Optical activity in extrinsically chiral metamaterial

E. Plum,[a] V. A. Fedotov, and N. I. Zheludev[b]
Optoelectronics Research Centre, University of Southampton, Hampshire SO17 1BJ, United Kingdom

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We demonstrate optical activity in an intrinsically non-chiral anisotropic planar metamaterial. The phenomenon is due to extrinsic chirality resulting from the mutual orientation of the metamaterial structure and the incident electromagnetic wave. The polarization effect, which has a resonant nature, features a spectral band where linear birefringence is practically absent and can be easily tuned by tilting the plane of the metamaterial relative to the incident beam. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3021082]

Recent predictions that strong optical activity could result in a negative index of refraction[1,2] inspired intense work on developing artificial three-dimensionally (3D) chiral metamaterials, i.e., arrays of identical meta-molecules, where the meta-molecules themselves are different from their mirror image and therefore *intrinsically 3D-chiral*.[3–9] Although not widely known, optical activity in the form of circular birefringence and dichroism can also be observed in *extrinsically chiral* systems. In such a system a non-chiral structure together with the incident wave forms a geometrical arrangement that cannot be superimposed with its mirror image and thus the whole arrangement is chiral. This mechanism of polarization rotation was first identified by Bunn[10] and has been observed in liquid crystals.[11]

In this letter we show that extrinsic chirality is a highly significant source of optical activity in metamaterials. We demonstrate strong polarization rotary power and circular dichroism at oblique incidence in a planar metamaterial, which is neither two-dimensionally (2D) chiral[12,13] nor 3D-chiral. The effect is inherently tunable: its sign and magnitude are controlled by the tilt of the metamaterial plane relative to the incident beam. Importantly, this type of tunable optical activity occurs in simple planar metamaterial designs that are ideally suited for well-established planar manufacturing technologies.

We studied optical activity in a planar metamaterial structure consisting of a regular 2D array of metal split rings supported by a 1.6 mm thick dielectric substrate (see Fig. 1). The rings were split asymmetrically into pairs of arcs of different lengths separated by equal gaps. Each split ring had a line of mirror symmetry but had no axis of twofold rotation. The planar metamaterial sample was approximately 220×220 mm^2 large and had a square unit cell of 15×15 mm^2, which ensured no diffraction at normal or oblique incidence for frequencies below 10 GHz. Our measurements were performed in an anechoic chamber using microwave broadband horn antennas (Schwarzbeck BBHA 9120D) equipped with lens concentrators and a vector network analyzer (Agilent E8364B). We measured losses and phase delays for circularly polarized waves transmitted by the metamaterial at various angles of incidence in the range from −30° to +30° achieved by tilting the sample around its symmetry axis. In practical terms we measured the complex transmission matrix $E_i^{\text{out}}=t_{ij}E_j^{\text{in}}$ relating the electric fields of the incident (E^{in}) and transmitted (E^{out}) waves, where subscripts + and − denote right and left circular polarizations correspondingly. Our measurements showed that the diagonal elements (t_{++} and t_{--}) were generally not equal indicating that the structure had true optical activity. The difference between the magnitudes of the diagonal elements $\Delta=|t_{++}|^2-|t_{--}|^2$ is a measure of circular dichroism, while the corresponding phase difference $\delta=\arg(t_{++})-\arg(t_{--})$ is a measure of circular birefringence. Within the experimental accuracy the off-diagonal elements of the matrix were nonzero but equal, indicating the expected presence of linear anisotropy in the structure. The metamaterial did not manifest the asymmetric transmission effect which was recently identified in 2D-chiral structures.[13]

Importantly, the structure's circular birefringence and dichroism cannot be explained by just linear anisotropy, as anisotropy does not contribute to either Δ or δ. Particularly, while linear anisotropy causes a polarization state dependent modulation of azimuth rotation, it has no effect on the material's average polarization rotary power $\Delta\Phi=-\delta/2$. In all

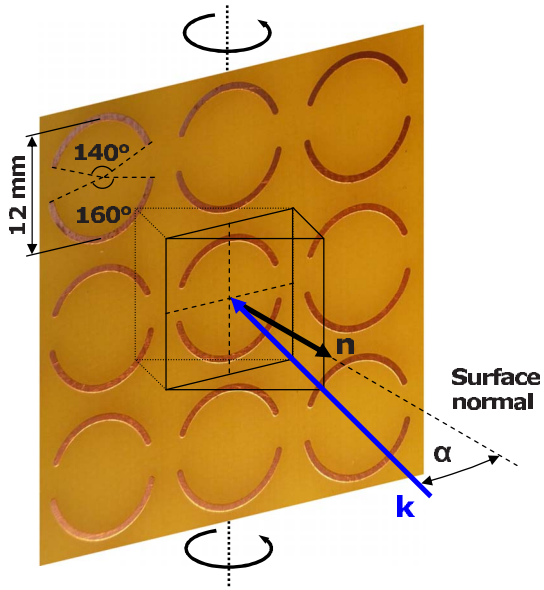

FIG. 1. (Color online) Extrinsically chiral optically active metamaterial: circular birefringence and dichroism are seen when the metamaterial plane is tilted around its symmetry axis, so that the plane normal n forms an angle $\alpha\neq0$ with the wave vector of the incident wave k.

[a]Electronic mail: erp@orc.soton.ac.uk.
[b]Electronic mail: n.i.zheludev@soton.ac.uk. URL: www.nanophotonics.org.uk/niz/.

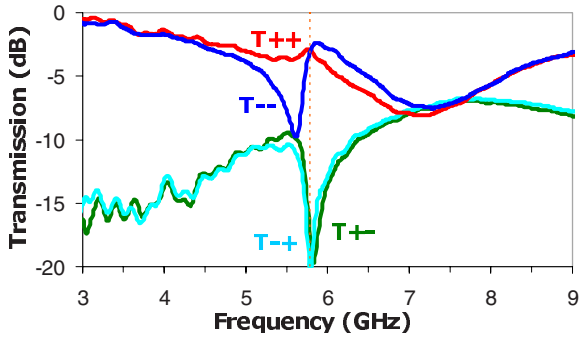

FIG. 2. (Color online) Circular transmission and polarization conversion measured for electromagnetic waves incident at a tilt angle of $\alpha=+30°$ (see Fig. 1). The dashed line marks a frequency of pure optical activity; here circular dichroism and linear anisotropy are virtually absent.

cases experiments performed in opposite directions of wave propagation yielded identical results.

Transmission spectra obtained for a tilt angle of $\alpha=+30°$ are presented in Fig. 2 in terms of $T_{ij}=|t_{ij}|^2$. A resonant region showing circular dichroism, i.e., $T_{++}\neq T_{--}$, can be seen between 5 and 7 GHz. Due to anisotropy the metamaterial shows weak polarization conversion $T_{+-}=T_{-+}$. At 5.8 GHz, however, linear anisotropy vanishes, resulting in circular polarization eigenstates and, as circular dichroism is also absent at this frequency, the material behaves like an isotropic optically active medium in the k-vector direction. As shown in Fig. 3, it rotates the polarization azimuth by about 20° without changing the polarization state, while transmission losses represented by T_{++} and T_{--} are less than 3 dB. Considering the metamaterial's thickness of only 1/32 of the wavelength, the rotary power of this non-optimized structure is remarkable. The non-chiral structure also shows substantial circular dichroism in the vicinity of the resonant frequency, which reaches more than 6 dB at 5.6 GHz.

Importantly, the strength (as well as sign) of the metamaterial's gyrotropic response depends on the tilt angle α, which is illustrated by Fig. 3. At normal incidence both circular dichroism and polarization azimuth rotation are absent. When the structure is tilted relative to the beam, as shown in Fig. 1, a continuous increase in the strength of its gyrotropic response is observed. For example, at 5.6 GHz circular dichroism increases from 0 to 2.3, 4.6, and 6.2 dB when the tilt angle is increased from 0° to 30° in steps of 10°. Simultaneously, the polarization azimuth rotation—at 5.8 GHz—increases almost linearly from 0° to 7°, 15°, and 21°. The shape and position of the corresponding resonance appear to depend weakly on the tilt angle. Importantly, we found that tilting the metamaterial in the opposite direction (i.e., $\alpha<0$) simply reverses the signs of rotation and circular dichroism.

In summary, the following key features of the gyrotropic response of planar non-chiral metamaterials have been identified: (i) no effect can be observed at normal incidence (i.e., $\alpha=0$); (ii) the magnitude of polarization rotation and circular dichroism is controlled by the tilt angle; and (iii) equal tilt in opposite directions yields circular dichroism and polarization rotation of opposite signs.

As with conventional optical activity exhibited by 3D-chiral molecules, the observed effect must result from simultaneous presence of electric and magnetic responses in the structure. Here, the asymmetry of the split rings plays a key role. For example, as illustrated in Fig. 4(a) a wave polarized along the split induces unequal currents oscillating in the upper and lower arches of the ring. Such a current configuration may be represented as a sum of symmetric and antisymmetric currents corresponding to an electric dipole **d** induced in the plane of the ring and a magnetic dipole **m** oscillating perpendicular to the plane, respectively.

For oblique incidence, the metamaterial shows optical activity if the split is not perpendicular to the plane of incidence, while the maximum effect is observed when the split is parallel to the plane of incidence [see Figs. 4(d) and 4(e)]. Indeed, in this case the wave vector **k**, **d**, and **m** are coplanar, and similarly to how it happens in conventional 3D-chiral media, the electric and magnetic dipole components perpendicular to **k** create scattered electromagnetic waves with orthogonal polarizations, so that the polarization of the transmitted wave acquires maximum rotation. The mutual phase difference between the electric and magnetic responses and thus the sign of optical activity depend on the sign of the tilt [compare projections of **d** and **m** in Figs. 4(d) and 4(e)].

On the contrary, if the split is perpendicular to the plane of incidence, **d** and **m**, as well as their projections, are orthogonal [see Fig. 4(c)]. In this case the structure does not show any optical activity as the oscillating magnetic and electric dipoles emit electromagnetic waves of the same po-

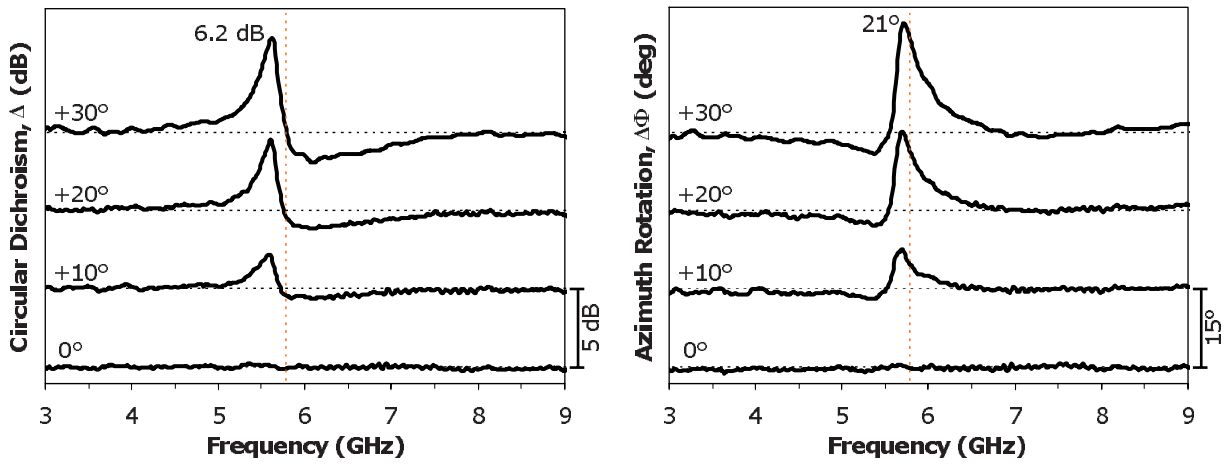

FIG. 3. (Color online) Circular dichroism and birefringence in the non-chiral planar metamaterial structure measured for tilt angles from $\alpha=0°$ to +30° in steps of 10°. Tilt angles of opposite sign result in reversed signs of circular dichroism and azimuth rotation. The frequency at which pure optical activity on a background of vanishing anisotropy can be seen is marked by a vertical dashed line.

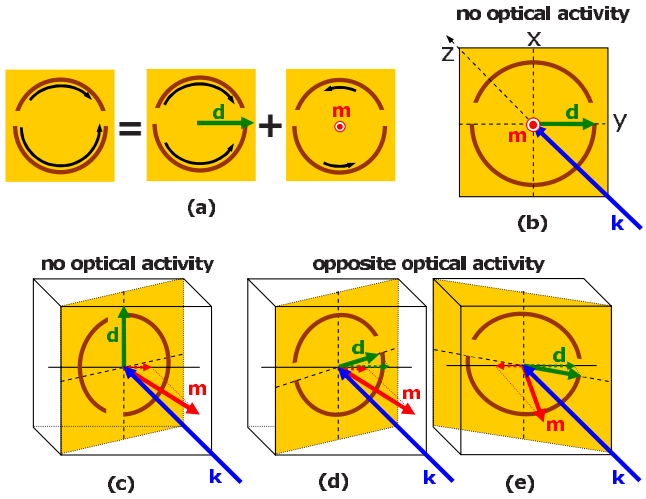

FIG. 4. (Color online) Electric and magnetic responses of asymmetrically split rings. (a) Oscillating currents in a split ring can be represented as a sum of symmetric and antisymmetric currents, corresponding to an electric dipole **d** (green arrow) and a magnetic dipole **m** (red arrow). Optical activity is controlled by the projections of **d** and **m** onto the plane perpendicular to the **k**-vector (green and red dashed arrows correspondingly): it is absent either when one of the projections is zero (b) or if the projections are orthogonal (c); the strongest polarization rotations, of opposite sign, occur if these projections are either parallel (d) or antiparallel (e).

larization as the incident wave. At normal incidence optical activity cannot be observed as the projection of **m** on the plane normal to the **k**-vector is zero [see Fig. 4(b)].

In conclusion we have demonstrated strong and tunable resonant extrinsic optical activity and circular dichroism in an intrinsically non-chiral planar metamaterial. We have shown that chirality arising from the mutual orientation of a non-chiral structure and the incident beam is sufficient to lead to very pronounced circular birefringence and dichroism. Even though the effect occurs only for anisotropic patterns, our results demonstrate the existence of a spectral band where optical activity is dominant and eigenstates are circularly polarized, while linear birefringence is practically absent. Tunability of the polarization response and simplicity of the structure, which can be easily scaled to the optical part of the spectrum, allow exploitation of the phenomenon in polarization control applications both in microwave and photonic devices.

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