Design of a composite right / left-handed slab-type material composed of multilayer metallic patterns

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Abstract

In this paper, a composite right/left-handed (CRLH) slab-type material excited by plane wave is proposed. It is composed of multilayer metallic patterns between dielectric substrates. The equivalent circuit is shown to design a balanced CRLH material. The balanced CRLH characteristics are measured. Next the CRLH material composed of four kinds of cells with different dispersion relation is designed. The propagating direction of wave through the material is also measured. It is confirmed that the propagating direction can be controlled from -10 deg. to +8 deg. by the frequency of the input plane wave.

1. Introduction

Negative refractive index artificial materials or left-handed (LH) materials [1] composed of an array of sub-wavelength pieces of particles have been actively studied [2], for potential applications exploiting the unique property such as sub-wavelength focusing exceeding the diffraction limit [3], beam scanning antennas [4], or zeroth-order resonators [5]. Recently fishnet-type metamaterials have showed high potentiality in terahertz and visible light regions [6]. However, the operation principle has not shown clearly enough to be applied to design.

In this paper CRLH slab-type materials composed of multilayer metallic patterns are proposed. The metallic patterns are printed on the dielectric substrates, and the patterns have rectangular windows put periodically in the slab plane. The structure resembles the structure of fishnet materials. On the other hand, the structure can be considered also as the two-dimensional array of waveguide-type CRLH transmission lines. The waveguide-type CRLH transmission lines are composed of the main-waveguide operating below cut-off frequency (cut-off waveguide) and the stab waveguide [7]. In the structure the series capacitances are given by the stab waveguide and the shunt inductances are given by the cut-off waveguide, then the CRLH transmission lines are realized. In this paper, the equivalent circuit of CRLH slab-type materials is shown by analogy from the operation of the waveguide-type CRLH transmission lines. Based on the circuit the CRLH slab-type material is optimized to satisfy the balanced condition. The dispersion characteristics of the CRLH slab-type material are measured. Moreover, we design the CRLH slab-type material composed of four kinds of cells with different dispersion relations to realize a function. It is confirmed experimentally that the propagating direction of wave transmitted through the slab can be changed from negative angle to positive angle for frequency of the plane wave incident normally to the slab plane.

2. Structure and operation of CRLH slab

Fig. 1 shows the proposed CRLH slab-type material and the unit cell. The metallic patterns are printed on the dielectric substrate with the thickness d=1.525mm and ε_r=2.17, and the metallic pattern has rectangular windows put in two-dimensional periodic arrangement. The window works like a waveguide for the electric field polarized in the x-direction, and the electric field distribution in the window is the same as TE_{10} mode of a conventional waveguide. Fig. 2 shows the equivalent circuit of the CRLH

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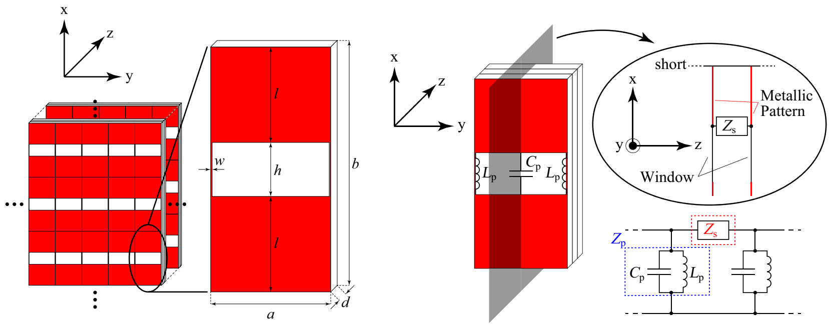


Fig. 1: CRLH slab-type material & the unit cell (left)
Fig. 2: Equivalent circuit of the unit cell (right)

slab-type material. Below the cut-off frequency f_c of the window Z_p becomes inductive. The CRLH slab-type material has multilayer structure, and the space between metallic patterns works as the stab for the propagating wave. The impedance of the stab is shown by Z_s. When the electric fields with same phase are excited for input plane wave, the top of the stub is short equivalently. Z_s changes from inductive to capacitive at the stub length l above a quarter wavelength of the stub line. Then, if Z_p is inductive, a LH mode can propagate in the material. Z_s changes from capacitive to inductive for a longer stub length. Then, if Z_p is capacitive, a right-handed mode can propagate. After all a balanced CRLH material can be realized by adjusting l so as to make the stub frequency of Z_s equal to f_c. By using HFSS, the CRLH slab-type material is simulated and optimized for realizing balanced dispersion relation at 5GHz band. These parameters are shown as follows: a = 10mm, b = 40.85mm, w = 0.25mm, h = 9mm, and l = 15.925mm.

3. Measurement of dispersion characteristics and control of propagating direction

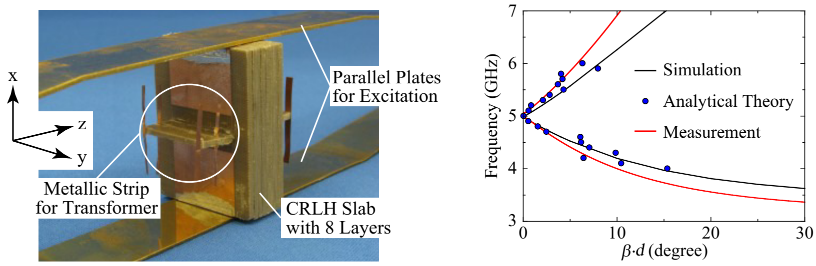
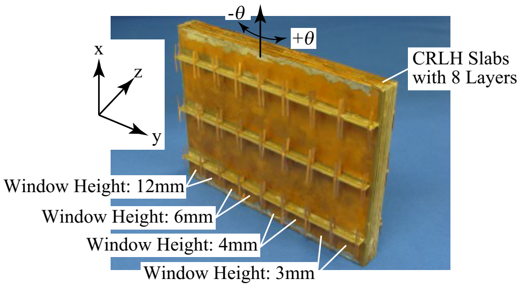


Fig. 3: Photograph of CRLH slab-type material & parallel plates for excitation (left)
Fig. 4: Simulated, calculated and measured dispersion diagram (right)

The CRLH slab-type material is fabricated and the dispersion characteristics are calculated from the measured phase constants. The CRLH slab-type material is composed of 8 layers and the slab is excited by using parallel plates shown in Fig. 3. The metallic strips are used for transformer between the CRLH slab-type material mode and the plane wave. S_{21} is measured near the side face along the material by a small electric probe. The phase constants of the material can be calculated from the phase distributions. In the Fig. 4 the solid line and the circular markers show the simulated dispersion curves and the measured phase constants, respectively. And the red solid line is calculated dispersion curves by using the analytical theory reported in the paper [8]. The measured results agree well with the simulated and calculated results. The measured results show the balanced dispersion characteristic, and the fabricated CRLH slab-type results, the material supports a LH operation.

Next, by the CRLH slab-type material, the control of propagating direction of plane wave through the slab is tried out. Fig. 5 shows the fabricated CRLH slab-type material with four kinds of cells designed to realize the function. 3 cells are arranged in the x-direction, 4 cells are arranged in the y-direction, and 8 layers are accumulated along the z-direction. The heights of each window of the cells arranged in y-direction are different for obtaining different dispersion relations, and the heights are 3mm, 4mm,



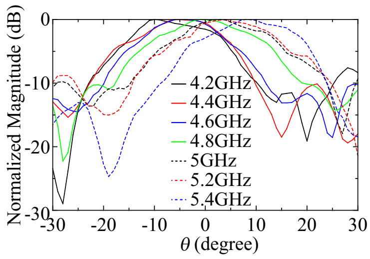


Fig. 5: Photograph of CRLH slab-type material composed of cells with different dispersion relation (left)
Fig. 6: Measured angular characteristics of propagating wave (right)

6mm and 12mm. The four kinds of cells have dispersion relations whose balanced frequencies are same and the slopes are different, so that the equi-phase plane of propagating wave through the material rotates depending on the frequency. Plane wave is fed normally to the fabricated CRLH slab-type material and the wave through the material is received by a horn antenna at a point 3m apart. The material and the source of the plane wave are rotated together on the z-y plane, the rotated angle is defined as θ shown in Fig. 5. The propagating direction is measured at some frequencies. Fig. 6 shows measured angular characteristics of the propagating wave. The vertical axis is the magnitude of propagating wave and the horizontal axis is θ. These curves are normalized with each maximum value. When the propagating direction is defined as the angle with maximum magnitude, the propagating direction at 4.2GHz is -10 degree, the direction at 4.8GHz is -1 degree, and the direction at 5.4GHz is +8 degree. These results show that the propagating direction can be continuously changed by the frequency of the input plane wave.

4. Conclusion

In this paper, a CRLH slab-type material is proposed. The CRLH slab-type material is composed of multilayer metallic patterns and it is easy to fabricate. And, the slab-type material can be excited by plane wave. It is experimentally confirmed that the CRLH slab-type material supports a LH wave. Moreover, the CRLH slab-type material designed specially can control the propagating direction of the wave through the material by changing the frequency of the input wave. The CRLH slab-type material can potentially be used for the applications with plane wave.

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