

Experimental Investitation of Polarization Rotation by Multilayer Chiral Metamaterial

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Abstract- Quasi-3D helix metamaterial is constructed from a multilayered 2D spiral structure with capacitive coupling between the adjacent layers. The sample is implemented with PCB, and a linearly polarized microwave source is used in the measurement. The polarization plane is rotated to the opposite directions with left- and right-handed samples. The rotation angle is consistent with theoretical prediction.

Keywords- Metamaterial; Chiral Structure; Polarization

I. INTRODUCTION

Forty years ago Veselago proposed the possibility of a metamaterial with simultaneously negative permittivity and permeability [1], and its feasibility was demonstrated thirty years later [2]. In the early works, the negative permittivity was realized by plasma resonance of the metallic structures, as the inertia of electrons can cause 180° phase lag in response to the rapid changing field. On the other hand, the negative permeability is achieved by a resonant LC circuit, again due to the 180° phase shift between the impedances of the inductor and capacitor. The resonant frequency at which these two effects occur is highly sensitive to the circuit geometry. As such, the design and implementation of such metamaterials are very challenging, as it requires a good match of these two narrow resonant peaks. In addition, such metamaterials are not suitable for wideband applications.

Chiral metamaterial is another route to achieve negative permittivity and permeability [3], and its early demonstration of polarization rotation effect can trace back to almost a century ago [4]. Recently, metamaterials with chiral structures are being investigated at different frequency domains [5-8]. Unlike isotropic non-chiral dielectric materials, where the electric and magnetic properties are described by permittivity and permeability separately, these material properties form an irreducible matrix for chiral materials and such a coupling effect can turn the refractive index into negative [9, 10]. Recently, it was demonstrated that a two-dimensional lattice of three-dimensional gold spirals can effectively block circular polarized light with the same handedness for a frequency range exceeding one octave [11].

From the point of view of applications, metamaterials must be fabricated easily and cheaply, and one way to achieve this goal is planarization. The simulation result in Ref. [11] shows that there are current nodes in the spiral structure, where currents either go out or come into these nodes in both directions, but the current at the nodes vanishes. Such behaviour of current is similar to what happens at a capacitor, and thus these three-dimensional spirals can be replaced by multilayered two-dimensional spiral sections with capacitive coupling at the nodes of zero current.

We designed a multiple-layer helix PCB structure with CST Microwave Studio[®] and had it fabricated. The sample was tested with an automated free space microwave material measurement system in the X-band. We found that the polarization plane is rotated in the opposite direction for the left- and right-handed samples, and the measured S-parameters agree with the simulation result relatively well.

II. CONCEPT AND DESIGN

As discussed in Ref. [11], helix metamaterials as illustrated in Fig. 1(a) will have nodes of zero current at certain points in the structure. Similar to the concept of cutting a ring resonator at the zero current node to produce a split ring resonator [2], the helix can also be cut at the zero current nodes, while still retaining the characteristic behaviour of a chiral structure. Thus, each of the sections of the split helix can be flattened into easily fabricated discrete layers, where each layer is effectively the same geometry but rotated with respect to adjacent layers. Capacitive coupling between these layers, as illustrated in Fig. 1(b), may help to retain the performance of the full helix despite the separation between elements.

The design proposed in this work is based on this concept. We propose a 3/4 octagon shaped transmission line for the geometry of each layer of a unit cell. Each consecutive layer is rotated 90° with respect to the previous layer. Thus, between two adjacent layers there will be overlap of the transmission lines where capacitive coupling can then take place. The full unit cell is illustrated in Fig. 2.

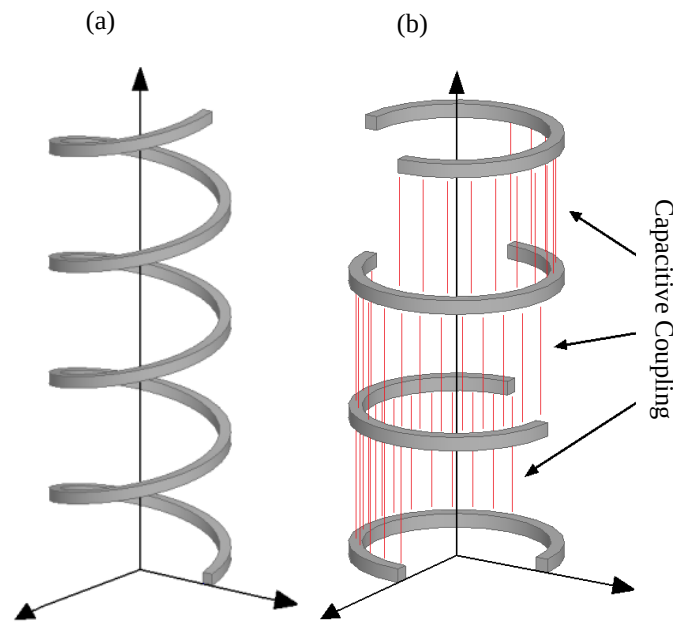


Fig. 1(a) Full 3D helix structure and (b) Reduced spiral structure with capacitive coupling between elements represented by the red lines

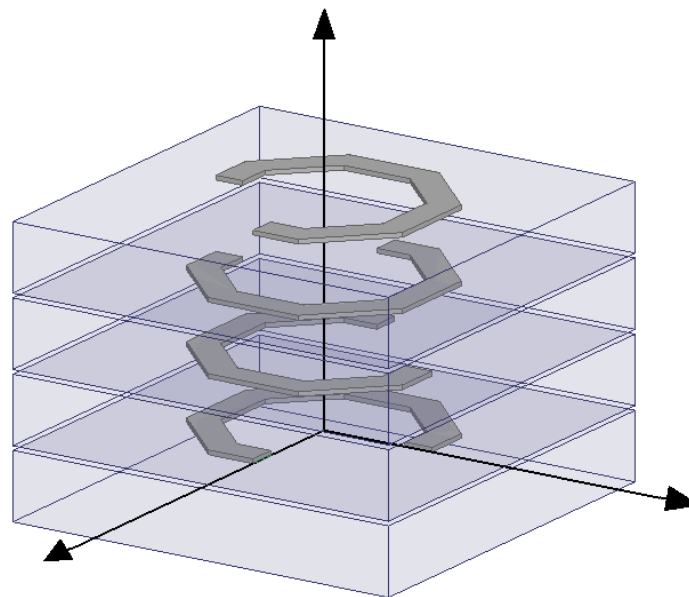


Fig. 2 3D model of the single unit cell of the multilayered spiral metamaterial

III. DEVICE STRUCTURE AND CHARACTERIZATION

Fig. 3 shows the device structure fabricated on standard FR4 PCB. A few layers of identical boards are stacked together with 90° rotation to each other. The dimension of the board is $7'' \times 7''$, and there are 19×19 spirals on it. The pitch of the cells is 9 mm, the outer dimension of the octagons (both horizontal and vertical) is 5.4 mm, and the width of the microstrip line composing each metal spiral is 0.7 mm. These dimensions are selected for applications around 10.5 GHz.

The simulation results of the transmission coefficient are shown in Fig. 4(a), where the polarization plane of the receiver can be parallel to the transmitter (red curve) or perpendicular to it (green curve). Ideally, the green curve should be zero with a non-chiral isotropic sample, as the polarization plane should not be rotated. The simulation result shows that at lower frequency the signal with 90° polarization rotation is at least 10 dB weaker than the signal without rotation. However, at around 10.5 GHz, these two curves meet with equal strength. Beyond 11 GHz there is a precipitous increase in loss, and both signals are below -37 dB beyond 12.2 GHz. Fig. 4(b) illustrates the experimental result. The transmission coefficient without polarization rotation is higher than the simulation result, while it is lower for the signal with 90° polarization rotation. However, the general trend of these two curves agrees with the simulation result pretty well.

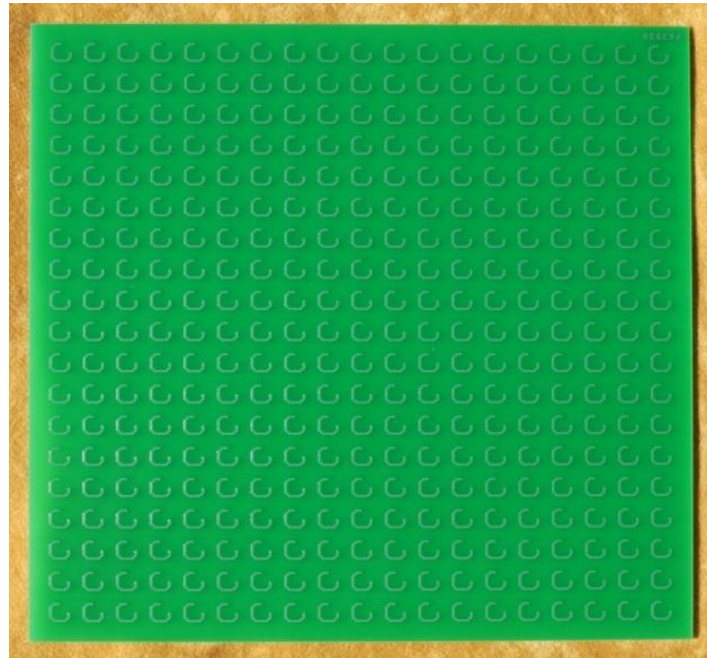


Fig. 3 Chiral copper structure on PCB

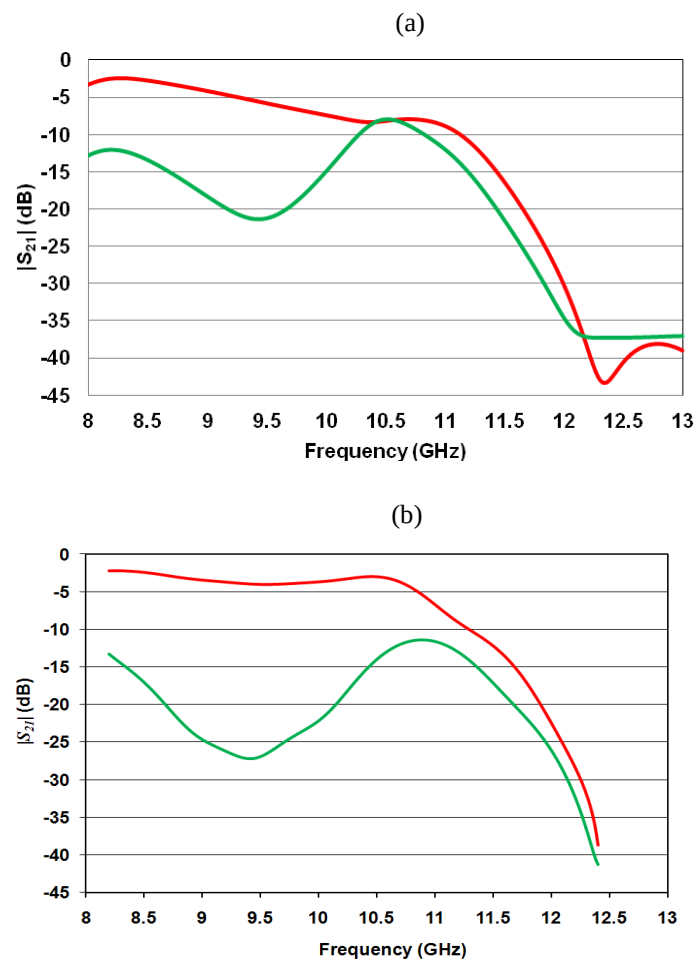


Fig. 4 Transmission coefficient with the polarization plane rotated by 0° (red) and 90° (green); (a) simulation, (b) experiment

IV. POLARIZATION ROTATION

These layers of PCB can be arranged in two different configurations: left-handed or right-handed helix. Fig. 5 shows the rotation of the polarization plane of these two different arrangements with six and eight layers of PCB, respectively. First, the

results show the symmetry between the left- and right-handed samples. Second, the angle of rotation with the eight-layer sample is larger than the six-layer sample at the designed frequency range. The polarization plane rotation angle is specified at 10.8 GHz, and they are 20° and 26° for the six-layer and eight-layer samples, respectively. This change can be explained by theoretical analysis.

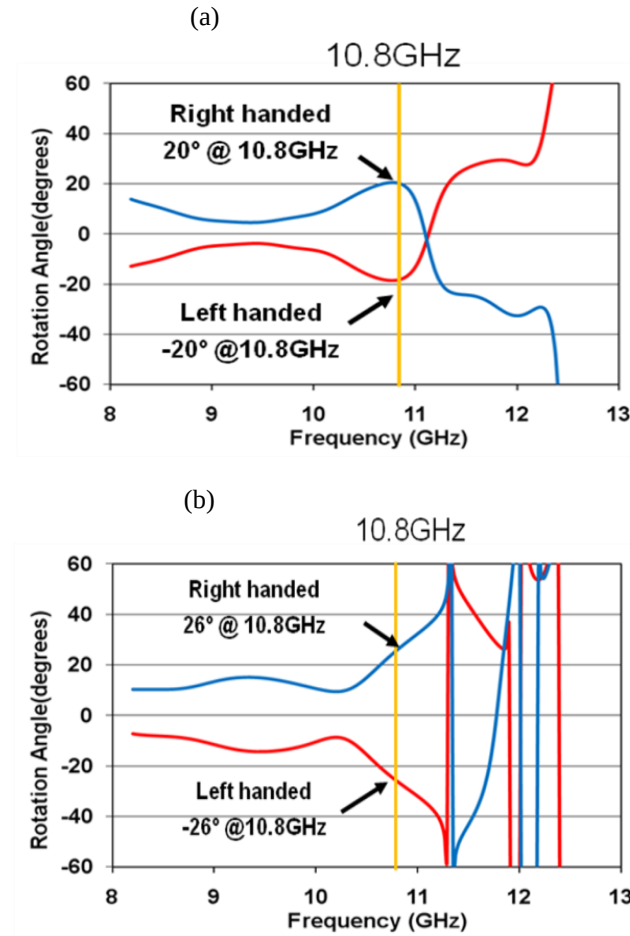


Fig. 5 Experimental result of polarization rotation, (a) six layers, (b) eight layers

V. THEORETICAL ANALYSIS

For an isotropic and non-chiral dielectric material, its electric and magnetic properties are described separately by its permittivity and permeability, respectively. However, for a chiral medium, there is a coupling between them [9]:

$$\begin{pmatrix} \vec{D} \\ \vec{B} \end{pmatrix} = \begin{pmatrix} \varepsilon & j\kappa/c_0 \\ -j\kappa/c_0 & \mu \end{pmatrix} \begin{pmatrix} \vec{E} \\ \vec{H} \end{pmatrix} \quad (1)$$

where κ is the chiral parameter, which vanishes for non-chiral media. Left-handed circularly polarized (LCP) or right-handed circularly polarized (RCP) waves going through a chiral medium, it will see different material properties:

$$n_{\pm} = \sqrt{\varepsilon\mu} \pm \kappa \quad (2)$$

It is well-known that a linearly polarized wave can be considered as the superposition of two circularly polarized waves with different handedness. As the refractive index is different for LCP and RCP components, the relative phase shift will cause a rotation of the polarization plane, and the angle of rotation will be proportional to the chiral parameter and the electrical thickness of the sample [8]:

$$\theta = \kappa k_0 d \quad (3)$$

The ratio of the polarization rotation angle between these two samples with different number of layers can be calculated: $\theta_1/\theta_2 = d_1/d_2 = 0.75$. For comparison this ratio can be calculated from the experimental results at 10.8 GHz shown in Fig. 3: $\theta_1/\theta_2 = 0.77$, which agrees with the theoretical results pretty well.

VI. CONCLUSIONS

Multi-layered helix metamaterial samples are fabricated from PCB with very low cost. The transmission coefficient is simulated and measured, and the results agree relatively well. The rotation of the polarization plane is measured directly, and the results are consistent with theoretical analysis.

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