Development of Semi-Planar Chiral Metamaterials

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Abstract — **Development of chiral metamaterial (CMM) structures in order to achieve miniaturized CMMs and dual-band CMMs are aimed in this paper. In achieving the first purpose, two general ideas are proposed: using dendritic fractal geometry, and using wideband antenna designs. Based on these methods, some miniaturized CMM structures are designed. Afterwards, a novel dual-band CMM structure is designed and fabricated. The results show that the proposed structure exhibits giant optical activity and negative refractive indices for the right and left circularly polarized waves (RCP and LCP) in two adjustable frequency bands.**

Index Terms — **Chiral metamaterials, negative refraction index, optical activity, miniaturization, dual-band structure.**

I. Introduction

Recently, chiral metamaterials (CMMs) have attracted increasing attention due to their interesting and individual properties such as giant optical activity and negative refraction. In fact, CMMs are metamaterials (MTMs) made of unit cells without any mirror symmetry. This results in the breaking of the degeneracy of between two circularly polarized waves, RCP and LCP that causes the difference of refractive index of RCP and LCP waves. For a time harmonic field with *exp(-j t)* convention, chiral media are characterized by the following constitutive relations [1]:

$$\mathbf{D} = \varepsilon\varepsilon_0\mathbf{E} + j\kappa\sqrt{\varepsilon_0\mu_0}\,\mathbf{H}, \quad \mathbf{B} = -j\kappa\sqrt{\varepsilon_0\mu_0}\,\mathbf{E} + \mu\mu_0\,\mathbf{H} \quad (1)$$

where, ε, μ, c and κ are the relative permittivity, relative permeability, the speed of light in free space, and the chirality parameter, respectively. The refractive indices for the RCP (+) and LCP (-) waves can be written as $n_\pm = n \pm \kappa$. Apparently, chiral media open up an alternative route to a negative refractive index. In particular, by varying only , a negative refractive index for one circular polarization can be obtained even if   and μ are both positive [2]. Based on this principle, several CMM structures have been proposed to achieve negative refractive index [3-7].

This paper firstly demonstrates some miniaturized CMM structures at microwave frequencies, and finally proposes a novel dual-band CMM based on the conjugated gammadions.

II. Miniaturization Of CMM Structures

The CMMs proposed recently, exhibit optical activity and negative refractive index for circular polarizations at parts of 4-8 GHz frequency band, when the transverse dimensions of their unit cells are 15×15 mm^2 or 10×10mm^2. The purpose of this section is to propose miniaturized CMM structures with smaller unit cells or lower resonant frequencies. Based on the mechanism of resonances in CMM structures, two general ideas to miniaturize CMMs are proposed: using fractal geometries and wideband antenna designs.

A. Miniaturized CMM Structures Based on the Dendritic Fractal Geometry

The bilayer cross-wires or twisted crosses design is an example of semi-planar CMM structures that have been already published. Investigation the behavior of this structure around resonant frequencies shows that its optical activity and negative refractive index can be attributed to the interaction of magnetic and electric dipole moments. Therefore, it is expected that the resonant frequencies of the structure drop as the length of cross-wires is increased.

One type of simple fractal geometry that can be utilized to increase the length of wires is a dendritic fractal structure. This fractal is generated by an iterative sequence to the starting simple wire structure. In the first iteration, the top segment of this wire is split at an almost optimized angle, θ = 60°. As the iterative process continues, the end segment of each branch splits into two branches. Observe that after fourth iteration the total electrical length of wire is tripled. The unit cell of the forth iteration dendritic fractal CMM structure is shown in Fig. 1. Numerical simulations show that for a twisted angle of 30°, performance of proposed structures is the best. Using a parameter retrieval method based on the causality principle, the real parts of RCP and LCP refractive indices and chirality parameter of the fourth iteration dendritic fractal CMM structure are retrieved and presented in Fig. 2. It is seen that after four iterations the resonant frequencies of the proposed structure change from 6.4 GHz and 7.5 GHz (resonances of the ordinary crosswire structure) to 3.4 GHz and 4.5 GHz, respectively. These drops in resonant frequencies are significant; since to achieve these resonant frequencies using the ordinary cross-wires, the transverse dimensions of the structure should be almost doubled.

B. Miniaturized CMM Structures Based on the Wideband Antenna Designs

As mentioned in the previous section, the performance of semi-planar CMM structures is based on the coupling of the electric or magnetic dipoles created on the opposite sides of

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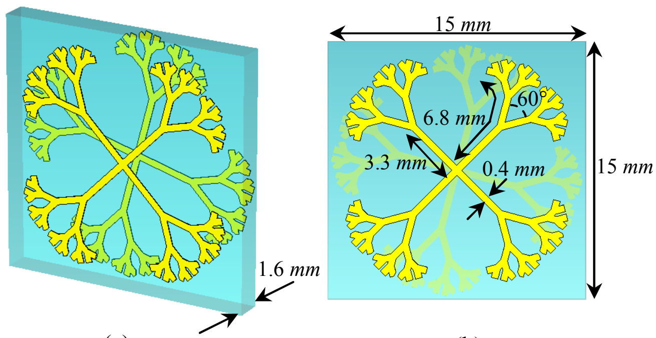


(a) (b)

Fig. 1. (a) Perspective view of the unit cell of dendritic fractal CMM structure; (b) top view of the unit cell structure with its geometric parameters. The FR-4 board with dielectric constant of 4.5, dielectric loss tangent of 0.025 is utilized.

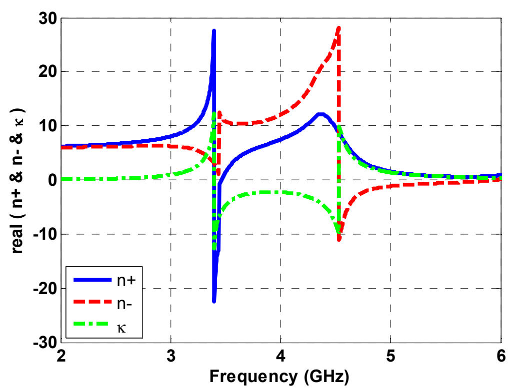
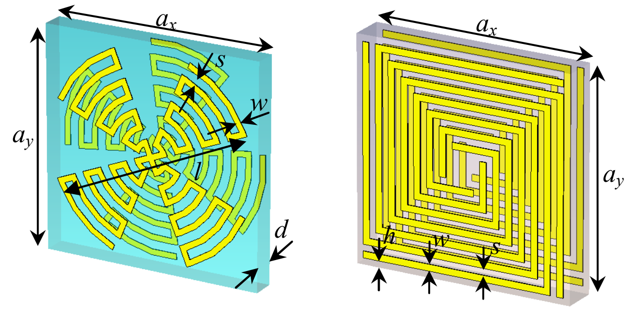


Fig. 2. The real parts of the RCP and LCP refractive indices and the chirality parameter of dendritic fractal CMM structure.

the dielectric board. Since, increasing the electrical length of these dipoles resulted in dropping the resonant frequencies; we can utilize the wideband dipole antenna designs instead of ordinary dipoles. This is due to the fact that common types of antennas such as bow-tie antenna, log-periodic toothed antenna, log-periodic wire antenna, and multi-arm spiral antenna, the effective electrical length of the dipole is increased considerably. Figure 3 shows two miniaturized CMM structures based on the multi-turn wire antenna and the four-arm square spiral antenna. The real parts of chirality and RCP and LCP refractive indices of the first structure presented in Fig. 4(a), show that the resonant frequencies of this structure decrease to 2.3 GHz and 3.25 GHz. Also, results of numerical simulation of the second structure illustrated in Fig. 4(b) shows that at frequency of 4.8 GHz, the polarization rotation angle [4, 8] is around 77° for 1.6-mm-thick CMM (i.e. the rotation angle is around 3008°/λ).

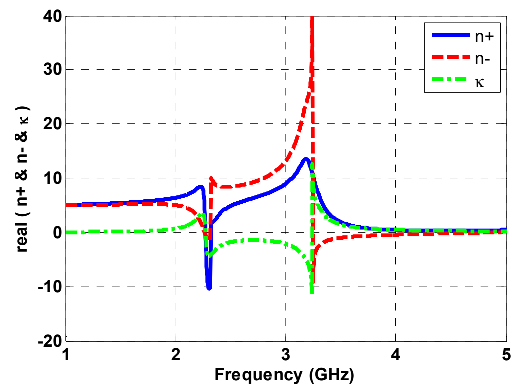
III. A Novel Dual-Band CMM Structure

In this section, we propose a dual-band CMM structure with giant optical activity and negative refractive index which may have many potential applications such as dual-band polarization devices, gain enhancement of dual-band antennas, dual-band absorbers, and dual-band focusing. The layout of the proposed structure is shown in Fig. 5. The unit cell of this structure constructed by two copper double arms conjugated gammadion patterned on the opposite sides of a FR-4 board is similar to the conjugated gammadion CMM structure one. In

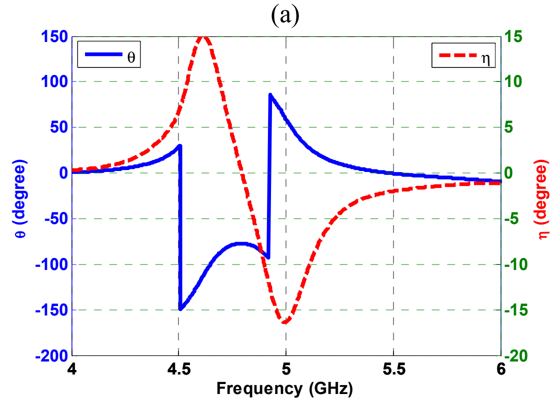


(a) (b)

Fig. 3. (a) Unit cell of multi-turn cross wires CMM structure. The geometric parameters are given by $a_x = a_y = 15$ *mm*, $l = 14.4$ *mm*, $w = 0.4$ *mm* and $s = 0.6$ *mm*, $d = 1.6$ *mm*. (b) Unit cell of four-arm spiral CMM structure. The geometric parameters are given by $a_x = a_y = 10$ *mm*, $d = 1.6$ *mm*, $w = s = h = 0.3$ *mm* The FR-4 board with dielectric constant of 4.5, dielectric loss tangent of 0.025 is utilized.

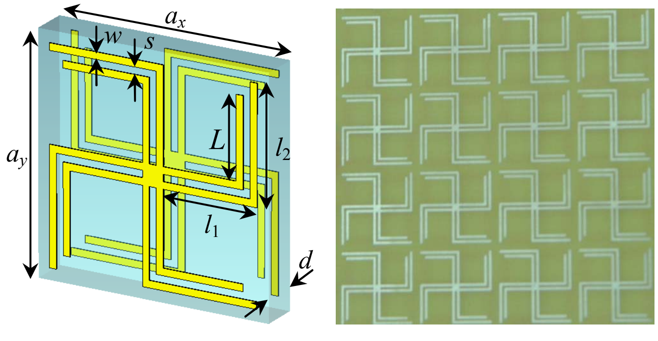


(a)



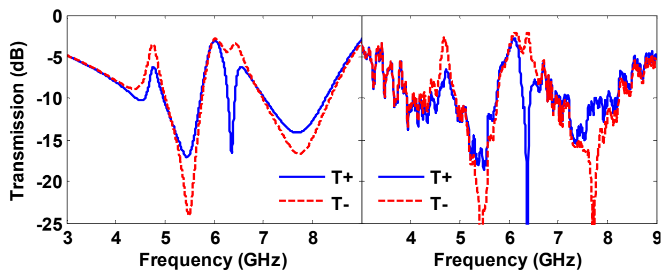
(b)

Fig. 4. (a) The real parts of the RCP and LCP refractive indices and the chirality parameter of multi-turn cross wires CMM structure. (b) The polarization azimuth rotation angle θ and the ellipticity angle η of the four-arm spiral CMM structure.



(a) (b)

Fig. 5. (a) Schematic representation of a unit cell of the dual-band CMM structure. (b) Photograph of the experimental sample. The geometric parameters are given by $a_x = a_y = 10$ mm, $L = 3.45$ mm, $l_1 = 4.05$ mm, $l_2 = 4.95$ mm, $w = s = 0.3$ mm and $d = 1.6$ mm.



(a) (b)

Fig. 6. (a) Simulation and (b) experimental results of the transmission coefficients for the dual-band CMM structure.

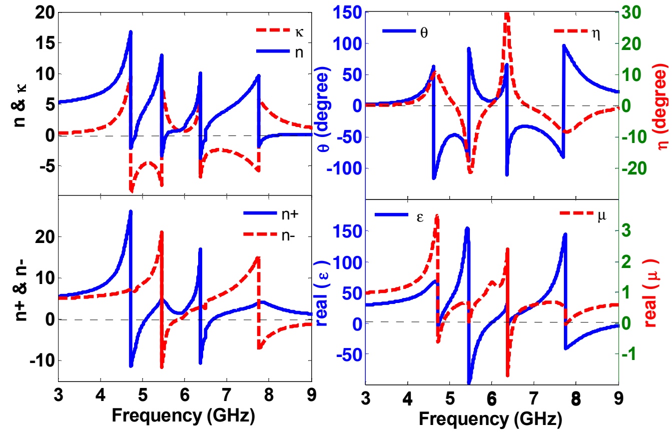


Fig. 7. The real parts of the refractive index n and κ for the dual-band CMM structure.

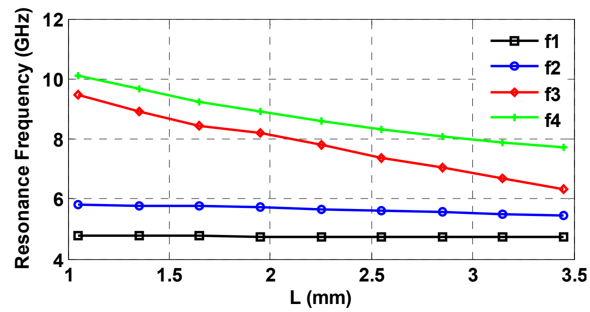


Fig. 8. The variations of resonant frequencies of the dual-band CMM structure with parameter L.

fact, the dual-band nature of this structure is caused by its double arms with the different lengths. The relative dielectric constant of the board is 4.2 with dielectric loss tangent of 0.02.

The simulated and measured transmission coefficients that are a very good agreement are shown in Figs. 6(a) and 6(b). Considering Fig. 7, observe that four resonances occurred at 4.7, 5.45, 6.4, and 7.75 GHz. Also, the polarization rotation angle is around 47° and 33.5° at frequencies of 5.1 GHz and 6.85 GHz, respectively. Investigation of the current density distributions (are not shown here) shows that in the first and second frequency band, the majority of induced currents flow on the longer and shorter arms, respectively. Numerical results show that the effective frequency bands of this structure are independent, and can be simply adjusted according to design curves presented in Fig. 8.

IV. Conclusions

In summary several miniaturized chiral metamaterial structures with smaller unit cells or lower resonant frequencies are designed. In addition, we design and study numerically and experimentally a novel dual-band CMM structure. The results show that the dual-band CMM possess giant optical activity, and the RCP and LCP negative refractive indices in two independent and adjustable frequency bands.

References

[1] I. V. Lindell, A.H. Sihvola, S.A. Tretyakov, and A.J. Viitanen, *Electromagnetic Waves in Chiral and Bi-isotropic Media*, Artech House, 1994.

[2] S. Tretyakov, I. Nefedov, A. Sihvola, S. Maslovski, and C. Simovski, “Waves and energy in chiral nihility,” *Journal of Electromagnetic Waves and Applications*, vol. 17, no. 5, pp. 695-706, 2003.

[3] E. Plum, J. Zhou, J. Dong, V. A. Fedotov, T. Koschny, C. M. Soukoulis, and N. I. Zheludev, “Metamaterial with negative index due to chirality,” *Phys. Rev. B* 79, 035407, 2009.

[4] J. Zhou, J. Dong, B. Wang, T. Koschny, M. Kafesaki, and C. M. Soukoulis, “Negative refractive index due to chirality,” *Phys. Rev. B* **79,** 121104, 2009.

[5] Z. Li, R. Zhao, T. Koschny, M. Kafesaki, and C. M. Soukoulis, “Chiral metamaterials with negative refractive index based on four “U” split ring resonators,” *Appl. Phys. Lett.* 97, 081901, 2010.

[6] R. Zhao, L. Zhang, J. Zhou, T. Koschny, and C. M. Soukoulis, “Conjugated gammadion chiral metamaterial with uniaxial optical activity and negative refractive index,” *Phys. Rev. B* 83,035105, 2011.

[7] J. Li, F.-Q. Yang, and J.-F. Dong, “Design and simulation of L-shaped Chiral Negative Refractive index structure,” *Progress In electromagnetic Research*, vol. 116, pp. 395-408, 2011.

[8] J. D. Jackson, *Classical Electrodynamics*, 3rd ed., Wiley, New York, 1999.