Analysis of extrinsic chirality in layer by layer structures distributed in non-planar unit-cell arrangements at microwave frequencies

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Abstract— In this communication, the authors study the behavior of a chiral metamaterial designed to modify the polarization state of the incident plane wave that impinges obliquely on the metamaterial unit cells. The novelty of this work lies on how the unit cells are arranged along the metamaterial. The analysis of the behavior of these metamaterials has been done using the commercial 3D EM simulator Keysight EMPro using the finite difference time domain technique. Thanks to this software, two different arrangements have been studied: the sawtooth profile and the zigzag profile. In both distributions, the mutual twist rosette is implemented to combine intrinsic chirality, controlled by the mutual twist angle, and extrinsic chirality, controlled by the tilt angle of the arrangements. This combination shows an improvement of the optical activity and/or circular dichroism.

1. INTRODUCTION

It is well known that planar chiral metamaterial (CMM) structures implemented on printed circuit board technology can provide high optical activity and circular dichroism [1-4]. These kind of complex media present different refractive indices for each of the two circularly polarized eigenwaves. Different real parts of the refractive indices produce different phase delays for the right- and left- handed circularly polarized eigenwaves and, consequently, a rotation of the polarization plane (optical activity). Meanwhile, different imaginary parts result in different absorption for each eigenwave, causing a transformation on the polarization conditions (circular dichroism). The aforementioned chirality is intrinsic to the media because it directly depends on the electric and magnetic field coupling.

In contrast to intrinsic chirality, extrinsic chirality [5] is produced by the mutual orientation of the propagation direction of the incident wave and the planar metamaterial normal. This kind of chirality is sometimes also called pseudochirality to distinguish it from intrinsic chirality.

In this communication, the behavior of two chiral metasurfaces that take advantage of oblique incidence to transform the polarization state of an incident wave is analyzed. The aim of this communication is obtaining chirality values that go beyond those provided only by intrinsic chirality. In contrast with other publications [5-7], the novelty of this work lies on the orientation of the chiral particles with regard to the incident wave propagation and the neighboring unit cells. We propose two different distributions of the unit cells along the metasurface: the sawtooth profile structure, Fig. 1a, and the zigzag profile structure, Fig. 1b. Moreover, to exploit the combination of intrinsic and extrinsic chirality dual layer unit cells are considered. The higher density of unit cells per unit area of the designed structures joined to the positive contribution of intrinsic and extrinsic chirality facilitates their use in real devices, as for example as superstrate that modifies the polarization of the antenna.

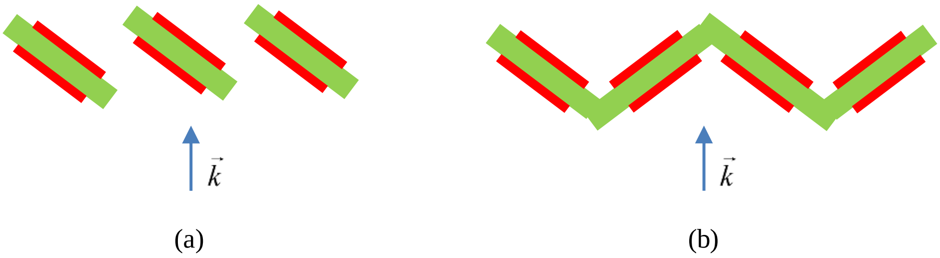


Fig. 1. Profile view (a) Sawtooth profile, (b) Zigzag profile. (Red: metallization/Green: substrate).

2. INTRINSIC AND EXTRINSIC CHIRALITY

The CMM structure used to introduce intrinsic chirality is the well-known four-fold symmetry rosette [4], although other planar structures would have been also valid. The rosette structure is a planar 2D chiral structure (which cannot be brought into congruence with their mirror image) that introduces very low levels of chirality. From this structure, Plum [4] proposed the addition of a second rosette, printed on the other side of the substrate and rotated a certain angle (ϕ) with respect to the first one. The resulting structure presents giant optical activity and circular dichroism. The chirality of this structure (intrinsic chirality), characterized for normal incidence, depends mainly on the mutual rotation angle ϕ between the rosettes. If ϕ is zero, the structure is not 3D chiral (*i.e.*, it does not present sense of twist in 3D). However, as the mutual twist angle increases, the chirality grows remarkably.

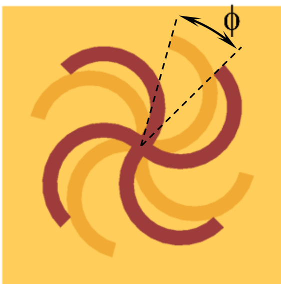


Fig. 2. Mutually twisted rosettes [4a]; ϕ represents the mutual twist.

When the incidence direction is oblique to the unit cell plane, the structure presents a different chiral behavior originated by the mutual orientation of the incident wave direction and the normal of the planar metamaterial. This pseudochiral effect or extrinsic chirality can be observed isolated from intrinsic chirality in situations wherein the structure is achiral, *i.e.*, $\phi = 0$.

Two novel distributions combining both intrinsic and extrinsic chirality are proposed. In these structures, the electromagnetic field impinges obliquely on the cells producing a different interaction between both metallic patterns of the unit cell. In addition, given their designs, different interaction between adjacent cells also occurs.

The first of the proposed distributions is the sawtooth profile structure presented in Fig. 3a. This configuration, based on mutually twisted rosettes arrangement, groups unit cells in a row along the *y*-axis. Each row is rotated by a certain angle α with respect to the propagation vector of the incident field. If $\alpha = 0$, the incident plane wave is normal to the metasurface. Finally, this pattern is repeated periodically along the *x*-axis.

The second distribution is the zigzag assembly, Fig. 3b. Similar to the sawtooth profile structure, the rosettes are grouped in rows. However, in this case the rows are rotated alternatively $+\alpha$ and $-\alpha$.

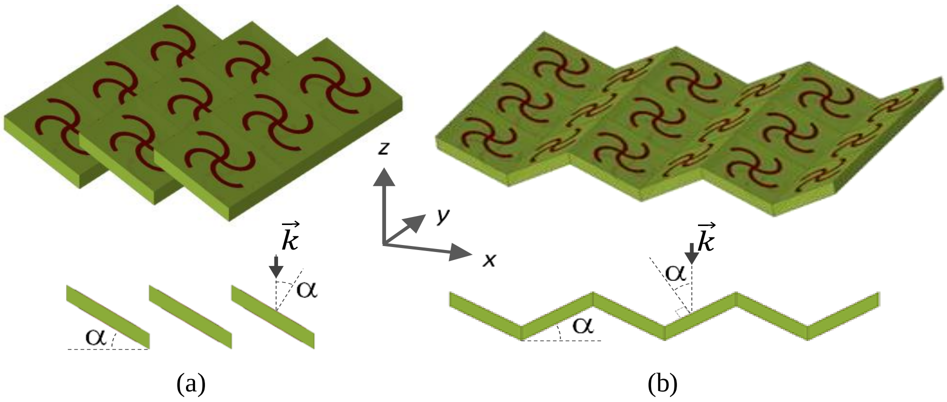


Fig. 3. Mutual twist rosettes distributed in a (a) Sawtooth profile, (b) Zigzag profile.

3. RESULTS

The proposed metasurfaces have been characterized using the finite differences time domain engine of the full wave 3D EM simulator, Keysight EMPro. For this purpose, a single unit cell is implemented with periodic boundary conditions in the *x* and *y* directions and absorbing in the *z* direction. The structures are characterized by means of the linear transmission coefficients t_{xx}, t_{yy}, t_{xy} and t_{yx}, where the first subscript represents the transmited polarization and the second one the incident one. From these coefficients, the linear to circular ($t_{\pm x}$, $t_{\pm y}$) and circular transmission coefficients ($t_{\pm\pm}$, t_{+-}, and t_{-+}) are obtained [8].

With the aid of the aforementioned electromagnetic software, different configurations of both structures have been studied. When α = 0º the sawtooth and the zigzag structures present the same configuration (Fig. 2).

First, we consider the influence of the oblique incidence in a configuration with no mutual twist between rosettes, ϕ = 0º, (*i.e.*, without intrinsic chirality), to isolate the effects of both intrinsic and extrinsic chirality types. Thus, we study the variation of the co-polar and cross-polar transmission for different values of α, from 0 to 60º. In the starting point situation, ϕ = 0º and α = 0º, the structures do not present 3D-chiral symmetry and, consequently, there is no chiral behavior. However, as α is increased, *i.e.* incidence is more oblique, the presence of a cross-polar transmission component, t_{xy}, (generated by the extrinsic chirality) can be observed in both structures (dashed blue lines of Fig. 4). Nevertheless, although there is cross-polar transmission in both cases, Fig. 4a and b, the transmission magnitude is lower than the co-polar one. Moreover, in these situations, with oblique incidence, the metasurface does not present C_4 symmetry and consequently, its response depends on the incident field polarization orientation.

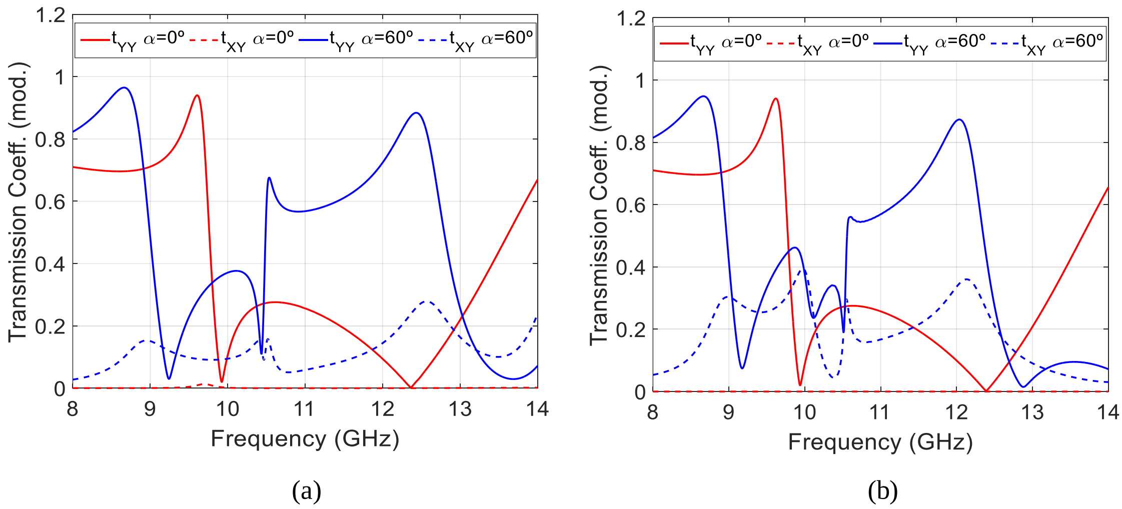
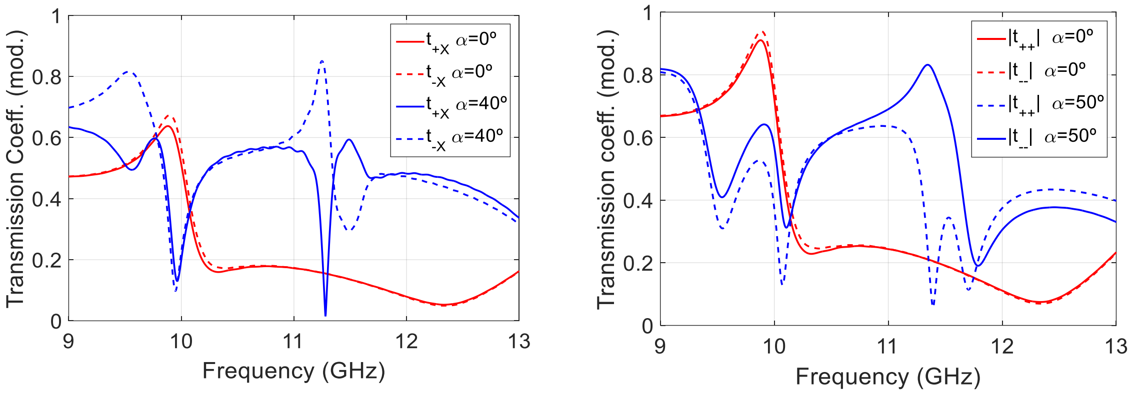


Fig. 4. Linear co-polar and cross-polar transmission coefficients with ϕ = 0º and α = 0º (red line), 60º (blue line) (a) sawtooth and (b) zigzag profile.

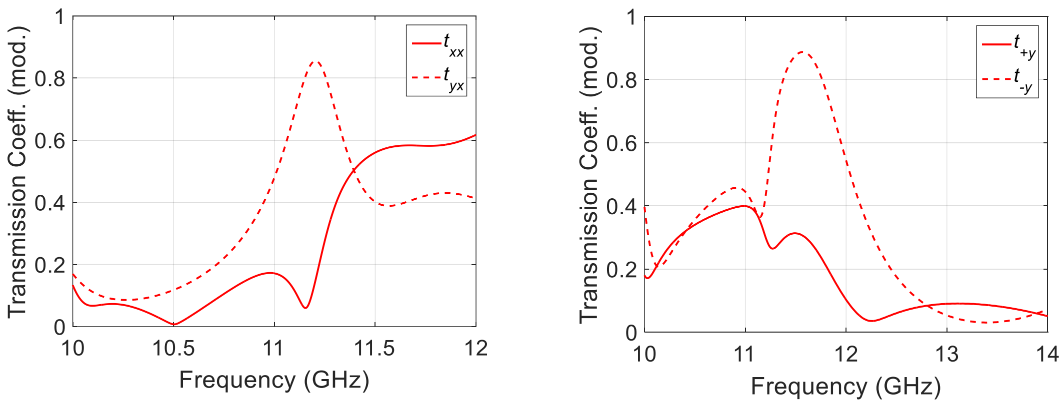
The previous results show the extrinsic chirality produced with oblique incidence. Next, the combination of intrinsic chirality (controlled by ϕ) and extrinsic chirality (controlled by α) is analysed. Fig. 5 presents the linear to circular transmission coefficients (a) and the circular transmission coefficients (b) corresponding to the sawtooth profile structure with a mutual twist $\phi = 30^\circ$. For normal incidence, the circular dichroism presented by this structure is low. With $\alpha = 0^\circ$, the linear to circular transmission coefficients are quite similar, $t_{+x} \approx t_{-x}$, (Fig. 5a). With that normal incidence, we also observe in Fig. 5b that the co-polar transmission of a left handed circularly polarized (LHCP) wave is similar to the transmission of a right handed (RHCP) one, $t_{++} \approx t_{--}$. However, when the incidence is oblique, the difference between t_{+x} and t_{-x}, and between t_{++} and t_{--} increases with α, i.e. the circular dichroism increases with the oblique incidence. Fig. 5a shows that for $\phi = 30^\circ$ and $\alpha = 40^\circ$, the sawtooth profile structure acts as a linear to circular polarization converter. Meanwhile for mutual twist $\phi = 30^\circ$ and $\alpha = 50^\circ$, at 11.3 GHz, this structure filters the RHCP wave but transmits the LHCP one (Fig. 5b).



(a) (b)

Fig. 5. Linear to circular (a) and circular (b) transmission coefficients of the mutual twist rosette structure with $\phi = 30^\circ$ arranged in a sawtooth profile distribution

The results of the zigzag profile structure, Fig. 6, also show a great influence of the combination of intrinsic and extrinsic chirality. Fig. 6a present the co-polar and cross-polar transmission coefficients of the structure for an x-polarized incident wave with $\phi = 30^\circ$ and $\alpha = 60^\circ$. For oblique incidence, the metasurface presents at 11.2 GHz high linear cross-polar transmission and low co-polar transmission. Thus, the structure transforms an x-polarized incident wave into a y-polarized transmitted one, i.e. acts as a 90° linear polarization rotator. We can also observe high circular dichroism, Fig. 6b, with high difference between t_{+y} *and* t_{-y}, showing high linear to circular polarization conversion.



(a) (b)

Fig. 6 Linear (a) and linear to circular (b) transmission coefficients of the mutual twist rosette structure with $\phi = 30^\circ$ arranged in a zigzag profile with $\alpha = 60^\circ$.

4. CONCLUSION

This communication presents two chiral metamaterial distributions, the sawtooth and the zigzag profiles, designed to introduce simultaneously intrinsic and extrinsic chirality. The mutual twist rosette is implemented in both arrangements to combine intrinsic chirality, controlled by the mutual twist angle, and extrinsic chirality, controlled by the tilt angle of the arrangements.

The numerical characterization of both structures has shown that with oblique incidence they present a pseudochiral behavior, even with achiral configurations (no mutual twist). Moreover, the combination of intrinsic and extrinsic chirality increases the optical activity and circular dichroism, thus modifying the polarization of the incident wave.

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