagnetic Parameter Retrieval from Inhomogeneous Metamaterials”, *Phys. Rev. E*, 71, 036617-1~11, (2005).

[14] W. J. Padilla, A. J. Taylor, C. Highstrete, et al., “Dynamical Electric and Magnetic Metamaterial Response at Terahertz Frequencies”, *Phys. Rev. L*, 96, 107401-1~4, (2006).