Novel Monolayer Windmill Structure Left-Handed Metamaterial

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***Abstract* ─** In this paper, a simple structure made of periodic arrays of windmill structure, printed on only one side of a dielectric substrate, is introduced. Simulation and measurement were carried out for one layer of infinite left-handed material (LHM) slab using monolayer windmill structure. The results showed that by carefully adjusting the dimensions of the windmill structure, magnetic and electric resonances can be coexistent in a frequency range where there are both negative magnetic and electric responses. To further verify the left-handed (LH) properties of this structure metamaterial, effective medium parameters were retrieved and a refraction phenomenon based on a wedge-shaped model was demonstrated. Equivalent circuits for the magnetic and electric resonance were also offered to give a qualitative explanation of the LH behaviours.

***Index Terms* ─** Double negative (DNG), left-handed material (LHM), monolayer, and negative refractive index (NRI).

I. INTRODUCTION

Artificial electromagnetic structures, called metamaterials, can be engineered to exhibit exotic electric and magnetic properties not realizable in nature. In 1968, Veselago [1] initially assumed a material with negative permittivity and permeability simultaneously and theoretically demonstrated the abnormal electromagnetic properties. However, research work in this area did not draw much attention in the engineering and physics communities because there are no such materials in natural world. His work was neglected for almost 30 years. In 1999, Pendry et al. [2] showed that negative ε can be realized by using conducting wires and negative μ by split-ring resonators (SRRs). Smith et al. [3] constructed a real structure composed of conducting wires and SRRs, and demonstrated its negative ε and μ at microwave frequencies. Subsequently, a great variety of left-handed metamaterials (LHMs) were proposed, such as split-triangle resonator (STRs) [4], multi-gap split-ring [5], SRR pairs [6, 7], single split-ring resonators [8], ferromagnetic host and wire array [9], etc. The above methods of realizing LHMs enrich greatly the content of LHMs. Nevertheless, there is an annoying problem for the LHMs realized by the above methods. Most of the above-mentioned LHMs share one thing in common that they print the metallic patterns on both sides of the substrates. It not only increases the complicacy of fabrication when the operating frequency increased to high frequency such as terahertz frequency but also increases the difficulty to add lumped active elements (for example, varactor diodes) on such structures to control their left-handed properties, because modern commercial components are generally designed for surface mount.

In this paper, a simple metamaterial structure based on the windmill is proposed and investigated experimentally and numerically at microwave frequency range. Although it derives from the bi-layered chiral metamaterial [10, 11], unlike the structure in [10] that requires the electromagnetic waves normal to the planes of the printed boards, this paper’s proposed structure requires electromagnetic waves travel along the planes of the thin dielectric sheet. Compared with the conjugated gammadions structure [11], this monolayer windmill metamaterial structure is more easily manufactured.

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II. UNIT-CELL DESIGN AND SIMULATION

A unit cell of the single-sided windmill structure is shown in Fig. 1, where the metallic strips are printed on one side of t = 0.6 mm thick FR4 substrate with the relative permittivity of 4.4 and $\tan\delta_s$ = 0.02. The metallization is copper with a thickness of 0.017 mm. The other geometrical dimensions are as follows, in millimetres: L = 5, a = 2.05, b = 0.3, c = 0.2, d = 2.4, g = 0.6. The Y structure has been demonstrated to have LH behaviours in some frequency ranges [12]. So for this paper, in response to the magnetic field, the capacitance between four adjacent L-shaped structures (seen the loop in Fig. 4 (a)) and their own self-inductance form an equivalent L–C loop, which can provide a negative permeability. In response to the electric field, the metal thin strips which, parallel to the electric field can provide a negative permittivity. So LH behaviours are expected for this structure.

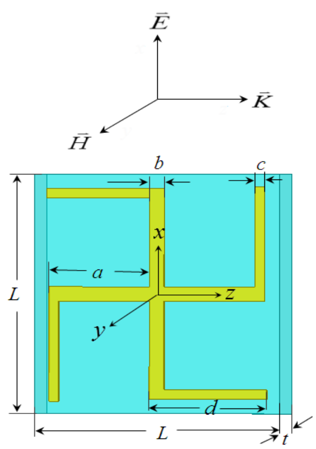

Fig. 1. Geometry of one unit cell of the windmill structure metamaterial.

In order to verify our speculation, the numerical simulations were performed for one layer of the windmill structure LHM slab by HFSS. A theoretical model based on an artificial waveguide with the transverse boundaries of two ideal magnetic conductors and two ideal electric conductor planes is employed. This enables the model to be equivalent to an infinite layer medium illuminated by a parallel incident plane wave. To be specific, input/output ports are imposed in z-direction, and perfectly electric conducting (PEC) and perfectly magnetic conducting (PMC) boundary conditions are imposed in x– and y–directions (perpendicular to the plane of the windmill structure), respectively. There are many methods to retrieve constitutive parameters of metamaterials [13-15]. Most of them use scattering parameters to obtain the impedance z and effective refractive index n and then calculating $\mu = nz$ and $\varepsilon = n/z$. In this paper, we use a standard algorithm [15] extracted from the scattering parameters. Figure 2 gives the simulated magnitudes of S_{11} and S_{21} parameters, as well as the retrieved real parts (solid curves) and imaginary parts (dashed curves) of effective permeability, permittivity, and refractive index. Figure 2 (a) shows that there is a transmission peak at 10.4 GHz, which indicates an LH passband. As clearly shown in Fig. 2 (b) and (c), there are obviously an electric resonance and a magnetic resonance. In Fig. 2 (b) and (c) show that the effective the effective permittivity is negative in 9.28 GHz–12 GHz while the frequency range of negative effective permeability is 10.2 GHz–10.7 GHz, much narrower than the negative electric permittivity. In the frequency range where both the effective permittivity and permeability are negative, an LH band is expected. Figure 2 (d) depicts the extracted effective refractive index of the metamaterial at various frequencies. Clearly, as the frequency increases, the effective index of refraction changes from positive to negative then to positive. The refractive index varies from n = -2.95 + j0.85 at 10.1 GHz to n = -0.018 + j2.54 at 11.35 GHz. So as the grey area shows, the windmill structure is double negative between 10.2 GHz and 10.7 GHz, and the negative index bandwidth is 500 MHz.

Please note that in Fig. 2 (c) and (d), the negative reflective region (shaded region) is much wider than the negative permeability region. This can be explained as follows. A wider negative n' frequency band is observed due to the dispersion of fabricated prototype. Since the real part of n (n') is given by $n' = \varepsilon' z' - \varepsilon'' z''$ from $n = \varepsilon z$ and z = sqrt(μ/ε), the imaginary parts of the permittivity (ε'') and the permeability (μ'') also accounts for n'. Therefore, a negative real part of n can be accomplished without having ε' and μ' simultaneously negative. The amplitude of Im (n) is relatively small compared to the real part, which suggests a low loss in the proposed left-handed metamaterial.

To further verify the LH properties and obtain a direct image of the negative refraction of the EM wave for the windmill structure, we utilize a wedge–shaped configuration, which is stacked by our designed single slab planar metamaterials with an inclined angle of 45°in simulation. Similarly to [16] described methods, it stacked one unit cell along the *y*-axis in the simulation. For the wedge model, 7 unit cells are used along the *x*–axis and the *z*–axis, respectively. The refraction interface has a staircase pattern with one unit cell step in the *x*–direction and the *z*–direction, which can be referred to as a wedge angle of 45°. All the unit cells are positioned between two conducting plates with the absorber boundary conditions at the side faces.

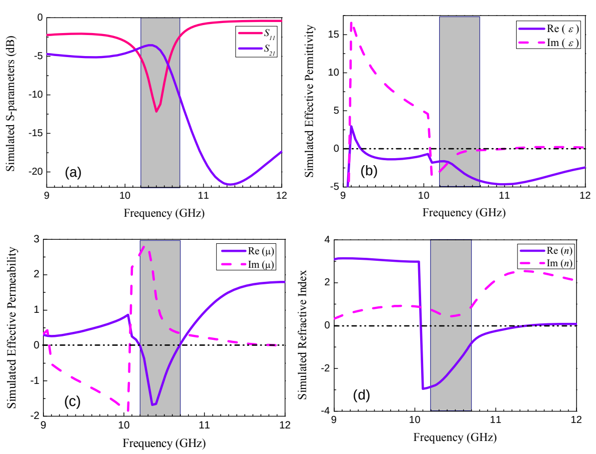

Fig. 2. (a) Simulated magnitudes of $S_{11}$and S_{21} parameters; real (solid curves) and imaginary (dashed curves) of the effective, (b) relative permittivity, (c) relative permeability, and (d) index of refraction.

Figure 3 shows the phenomenon of refraction of the EM radiation at the interface between designed metamaterial and vacuum. The typical electric field distributions at 10.4 GHz and 9 GHz are presented in Fig. 3 (a) and (b), in which the negative and the positive refractive behaviors are demonstrated clearly, respectively. The unambiguous negative refraction phenomenon is observed in the LH transmission passband, which has been ascertained from the retrieved effective parameter procedures as discussed above. The arrow lines indicate the transmission direction of the refracted waves, while the dashed lines are along the surface normal.

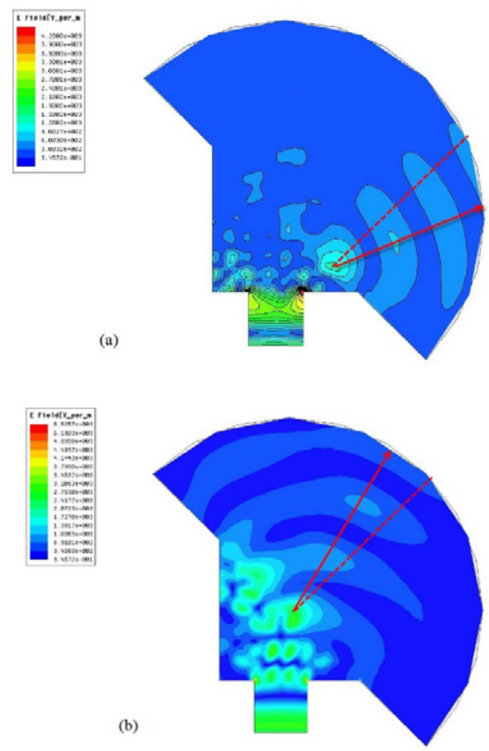

Fig. 3. The distribution of the electric field in the wedge-shaped configuration at different frequency points; (a) the negative refraction at 10.4 GHz and (b) the positive refraction at 9 GHz.

III. EQUIVALENT CIRCUIT MODEL AND PARAMETRIC STUDY

Negative effective permittivity and permeability can be obtained by electric and magnetic resonances, respectively. Both the electric and magnetic resonances are equivalent to L–C resonant circuits. The windmill structure has an intrinsic relation with the Jerusalem cross [17-19]. We start with the equivalent circuit model in Fig. 4 when the proposed LHM responds to incident electromagnetic waves. The wires along the electric field **E**-direction of the incident electromagnetic wave excite the electric response and produce negative permittivity ε up to the plasma frequency. The linear arrow in Fig. 4 (a) denotes the equivalent current of electric resonance. In Fig. 4 (a), both *A* and *B* are equivalent to *A*' and *B*' for periodicity. Equivalent L–C circuit of electric resonance is given in Fig. 4 (b), where L_e is the inductance of the cross bar and C_e is the capacitance between four L-shaped gaps. Due to anti-parallel currents induced by the magnetic field of the incident electromagnetic wave, The four L–shaped structures perpendicular the magnetic field **H** direction act as magnetic resonators, providing negative permeability μ. The corresponding equivalent current is denoted by the circular arrow. According to the orientation of the equivalent current, the equivalent circuit of magnetic resonance can be illustrated by Fig. 4 (c), where L_m and C_m are, respectively the equivalent mutual inductance and capacitance around one windmill structure. The similar formulas for L_e, C_e, L_m, and C_m can be found in references [16, 17]. Figure 5 (a)–(d) present the relations between the electromagnetic resonance and geometric parameters. It is shown that the electric resonance f_e and the magnetic resonance f_m are proportional to *1/a, b, 1/c*, and *1/d*, for the parallel incidence case.

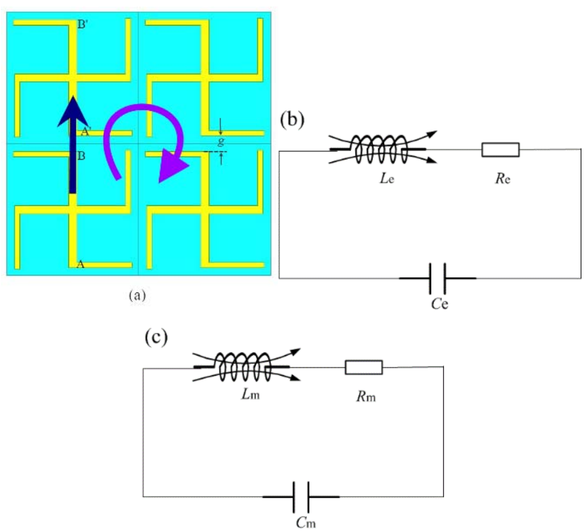

Fig. 4. Equivalent circuit description of the proposed LHM; (a) illustration of equivalent current in windmill structure, (b) equivalent circuit of the electric resonance, and (c) equivalent circuit of the magnetic resonance.

IV. EXPERIMENTAL VERIFICATION

The expected behaviour has been confirmed experimentally by measuring the transmission and reflection properties of the proposed metamaterial using the waveguide method [20]. Because the waveguide measurement method is easy to carry out, and there no tough requirements for the material sample. In the experiment, the slab like sample being placed in the middle of the waveguide makes the higher order incident evanescent modes significantly attenuated prior to reaching the sample under test. The transmission properties of a slab like sample are firstly measured to verify the existence of the pass band 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 *x* direction, and 35 unit cells in the *y* direction. There is no need for spacers between stacked layers in *y*-direction, which makes the setup easier [21]. The measurement setup consists of two coaxial-to-waveguide adapters connected to a BJ100 standard waveguide and an Agilent E8361A network analyser. The experimental setup is shown in Fig. 6. Using the recorded scattering parameters, the constitutive effective parameters are retrieved. Figure 7 (a)–(d) illustrate the experimented parameters. There exist some discrepancies between measured date and the simulated results. This could be due to the fabrication error as the design we used.

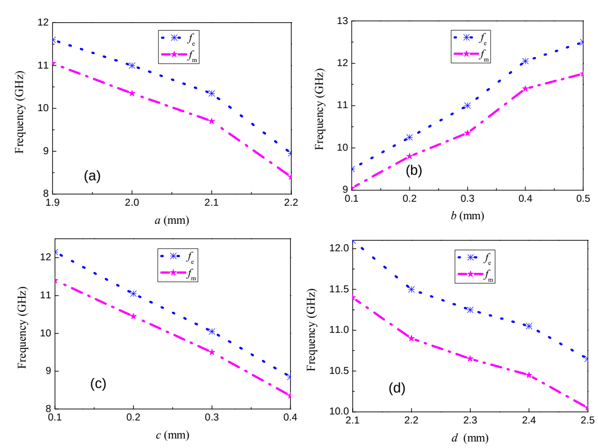

Fig. 5. Magnetic resonance frequency and electric resonance frequency versus; (a) wire length "*a*", (b) wire width "*b*", (c) wire width "*c*", and (d) wire length "*d*".

Fig. 6. Photograph of the experimental setup.

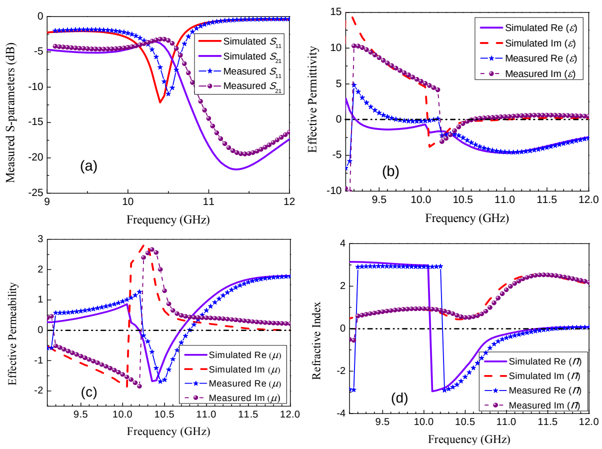

Fig. 7. Comparison between simulation and measurement result of (a) S_{11} and S_{21} parameters, (b) permittivity, (c) permeability, and (d) index of refraction.

V. CONCLUSION

In summary, we studied the LH properties of the monolayer windmill structure by simulation and experiment in the microwave frequency regime. The windmill structure metamaterial simultaneously shows an electric and magnetic response to incident EM wave, and the LH transmission passband is expected. The negative refraction is demonstrated by simulating the wedge-shaped model. Furthermore, the design parameters and their relation to the magnetic and electric resonances have been investigated. The simplicity of structure makes the LHM easy to fabricate, which may be useful for potential applications in the future.

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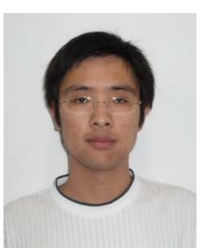

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