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Planar metamaterial with transmission and reflection that depend on the direction of incidence

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We report that normal incidence reflection and transmission of circularly polarized electromagnetic waves from and through planar split-ring microwave metamaterials with chiral symmetry breaking depends on the incidence direction and handedness of circular polarization. The effect has a resonant nature and is linked to the lack of mirror symmetry in the metamaterial pattern leading to a polarization-sensitive excitation of electric and magnetic dipolar responses in the meta-molecules. It has striking phenomenological resemblance with the reflective circular dichroism of high-temperature "anyon" superconductors. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3109780]

Directional asymmetry of transmission and reflection is normally associated with the presence of a static magnetization of the medium which breaks the reciprocity of the light-matter interaction. Here the optical Faraday effect is the most important example. However, it was recently understood that asymmetric transmission of circularly polarized electromagnetic waves is also possible in reciprocal systems if circular polarization conversion is involved.[1] This has been investigated for lossy, planar chiral metamaterial structures.[2–4] Several other ideas using chirality in asymmetric and polarization-sensitive devices have recently been suggested.[5–8] In this letter we demonstrate a type of microwave metamaterial that shows strong *resonant* asymmetric transmission at normal incidence and we report that this is accompanied by *asymmetric reflection*. Transmission and reflection of circularly polarized waves are both controlled by the chiral asymmetry of the metamaterial pattern and depend on the direction of incidence and on the handedness of the incident circular polarization state in exactly the same way. We show that such behavior is associated with the asymmetric nature of dissipation in the substrate imposed by two-dimensionally chiral (2D-chiral) patterning and we provide a detailed description of the effect's microscopic mechanism along with a complete characterization of its eigenstates.

The effect has been observed in a planar metamaterial based on asymmetrically split rings, which belongs to a recently identified class of structures supporting high-Q trapped-mode resonances of collective/coherent nature.[9,10] To see the asymmetric effects we modified a previously used design by introducing an asymmetry in both arcs and gaps so that the resulting metamaterial has no line of mirror symmetry and is thus 2D-chiral. A "twist vector" **W** governed by the corkscrew law (rotation from small gap towards large gap along the short arc) may be associated with the handedness (twist) of the pattern [see Fig. 1(b)]. In our structures the metal rings had a radius of 6 mm and a width of 0.8 mm and were split to create two arcs of 160° and 140° with gaps corresponding to 30° and 10°. They were etched from 35 μm copper cladding covering 1.6 mm thick FR4 PCB substrate ($\varepsilon \simeq 4.5$). The metamaterial was formed by a regular array of these rings with an overall size of approximately 220×220 mm^2 and a square unit cell of 15×15 mm^2 [see Fig. 1(a)].

Transmission and reflection properties of the metamaterial were studied in an anechoic chamber in the 3.0–9.0 GHz spectral range for waves normally incident on both "front" and "back" of the structure using two linearly polarized broadband horn antennas (Schwarzbeck BBHA 9120D) and a vector network analyzer (Agilent E8364B). Note that waves incident from the material's front and back propagate parallel and antiparallel to **W**, respectively. The complex circular transmission and reflection matrices, defined as $E_i = t_{ij}E_j^0$ and $E_i = r_{ij}E_j^0$, where the indices i,j denote either right-handed circularly polarized (RCP, +) or left-handed circularly polarized (LCP, −) components, were calculated directly from the measured transmission and reflection matrices for orthogonal linear polarizations. Intensities of the corresponding transmitted, reflected, and converted components for incident RCP and LCP waves were calculated as $T_{ij} = |t_{ij}|^2$ and $R_{ij} = |r_{ij}|^2$.

We found that total transmission through the metamaterial (as it would be measured with a polarization insensitive detector), defined as $T_j = T_{jj} + T_{ij}$, was different for circularly polarized waves of either opposite handedness or opposite

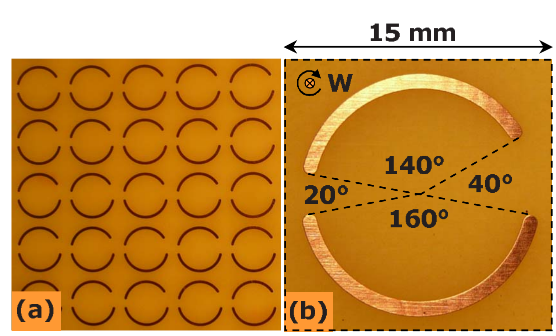

FIG. 1. (Color online) (a) Front side of a section of planar metamaterial formed by a square array of 2D-chiral asymmetrically split rings. (b) Unit cell of the metamaterial. The twist vector **W**, associated with the chirality of the unit cell, points away from the reader indicating an overall clockwise twist.

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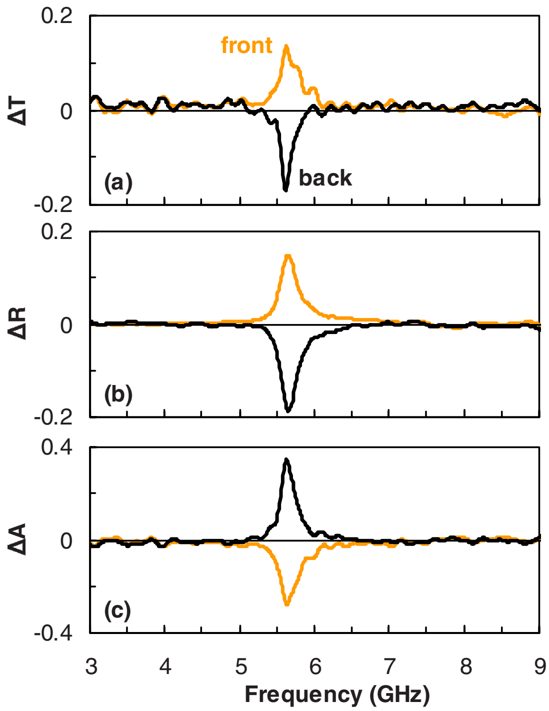

FIG. 2. (Color online) Difference in total transmission (a), reflection (b) and absorbtion (c) of RCP- and LCP-waves normally incident on the front (orange) and back (black) of the planar chiral metamaterial.

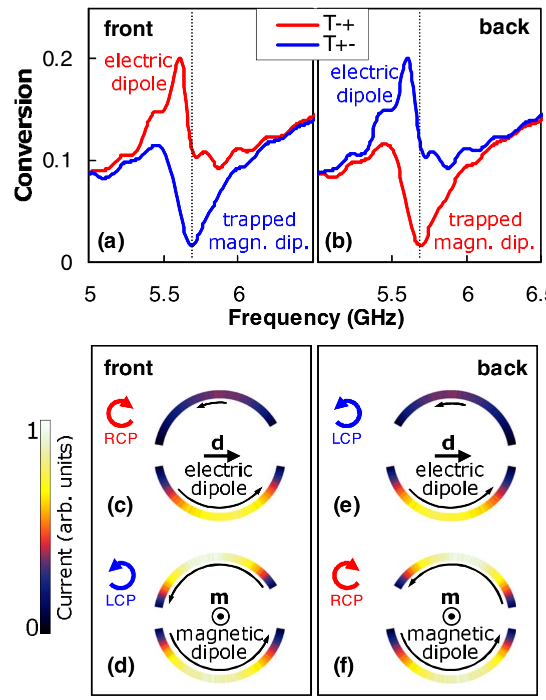

FIG. 3. (Color online) Resonant circular conversion dichroism. Panels (a) and (b) show polarization conversion spectra measured in transmission for RCP (red) and LCP (blue) microwaves normally incident on the structure's front and back. Panels (c)–(f) present the magnitude of resonant currents along the ring at about 5.7 GHz. The instantaneous direction of the currents is indicated by arrows: (c) RCP incident on the structure's front excites a strongly scattering electric dipole-like current mode (strong polarization conversion). (d) LCP excites a weakly scattering magnetic mode (conversion minimum). Panels (e) and (f) show current distributions for circularly polarized waves incident on the structure from the opposite side.

directions of incidence. Figure 2(a) presents the absolute difference in total transmission of RCP and LCP waves $\Delta T = T_+ - T_-$, plotted for different directions of incidence. The difference is resonant in a narrow range of frequencies from 5.5 to 5.9 GHz reaching a maximum of about 15% near 5.7 GHz. The plot shows that for circularly polarized waves incident on the front of the structure the total transmission for RCP is substantially higher than for LCP, while for waves incident on the back the situation is reversed and the metamaterial appears to be more transparent to LCP. A similar polarization and directional asymmetry can be seen in reflection: the total reflectivity (i.e., reflectivity that would be measured with a polarization insensitive detector) for RCP-waves incident on the metamaterial's front is larger than that for LCP-waves and the reflectivity difference changes sign upon reversal of the propagation direction [see Fig. 2(b)]. Importantly, no such directional asymmetries could be observed for linear polarization. Indeed, any linear polarization can be decomposed into right and left circular components. When the propagation direction is reversed, components of opposite handedness propagating in opposite directions behave in the same way, canceling the asymmetric effects for linearly polarized waves.

Figure 2(c) shows the asymmetric behavior of the metamaterial in terms of losses. Here we present the absolute difference in metamaterial absorption of RCP and LCP calculated as $\Delta A = A_+ - A_-$, where $A_\pm = 1 - T_\pm - R_\pm$. The structure appeared to be dichroic with respect to the incident circular polarization, but more importantly its dichroic response also depended on the direction of propagation, exhibiting asymmetry very similar to that of total transmission and reflection. Since at microwave frequencies copper is a very good conductor, while the metamaterial grating did not diffract below 20 GHz, the losses must have resulted from absorption in the dielectric substrate (Im $\varepsilon \simeq 0.2$).

Within the accuracy of our measurements, we found that the direct transmission of circular polarization was identical for opposite polarization states, i.e., $t_{++} = t_{--}$, as well as for opposite directions of propagation. The same applied to the reflected unconverted polarization components r_{-+} and r_{+-}. Thus the asymmetric response must have been completely controlled by circular polarization conversion. This is illustrated by Fig. 3(a), which shows the polarization conversion levels for LCP and RCP incident on the metamaterial's front. Within experimental accuracy the efficiencies of conversion in transmission and reflection are the same, i.e., $T_{-+} = R_{++}$ and $T_{+-} = R_{--}$. At around 5.7 GHz the polarization conversion for RCP reaches 20%, while the conversion for LCP drops below 2%, leading to a very large circular conversion dichroism within a narrow spectral range. The situation is similar for waves incident on the back of the metamaterial, however, with reversed roles of RCP and LCP.

To understand the nature of the large circular conversion dichroism we numerically calculated the distribution of currents in the split rings excited by circularly polarized waves normally incident on the metamaterial using a full three-dimensional Maxwell finite element method solver in the frequency domain [see Figs. 3(c)–3(f)]. The pattern of the metamaterial was modeled as an array of ideally conducting metal split rings of zero thickness (which is a fair approximation at microwave frequencies), while all other parameters of the structure were chosen identical to those of the real sample. Our modeling took advantage of the periodicity of the structure, which was represented by a single unit cell with periodic boundary conditions imposed on the computational domain in the lateral directions. We found that there are two distinct regimes of resonant excitation which depend on the handedness of the incident wave and the direction in which the wave enters the structure. The response to excitation with a RCP, + wave incident on the front of the structure is essentially electric dipolar in nature with the dipole oriented along the split of the ring [Fig. 3(c)]. The emission of the induced oscillating linear dipole can be presented as a sum of left and right circular polarizations where the left-handed component of scattering gives rise to strong resonant polarization conversion [red curve, Fig. 3(a)]. On the contrary, the response to excitation with a LCP, − wave is essentially magnetic dipolar. Here the induced magnetic moment is perpendicular to the metamaterial plane and is created by antisymmetric currents flowing in opposite sectors of the ring [see Fig. 3(d)]. The antisymmetric current mode is weakly coupled to free space, scattering is low[9] and polarization conversion is at its minimum [blue curve, Fig. 3(a)]. Due to weak scattering, energy coupled to the magnetic mode is trapped in the antisymmetric current oscillation and eventually dissipated in the lossy dielectric substrate, which results in large absorption losses [Fig. 2(c)]. When the propagation direction is reversed, i.e., the wave enters the structure from the opposite side, the perceived sense of planar chirality of the design reverses, and the larger split on the right now appears to be on the left of the ring. Now the roles of left and right circular polarizations are swapped around; the left circular polarization excites an electric response [Fig. 3(e)] while the right circular polarization excites a predominantly magnetic response in the metamaterial [Fig. 3(f)]. Indeed, polarization conversion is now at its maximum for left circular polarization and at a minimum for right circular polarization, as shown in Fig. 3(b).

Thus the asymmetric phenomena arise from excitation of an electric dipole-like "conversion" mode and a weakly scattering antisymmetric "absorption" mode by opposite circular polarizations. Note that this microscopic mechanism should in general apply to all planar metamaterials exhibiting asymmetric transmission/reflection.

Although the structure shows strong resonant polarization conversion for circularly polarized electromagnetic waves, certain polarization states remain unchanged on transmission. Figure 4 shows the ellipticity angle and azimuth of the metamaterial's transmission eigenstates. In non-resonant regions the eigenstates are a pair of orthogonal linear polarizations with the azimuth corresponding approximately to the directions along and perpendicular to the ring's split. At the resonance, however, the eigenstates become co-rotating orthogonal ellipses. The reflection eigenstates are the same as the transmission eigenstates, while for the eigenstates of the opposite propagation direction the handedness is reversed.

It is curious to note that the observed effect of circular differential reflection has a striking resemblance with reflective circular dichroism of anisotropic high-temperature superconductors[11,12] that was investigated in search for anyons (fractional statistic quasi-particles and agents of superconductivity that simultaneously violate time reversal and

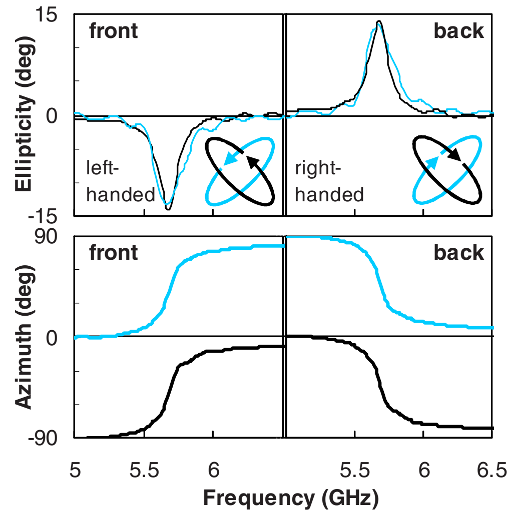

FIG. 4. (Color online) Dispersions of ellipticity angle and azimuth of both of the structure's transmission eigenstates represented by blue and black lines correspondingly.

parity symmetry) and still remains a topic of intensive research.[13]

In conclusion, we have demonstrated strong resonant directional and polarization asymmetry of normal incidence reflection and transmission of circularly polarized light from and through a planar chiral metamaterial. Nanoscaled versions of the metamaterial structure will depend on the resonant plasmonic response at optical frequencies. They are naturally suited for the existing planar fabrication technologies and may have wide potential applications in photonic devices that exploit direction/polarization-dependent operation, such as asymmetric wave splitters and circulators.

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