Chiral Metamaterials: From Negative Index to Asymmetric Transmission

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***Abstract*—Chiral metamaterials are attractive for their intriguing properties such as negative refractive index, optical activity and circular dichroism, and asymmetric transmission. In this paper, we review the research we have conducted for the purpose of investigating these exciting properties.**

***Index Terms*—metamaterial; chirality; negative index; optical activity; circular dichroism; asymmetric transmission**

I. INTRODUCTION

A chiral metamaterial (CMM) is not identical to its mirror image, i.e., it cannot be brought into congruence with its mirror image unless it is lifted off the substrate. For such materials, at the resonance frequencies, cross-coupling between electric and magnetic fields exists and, therefore, right-hand circularly polarized (RCP, $+$) and left-hand circularly polarized (LCP, $-$) waves encounter different transmission coefficients. In other words, a CMM can lead to the modification of the polarization state of an incident wave. Due to their interesting properties, e.g., giant optical activity and circular dichroism, CMMs can be important for optical applications. For CMMs, the chirality parameter, κ, characterizes the strength of the cross-coupling between the magnetic and electric fields. Thus, the constitutive relations in a chiral medium are written as [1]

$$\begin{pmatrix} \mathbf{D} \\ \mathbf{B} \end{pmatrix} = \begin{pmatrix} \varepsilon_0 \varepsilon & i\kappa / c_0 \\ -i\kappa / c_0 & \mu_0 \mu \end{pmatrix} \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix}. \qquad (1)$$

Using the definitions of **D** and **B** as given in Eq. 1 and the source-free Maxwell equations in the frequency domain, one can easily show that the RCP and LCP waves, which are the eigenmodes, propagate with unequal wave-vectors inside a chiral medium, given by $k_{\pm} = k_0 (n \pm \kappa)$, where $n = \sqrt{\varepsilon\mu}$. Accordingly, one can define two refractive indices for the RCP and LCP eigenmodes as $n_{\pm} = n \pm \kappa$. The chirality effect becomes strongly pronounced at this point. For instance, if $\kappa > n$, n_- becomes negative and this constitutes an alternative approach for the realization of negative refractive index.

Furthermore, the fact that n_+ and n_- can be different in the vicinity of resonance frequencies has a natural consequence, such that the transmission (T_+ and T_-) and the extinction coefficients of the RCP and LCP waves can be different. This fact leads to two important properties of CMMs: optical activity and circular dichroism. For a wave transmitted through a CMM, the rotation of the polarization plane (as a consequence of optical activity) can be calculated as $\theta = 1/2 \left[\arg(T_+) - \arg(T_-)\right]$. Similarly, the ellipticity (as a consequence of circular dichroism) of a transmitted wave is calculated as $\eta = 1/2 \tan^{-1}\left[\left(|T_+| - |T_-|\right) / \left(|T_+| + |T_-|\right)\right]$.

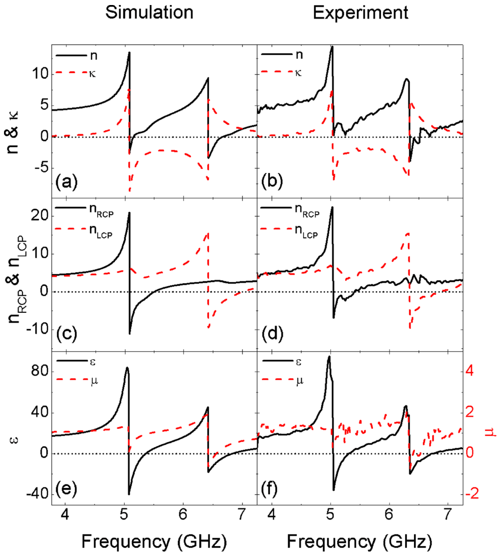

Fig. 1. The retrieved effective parameters of the CMMs based on the simulation (left) and experimental (right) data. (a) and (b) show the real parts of the refractive index n and chirality κ. (c) and (d) show the real parts of the refractive indices for RCP and LCP waves. (e) and (f) show the real parts of the permittivity ε and permeability μ.

In this paper, we will provide a brief overview of the CMM related studies we have conducted.

II. REVIEW OF CMM RELATED STUDIES

Considering the main focuses of the conducted studies, we can examine the CMM related research under three categories: negative refractive index, optical activity and circular dichroism, and asymmetric transmission.

A. Negative Refractive Index

The C_4 symmetric planar chiral metamaterial, which is given in [2] and composed of four split-ring resonator (SRR) pairs that are rotated by 90° with respect to the neighboring ones, proposed by Li *et al.* exhibits a polarization-independent negative refractive index for RCP and LCP waves in the vicinity of 5.1 GHz and 6.4 GHz, respectively. The numerically and experimentally retrieved parameters for this design (n, κ, n_+, n_-, ε, and μ) are shown in Fig. 1.

In Reference [3], Li *et al.* study a complementary bilayer cross-wire CMM numerically and experimentally. The proposed structure is found to exhibit a giant optical activity and a small circular dichroism in addition to the realization of negative refractive index for RCP waves, which occurs due to strong chirality. Retrieval of the chirality parameter, κ, shows that two peaks, at $f_L = 5.28$ GHz and $f_H = 8.77$ GHz, associated with chirality occur. Below f_L, n is positive while κ is negative and therefore, n_+ is pushed to negative below this frequency. As a result of the resonance at f_H, κ becomes negative again and conduces to a negative n_+. Investigation of the magnetic field and current distributions reveal that the resonance at f_L is caused by the coupling effects between the two sets of mutually twisted virtual magnetic dipoles, where the resonance at f_H exhibits complicated nonlocal features.

In a recent study [4], Li *et al.* construct a composite CMM by combining a conjugated rosette CMM with continuous metallic wires with the purpose of achieving negative refractive index for the circularly polarized eigenmodes. A negative n_- band is achieved below the chiral resonance, whereas a negative n_+ band above the chiral resonance is obtained. Furthermore, these bands correspond to transmission peaks and have significantly high values of figure-of-merit.

B. *Optical Activity and Circular Dichroism*

By modifying the geometric parameters of the two of the four SRR pairs given in [2], Mutlu *et al.* introduce an *asymmetric* CMM that enables the transmission of LCP and RCP waves at 5.1 GHz and 6.4 GHz, respectively, under the assumption that the structure is illuminated by an x-polarized incident plane wave [5]. It is shown that, at 5.1 GHz (6.4 GHz), the transformation to RCP (LCP) wave is -37 dB (-43 dB), leading to an LCP (RCP) wave in transmission. For such stereometamaterial structures, the resonance levels are determined in line with the longitudinal magnetic dipole to magnetic dipole coupling. Numerical results reveal that at the lower (higher) resonance frequency, the surface currents on the SRR pairs are parallel (antiparallel), which conduce to the excitation of parallel (antiparallel) magnetic dipole moments.

In Reference [6], Mutlu *et al.* modify the geometric parameters of the design given in [2] and position a subwavelength mesh in between the two layers in order to obtain a C_4 symmetric, polarization-independent, and *unity* conversion efficiency 90° polarization rotator. The unity conversion efficiency is achieved due to the electromagnetic tunneling effect exerted by the negative effective permittivity subwavelength mesh. The existence of the tunneling effect is proved by modelling the trilayer structure as an effective medium and applying the transfer matrix method.

C. *Asymmetric Transmission*

Mutlu *et al.* design an asymmetric CMM and position a subwavelength mesh between the two layers for the achievement of diodelike asymmetric transmission [7]. The exploited physical mechanism is based on the maximization of the cross-polarized transmission in one direction, while suppressing cross-polarized transmission in the other direction. It is theoretically shown that the peculiar eigenmode combination and the transmission of the elliptical eigenmodes with a phase difference of π results in the diodelike effect. The forward and backward transmission coefficients and the asymmetry factor for the proposed structure are shown in Fig. 2.

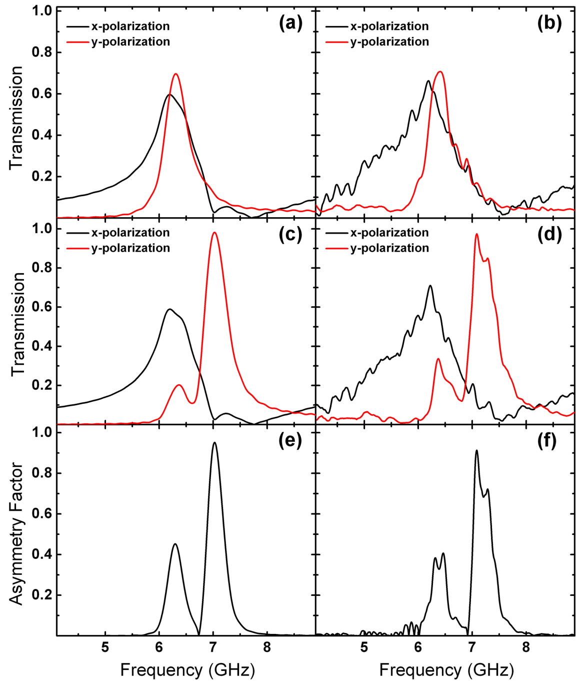

Fig. 2. Numerical and experimental transmission spectra, for x-polarized (a), (b) forward and (c), (d) backward propagating waves; (e), (f) numerical and experimental asymmetry factor.

III. Conclusion

We have reviewed several CMM structures that we have designed, and numerically and experimentally characterized. Such structures can be promising for and employed in security and defense applications, such as RF signature reduction (by control of anisotropy), infrared signature control (cloaking), imaging and sensing applications, radar and satellite applications, and remote sensors.

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