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DESIGN OF A COPLANAR LABYRINTH-BASED LEFT HANDED MATERIAL AND ITS APPLICATION TO HORN ANTENNAS

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Abstract—A coplanar left-handed material, symmetric square labyrinthine ring (SSLR), is proposed in this paper based on labyrinth structure. The effective permittivity and permeability of the SSLR structure are retrieved using NRW (Nicolson-Ross-Wire) method and approach zero at 5.8 GHz. Then the proposed structure is applied to an open-ended waveguide antenna, and simulation results indicate that the proposed SSLR structure can effectively improve the gain about 5.5 dBi. The far-field of a dual ridge horn antenna with and without SSLR structure is also measured. Results show that the gain of the antenna is enhanced about 3.2 dBi, and the back lobe is suppressed.

1. INTRODUCTION

In 1968, Veselogo theoretically studied the electromagnetic properties of substances with simultaneously negative permittivity (ε) and permeability (μ) [1]. He called these substances left-handed materials (LHM) in which the propagation of electromagnetic waves with the electric field $\mathbf{E}$, magnetic field $\mathbf{H}$, and phase constant vector $\mathbf{k}$ form a left-handed set, compared with conventional materials where this set is known to be right-handed materials (RHM). Though this kind of material does not violate Maxwell's equations, it did not attract much attention at that time because the lack of natural material with negative permeability restricts one's freedom in researching.

Almost 30 years past until Pendry [2] renewed the interest in LHM. He found out that a medium constructed by periodic metallic strip wires could exhibit an effective negative permittivity, and split ring

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resonators (SRR) could result in an effective negative permeability over a respective frequency region [2, 3]. With Veselogo's theory and Pendry's pioneering work, Smith et al. successfully fabricated the first LHM and demonstrated experimentally that the index of refraction is negative [4, 5]. Since then, more and more researchers began to engage in this field because the left-handed materials possess very fascinating electromagnetic properties compared with conventional right-handed materials, such as the reversed Snell refraction [6], reversed Doppler shift [7], reversed Cherenkov radiation [8, 9], etc.

Many properties and potential applications of LHM have emerged in the past few years [10, 11]. One of the applications is to improve radiation performance of antennas [12–14]. Enoch et al. [15] presented the theoretical feasibility of applying LHM to antenna and demonstrated that under proper conditions the energy radiated by a source embedded in a slab of LHM will be concentrated towards the normal of the substrate. Many researches show that LHM can improve the directivity of conventional patch antennas [16, 17] or the gain of rectangular waveguide [18] and circular waveguide antenna arrays [19].

In this paper, we present a coplanar structure, symmetric square labyrinthine ring (SSLR) and apply it to the waveguide aperture and dual ridge horn antenna. The SSLR structure and its characteristics are described in Section 2. Some numerical results and analysis are provided in Section 3. Experimental results and discussion are shown in Section 4, and we summarize our conclusions in Section 5.

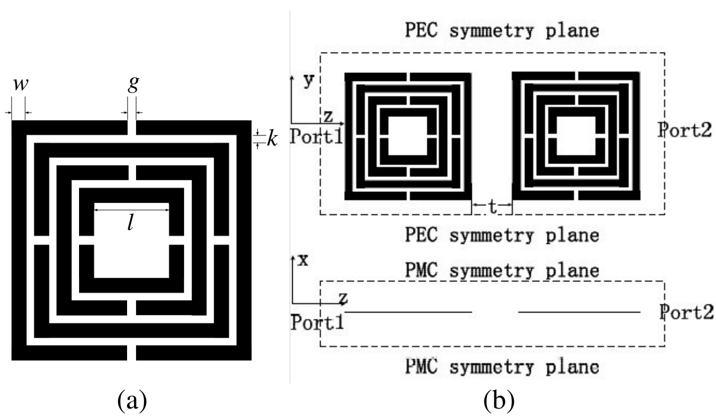


Figure 1. (a) Structure of the proposed symmetric square labyrinthine ring (SSLR) unit cell. (b) Simulation model to study wave propagation characteristics in periodic array of SSLR structure.

2. STRUCTURE OF SSLR AND ITS CHARACTERISTICS

LHM structure is usually composed of split-ring resonators (SRR) acting as magnetic resonator and continuous metallic strip wires as electric resonator. However, the SRR and wires need to be designed and arranged respectively, leading to a complicated 3-dimensional structure or a multi-layer printed board structure. In this paper, we present a coplanar LHM structure, symmetric square labyrinthine ring (SSLR), which is shown in Fig. 1(a).

Conventional labyrinth structure consists of four concentric circular rings with two symmetric cuts on each of them [20, 21]. Because of its complete symmetry, the labyrinth structure eliminates two disadvantages of conventional SRR structures, electric coupling and bianisotropy [22–24]. However, the labyrinth structure has to combine with metallic wires in order to achieve LHM characteristics. In the proposed structure shown in Fig. 1(a), we replace the circular rings with square rings to obtain a coplanar structure. The sides of the square rings just play the role of the metallic wires. LHM characteristics for such a structure can be achieved by optimizing the side length of the square rings.

Figure 1(b) shows the model depicted in [25] to calculate characteristics of the SSLR structure, which allows to simulate effectively the semi-infinite slab with a semi-infinite periodic array of SSLR cells by using a pair of perfect electric conductors (PEC) and a pair of perfect magnetic conductor (PMC) walls. A dielectric slab with $\varepsilon_r = 2.65$ is centered in the region bounded by those PEC and PMC walls, with two SSLR cell units located on the dielectric substrate

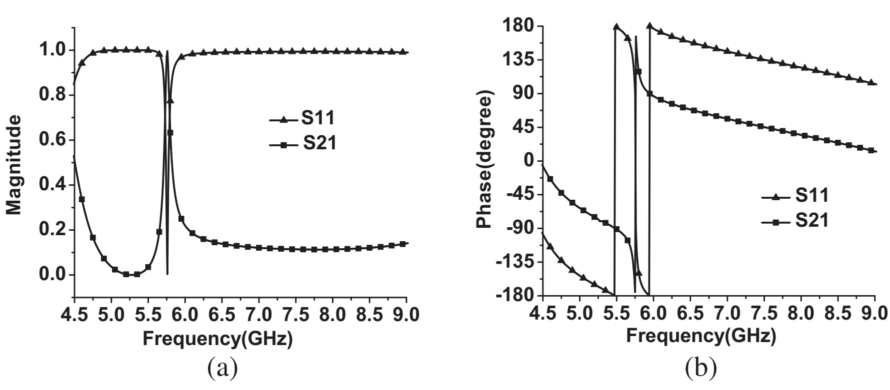


Figure 2. (a) Magnitude of S-parameters, (b) phase of the S-parameters.

along z direction.

The polarization of normally incident wave is $(E_y,\ H_x)$, so that electric field is parallel to the plane of the SSLR, while magnetic field is perpendicular to the plane of SSLR. In Fig. 1(b), the optimized dimensions are $w = 0.4\,\mathrm{mm}$, $k = 0.2\,\mathrm{mm}$, $g = 0.2\,\mathrm{mm}$, $l = 1.2\,\mathrm{mm}$, and the space between each SSLR unit cell is $t = 3\,\mathrm{mm}$.

We calculated S-parameters using HFSS and results at the frequency range of 4.5–9 GHz are plotted in Figs. 2(a) and (b) respectively. The phase of S_{21} goes to zero, and the magnitude approaches unity at 5.8 GHz, which indicates that electromagnetic energy passes the SSLR structure almost without any loss at this frequency. The effective permittivity (ε_r) and permeability (μ_r) are retrieved from S-parameters using Nicolson-Ross-Wire (NRW)

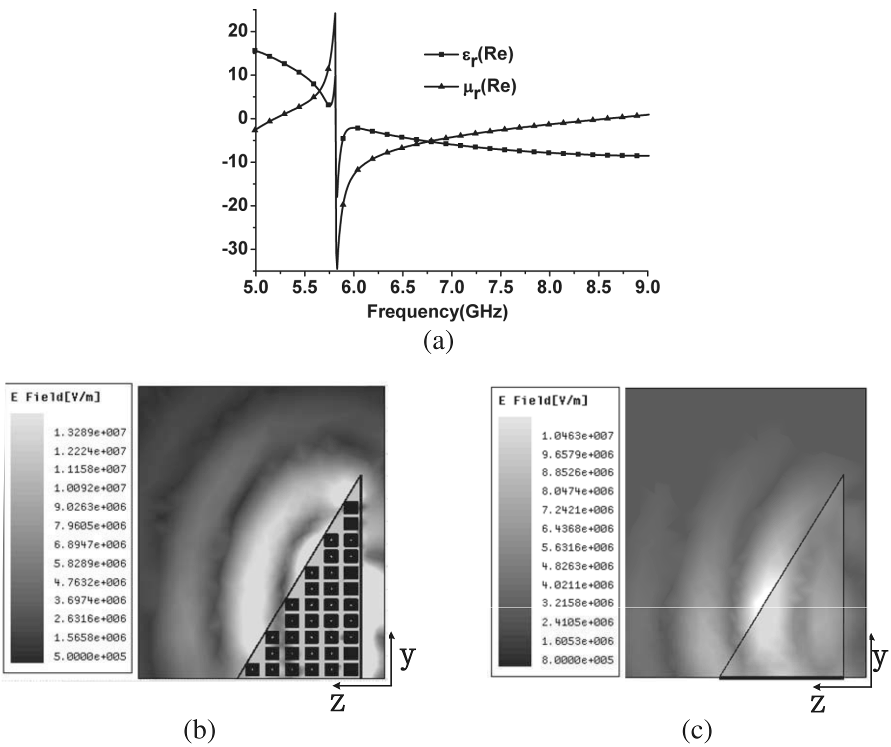


Figure 3. (a) Effective permittivity and permeability of the proposed structure. (b) Electric field distribution when a vertical polarized Hertzian dipole is put in front of a prism-shaped LHM structure. (c) Same as (b), except for dielectric structure.

approach [25] and shown in Fig. 3(a).

It can be seen in Fig. 3(a) that both ε_r and μ_r approach zero at 5.8 GHz and are simultaneously negative within a frequency range. In the region where both ε_r and μ_r are simultaneously negative, when the index of refraction (defined as $n = \sqrt{\mu_r \varepsilon_r}$) is less than 1 and tends to zero, the refractive waves in LHM will concentrate around the normal of it. Therefore, we can use the proposed structure as antenna cover to congregate the energy at the frequency 5.8 GHz.

Numerically experiments were also performed at 5.8 GHz with a prism-shaped LHM structure, as well as with a similarly shaped dielectric material as a control. The prism-shaped LHM is composed of SSLR unit cells arranged on slabs with $\varepsilon_r = 2.65$ and thickness of 1 mm. The space between cells on each slab is 3 mm along z direction and 1.6 mm along y direction. And the gap between adjacent slabs is 3 mm. The similarly shaped dielectric material consists of the same number of slabs but without any SSLR cells on them. A vertically polarized Hertzian dipole is put in front of the structures as a source, and the electric fields distribution for both cases are shown in Figs. 3(b) and (c). It can be seen obviously that the wavefronts go almost to the normal direction of the interface when refracted from LHM structure, while go left down when refracted from the dielectric material. That demonstrates that the proposed LHM structure shows negative effective parameters.

The property dependence of proposed SSLR structure on the orientation is also studied here. Two interesting orientations are depicted in Figs. 4(a) and (b). Fig. 4(c) shows that both S_{11} and S_{21} are almost the same for two orientations shown in Figs. 4(a) and (b).

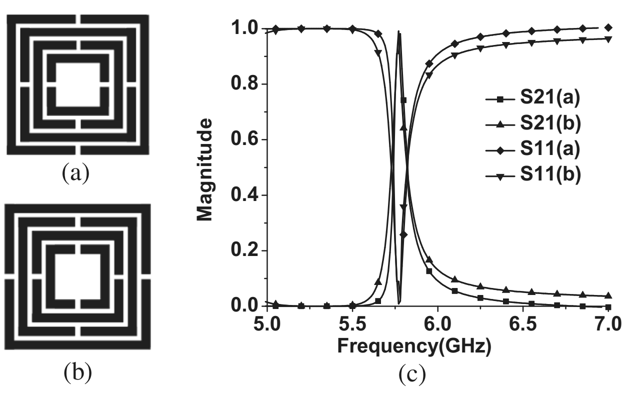


Figure 4. (a) The original structure, (b) the structure rotated 90°, (c) the comparisons of S_{11} and S_{21} between structure (a) and (b).

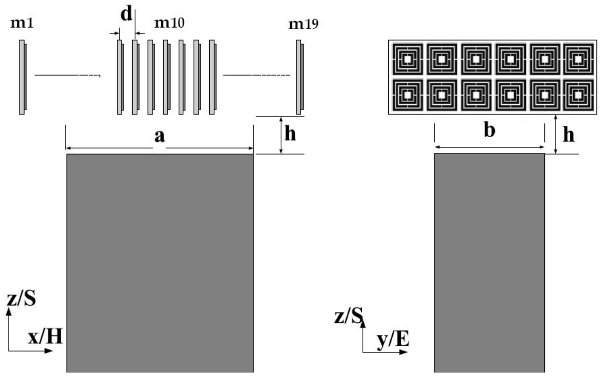


Figure 5. Model of the waveguide aperture with periodically arranged SSLR structures.

3. SIMULATION RESULTS AND DISCUSSION

The proposed structure is applied to a waveguide antenna to verify numerically if it can improve the radiation performance of antenna. Fig. 5 shows the simulation model where the SSLR structure is placed periodically in front of the waveguide with aperture 34.85 mm $\times$ 15.8 mm. Two SSLR unit cells spaced 3 mm along z-direction and six cells spaced 1.6 mm along y-direction are arranged on a 43.2 mm $\times$ 17.6 mm substrate with $\varepsilon_r = 2.65$ and thickness of 1 mm, and the whole LHM structure composes 19 such substrate boards. The gap between adjacent substrates is d, and distance between the LHM structure and waveguide aperture is h.

Figure 6(a) shows the effect of d on the gain of waveguide antenna. We can find that the gain increases about 1.5 dBi when d decreases from 5 mm to 2 mm, and back lobe decreases about 2.0 dBi. Taking the side lobe into considering, we chose $d = 3$ mm as the optimal space between SSLR unit cells along x direction.

As for the distance h between waveguide aperture and SSLR structure, it can be seen in Fig. 6(b) that when h is increased from 5 mm to 40 mm the gain increases gradually, and the number of sidelobe rises at the same time. However, the sidelobe level is lower than that of antenna without LHM, except for the case of $h = 40$ mm. That makes sense, because when the LHM structure is placed close to the aperture of waveguide, the structure can show double negative characteristics only for the modes whose polarization satisfy the resonance condition, namely electric field is parallel to the SSLR plane while magnetic field is vertical to it. As a result, the main lobe is not greatly narrow. When the LHM structure is away from the aperture more than $\lambda/4$

($\approx$ 13 mm), the higher modes attenuate greatly, and power is mainly carried by the dominant mode. The structure shows double negative characteristics and congregates the power. Consequently, the main lobe becomes narrower, and maximum gain increases, as shown in both Figs. 6(b) and (c). However, when the LHM structure is far away from the aperture close to or even more than one wavelength ($\approx$ 52 mm), not all of the power radiated from the aperture travel through the LHM structure which has limited dimension size, so the sidelobe level increases, and the maximum gain decreases gradually (see Figs. 6(b) and (c)).

In order to find if the thickness of the whole LHM structure influence the antenna performance, the gain of waveguide aperture is calculated with $d = 3$ mm and $h = 5$ mm when there are two SSLR unit cells and four SSLR unit cells along z-direction of LHM respectively. Results show that the gain is improved by 1.4 dBi for the case of four SSLR unit cells.

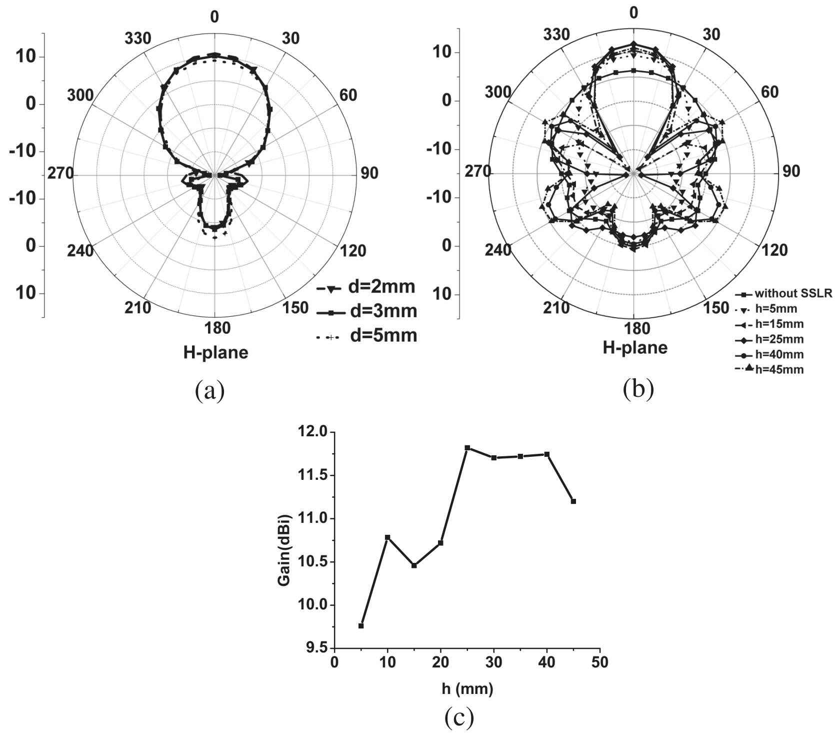


Figure 6. (a) Gain in terms of d ($h = 5$mm). (b) Gain in terms of h ($d = 3$mm). (c) Maximum gain of the antenna with different distance h ($d = 3$mm).

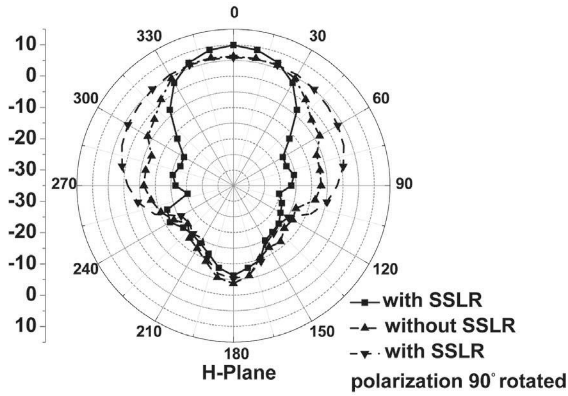


Figure 7. Gain with and without LHM

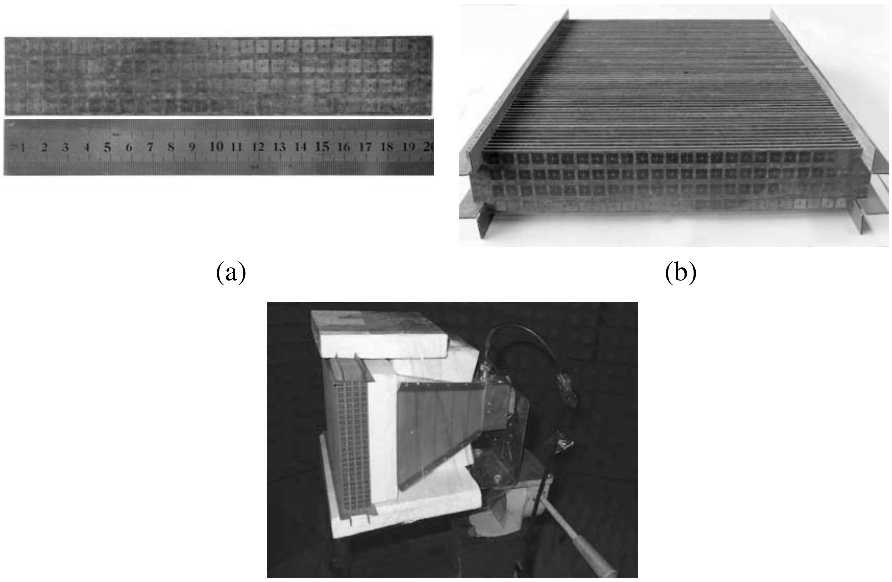
The gain of the waveguide antenna with LHM structure and polarization 90° rotating around z-axis is calculated at 5.8 GHz with $d = 3$ mm and $h = 5$ mm and compared to that with and without LHM structure. Results shown in Fig. 7 indicate that the gain of antenna with LHM structure is enhanced from 6.29 dBi to 9.75 dBi, and the HPBW is decreased from 60° to 45°. That implies the proposed structure can improve radiation characteristics of antenna effectively. However, when the proposed structure is rotated 90° while the waveguide aperture kept the same, the gain degenerates greatly, and main lobe becomes even wider than that of waveguide aperture without LHM structure. The reason for that is that the polarization in this case does not satisfy the LHM resonance condition, and the structure is not double negative material but normal medium composed of 19 substrate layers printed with metal lines. Moreover, the return loss decreases by nearly -4 dB compared to the case without SSLR, resulting in more energy radiated from the waveguide aperture.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The gain of a dual-ridge horn antenna with and without proposed LHM structure was measured in a microwave chamber. The whole LHM structure composes of 64 PCBs, as shown in Fig. 8(b). Each PCB has a dimension of 3.5 cm $\times$ 20 cm and 4×25 cells on it (see Fig. 8(a)). The gap between adjacent PCBs is 3 mm, and spaces between adjacent cells are the same as shown in Fig. 5. The whole LHM structure is fixed in front of the dual-ridge horn antenna by foam, as shown in Fig. 8(c).

The H-plane gain of the dual-ridge horn antenna with and without the LHM structure at 5.8 GHz is measured, and results are shown in

Fig. 9. It can be seen that a 3.2 dBi gain improvement is obtained at the maximum radiation direction using proposed SSLR structure, and the back lobe is suppressed a little.



(a) (b)

(c)

Figure 8. (a) A PCB with 4×25 cells. (b) The whole LHM structure composed of 64 PCBs. (c) Picture of the dual-ridge horn antenna with the LHM structure.

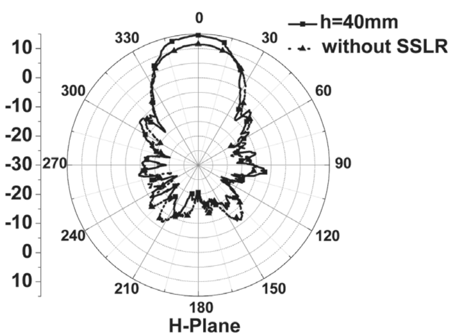


Figure 9. Measured gain of the dual-ridge horn antenna with and without LHM structure.

5. CONCLUSION

A left-handed material based on labyrinth structure, symmetric square labyrinthine ring (SSLR), is presented in this paper. Compared to the conventional LHM structure, the proposed co-planar structure can achieve double negative characteristics in a two-dimensional plane. Both the retrieved effective parameters and prism-shaped structure simulation show that the index of refraction tends to zero at 5.8 GHz. Simulated results of the open-ended waveguide antenna with and without proposed structure indicate that the maximum gain enhancement is about 5.5 dBi. The gain of a dual-ridge horn antenna with and without proposed structure is also measured, and results show that the gain is enhanced about 3.2 dBi, and the back lobe is suppressed a little. Both simulated and measured results demonstrate that the proposed SSLR structure can improve the radiation properties of the antenna.

ACKNOWLEDGMENT

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