Metamaterial Design Applying Babinet's Principle

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Abstract

Babinet's principle is applied to three kinds of metamaterial designs, including SRR structure, S structure, and single side paired S-ring. The retrieval results for each complementary unit cell group are obtained based on their S11 and S21 simulation data. By means of comparison, the complementary metamaterial's negative permittivity happens at the same frequency band, where is supposed to be a magnetic resonance for the original metamaterial structure; And on the other side, the effective permeability of complementary metamaterial acts in a similar way which is corresponding to the effective permittivity of the prototypes. The results show that the Babinet's principle is useful and helpful while designing metamaterials. After proper design, some complementary metamaterials' structures can also possess both electric resonances and magnetic resonances at the same time, which conform to the condition for left-handed metamaterials.

1. Introduction

Metamaterials[1-4] are defined as artificial composite materials, which are comprised of periodically arranged effective structures and exhibit exotic and useful electromagnetic properties not readily available in nature, constituting a new paradigm in science and engineering. They usually make use of metal and dielectric substrate geometries to form their unit cells as atoms in order to achieve desirable effective permittivity and permeability, such as split ring resonators (SRRs)[5], S-shaped resonators[1], single side paired S-ring resonators[4], etc. While worldwide metamaterial designers are making great effort to kinds of structural designs, many researchers turn to investigate the complementary metamaterials[2,3] that may interest them, some of which have already applied the Babinet's principle to deal with certain problems[2,3]. For examples, F. Falcone et al. applied Babinet's principle to artificial metasurfaces and metamaterials and proposed the complementary split rings resonator, which could be a design for the metasurfaces with high frequency selectivity and planar metamaterials with a negative dielectric permittivity[2]; After that, T. Zentgraf et al. considered Babinet's principle for metamaterials at optical frequencies and included realistic conditions which deviate from the theoretical assumptions of the classic principle such as an infinitely thin and perfectly conducting metal layer[3].

2. Babinet's principle

Babinet's principle[2,3,6] can be described in optics as that, the sum of the wave transmitted through a screen (usually considered to be "black" except for its apertures) plus the wave transmitted through the complementary screen is the same as if no screen were present. An electromagnetic version of Babinet's principle was modified[6] in a more detailed form, which requires perfectly electrically conducting screens and requests that the electromagnetic fields in the case of the complementary screen should be the dual fields rather than the nominal fields. Furthermore, the electromagnetic fields incident on the screen should be considered to be a plane electromagnetic wave of angular frequency ω, and the fields dual to the plane electromagnetic wave with linear polarization are those obtained on rotating the direction of the polarization by 90º.

3. Metamaterial Design

In this paper, by applying Babinet's principle, three kinds of metamaterials' structure will be discussed based on their unit cells' simulation data and theoretical calculation results, including SRR structure[5], S structure[1], and single side paired S-ring[4], as shown in Fig. 1. The purpose is to show the usefulness of the Babinet's principle in designing metamaterials and metasurfaces. After applying the Babinet's principle, the metasurface units with the patterns etched on metallic screens are also shown in Fig. 1 beside each metamaterial's structure, where the white parts correspond to the air and the gray parts correspond to the PEC.

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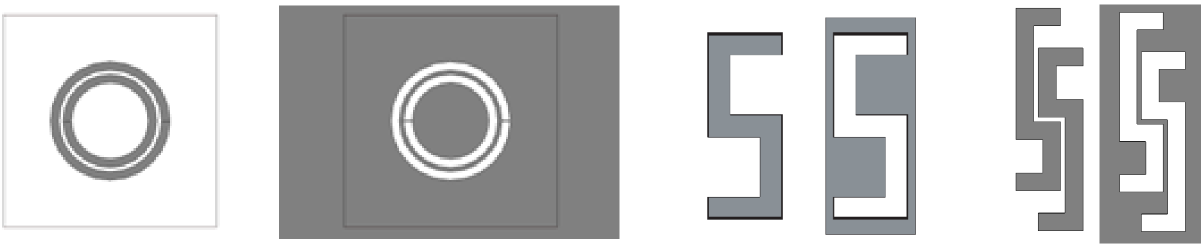
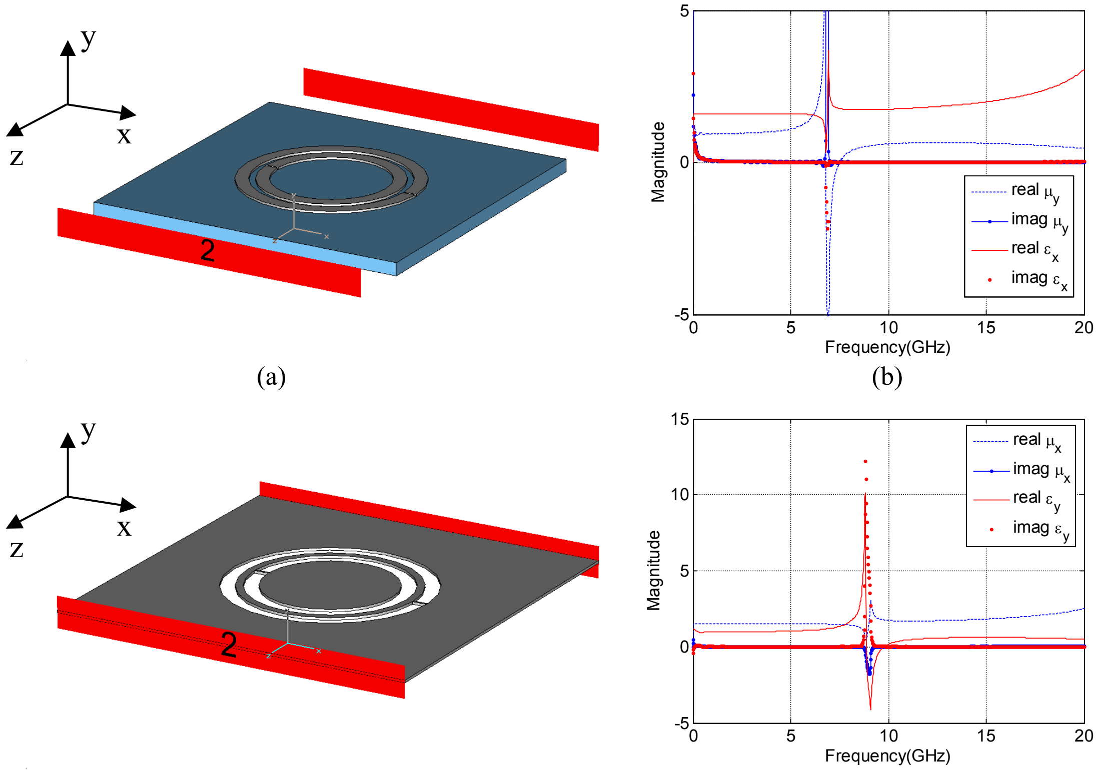


(a) (b) (c)

Fig. 1. Examples of designs for metamaterials and their complementary metasurfaces: (a) SRR structure and CSRR structure; (b) S structure and CS structure; (c) single side paired S-ring and its complementary pattern.

3.1 SRR Structure

For SRR and CSRR structures, their S11 and S21 parameters for each one unit cell are calculated by the *CST Microwave Studio* electromagnetic solver, and their effective permittivity and permeability are retrieved from the simulation results. The results are shown in Fig. 2. According to the Babinet's principle, the incident waves should be polarized in different or dual ways for SRR and CSRR structures, and both are propagating along the *z* direction. In Fig. 2(a), the electric field is polarized along *x* direction and the magnetic field along *y* direction; while in Fig. 2(c), the magnetic field is polarized along *x* direction and the electric field along *y* direction, which are complementary to each other. From the retrieval results shown in Fig. 2(b) and (d), we can see that the original magnetic resonance along *y* direction for the SRR turns to an electric resonance in the same direction for the CSRR, which agrees with what is predicted by the Babinet's principle.



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

Fig. 2. Comparisons of the simulation setups and the retrieval results for both SRR [(a) and (b)] and CSRR structures [(c) and (d)].

3.2 S Structure

For S-shaped left-handed metamaterial, its S11 and S21 parameters for one unit cell are also calculated from simulation, and its effective permittivity and permeability are obtained from retrieval procedure, as shown in Fig. 3, where a clear double negative pass band is from around 13 GHz to around 17 GHz. The complementary structure of S-ring is different from SRR since S-ring is not a planar but a solid structure, which is composed of two layers of opposite S-shaped metallic strips, so firstly the complementary of one layer S-ring is studied, as shown in Fig. 4, where the gray slice trimmed by a S-shaped pattern is PEC, the thick part before PEC slice is air and the thin part with thickness equal to 0.2 mm behind the PEC is a dielectric with relative permittivity equal to 4.

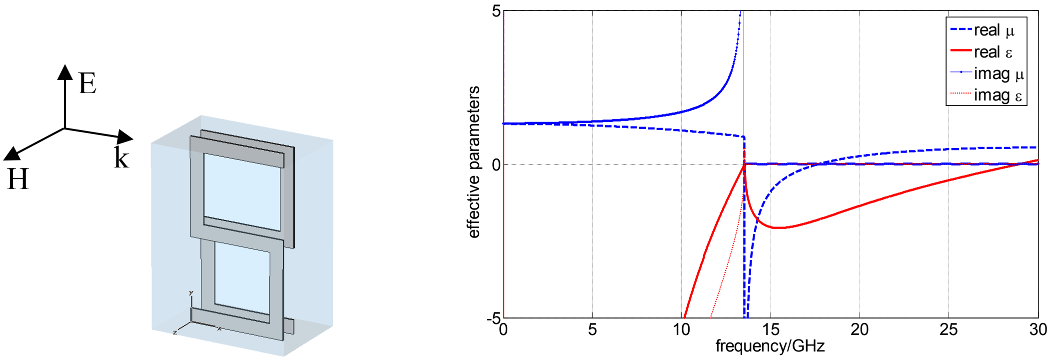


Fig. 3. S-shaped left-handed metamaterial and its retrieved effective parameters under certain polarized incident wave.

The boundary conditions for the CS ring setup shown in Fig. 4 is that in y direction both PMC are used, in upper z boundary PEC is used while in lower z boundary the open (add space) boundary is applied. Under such boundary conditions, wave is polarized in z direction and propagating in the air part along x direction. The corresponding retrieval results are also presented in Fig. 4, which possess a Drude model of permeability and a Lorentz model of permittivity, but their negative regions don't overlap to form a negative pass band. However, it is very interesting that there is still an electric resonance along z direction for the single layer of complementary S-ring structure.

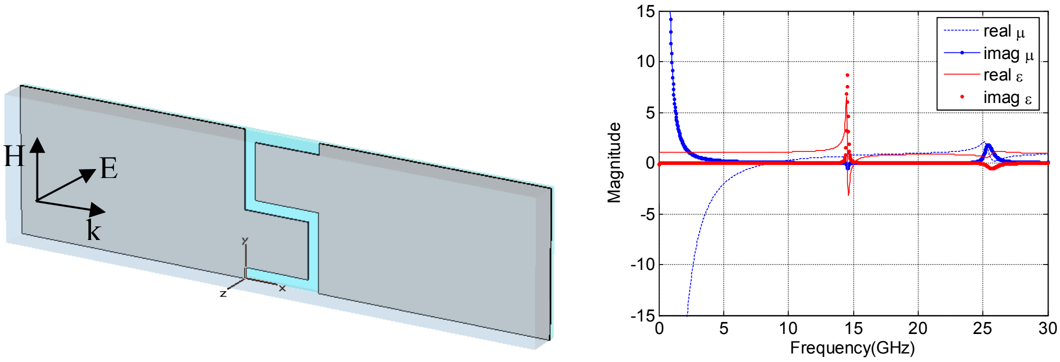


Fig. 4. Complementary S-shaped metasurface and its retrieved effective parameters under the certain polarized incident wave.

In order to search a negative pass band, then the two-layer complementary S-ring is investigated as shown in Fig. 5, where one more PEC slice with the opposite S-ring pattern and one more dielectric layer are added at the upper edge of the air part. At this time, both boundaries in z directions are set to be open (add space) since the PEC itself can act as the modified boundary conditions, which makes the wave also polarized in z direction and propagating in the air part between two PEC slices along x direction. From the retrieval results in Fig. 5, we can see that the double negative region comes out in a narrow frequency band. And this pass band is further confirmed by a phase tracking method as a negative pass band.

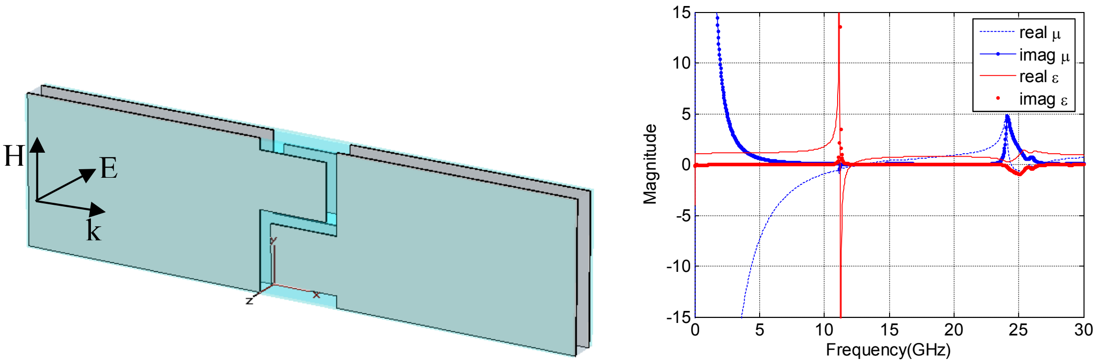


Fig. 5. Two-layer complementary S-shaped metamaterial and its retrieved effective parameters under the certain polarized incident wave.

3.3 Single Side Paired S-ring

For the single side paired S-ring and its complementary structures, the Babinet's principle can be applied in the same way, as shown in Fig. 6, where both structures own their double negative pass band (Single side paired S-ring has negative pass band from 8.2 to 8.8 GHz, while complementary Single side paired S-ring has negative pass band around 9.5 GHz), with their permittivity and permeability complementary to each other.

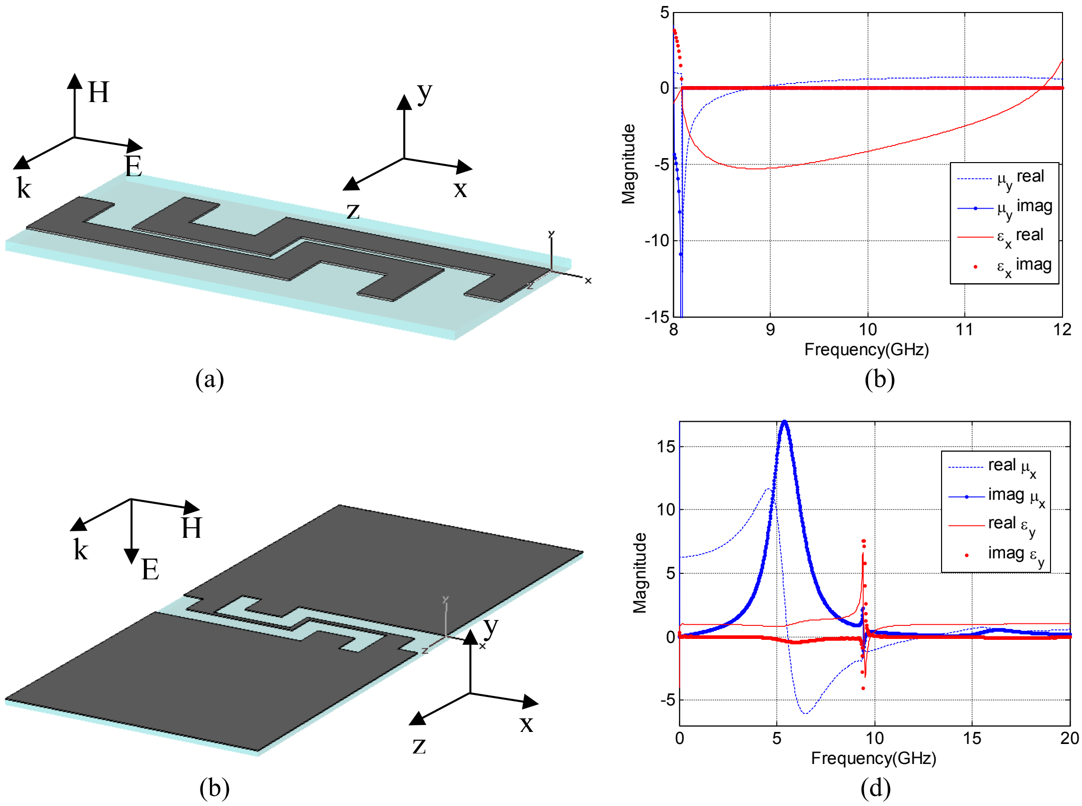


Fig. 6. Comparisons of the simulation setups and the retrieval results for both single side paired S-ring [(a) and (b)] and its complementary structures [(c) and (d)].

4. Conclusion

In conclusion, Babinet's principle is applied to three kinds of metamaterial designs. The retrieval results based on simulation data indicate that the Babinet's principle is useful and helpful while designing metasurfaces. For the complementary metamaterials after structures' transformation, not only the negative permittivity which is caused by magnetic resonance of the original metamaterial's structure is discussed, but also their effective permeability related to the effective permittivity of the former ones is investigated as well in this paper. If being designed properly, these kinds of complementary structures can possess electric resonances and magnetic resonances at the same time, which satisfies condition for left-handed metamaterials. It should be noted that all the examples in this paper are simulated and analyzed in normally incident case.

5. References

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