A novel structure for broadband left-handed metamaterial*

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A low absorptivity broadband negative refractive index metamaterial with multi-gap split-ring and metallic cross (MSMC) structure is proposed and investigated numerically and experimentally in the microwave frequency range. From the numerical and experimental results, the effective media parameters were retrieved, which clearly show that there exists a very wide frequency band where the permittivity and permeability are negative. The influence of the structure parameters on the magnetic response and the cut-off frequency of the negative permittivity are studied in detail. This metamaterial would have potential application in designing broadband microwave devices.

Keywords: metamaterial, negative refractive index (NRI), broadband

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1. Introduction

In 1968, Veselago proposed a medium with simultaneously negative permittivity and permeability, namely left-handed metamaterial (LHM).[1] Because of their unusual electromagnetic properties and potential applications in such as invisibility cloaks[2−6] and perfect lenses,[7] LHMs have gained great impetus. The first LHM idea in the world [8] was revived in the late 1990s when Pendry proposed two structures, metallic wires, and split ring resonators, which can exhibit negative electric and magnetic responses at designed frequencies. Subsequently, a great variety of LHMs were proposed, such as Ω-shaped,[9] S-shaped,[10] H-shaped,[11] cut wires,[12,13] and fish-net structure.[14] However, the narrow double negative (DNG) frequency band is one of the restricting factors in practical applications. In most split-ring resonators (SRR)-based LHMs, the negative refraction band is around their magnetic resonance frequency, which is often narrow, whereas the negative permittivity frequency band is often wide due to the wire resonance behavior. Efforts[13,15,16] have been made to broaden the bandwidth by packing two or more resonators with different geometries into a single unit cell for multi-band responses.

In this paper, we report the design, simulation and experimental verification of a multi-gap split-ring and metallic cross (MSMC) structure metamaterial with a broad fundamental resonance behavior. Owing to its highly symmetrical structure, this metamaterial exhibits an isotropic left-handed behavior to any linearly polarized incident wave. The MSMC structure aligned with the incident electric field exhibits Drude-like plasmonic behavior for the permittivity. The DNG passband is very wide, obtained by overlapping the wide negative permittivity and the wide negative magnetic conductivity. The magnetic resonance and cut-off frequency of the negative permittivity can be easily tuned by the structural parameters such as the width, length and the distances between the multi-gap split-rings. Thus, it is readily scaled and fine-tuned to any desired frequency. Using the scattering parameters, obtained by Ansoft HFSS and experiment, the complex constitutive effective parameters of the metamaterial are retrieved.[17] A sample of the structure is fabricated and tested in a waveguide measurement setup.

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2. MSMC structure as a unit cell of the broadband LHMs and simulation

A unit cell of the MSMC resonator is shown in Fig. 1(a), where multi-gap split-ring metallic strips and metallic cross are printed on two sides of a $d = 0.5$ mm thick FR4 substrate with a relative permittivity of 4.4 and $\tan\delta = 0.02$. The metallization is copper with a thickness of 18 μm. The top and bottom views of the unit cell are shown in Figs. 1(b) and 1(c). The single unit cell of the metamaterial structure is optimized and the other geometry dimension parameters are as follows: $L = 5$ mm, $L_{u1} = 2.05$ mm, $L_{u2} = 1.45$ mm, $k_1 = 0.6$ mm, $k_2 = 0.3$ mm, $k_3 = 0.15$ mm, $W_u = 0.3$ mm, and $W_d = 0.2$ mm. The MB–LHMs structures[18,19] have been demonstrated to have left-handed (LH) behaviors in some frequency ranges. The frame perpendicular to the magnetic field $\boldsymbol{H}$ direction acts as a magnetic resonator, providing negative permeability μ due to anti-parallel currents induced by the magnetic field of the incident electromagnetic wave. The wire along the electric field $\boldsymbol{E}$ direction of the incident electromagnetic wave excites the plasmonic response and produce negative permittivity ε up to the plasma frequency. Thus, LH behaviors are expected for this structure.

In order to verify our speculation, firstly, we characterized the properties of the MSMC structures using simulations. The properties are characterized numerically using finite element method simulations carried out with Ansoft's commercial electromagnetic solver HFSS. Numerical simulation is performed with a slab consisting of one unit cell in the x direction and z direction. The perfect electric conductor and perfect magnetic conductor boundaries are used in the x and y directions, respectively. The electromagnetic (EM) wave is incident along the z direction with the electric field polarized in the x direction. Detailed calculations were used to determine the reflection and the transmission coefficients from a single unit cell.

The effective numerical parameters can be retrieved by using the calculated scattering parameters.[17] Figures 2(a), 2(b), 2(c) and 2(d) show, respectively, the retrieved permittivity ε, permeability μ, refractive index n, and absorptivity of the MSMC LHMs. Figures 2(a) and 2(b) show that the effective permittivity is negative in the 6.2–14.7 GHz frequency range while that of the negative effective permeability is 11.36–16 GHz, much narrower than that of the negative effective permittivity range. Figure 2(c) shows clearly that the negative refractive index band is 6.2–15 GHz and the negative refraction bandwidth is 8.8 GHz. Note that in the frequency range of 11.36–14.7 GHz (shaded areas) where both the effective permeability and permittivity are negative, an LH band is expected.

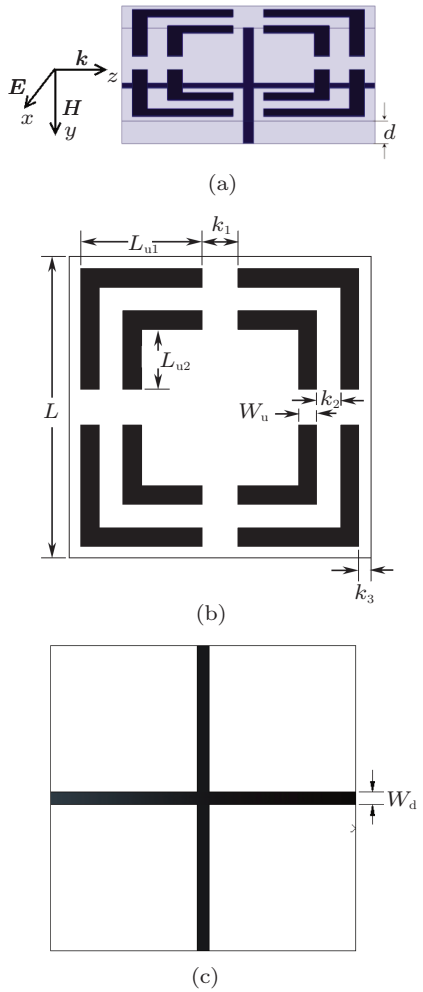


Fig. 1. Schematic diagram of (a) the bilayered MSMC structure, (b) the upper surface, and (c) the bottom surface.

Though we have chosen FR4 with a loss tangent $\tan\delta = 0.02$ substrate, the absorptivity is very low. As shown in Fig. 2(d), the peak of absorptivity is about 8.74% at 14.7 GHz. What should be pointed out is that the substrate material, thickness and the pattern of LHMs have a significant influence on the absorptivity. For instance, in Ref. [20], the pattern of LHMs is SRR pairs with the substrate same as that in this paper, but the maximum absorptivity reaches up to 40%, which makes the left-handed behavior invalid in practical applications due to high losses.

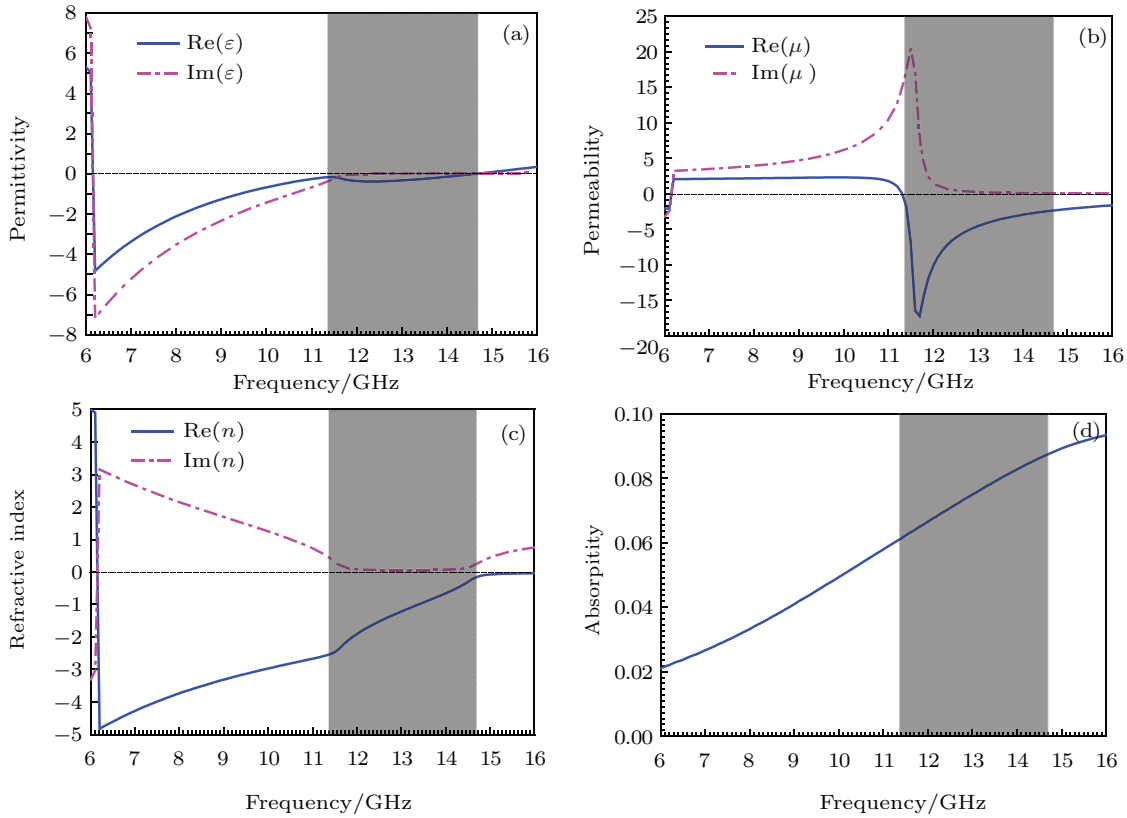


Fig. 2. (colour online) (color online) Retrieved effective constitutive parameters. Real (solid line) and imaginary (dashed line) of the effective (a) relative permittivity, (b) relative permeability, (c) index of refraction, and (d) absorptivity.

3. Structure analysis

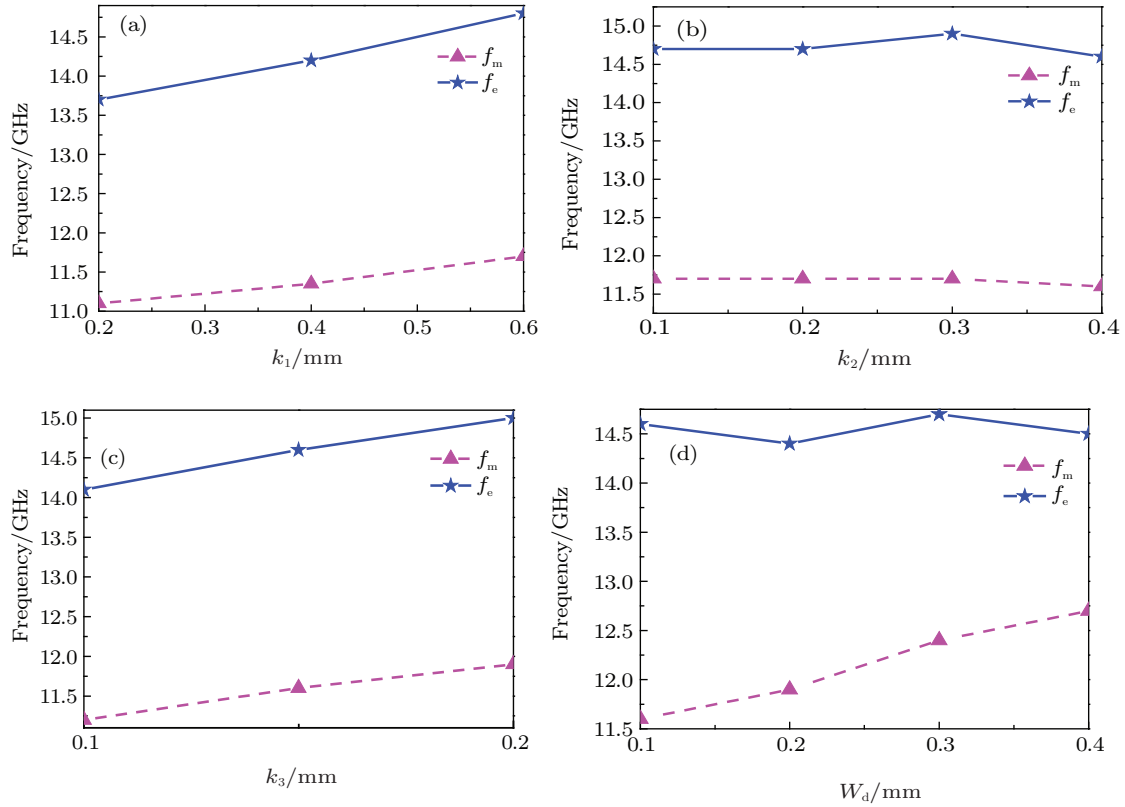


Fig. 3. (color online) Magnetic resonance frequency f_m and cut-off frequency f_e of the negative permittivity versus (a) distance between each cut-wire pair k_1, (b) interval between the inside and outside of the wire k_2,(c) interval k_3, and (d) width of the underlying wire W_d.

The MSMC structure has an intrinsic relation with the fishnet[21] and the split ring resonators (SRRs) structure.[22] It is shown in Ref. [21] that the magnetic resonance of a short-wire is only proportional to $1/l$. Here, with detailed simulations, the dependence of the magnetic resonance $f_{\rm m}$ and the cut-off frequency $f_{\rm e}$ of the negative permittivity on the geometric parameters is shown in Fig. 3. As shown in Figs. 3(a) and 3(c), $f_{\rm m}$ and $f_{\rm e}$ are linear functions of k_1 and k_3. Figure 3(b) shows that while the interval k_2 changes from 0.1 mm to 0.4 mm (increases by a factor of 4), $f_{\rm e}$ and $f_{\rm m}$ are almost fixed. It can be seen from Fig. 3(d) that $W_{\rm d}$ has a greater impact on $f_{\rm m}$ than $f_{\rm e}$.

4. Experimental verification

The expected behavior has been confirmed experimentally by measuring the transmission and reflection properties of the proposed metamaterial using the waveguide method. In the experiment, the transmission properties of a slablike sample are firstly measured to verify the existence of the passband due to the double negative property. The geometrical dimensions of the fabricated sample are the same as the simulation. The sample under measurement contains 3 unit cells in the z direction, 2 unit cells in the x direction, and 7 unit cells in the y direction, as shown in the inset of Fig. 4(c). The measurement setup consists of two coaxial-to-waveguide adapters connected to a nonstandard waveguide and an Agilent E8361A network analyzer. The experimental setup is shown in Fig. 4(a). In the transmission and reflection measurements, the microwaves were incident parallel to the sample surface. Experimental transmission and reflection data were obtained by building and measuring the microwave frequency versions of the MSMC structures.

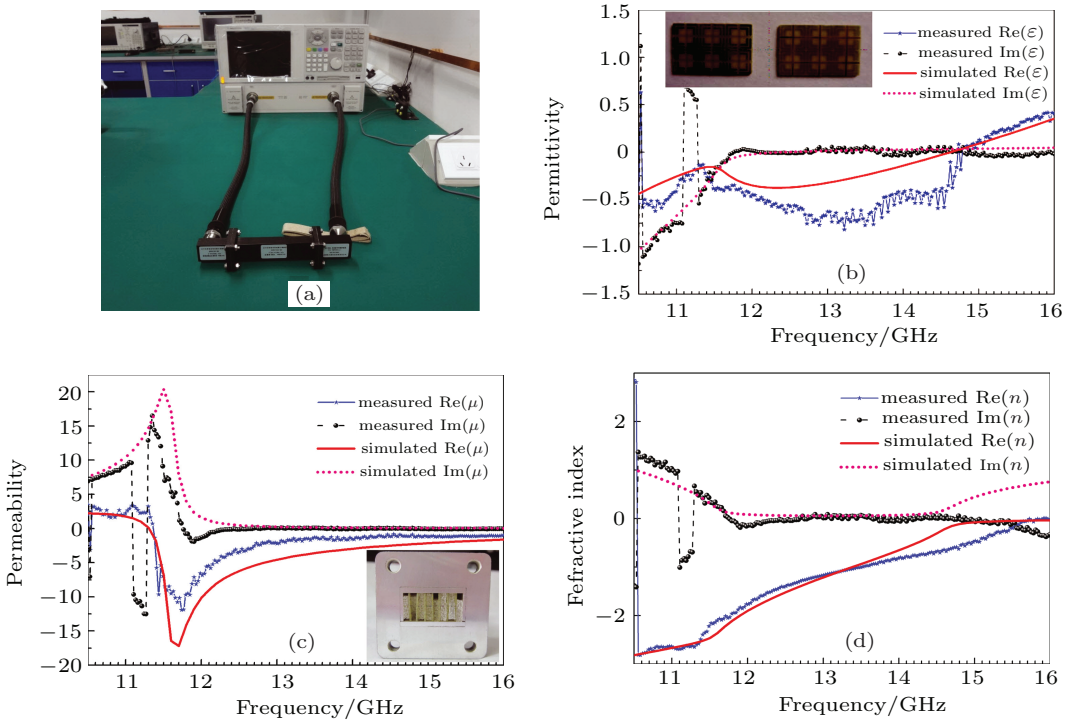


Fig. 4. (color online) (a) Photograph of the experimental setup. Comparison between simulation and measurement results of (b) permittivity, (c) permeability and (d) refractive index.

The measured results obtained by this analysis are shown by the data points in Figs. 4(b), 4(c) and 4(d). The measurements are quantitatively in excellent agreement with the simulated results and confirm the existence of a band of double negative between 11.36 and 14.7 GHz. The LH bandwidth is 3.34 GHz.

5. Conclusion

In this paper, a structure of MSMC is proposed to form a negative index material in the microwave regime. This structure achieves broad DNG frequency band and relatively low absorptivity. By a standard

algorithm, the effective, constitutive parameters are extracted from the scattering parameters, which have a quantitative agreement between simulations and experiments. The results show that the LH bandwidth is 3.34 GHz. This study offers an important flexibility in designing broadband metamaterial. Future research work will be carried out for its application in designing broadband microwave devices.

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