A Novel Single-Sided Wideband Metamaterial

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Abstract ─ A simplified structure made of double P-like rings (DPLs), printed on only one side of a dielectric substrate was proposed. A metamaterial sample is investigated numerically and experimentally. The results clearly show that the negative refraction occurs at the transmission band, and one very wide left-handed passband is obtained. A circuit model is also carried out to be a further analysis of the DPLs unit cell.

Index Terms ─P-rings, left-handed material (LHM), metamaterials, double negative (DNG), wideband metamaterials.

I. INTRODUCTION

Metamaterials is a sort of artificial composite material, in which both the electric permittivity (ε) and the magnetic permeability (μ) are negative. Since Smith first experimented the combination of split ring resonators (SRRs) and continuous wires [1, 2], LHMs have attracted a great amount of attention from researchers in view of their novel characteristics and fabrications [3-10]. Then many structures are proposed, such as, symmetrical-rings [11], Ω-shaped [7], and S-shaped [12, 13]. SRRs are magnetoelectric particles making bianisotropic materials where the rod induced electric resonance and split-ring provided magnetic resonance. The Ω-shaped geometries are printed in reverse directions, yielding a material, in which electric and magnetic effects are separate like the SRRs. Then Chen proposed the symmetric S-shaped configuration, in which there is no obvious electric and magnetic response. Most of above-mentioned structures are printed on both sides of the substrates and has a narrow band, which faced many problems from fabrication and application.

In contrast, we proposed a novel single-sided double P-like left-handed metamaterial. The unit cell of the DPLs structure was introduced detailly, in which bandwidth is extended and the loss is very low. From an experimental point of view, this structure can be easily fabricated and used in real-life applications. The DNG passband is obtained by overlapping the negative permeability and the permittivity. The electric and magnetic resonances can be easily tuned by the parameters, such as width, length, and distances. Then the negative permittivity can coincide with the negative permeability by tuning these variables. The two rods induced the electric response, and the magnetic response is due to antiparallel current distribution between two rings and the adjacent wires [14]. Using the scattering parameters, obtained by HFSS, the complex constitutive effective parameters of the metamaterial are retrieved. A sample is fabricated and tested in a waveguide measurement setup. Also, an equivalent circuit of the unit cell is given to verify the results.

II. UNIT-CELL DESIGN AND SIMULATION

The unit cell of the DPLs is shown in Fig. 1, where the metallic strip is printed on one side of $h=0.508mm$ thick substrate Rogers5880 (ε_r=2.2) and the metallization is a 0.018 mm copper. Dimensions of the unit cell are: a=5.05mm, b=4.5mm, c=2.5mm, $a1$=1.3mm, $w1$=$w2$=0.3mm, $b1$=3.5mm, L=2.575mm, s=0.1mm, $s1$=$s2$=0.2mm. In order to verify the DPLs, numerical simulations were first carried out using HFSS. The electromagnetic wave is incident along the x direction with an electric field polarized in the y direction. This structure can be stacked along

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z direction without space as it is printed on only one side of the dielectric medium. The novel method simplified the manufacturing process.

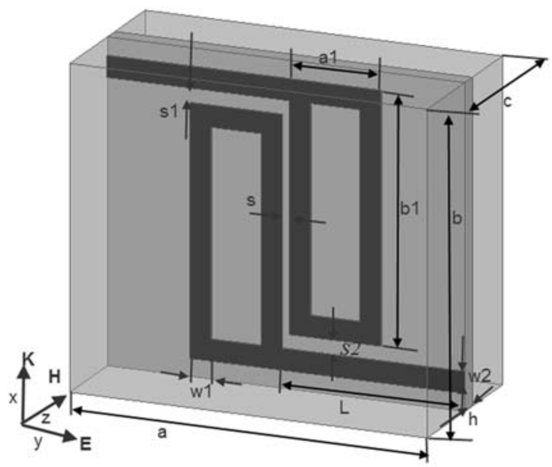


Fig. 1. Geometry of the double-P unit cell.

There are many known methods to retrieve constitutive parameters of metamaterials [2,15-18], scattering parameters are used mostly to obtain impedance z and effective refractive index n. The refractive index and the wave impedance can be related as follows:

$$n = \frac{1}{kd}\cos^{-1}\left(\frac{1 - S_{11}^2 + S_{21}^2}{2S_{21}}\right),\ z = \sqrt{\frac{(1+S_{11})^2 + S_{21}^2}{(1-S_{11})^2 + S_{21}^2}} \quad (1)$$

Then we can calculate the $\varepsilon = n/z$ and $\mu = nz$. It must be mentioned that most of the retrieval procedures obtained the z and n used only one unit cell and assumed the results of period structures will be the same as for a single unit cell.

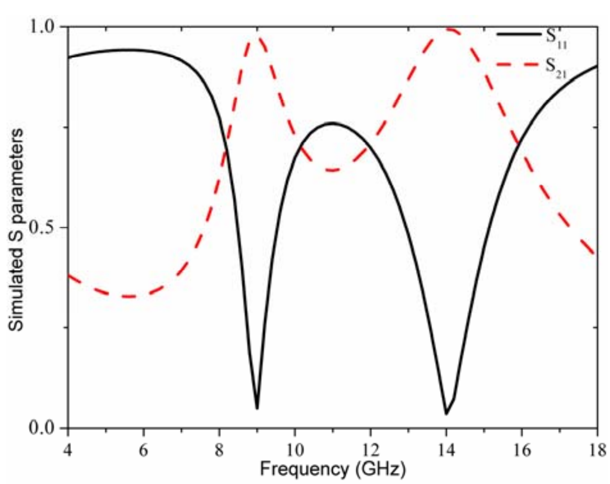


Fig. 2. The simulated S parameters.

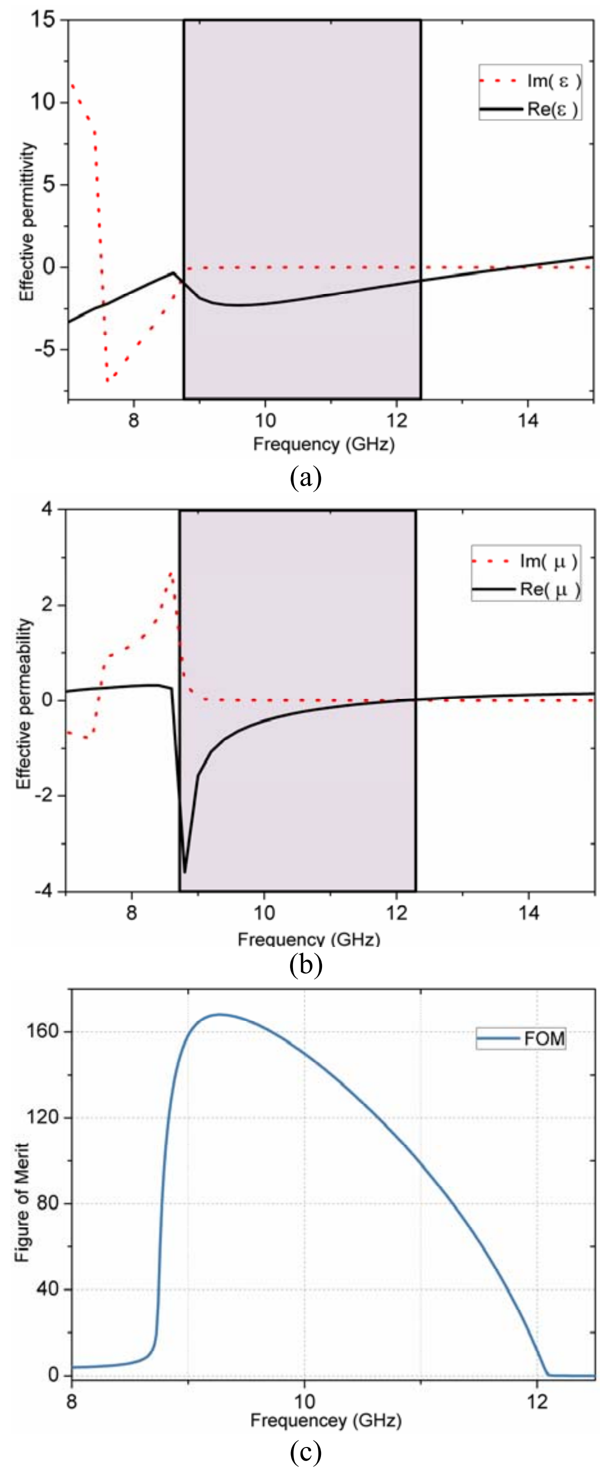


Fig. 3. Retrieved effective parameters. Real (solid line) and imaginary (dashed line) part. (a) permittivity, (b) permeability, (c) figure of merit for the unit cell.

The simulated reflection and transmission spectra are given in Fig. 2, as we can see, at the low frequency side, the transmission is high and approaches 0.98 near 9GHz. Figure 3 clearly depicts the retrieved effective parameters. The effective permittivity is negative in 7.8-13.5GHz, while the effective permeability is negative in 8.75-12.2GHz, respectively. By overlapping the negative permittivity and the permeability, we obtain a wide negative frequency passband, and the relative frequency band is 33.5%. From Fig. 3(c), the figure of merit (FOM), which is a factor of loss and defined as $\left|\mathrm{Re}(n)/\mathrm{Im}(n)\right|$, is from 168 to 14.3 for the DNG band (8.75-12.2GHz). And outside the passband, the FOM is near zero. This indicates that this left-handed metamaterial performs well in the DNG band and can be a good candidate for the potential real-life applications. The equivalent circuit of the unit cell is also given in Fig. 4. The electric and magnetic resonant behaviours are due to a number of capacitances and inductances within this structure, where the C_i (i=1,2,3) are the gap capacitances, L_1 and L_2 are the inductances of the two lines, L_{p1}, L_{p2} and *Cp1, Cp2* are the inductances and capacitances of the two rings.

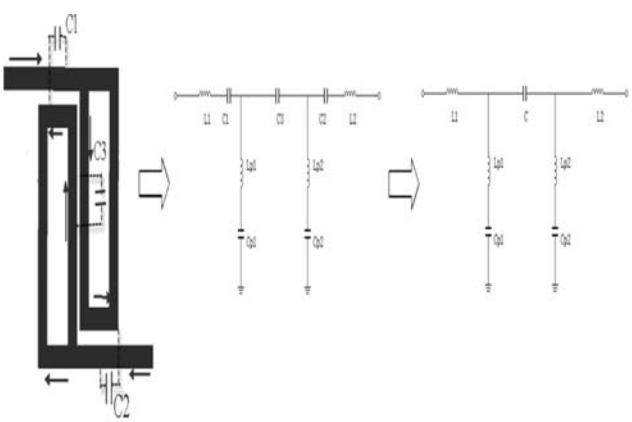


Fig. 4. The equivalent circuit of the unit cell.

The current distribution of the unit cell at 10GHz is given in Fig. 5, which confirms the equivalent circuit analysis in Fig. 4. As one can see in Fig. 5, there exist three gaps in this structure, on two sides of these gaps (*s, s1, s2*), the currents is antiparallel which induced the magnetic response. And the electric response is attributed to the plasma-electron oscillations of the two cut wires.

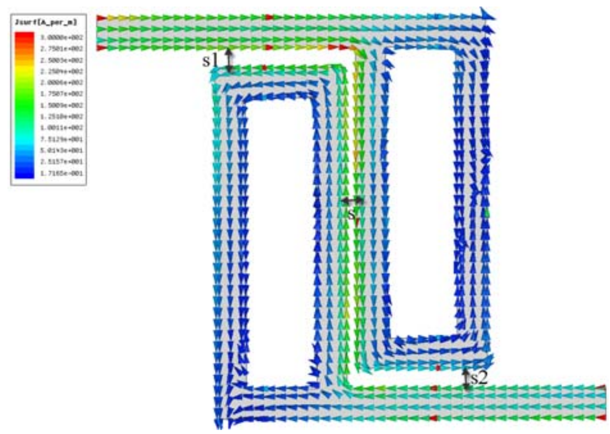


Fig. 5. Surface current distribution for the double P-like structure at 10GHz.

Here, with detailed simulations, the dependence of the magnetic resonance f_m and the electric resonance f_e is shown in Fig. 6. As shown in Fig. 6(a), 6(b), and 6(c), f_m and f_e are linear functions of 1/a1, 1/b1, and 1/L. Figure 6(d) shows that f_m is proportional to s and f_e is inversely proportional to s while it changes from 0.1 mm to 0.5 mm.

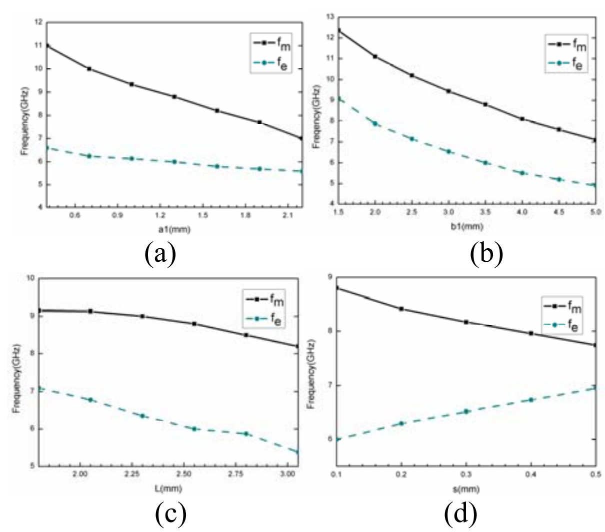


Fig. 6. Magnetic resonance frequency f_m and electric resonance f_e versus (a) the width of the ring, (b) the height of the ring, (c) the length of the branch, (d)the distance of the two P-like rings.

III. EXPERIMENT VERIFICATION

The proposed double P-shaped resonator was also manufactured and tested. In practical fabrications, periodic array is 2 unit cells along *x* and *y* direction. And there is no need for spacers between stacked layers in *z* direction. The sample is put into a standard waveguide BJ100. Scattering parameters were measured by Agilent E8361A [19, 20]. The measured S_{11} and S_{21} parameters are shown in Fig. 7. The transmission peak is near the 9 GHz respectively. A closer view of fabricated sample and its direction inside the waveguide are also depicted in Fig. 7.

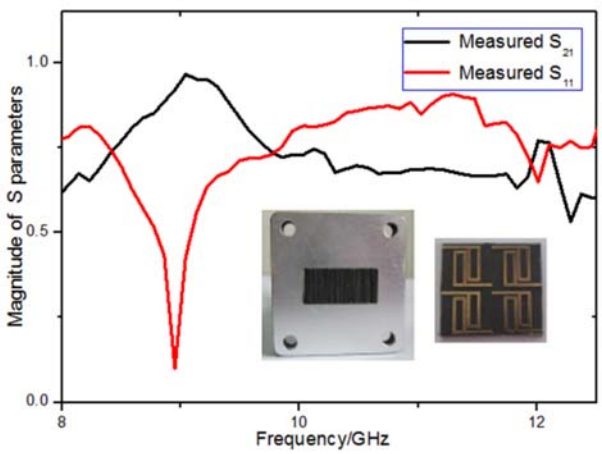
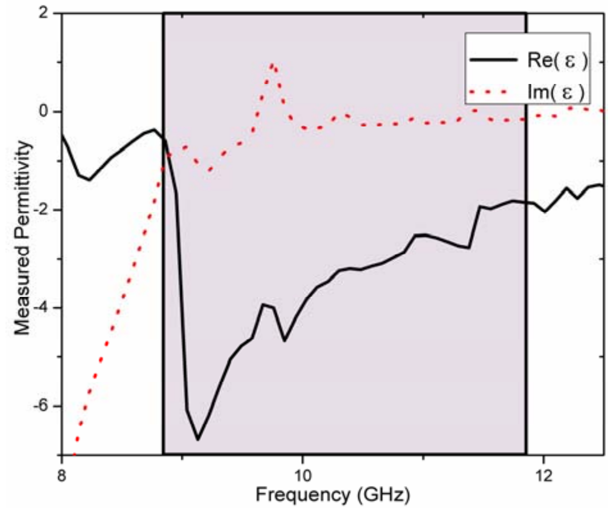


Fig. 7. Measured S parameters.

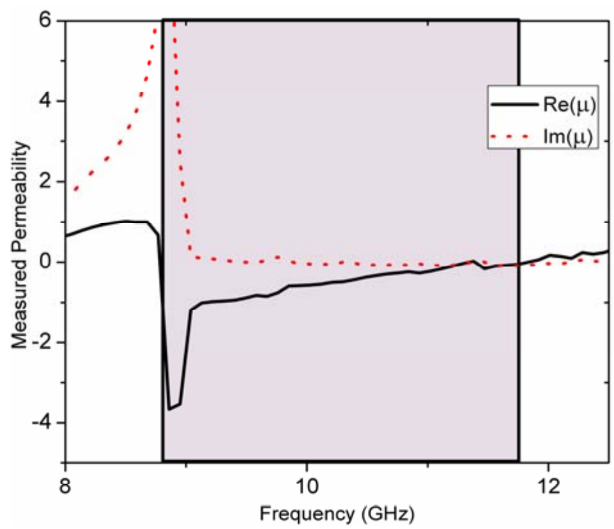
Figure 8 illustrates the real part and the imagery part of the permittivity and the permeability. It can be seen that the real part of effective permittivity is negative in 8.8-12.5GHz, while the real part of effective permeability is negative in 8.8-12.2GHz. Thus, the DNG band is 8.8-11.8GHz. Comparing the simulated DPL unit cell, the refraction index is negative in 8.75-12.2GHz. Note the measured DNG band is narrower than the simulated one. The difference may be caused by the fabrication error, such as the layers are not precisely parallel and the cut-wires did not touch the waveguide wall completely.

IV. CONCLUSION

A novel single-sided double P-shaped resonator has been proposed. Both the numerical simulation and the experiment have confirmed the obvious transmission peak and the negative effective permittivity, permeability, and the negative refraction index happened around the resonant frequency peak. In addition, this single-sided structure has a wide band and can be easily fabricated. Thus, this novel geometry can be used in various potential real-life applications and this manufactured LHM can be a good candidate for being used optical metamaterial.



(a)



(b)

Fig. 8. Measured effective parameters.

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