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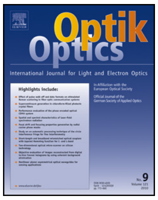

Dynamic and tunable chiral metamaterials with wideband constant chirality over a certain frequency band

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ABSTRACT

We present numerically and experimentally a dynamic chiral metamaterial (MTM) that creates strong optical activity and circular dichroism. The proposed tunable structure has a very simple and more efficient configuration which introduces flexibility to adjust its EM properties. In addition, it gives a giant negative refractive index due to the high chirality. Our experimental results confirm the strong optical activity for a wide frequency range and agree with the simulation results. Moreover, the proposed chiral MTM provides a wideband and constant/flat chirality over a certain frequency band and thus it can be concluded that the developed chiral MTM based model offers a strong optical activity in terahertz, infrared and even in visible frequencies.

1. Introduction

Chiral MTMs have received considerable attention in recent years for their ability to exhibit unusual electromagnetic (EM) properties such as strong optical activity [1], circular dichroism [2] and negative refraction [3], which are not seen in conventional materials. They are characterized by the quantity of chirality parameter, $\kappa = (n_R - n_L)/2$, where n_R/n_L is ratio representing the refractive indexes of the right circularly polarized (RCP) and left circularly polarized (LCP) waves and high chirality values lead to negative refractive index [4–13].

Chiral MTMs are artificial and handmade structures. In addition, they can be specifically constructed for many desired frequencies and potential applications. They have gained a great deal of interest due to their large applicability in the development of efficient devices because of these features. There are many chiral MTM studies in the literature [4–21].

Unlike the other chiral MTM studies, this study presents a novel design having a very simple geometrical pattern which allows simplification in the manufacturing process and shows a strong chirality which is validated by both simulation and experimental studies. Besides, the mechanism can be adopted (rescaling, scale-up or down) for other electromagnetic spectrum regimes such as millimeter-wave, THz, and so on. Hence, it can be concluded that the suggested model has many advantages such as simplicity, flexibility, mechanical tunability, strong chirality, and can be used to realize myriad polarization rotator applications. Furthermore, one important issue to be discussed in terms of the practical realization of the chiral MTMs is the dispersion character of the chirality. In general, it possesses a frequency-dependent nature in such structures. The suggested model provides a wideband and constant/flat chirality over a certain frequency band. This is very important especially for the polarization rotator applications [22,23]. In his study, Sabah stated that any arbitrary polarized monochromatic plane wave can be expressed as a sum of circularly polarized waves and two propagation constants would be obtained for left and right circularly polarized (LCP and RCP) plane waves [23] and negative phase velocity (NPV) can be obtained by using chiral MTMs. The expressions for these constants are directly related with the chirality and having constant and wideband chirality would give a distinct advantage of having wider operating band especially for polarization rotation applications. More importantly, unlike in many other studies, our structure offers negative permittivity and permeability values at the resonances. This feature of our structure allows us to obtain NPV.

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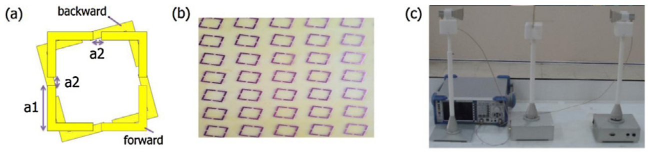

Fig. 1. Proposed tunable chiral MTM, (a) dimensions representation, (b) fabricated view and (c) A picture of the measurement setup.

2. Experiment and simulation setup

The proposed chiral MTM structure consists of a square-shaped resonator with gaps in the unit cell and the same shape rotated (15°) on the other side. Dimensions of the designed chiral MTM structure are shown in Fig. 1(a). It is fabricated on the two sides of FR-4 printed circuit boards (PCBs) and overall size of our slab is $280 \times 280\,\text{mm}^2$ (Fig. 1(b)), the thickness, loss tangent and relative permittivity of the chosen FR4 are 1.6 mm, 0.02 mm, and 4.2 mm, respectively. The metal structures are selected as copper (electrical conductivity of 5.800×10^7 S/m and thickness of 0.036 mm).

The proposed structure is simulated and analyzed with a commercial full-wave electromagnetic solver (CST Microwave Studio) based on finite integration technique. Unit cell (x, y) and open add space (z) boundary conditions are assigned in the simulation. To compare and confirm the numerical results, the experimental study is carried out for the fabricated chiral MTM as shown in Fig. 1(c). The experimental measurement setup consists of a R&S ZVL6 vector network analyzer (VNA) and two microwave horn antennas (to measure S-parameters). Firstly, free space measurement without the chiral structure is carried out in order to obtain calibration data. Secondly, the structure is then inserted into the experimental measurement setup and measurements of S parameters are realized and achieved.

3. Numerical and experimental results

Fig. 2(a–e) shows the simulation and experimental results of $Abs(T_L)$, $Abs(T_R)$, ellipticity and theta coefficients as a function of frequency, respectively. Chiral MTMs provide different responses for a left circularly polarized (LCP) wave and a right circularly polarized (RCP) wave because of the cross-coupling effect between the electric and magnetic field propagating through a chiral medium. $Abs(T_L)$ and $Abs(T_R)$ represent the LCP and RCP transmission coefficients of the proposed chiral MTM, in order. Also, ellipticity can be defined as the differences between RCP and LCP waves in absorption and distortion of two polarizations propagating through the medium. The other parameter is theta coefficient (optical activity) which could rotate the polarization plane of a linearly polarized wave when EM wave passes through a chiral medium.

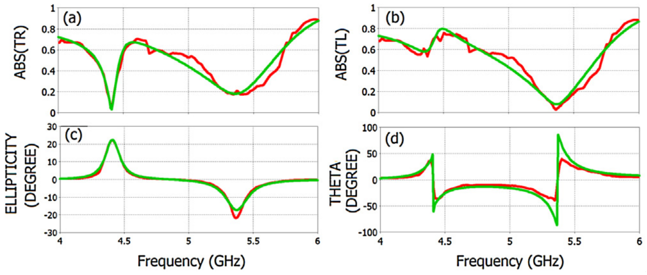

Fig. 2. Proposed chiral MTM (a) $Abs(T_R)$, (b) $Abs(T_L)$, (c) ellipticity angle, η and (d) polarization azimuth rotation angle, θ. Red lines represent measurement and green lines correspond to simulation study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

It can be seen that the experimental results are in a good agreement with the numerical simulation. There are two resonances in the transmission spectrum. First one corresponds to a peak at around 4.41 GHz and the second peak occurs at around 5.36 GHz. The first resonance is much smaller than the second one. At the resonances, the transmission spectra for the RCP and LCP waves are significantly different. This phenomenon is called as circular dichroism. Since the impedance of the chiral medium is the same for the two different polarizations, the reflections of the two polarizations are the same. This difference between the amplitudes of two transmissions is characterized by ellipticity of the transmitted wave as $\eta = (1/2)\sin^{-1}\left(\left(|T_L|^2 - |T_R|^2\right) / \left(|T_L|^2 + |T_R|^2\right)\right)$. In addition the difference between the phases is characterized by the polarization azimuth rotation angle θ which is calculated as $\theta = (1/2)\delta = (1/2)[arg(T_L) - arg(T_R)]$ [4–13].

Parameter retrieval is an important method to characterize the EM properties of the effective media and commonly used by researchers. There are some available methods in the literature for determining the electromagnetic properties of metamaterials [14–19]. While some of them are suitable and efficient for numerical simulations, others are appropriate for analytical models. Among these methods, S parameters retrieval method is preferable for an analysis based on simulations as well as experimental point of view. Depending on the wave polarization and its direction, metamaterials can exhibit bianisotropic property [15,17–20].

Effective constitutive parameters are evaluated using transmission and reflection parameters with retrieval formulas. These formulas can also be used to obtain chirality of an effective media from the RCP and LCP elements of the transmitted wave. The chirality κ can be obtained directly from the transmissions as $\text{Re}(\kappa) = (\phi_L - \phi_R + 2m\pi)/(2k_0 d)$, $Im(\kappa) = (\ln|T_L| - ln|T_R|)/2k_0 d$ where k_0 is the vacuum wave number, d is the thickness of the structure (it is chosen as 1.6 mm in this study), and m is an integer determined according to the branch number.

For the first resonance, the chirality is very large, $\kappa = 7.84 - 4.68$ at which corresponds to frequency $f = 4.41$ GHz for simulation-experimental results. For the second resonance, $\kappa = 9.24 - 4.25$ at which corresponds to the frequency $f = 5.36$ GHz for simulation-experimental results. Also, especially, there is a wideband and constant/flat chirality between the frequencies of 4.63 GHz and 5.05 GHz as desired. The value is 1.63. Thus, we succeed to accomplish the wideband and very constant chirality over a certain frequency region. Note that the discrepancies between the experimental and simulation data are imputed to fabrication tolerances and dielectric dispersion of the substrate. The misalignment during the experiment may also be considered as another source of error. The accuracy of the measurements can be clarified by the good agreement between the simulation and experimental results.

One of the main attractive properties of Chiral MTMs is to obtain negative refraction via a chiral route. Both simulation and experimental results for negative refractive index can be seen in Figs. 3(b)–(d). One can see from the figure that strong chirality κ causes the refractive index to be negative at around the resonance frequencies of 4.41 GHz and 5.36 GHz. It is also notable that the simulation results are in a good agreement with the numerical results. For further examination, retrieved permittivity and permeability results for the proposed structure are shown in Fig. 3(e) and (f), respectively.

Then, the other retrieval parameters can be calculated by $n_\pm = n \pm \kappa$, $\varepsilon = n/z$, and $\mu = nz$ [4–13].

In order to show the operating mechanism, it would worth to examine the electric field and current distribution of the proposed design. The electric field distributions for the resonance frequencies of $f = 4.41$ GHz and $f = 5.36$ GHz are shown in Fig. 4. It is clear from the figure that the electric fields are stronger at the sides of all the gaps for both front and back-sides. Current distributions of the