Asymmetric transmission: a generic property of two-dimensional periodic patterns

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Abstract
Asymmetric transmission of circularly polarized waves is a well-established property of lossy, anisotropic, two-dimensionally chiral patterns. Here we show that asymmetric transmission can be observed for oblique incidence onto any lossy periodically structured plane. Our results greatly expand the range of natural and artificial materials in which directionally asymmetric transmission can be expected, making it a cornerstone electromagnetic effect rather than a curiosity of planar chiral metamaterials. Prime candidates for asymmetric transmission at oblique incidence are rectangular arrays of plasmonic spheres or semiconductor quantum dots, lossy double-periodic gratings and planar metamaterial structures.

Keywords: planar chirality, metamaterial, asymmetric transmission

Since Hecht and Barron [1], and Arnaut and Davis [2] first introduced planar chiral structures to electromagnetic research they have become the subject of intense theoretical and experimental investigations with respect to the polarization properties of scattered fields in both linear and nonlinear regimes [3–11]. It was understood that planar chirality is essentially different in symmetry from 3D chirality and should lead to a new fundamental polarization phenomenon, the sense of which reverses for opposite directions of light propagation. Recently such a phenomenon has indeed been discovered in the form of asymmetric transmission, which manifests itself as a difference in both normal incidence transmission and retardation of circularly polarized waves incident on opposite sides of a planar chiral structure. It was observed in regular sub-wavelength arrays of anisotropic intrinsically 2D-chiral metamolecules in the microwave [12, 13], terahertz [14] and optical [15] parts of the spectrum as well as isolated plasmonic nanostructures [16] and has been linked to directionally asymmetric absorption losses [13, 17].

In this paper, we demonstrate that asymmetric transmission can be observed at any lossy periodically structured interface. We show that structural 2D chirality [18]—which causes the effect—can arise from oblique incidence onto any periodic pattern.

Like the electromagnetic effects of molecular chirality [19], electromagnetic manifestations of structural chirality can arise in two ways: intrinsically or extrinsically. As illustrated in figures 1(a) and (b), the intrinsic form of structural 2D chirality results from the orientation of achiral metamolecules placed in a planar regular array, when the lines of mirror symmetry of the molecules and the mirror lines associated with the array’s lattice do not coincide. Note that in this case mirror forms of the array cannot be superimposed by translations and rotations in the plane, which makes the entire structure 2D-chiral.

As shown by figures 1(c) and (d), structural 2D chirality can also be imposed extrinsically even in a regular array containing metamolecules of the highest symmetry. This is achieved by tilting the array around any in-plane axis that does not coincide with one of the array’s lines of mirror symmetry. It is easy to see that in this case the metamaterial’s projection onto the plane normal to the incidence direction becomes structurally 2D-chiral and anisotropic. Note that chirality here arises from the arrangement of the metamolecules, rather
than their internal structure. This implies that various 2D-chiral phenomena may be expected at any planar regular array containing identical particles of any symmetry. In particular asymmetric transmission, which has been previously perceived as an exotic effect specific to metamaterials, may, in fact, be a common phenomenon.

In the experiments reported here we studied two different types of planar metamaterials based on asymmetrically split rings and pairs of concentric rings, respectively, with the dimensions specified in figure 2. Both metamaterial structures were formed by a square array of about 200 metamolecules separated by 15 mm, which rendered our structures non-

Figure 1. Intrinsic structural chirality: anisotropic achiral metamolecules (a) can form a structurally planar chiral array (b). While a single metamolecule (blue) and its mirror image (red) can be superimposed by translation and rotation (purple), certain arrays of such metamolecules show planar enantiomorphism: congruency can only be achieved for one metamolecule in the array (purple) while the rest of the mirrored arrays do not coincide. Extrinsic structural chirality: an array (c) of highly symmetric metamolecules (blue) is congruent with its mirror image (red) and therefore does not have intrinsic chirality. However (d), when it is tilted with respect of the observation direction its projection onto the plane normal to this direction becomes planar chiral.
projection of the double-ring array onto the plane normal to the direction of incidence is 2D-chiral. For transmission and polarization conversion levels are given by the plane of incidence. For different orientations $\varphi \neq n \times 45^\circ$, $n \in \mathbb{Z}$ the projection of the double-ring array onto the plane normal to the direction of incidence is 2D-chiral.

The patterns were etched on 1.6 mm thick lossy FR4 printed circuit boards (Im $\varepsilon \sim 0.1$) covered with a 35 $\mu$m copper layer using standard photolithography. The transmission properties of the metamaterials were measured between 5 and 12 GHz in a microwave anechoic chamber using a vector network analyser (Agilent E8364B) and linearly polarized broadband horn antennas (Schwarzbeck BBHA 9120D) equipped with lens concentrators. In particular, we measured the structures’ transmission matrix $E_{ij}^0 = t_{ij}E_j^0$. To study chirality-related effects the matrix was transformed to the circular polarization basis, where indices $i$ and $j$ denote the handedness of the circularly polarized components: ‘+’ for right-handed (RCP) and ‘−’ for left-handed (LCP). In terms of power the transmission and polarization conversion levels are given by $T_{ij} = |t_{ij}|^2$.

Eight different versions of the asymmetric split ring array were studied at normal incidence, where the orientation of the split $\alpha$ was varied in steps of $11.25^\circ = \pi/16$ rad relative to the achiral arrangement shown in figure 2(a). As illustrated in figure 2(c), $\pm \alpha$ correspond to structural planar chirality of opposite handedness, while rotations by $\alpha$ and $\alpha + 90^\circ$ yield identical metamaterial arrays.

The double-ring array was characterized at $30^\circ$ oblique incidence for different orientations $\varphi$ of the array relative to the plane of incidence. For $\varphi \neq n \times 45^\circ$ ($n \in \mathbb{Z}$) the projection of the entire pattern onto the plane normal to the propagation direction becomes 2D-chiral. Similarly to the case of asymmetrically split rings, orientations $\pm \varphi$ correspond to extrinsically 2D-chiral arrangements of opposite handedness, while an in-plane rotation of the metamaterial by $90^\circ$ results in an identical experimental configuration.

Figure 3 presents typical spectra of direct transmission intensities $T_{++}$, $T_{--}$ and circular polarization conversion $T_{+-}$, $T_{-+}$ for achiral and chiral arrangements of both types of planar metamaterial2. In all studied cases, the direct transmission intensities (as well as field transmission coefficients $t_{++}$ and $t_{--}$) did not depend on the handedness or propagation direction of incident circularly polarized waves. In particular, this shows that in our case any 3D chirality introduced by the presence of the substrate [7] is too small to lead to significant optical activity, that is, circular birefringence $\arg(t_{++}) - \arg(t_{--})$ or circular dichroism $T_{++} - T_{--}$. The presence of circular polarization conversion indicates a linearly birefringent/dichroic metamaterial response in all cases. Figures 3(a) and (b) show that, for both arrays of split rings and double rings in the absence of structural 2D chirality, the intensities of circular polarization conversion are identical and independent of the propagation direction, indicating the complete absence of asymmetric transmission. When, however, the split rings were rotated by an angle $\alpha$

\[ T_{++} = \text{co-coupling transmission intensity to a RCP wave from an incident RCP wave.} \]
Figure 3. Direct transmission $T_{++}$, $T_{--}$ and circular polarization conversion $T_{+-}$, $T_{-+}$ spectra for: (a) normal incidence onto an achiral array of asymmetrically split rings ($\alpha = 0^\circ$). (b) $30^\circ$ oblique incidence onto the double-ring array oriented in a way which does not lead to extrinsic chirality ($\phi = 0^\circ$). (c) Normal incidence onto an array of asymmetrically split rings which has intrinsic structural planar chirality ($\alpha = 22.5^\circ$). (d) $30^\circ$ oblique incidence onto the double-ring array rotated to become extrinsically structurally 2D-chiral ($\phi = 22.5^\circ$). Insets show the metamaterial patterns projected onto the plane normal to the incident beam.

Figure 4. (a) Conversion asymmetry, $T_{-+} - T_{+-}$, for normal incidence onto arrays of asymmetrically split rings as a function of the split’s orientation $\alpha$. (b) Conversion asymmetry for $30^\circ$ oblique incidence onto the double-ring metamaterial as a function of its in-plane orientation $\phi$. Insets show the metamaterial patterns as seen by an observer looking along the incident beam.

$\alpha$ to form a structurally 2D-chiral array, normal incidence transmission through the metamaterial showed a resonant region around 6 GHz where the right-to-left and left-to-right polarized conversion efficiencies were different from each other, $T_{+-} \neq T_{-+}$, as illustrated in figure 3(c) for $\alpha = 22.5^\circ$. Here, resonant excitation of the metamaterial occurs, when the effective wavelength is twice as large as the average arc length [20]. Similarly, when the double-ring array was rotated in its plane by an angle $\phi$, so that for oblique incidence its projection onto the plane normal to the wave propagation direction became 2D-chiral, a broad band of asymmetric circular polarization conversion appeared (as shown in figure 3(d) for $30^\circ$ incidence and $\phi = 22.5^\circ$). We note that the pronounced transmission resonance at 8 GHz is associated with an electric dipole excitation occurring when the length of the inner ring corresponds to the effective wavelength [21]; however, in this case the transmission asymmetry is not a resonant phenomenon. Our data indicate that in both cases the conversion efficiencies are simply interchanged for opposite directions of propagation, $\rightarrow T_{ij} = \leftarrow T_{ji}$, and thus, for example, RCP waves incident on the front and back of the metamaterials will experience different levels of circular polarization conversion, $\rightarrow T_{-+} \neq \leftarrow T_{+-}$. Given that the direct transmission terms are independent of the propagation direction, the total transmission (i.e. transmission measured with a polarization-insensitive detector) $T_+ = T_{++} + T_{+-}$ is different for the circularly polarized waves incident on the front and back of the metamaterial arrays.

Figure 4 illustrates the dependence of the asymmetric effect on the arrangement of the metamolecules in both types
of planar metamaterial array. When the split rings were rotated by a multiple of 45°, structural 2D chirality of the array was absent and asymmetric transmission could not be detected. Other orientations of the split rings used in our experiments led to a 0.2 GHz wide band of asymmetric transmission observed between 5.5 and 6.5 GHz (see figure 4(a)), whose exact spectral position and magnitude were controlled by the split’s orientation α. The largest asymmetry was observed for α = ±22.5° = ±π/8 rad, where the difference in circular polarization conversion T−→ + T−→ was about 4 dB. As should be expected, mirror forms ±α of the split-ring array show asymmetric transmission of opposite sign (see figure 4(a)). The double-ring array was intrinsically 2D-chiral at oblique incidence for in-plane orientations ϕ excluding multiples of 45° and, as figure 4(b) illustrates, exhibited relatively wide bands of asymmetric transmission with the sign of the effect being reversed for enantiomeric forms of the array’s projection.

Thus, our data confirm the existence of asymmetric transmission due to both intrinsic and extrinsic structural chirality in arrays of achiral metamolecules. While asymmetric transmission was initially only known for normal incidence onto lossy arrays of anisotropic and intrinsically 2D-chiral metamolecules [12], we are now able to identify a much larger class of structures exhibiting the effect: asymmetric transmission can occur for any lossy array of particles, when its projection onto the plane normal to the direction of incidence is 2D-chiral and anisotropic. At oblique incidence any regular array of even perfectly symmetric particles can become planar chiral and anisotropic in projection, while at normal incidence—when the structure and its projection coincide—planar chirality and anisotropy must be properties of the array itself.

However, our findings have much more far-reaching implications: the observation of a signature 2D-chiral phenomenon (asymmetric transmission) implies that other effects connected to 2D chirality should also be observable in arrays of achiral building blocks. For example, 2D-chiral patterns show polarization rotation in diffracted beams [3, 5]. Our results imply that this 2D-chiral diffraction effect may be possible at any regularly patterned interface. Furthermore, optical activity in the form of circular birefringence [7–9] and circular dichroism [10] as well as circularly polarized second harmonic generation [11] have been observed at non-diffracting planar chiral patterns on dielectric substrates, making 3D-chiral objects. Also patterns with extrinsic 2D chirality will become 3D-chiral if they are placed on a substrate or at the interface between two different media. Therefore we may expect that even a simple square array of spherical particles on a substrate could also exhibit optical activity and circularly polarized second harmonic generation at oblique incidence. Finally, as extrinsic 2D chirality can arise from interaction of any directed quantity with a regular pattern, chiral effects could even be envisaged for, for example, a beam of chiral molecules interacting with a regular achiral surface.

In summary, we have experimentally demonstrated that asymmetric transmission can occur at highly symmetric periodically structured interfaces. Our results imply that the effect may be expected for oblique incidence onto any lossy periodically structured plane. Our findings greatly expand the range of natural and artificial materials in which the phenomenon may be expected, making asymmetric transmission a mainstream electromagnetic effect rather than a curiosity of planar chiral metamaterials. Indeed, while only a few natural examples of intrinsically 2D-chiral interfaces are known, regular arrays of simple particles are much more common and much easier to manufacture. This indicates that asymmetric transmission should be observable in natural and self-assembled structures. Prime candidates for asymmetric transmission at oblique incidence are planar metamaterial structures, square arrays of plasmonic spheres or semiconductor quantum dots and lossy double-periodic gratings, which have the same symmetry, as the double-ring array studied here.

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