A Dual-Resonant Metamaterials Composed of Electromagnetic-Field-Coupled Resonators

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Abstract

In this paper, electromagnetic-field-coupled resonators are introduced and investigated. The electric mode at lower frequency and magnetic mode at higher frequency, originated from coupling of the electric field and magnetic field, are validated through a measurement inparallel-plate waveguide system, parameter retrieval algorithm and surface currents distributions. The new resonators with distinct electric resonance as well as magnetic resonance could provide us a new way to design double negative material.

1. Introduction

The characteristics of metamaterials, especially the double negative material (DNM), have attracted more and more researchers' attentions due to its unusual electromagnetic properties [1-3]. So far, there are two main kinds of methods to form the DNM: one is based on the split-ring resonators (SRRs) and wire media, the other is a combination of SRRs and electric LC (ELC) resonators. The SRR-wire design is convenient to construct because it is relatively easy to overlap the narrow negative permeability band of the SRRs with the much broader negative permittivity band of the wires. However, the ELC resonators are an alternative artificial electric medium to replace the role of wires and create negative value of permittivity. Those methods above are effective and accurate for designing DNM.

In this paper, a new type of electromagnetic resonators consists of triangular electromagnetic resonators (EMRs), is introduced and discussed. The EMRs have parallel or antiparallel induced magnetic dipoles from the two ring-resonators in different frequencies, which are termed as electric and magnetic mode in this paper, respectively. In other words, EMRs possess both obvious magnetic and electric response. More importantly, DNM may be created by combing same units of EMRs with different sizes.

2. Configuration and simulation

Fig.1(a) illustrates the geometry of the electromagnetic-field-coupled resonators (EMRs), which comprise two triangular open-loop resonators and a wire in the middle. A substrate of FR4 (thickness of 0.5mm, $\varepsilon = 4.4$, and loss tangent of 0.02) is assumed. Fig.1(b) shows the equivalent circuit of EMRs and the resonant frequency of equivalent circuit is $\omega_0 = \sqrt{1/2LC}$. S-parameter simulations on unit cell were then performed using Ansoft HFSS, a full-wave electromagnetic solver. The dispersion curves of constitutive parameters can be found by a standard retrieval algorithm, which includes four main equations to calculate the four constitutive parameters, respectively.

Fig.2 plots the dispersion curves of effective permeability, permittivity, index and impedance. It can be seen

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that around 8GHz, effective permittivity has a strong resonance behavior with the real part raging from 18 to –6.5. This indicates that the first resonance results from the electric mode. However, there is an anti-resonance in the effective permeability curve around 8GHz, which is caused by the bounded refractive index of the structure which possesses intrinsic finite periodicity[8]. At around 11GHz, effective permeability has a clear resonance with its value changing from 6 to –2. Accordingly, effective permittivity also has an anti-resonance behavior.

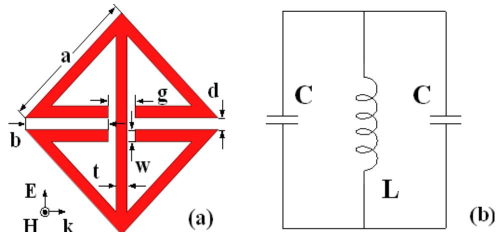
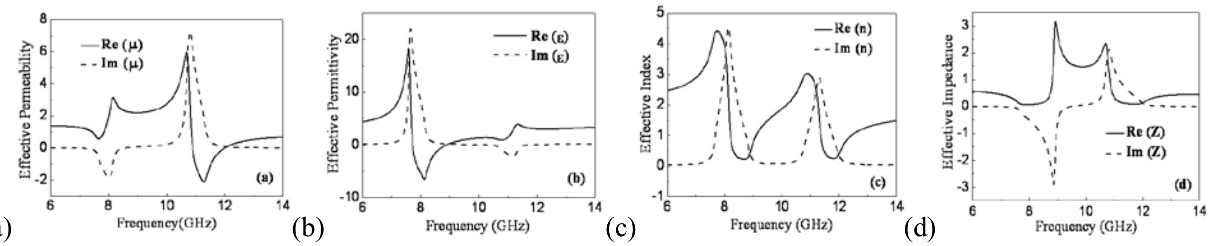


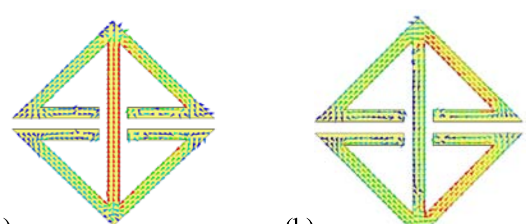
Fig. 1. (a) A unit cell of EMRs with geometric dimensions a=2.5mm，b=1.52mm，d=0.2mm, g=0.5mm, and t=w=0.2mm. The polarized electromagnetic wave direction of electric field, magnetic field and transmission are all clearly shown above; (b) an equivalent circuit.



(a) (b) (c) (d)

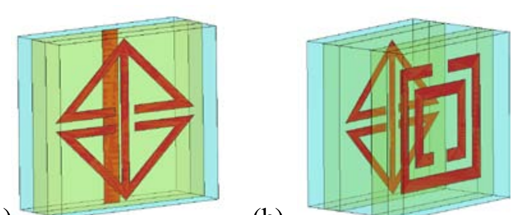
Fig. 2. The dispersion curves from the simulated S-parameters of the unit cell, the solid lines represent the real part while the dash lines represent the imaginary part. (a) the effective permeability; (b) the effective permittivity; (c) the effective index; (d) the effective impedance.

Fig.3 illustrates the surface current for the magnetic resonance and electric resonance, respectively, which enable us to have better understanding of the different physical mechanisms of the two resonances. At the electric resonance of 8.43 GHz, the surface current mainly exists in the middle arm of EMRs which means the structure has electric mode resulting from electric coupling, acting as the wires, and that could produce negative permittivity. However, at the magnetic resonance of 10.73GHz, the surface current mainly exists in the both rings of EMRs, which is the origin of the magnetic mode resulting from magnetic coupling, and that could produce negative permeability.



(a) (b)

Fig. 3. Distribution of surface current at the electric resonance of 8.43GHz (a) and magnetic resonance of 10.73GHz (b)



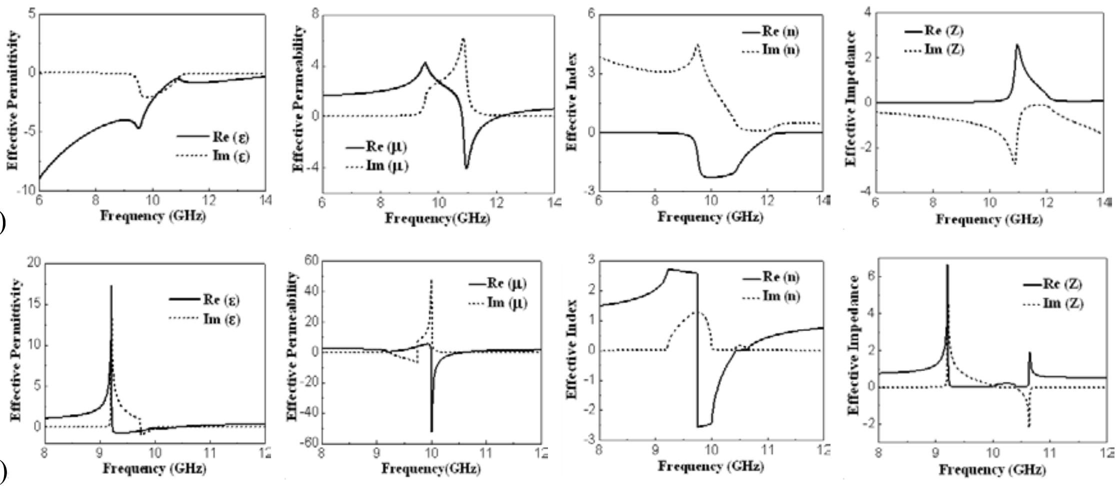
(a) (b)

Fig. 4. Models of EMRs structures. (a) TER-wire structure. (b) TER-SRR structure.

According to the analysis above, we know that EMRs have both electric and magnetic resonance, which means that they can play the roles of traditional SRR or wire array. Therefore, in order to validate the electric and magnetic properties of EMRs, EMRs are combined with wires and SRR. The models of EMRs-wire and

EMRs-SRR structures are built to calculate the transmission properties, shown in Fig.4. Then, the retrieved effective parameters of above two structures are calculated based on the simulated S-parameters, shown in Fig.5, respectively.

The retrieved constitutive parameters of both EMRs-wire and EMRs-SRR structure are shown in Fig.5(a) and Fig.5(b), respectively. For the EMRs-wire structures, the EMRs play the role of traditional SRRs. The combination of EMRs and wire is validated to be a kind of DNM and its negative index span a frequency range from 9.06 to 12.19 GHz, which is much broader than that of the traditional SRR-wire structures. Meanwhile, for the EMRs-SRR structures, the EMRs play the role of traditional wires. The combination of EMRs and SRR is also validated to be a kind of DNM and its negative index spans a limited frequency range from 9.75 to 10.43 GHz. In a word, two groups of plots both validate left-handed characteristic of EMRs-wire and EMRs-SRR structures, which means that EMRs do have electric resonance and magnetic resonance.



(a)

(b)

Fig.5. Effective material parameters extracted from the simulated S-parameters, the solid lines represent the real part while the dash lines represent the imaginary part. (a) Retrieval results of EMRs-wire structure. (b) Retrieval results of EMRs-SRR structure.

3. Experimental validations

In order to experimentally confirm the EMRs characteristic, a parallel-plate waveguide (PPW) system was built to measure the transmission properties, as shown in Fig.6. The two probes inside the PPW act as the transmitter and receiver at each side. The slab, six units along the propagation direction, filled the section between the two probes. Since the field energy is almost confined between the two plates of the waveguide in a linearly polarized EM wave, the PPW system is approximately equivalent to a uniform EM wave normally incident on the slab in free space, and thus the standard free-space extraction procedure is valid for our system. The measured transmission property of EMR structures in Figure 7 shows that there are two transmission minima at 8.4 GHz and at 10.8 GHz, which correspond to the two resonant frequencies for electric and magnetic resonance in Figure3.

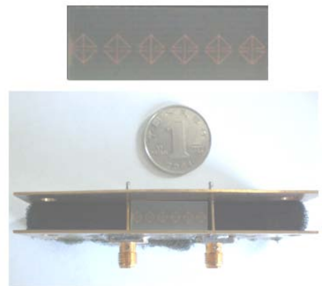


Fig.6. Photograph of the parallel-plate waveguide (PPW) system to measure the transmission properties.

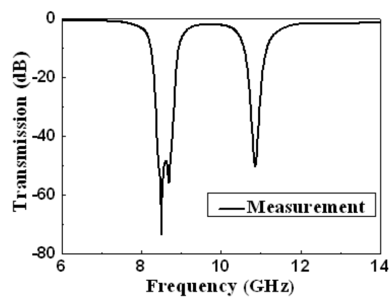


Fig.7. Measured transmission property of the 6 units EMRs sample.

4. Conclusion

In summary, the electromagnetic-field-coupled resonators (EMRs) have been carefully investigated both theoretically and experimentally. The measurement results of PPW system and the dispersion curves of retrieved effective parameters, both illustrate that EMRs have electric resonance at lower frequency and magnetic resonance at higher frequency, which provide an effective and convenient method to build double negative material (DNM).

6. References

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