Asymmetric Propagation of Electromagnetic Waves through a Planar Chiral Structure

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We report that normal incidence transmission of circularly polarized waves through the lossy anisotropic planar chiral structure is asymmetric in the opposite direction. The new effect is fundamentally distinct from conventional gyrotropy of bulk chiral media and the Faraday effect, where the eigenstates are a pair of counterrotating elliptical states, while the eigenstates of the lossy anisotropic planar chiral structure are two corotating elliptical polarizations.

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Planar chiral structures possess a sense of twist that is reversed when they are observed from opposite sides (for example, Archimedes spiral), while for 3D-chiral structures (think of a helix) the sense of perceived rotation remains unchanged for opposing directions of observation. Consequently, if a planar chiral structure were to exhibit a transmission polarization effect at normal incidence, the sense of the effect would be reversed for an electromagnetic wave propagating in opposite directions. Such a transmission effect has never been observed before, but if proven would be of profound benefit for the development of a new class of microwave and optical devices.

In this Letter we report the first experimental observation of such a previously unknown fundamental phenomenon of electromagnetism. It is a polarization sensitive transmission effect asymmetric with respect to the direction of wave propagation. The new effect in some ways resembles the famous nonreciprocity of the Faraday effect in magnetized media but requires no magnetic field for its observation. It results from the interaction of an electromagnetic wave with a *planar* chiral structure patterned on a subwavelength scale. Both in the Faraday effect and in that produced by planar chirality, the transmission and retardation of a circularly polarized wave are different in opposite directions. In both cases the polarization eigenstates, i.e., polarization states conserved on propagation, are elliptical (circular).

There are also essential differences between the two phenomena. The asymmetry of the Faraday effect applies to the transmission and retardation of the *incident* circularly polarized wave itself, and the eigenstates of an anisotropic Faraday medium are two elliptically polarized waves of *opposite* handedness. The planar chirality effect leads to partial conversion of the incident wave into one of opposite handedness, and it is the efficiency of this *conversion* that is asymmetric for the opposite directions of propagation (see Fig. 1). The eigenstates in this case are two elliptical polarizations of the *same* handedness. The newly observed effect is also radically different from conventional gyrotropy in 3D-chiral media (such as sugar solution or quartz), which is known to be completely symmetric for the wave propagating in opposite directions.

The reported *asymmetric* phenomenon requires simultaneous presence of *planar chirality* and *anisotropy* in the structure and involves no change in the direction of transmitted waves. It is therefore fundamentally different from recently studied polarization phenomena in *scattered* and *diffracted* fields, implying a change in the wave propagation direction [1–8]. The new effect is forbidden in isotropic planar chiral arrays of high symmetry such as array of 4-fold gammadions. Moreover, it is different from the symmetric effect analogous to conventional optical activity, which is observed in *L*-shaped gold nanoparticles [9,10] and gammadion arrays on dielectric substrate making 3D-chiral objects [11] or achieved through 3D-chiral arrangement in bilayered structures [12].

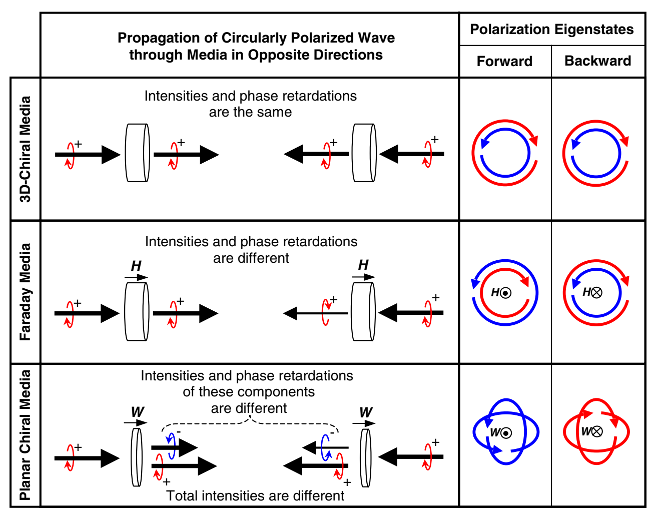

FIG. 1 (color online). Propagation of circularly polarized waves through 3D-chiral, Faraday, and anisotropic planar chiral media, and polarization eigenstates corresponding to propagation in forward and backward direction in each media. Circular arrows denote polarization states: blue for RCP, red for LCP. Vector **H** denotes the external magnetic field, while **W** indicates the 2D-chiral twist.

If a medium is described by a complex transmission matrix χ for the field amplitudes of the incident E^0 and transmitted E^T circularly polarized waves, then $E_i^T = \chi_{ij} E_j^0$, where indices i and j correspond to polarization states of the transmitted and incident wave, which could be either right (RCP, $+$) or left (LCP, $-$) circular polarizations. The matrix χ^F for an isotropic magnetized Faraday medium and matrix χ^{3D} for the isotropic 3D-chiral medium are *diagonal* matrices. In the Faraday medium the transmission matrices for opposing directions of propagation (denoted by arrows), i.e., $\overrightarrow{\chi^F}$ and $\overleftarrow{\chi^F}$, are related by the permutation of their diagonal elements, while in the 3D-chiral medium $\overrightarrow{\chi^{3D}}$ and $\overleftarrow{\chi^{3D}}$ are identical. In these terms the transmission matrix for a planar chiral anisotropic medium is a *non-Hermitian* matrix with equal diagonal elements,

$$\chi^{2D} = \begin{Bmatrix} \alpha & \beta \\ \gamma & \alpha \end{Bmatrix}.$$

The transmission matrices for opposing directions of propagation will be mutually transposed: $\overrightarrow{\chi^{2D}_{ij}}$ $\overleftarrow{\chi^{2D}_{ji}}$. For a given direction of propagation the equality of the diagonal elements $\chi_{++} = \chi_{--} = \alpha$ implies that losses and retardation are identical for RCP and LCP waves passing through the structure. However, since $\chi_{+-} \neq \chi_{-+}$, switching between RCP to LCP incident waves leads to a change in the intensity and phase of the corresponding LCP and RCP converted components.

The new propagation phenomenon described by the matrix χ^{2D} has been observed in a chiral "fish-scale" planar structure. This is a chiral version of a novel type of electromagnetic metamaterial, the nonchiral form of which was recently investigated for its frequency selective properties and "magnetic wall" behavior [13,14]. The chiral fish scale is a continuous 2D pattern of tilted meanders existing in two enantiomeric (mirror) forms interconnected by reflection across a mirror line in the plane of the structure (see Fig. 2). For any planar chiral pattern a unit vector of "twist" **W** can be introduced. It is directed normal to the plane of the pattern and points according to the cork-screw law: if the cork screw rotates in the same direction as the chiral pattern then it moves along **W**. Vector **W** is invariant to which side of the pattern the definition is applied to. The twist vectors of the enantiomeric patterns are antiparallel. Now, if vector **W** points along the direction of observation, the structure is perceived to be clockwise. Similarly, it is perceived to be anticlockwise if **W** points towards the observer.

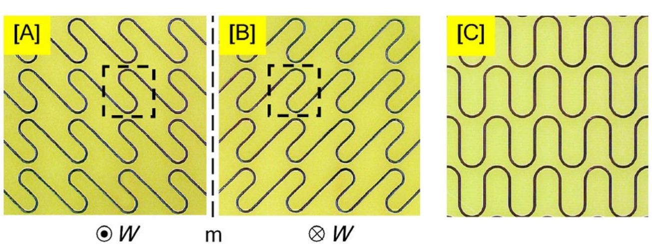

FIG. 2 (color online). Fragments of two enantiomeric forms A and B of the chiral fish-scale pattern made of copper strips on a dielectric substrate. The dashed line box indicates the elementary translational cell of the structure. Part C shows a fragment of the nonchiral fish-scale structure.

In the experiments reported here we used chiral metallic fish-scale structures with overall size of approximately 220×220 mm etched from a 35 μm copper film on a 1.5 mm thick dielectric substrate (see Fig. 2). The width of the strips was 0.8 mm. The size of the square translation cell was 15×15 mm, which ensured that the periodic structure did not diffract radiation at frequencies lower than 20 GHz. We studied transmission of the samples at normal incidence in the 4–18 GHz spectral range using vector network analyzer (Agilent E8364B).

Measuring the circular polarization transmission matrix χ^{2D} directly requires a circularly polarized emitter and receiver. The existing circular polarization antennas, however, are only capable of producing high purity circular polarization in a narrow spectral range and are therefore not suitable for broadband measurements. Instead, we used broadband linearly polarized log-periodic antennas (Schwarzbeck M. E. STLP 9148) and measured the complex transmission matrix t for linearly polarized fields. All parameters for the incident and transmitted waves were defined in the right-handed Cartesian coordinate frame with the Z axis directed perpendicular to the plane of the structure, while the X and Y axes were directed along and perpendicular to the meandering strips, respectively. The complex circular polarization transmission matrix χ^{2D} and the intensity transmission and conversion matrix $\Xi = |\chi^{2D}|^2$, were then calculated using this data. Matrix Ξ for fish-scale structures A and B will be denoted, respectively, as $\overrightarrow{\Xi^A}$ and $\overrightarrow{\Xi^B}$ for waves entering the structure from the side of the metal pattern, while matrices $\overleftarrow{\Xi^A}$ and $\overleftarrow{\Xi^B}$ correspond to waves entering the structures from the opposite side, i.e., through the dielectric layer first.

The transmission properties of the chiral fish-scale structure were also rigorously modeled using the well-established method of moments [15], assuming the presence of losses in the dielectric substrate, $\varepsilon = 4.5 + i0.2$.

The data presented in Fig. 3 together with corresponding phase information (not shown) indicate that within experiential accuracy, the diagonal elements of matrix χ^{2D} are equal across the whole spectral range of interest. This fact is fully consistent with the outcome of the calculations based on the method of moments. Moreover, the diagonal elements are the same for the two enantiomeric fish-scale structures A and B, and for propagation in both directions. In particular $\overrightarrow{\chi^{2D}_{\pm\pm}} = \overrightarrow{\chi^{2D}_{\mp\mp}}$ and $\overrightarrow{\chi^{2D}_{\pm\pm}} = \overleftarrow{\chi^{2D}_{\pm\pm}}$, which means that the structure does not manifest polarization effects of the same symmetry as conventional optical activity or the optical Faraday effect in bulk media. However, it shows an intriguing new *asymmetric polarization conversion* effect.

The data presented in Fig. 4 illustrate asymmetry of polarization conversion observed in the chiral fish-scale

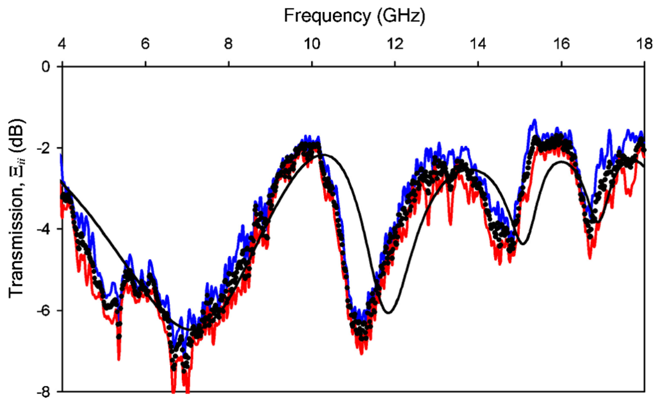

FIG. 3 (color online). Mean value of Ξ_{ii} (black circles) calculated as an average over eight different sets of data, which were obtained for both enantiomeric forms of the structure (*A* and *B*) for RCP and LCP incident waves in both forward and backward directions of propagation. The solid red and blue lines show the limits of the observed transmission variation. The solid black line shows the theoretical value of Ξ_{ii}.

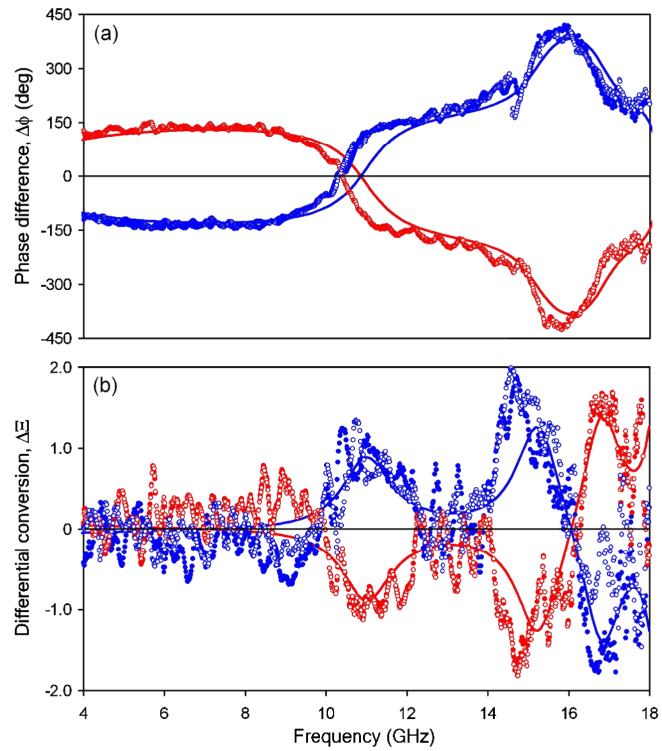

FIG. 4 (color online). Polarization conversion of circularly polarized waves by two enantiomeric forms of chiral fish-scale structure in forward and backward directions of propagation. Part (a) shows phase difference $\Delta\phi$ between converted polarization components corresponding to incident waves of opposite handedness. Part (b) shows normalized differential intensity of conversion, $\Delta\Xi$. Blue and red solid circles correspond, respectively, to *A* and *B* enantiomers in the forward direction, while blue and red open circles correspond to *B* and *A* forms in the backward direction. Solid curves are obtained theoretically.

structure. Figure 4(a) shows the phase difference between converted polarization components resulting from excitation with circularly polarized waves of opposite handedness measured as $\Delta\phi = \arg\{\chi_{-+}\} - \arg\{\chi_{+-}\}$. It appears to have opposite signs for different enantomeric forms of the structure, i.e., $\Delta\phi^A = -\Delta\phi^B$. On the other hand, for a given structure the differential phase delay observed in the forward direction is the same as the delay for its *enantiomer* observed in the *opposite* direction, i.e., $\overrightarrow{\Delta\phi^A} = \overleftarrow{\Delta\phi^B}$. Similar symmetries are observed for the normalized difference in the intensities of the converted waves, measured as $\Delta\Xi = 2(\Xi_{-+} - \Xi_{+-})/(\Xi_{-+} + \Xi_{+-})$. Here again $\overrightarrow{\Delta\Xi^A} = -\overrightarrow{\Delta\Xi^B}$ and $\overrightarrow{\Delta\Xi^A} = \overleftarrow{\Delta\Xi^B}$ [see Fig. 4(b)]. This is in sharp contrast to conventional gyrotropy in three-dimensional chiral media where the observable effect does not depend on the direction of propagation. Furthermore, this indicates that the sign of the effect is controlled *only* by the perceived sense of rotation associated with the metallic pattern itself and does not depend on whether the pattern is placed on top or behind the dielectric layer.

Our raw experiential data and the results of computational analysis show that in all cases $\overrightarrow{t_{xy}} = \overrightarrow{t_{yx}}$, $\overleftarrow{t_{xy}} = \overleftarrow{t_{yx}}$,and $\overrightarrow{t_{xy}} = \overleftarrow{t_{yx}}$, $\overleftarrow{t_{xy}} = \overrightarrow{t_{yx}}$. The last two equalities constitute the requirement imposed on transmission by the Lorentz lemma [16]. In terms of circular polarizations the lemma may be rewritten as an equality $\overrightarrow{\chi_{ij}^{2D}} = \overleftarrow{\chi_{ji}^{2D}}$, which also holds within experimental and computational tolerance. Thus, the effect presented here does not mount any challenge to the validity of the reciprocity lemma. The somewhat surprising compatibility of the asymmetric effect with the Lorentz lemma is easily explained by the fact that the lemma only requires that $\overrightarrow{\chi_{-+}^{2D}} = \overleftarrow{\chi_{+-}^{2D}}$, while in our case $\overrightarrow{\chi_{-+}^{2D}} \neq \overleftarrow{\chi_{-+}^{2D}}$. In comparison, for the Faraday effect $\overrightarrow{\chi_{++}^{F}} \neq \overleftarrow{\chi_{++}^{F}}$ and the reciprocity does not hold, nor indeed is it supposed to in the presence of magnetic field.

The origin of the asymmetric interaction may be traced to the structure of the transmission matrix χ^{2D}. It can be presented as a sum $\chi^{2D} = \chi_0^{2D} + it_{xy}\mathrm{sgn}(\mathbf{k}\cdot\mathbf{W})\hat{g}$, where $\mathbf{k}$ is the wave vector of the incident wave,

$$\chi_0^{2D} = \frac{1}{2}\begin{Bmatrix} t_{xx} + t_{yy} & t_{xx} - t_{yy} \\ t_{xx} - t_{yy} & t_{xx} + t_{yy} \end{Bmatrix}$$

and antisymmetric matrix

$$\hat{g} = \begin{Bmatrix} 0 & -1 \\ 1 & 0 \end{Bmatrix}.$$

The antisymmetric part is proportional to the pseudoscalar combination $(\mathbf{k}\cdot\mathbf{W})$, which changes sign on reversal of the propagation direction. It gives rise to the difference between $\overrightarrow{\chi^{2D}}$ and $\overleftarrow{\chi^{2D}}$ and is therefore responsible for the direction-dependent transmission. The antisymmetric part is also proportional to t_{xy}; i.e., it may only exist in anisotropic patterns of low symmetry (if the structure possesses a fourfold symmetry axis, $t_{xy} = 0$). Moreover, only in dissipative systems t_{xy} cannot be eliminated by the choice of an appropriate coordinate system. In other words, transmission asymmetry is only possible in anisotropic dissipative planar chiral structures.

The origins of $\Delta\phi$ and $\Delta\Xi$ are completely different. $\Delta\phi$ results from the anisotropy of the structure and depends on the orientation of the meander strips with respect to the line of mirror symmetry interconnecting enantiomeric structures. $\Delta\phi$ does not lead to any asymmetrical effects that can be detected in the intensity of propagating waves. In contrast, $\Delta\Xi$ results in an *observable intensity effect*. The effect is astonishing: the planar chiral structure is more transparent to a circularly polarized wave from one side than from another. For instance for an incident RCP wave the total transmitted intensity in the forward direction is given by $\overrightarrow{\Xi^A_{++}} + \overrightarrow{\Xi^A_{-+}}$, while in the opposite direction it is given by $\overleftarrow{\Xi^A_{++}} + \overleftarrow{\Xi^A_{-+}}$. In spite of the fact that $\overrightarrow{\Xi^A_{++}} = \overleftarrow{\Xi^A_{++}}$, polarization conversion is asymmetric, i.e. $\overrightarrow{\Xi^A_{-+}} \neq \overleftarrow{\Xi^A_{-+}}$, leading to a difference in the total transmitted intensities of about 40% at 11 GHz. No such dependence on the direction of propagation would be seen in an anisotropic nonchiral planar or bulk material of any description (indeed, $\Delta\Xi = 0$ for anisotropic nonchiral fish-scale structure C). Therefore this phenomenon is somewhat analogous to the magnetic circular dichroism and may be called *planar chiral circular conversion dichroism*. Our calculations show that it is inherently linked to losses and increases in proportion to the imaginary part of the relative permittivity of the substrate material. In lossy anisotropic planar chiral structures the asymmetry of total transmission is accompanied by similar asymmetries in reflection and absorption. Lossless planar chiral structure shall not display asymmetric intensity effect in transmission.

The fundamental novelty of this effect may be explained by comparing polarization eigenstates (i.e., the polarization states that are not affected upon transmission) of anisotropic planar chiral structure with that of the Faraday medium and conventional bulk optical activity. In contrast to the Faraday effect, or conventional 3D optical activity in bulk media for that matter, where the eigenstates are a pair of *counterrotating* elliptical states, the eigenstates of a lossy anisotropic planar chiral structure are two *corotating* elliptical polarizations, as illustrated in Fig. 1. These eigenstates only differ in the azimuths of their main axes (they are orthogonal). The corresponding ellipticity angle reaches a maximum of about 20° at 17 GHz. As in the case of the Faraday effect (but in contrast to gyrotropy in conventional 3D-chiral media), the sense of rotation of the elliptically polarized eigenstates is reversed for the opposite direction of propagation.

In conclusion, we reported the first experiential observation and theoretical analysis of circular conversion dichroism in a planar chiral structure, which is a unique, previously unknown effect. It results from 2D chirality and anisotropy and is inherently linked to dissipation in the structure. The effect may be put on the same raw with optical activity and Faraday effect. The discovery may result in the development of new spectroscopic techniques for solid state physics, chemistry, and biosciences. We expect the effect to be seen in the optical part of the spectrum in appropriately scaled anisotropic planar chiral nanostructure. Numerous optoelectronic applications of such a kind of structure could be envisaged. For instance, when placed into a ring resonator, it will enforce generation of left and right elliptically polarized waves in opposite directions of circulation.

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