Terahertz metamaterial with asymmetric transmission

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We show that a planar metamaterial, an array of coupled metal split-ring resonators with a unit cell lacking mirror symmetry, exhibits asymmetric transmission of terahertz radiation (0.25–2.5 THz) propagating through it in opposite directions. This intriguing effect, that is compatible with Lorentz reciprocity and time reversal, depends on a directional difference in conversion efficiency of the incident circularly polarized wave into one of opposite handedness, that is only possible in lossy low-symmetry planar chiral metamaterials. We show that asymmetric transmission is linked to excitation of enantiomerically sensitive plasmons, these are induced charge-field excitations that depend on the mutual handedness of incident wave and metamaterial pattern. Various bands of positive, negative and zero phase and group velocities have been identified indicating the opportunity to develop polarization sensitive negative index and slow light media based on such metamaterials.

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In contrast to three-dimensionally chiral structures (e.g., helices), planar chiral patterns (e.g., flat spirals) have the intriguing property that their sense of twist is reversed for observation from opposite sides. Not only human observers, but also circularly polarized waves incident on opposite sides of a planar chiral structure, see materials of opposite handedness. It has recently been discovered that planar chiral metamaterial patterns can show different levels of total transmission for circularly polarized waves of the same handedness propagating in opposite directions. The effect, which has been detected in microwave[1–4] and photonic[5,6] metamaterials and plasmonic nanostructures,[7] is known as *asymmetric transmission*. Such asymmetric transmission phenomenon has not yet been observed for terahertz radiation. The terahertz spectral region has tremendous technological importance since many biological materials and substances have molecular vibration frequencies in this regime, making it highly attractive for sensing, material characterization, spectroscopy and biomedical imaging.[8] In spite of intense research activity in this domain over the past decade terahertz radiation has proved to be extremely challenging to detect, measure, propagate and manipulate since electronic and magnetic responses of natural materials die out at these frequencies, thus earning the name of the so-called "terahertz gap." Recently, terahertz metamaterials[9–18] have shown potential for use in the terahertz gap with their fascinating novel properties but the region still suffers from a severe shortage of devices needed for fully exploiting the attractive potential applications of terahertz radiation.

In this Brief Report we describe the experimental observation of asymmetric transmission in the terahertz domain. We demonstrate a polarization sensitive terahertz metamaterial device showing directionally asymmetric transmission of circularly polarized waves between 0.25 and 2.5 THz. The phenomenon resembles the nonreciprocal Faraday effect in magnetized media, but takes place in absence of any magnetic field. Experimentally and numerically we show that the total transmission level of circularly polarized waves through a planar chiral metamaterial pattern depends on both the wave's handedness and propagation direction. Unlike the Faraday effect in which the asymmetry applies to the transmission and retardation of the incident circularly polarized wave itself, asymmetric transmission is a completely reciprocal phenomenon arising from partial conversion of the incident circularly polarized wave into one of the opposite handedness. As illustrated by Fig. 1, it is the efficiency of circular polarization conversion that depends on the incident wave's handedness and propagation direction, and which gives rise to the asymmetry in total transmission.

The metamaterial structure, which is shown in Fig. 2(a), is based on pairs of split rings of orthogonal orientation that are joined together[19,20] forming a two-dimensionally chiral (2D-chiral) pattern. The planar twist of the structure can be defined as from "gap on long side" to "gap on short side," making the structure right-handed when observed from the structured front and left-handed when observed from the back, see insets of Fig. 1. The planar chiral metamaterial sample was fabricated by conventional photolithography from a 200 nm thick aluminum layer deposited on a 640 μm thick silicon substrate with n-type resistivity 12 Ω cm and an absorption constant of 5/cm.[20] Figure 2(b) shows detailed dimensions of the metamaterial's rectangular unit cell which is 100×50 μm^2 in size rendering the structure nondiffracting at normal incidence for frequencies up to 3 THz. We studied the structure using terahertz time-domain spectroscopy (THz-TDS).[21,22] The terahertz beam incident on the sample had a frequency independent diameter of 3.5 mm and thus illuminated about 2000 unit cells at the center of the 10×10 mm^2 metamaterial array. Using parallel or crossed linear polarizers placed before and after the sample, we measured all components of the metamaterial's transmission matrix $E_i^{\mathrm{trans}}=\tau_{ij}E_j^{\mathrm{inc}}$, which relates the incident and transmitted electric fields in terms of linearly polarized components.[15] Amplitude $|\tau_{ij}(\omega)|=|E_{ij}^{\mathrm{sample}}(\omega)|/|E^{\mathrm{ref}}(\omega)|$ and phase $\arg(\tau_{ij}(\omega))=\angle[E_{ij}^{\mathrm{sample}}(\omega)/E^{\mathrm{ref}}(\omega)]$ of the transmission matrix elements were calculated from transmission measurements taken on the metamaterial $E_{ij}^{\mathrm{sample}}(\omega)$ with a blank sili-

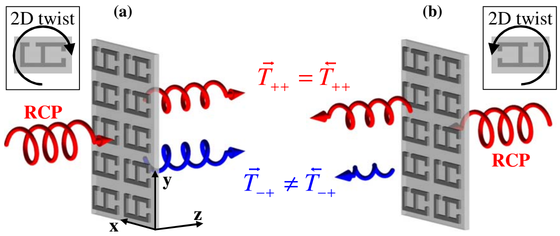

FIG. 1. (Color online) Asymmetric total transmission of a circularly polarized wave incident on (a) front and (b) back side of a planar chiral metamaterial. The incident right-handed circularly polarized wave (red spiral) is partially converted to the left-handed (blue spiral) polarization when propagating through the metamaterial. The conversion efficiency differs for opposite directions of wave propagation resulting in different levels of total transmission. Insets show the 2D-chiral twist of the unit cell, as perceived by the incident wave.

con substrate $E^{\text{ref}}(\omega)$ used as a reference. In order to study the effect of asymmetric transmission, which occurs for circularly polarized waves, we transformed the transmission matrix τ_{ij} from the linear polarization basis to the circular polarization basis

$$t = \begin{pmatrix} t_{++} & t_{+-} \\ t_{-+} & t_{--} \end{pmatrix} = \frac{1}{2}\begin{pmatrix} \tau_{xx}+\tau_{yy}+i(\tau_{xy}-\tau_{yx}) & \tau_{xx}-\tau_{yy}-i(\tau_{xy}+\tau_{yx}) \\ \tau_{xx}-\tau_{yy}+i(\tau_{xy}+\tau_{yx}) & \tau_{xx}+\tau_{yy}-i(\tau_{xy}-\tau_{yx}) \end{pmatrix}.$$

Transformed in this way the transmission matrix $E_i^{\text{trans}} = t_{ij}E_j^{\text{inc}}$ directly relates the incident and transmitted electric fields in terms of right-handed (RCP, +) and left-handed (LCP, −) circularly polarized components, while the squares of its elements $T_{ij}=|t_{ij}|^2$ correspond to transmission and circular polarization conversion in terms of power. The metamaterial's transmission characteristics, as well as the current configurations excited in the metamaterial unit cell, were also simulated using the Fourier modal method.[23]

As illustrated by Fig. 3, our numerical and experimental results show that the metamaterial's direct transmission for circular polarization is reciprocal as coefficients $t_{++}=t_{--}$ are both identical and independent of the direction of propagation. Thus optical activity $\arg(t_{++})-\arg(t_{--})$ and circular dichroism $T_{++}-T_{--}$, which are associated with three-dimensional chirality, are negligible indicating that the metamaterial—which is formally three-dimensionally chiral

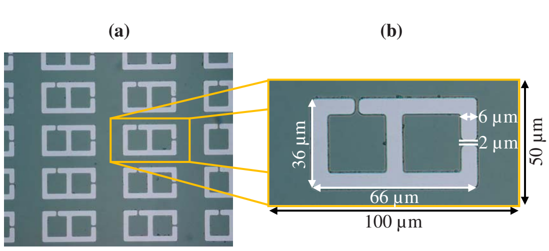

FIG. 2. (Color online) (a) Front side of the planar chiral terahertz metamaterial consisting of 200 nm thick aluminum wires on an n-type silicon substrate. (b) Metamaterial unit cell.

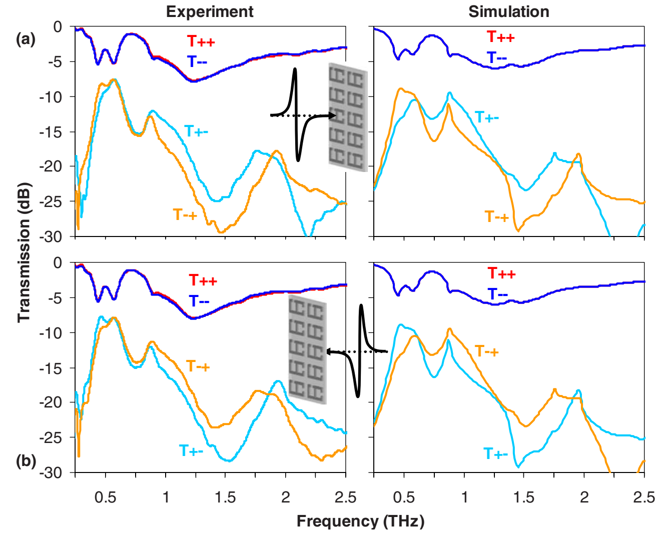

FIG. 3. (Color online) Transmission spectra for circularly polarized terahertz waves incident on (a) front and (b) back of the metamaterial array. It can be clearly seen that the circular polarization conversion efficiencies T_{-+} and T_{+-} are reversed for opposite directions of propagation.

due to the substrate on only one side of the metal pattern[24]—behaves like a truly planar structure. Furthermore the fact that t_{++} and t_{--} do not depend on the direction of propagation demonstrates complete absence of the Faraday effect.

In contrast to direct transmission, the right-to-left T_{-+} and left-to-right T_{+-} circular polarization conversion levels depend on both the direction of wave propagation and the handedness of the incident wave, indicating the presence of the asymmetric transmission effect. Importantly counter-

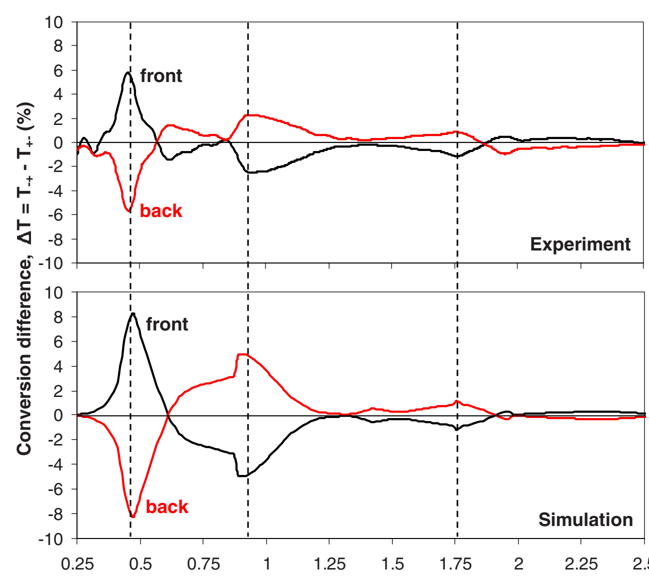

FIG. 4. (Color online) Transmission difference $\Delta T=T_+-T_-=T_{-+}-T_{+-}$ for right-handed and left-handed circularly polarized waves incident on either front (black curves) or back (red curves) of the metamaterial sample.

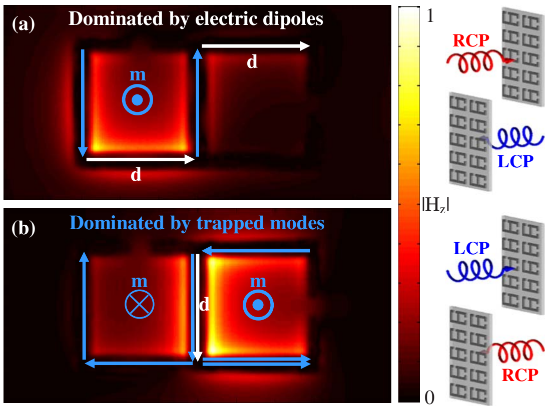

FIG. 5. (Color online) Enantiomerically sensitive plasmons linked to the resonant transmission asymmetry at 0.47 THz. The current oscillations in the wires of the structure are represented by arrows, while the color-scale indicates the magnitude of the magnetic field the currents induce normal to the metamaterial's plane. Note the radical difference in the excitation patterns caused by circular polarizations of either opposite handedness or opposite propagation direction.

propagating circularly polarized waves of the same handedness experience different levels of circular polarization conversion, while their direct transmission levels are identical, for example $\vec{T}_{-+} \neq \overleftarrow{T}_{-+}$ and $\vec{T}_{++} = \overleftarrow{T}_{++}$ in case of RCP. It follows that the metamaterial's total transmission for RCP, defined as $T_{+} = T_{++} + T_{-+}$, is asymmetric with respect to opposite directions of wave propagation. Furthermore it must be noted that the conversion efficiencies for RCP and LCP are simply interchanged for opposite directions of wave propagation, i.e., $\vec{T}_{+-} = \overleftarrow{T}_{-+}$. This has two significant consequences: first, the directional transmission asymmetry $\vec{T}_{+} - \overleftarrow{T}_{+} = \vec{T}_{-+} - \overleftarrow{T}_{-+}$ is identical to the total transmission difference for opposite circular polarizations propagating in the same direction, $\vec{T}_{+} - \vec{T}_{-} = \vec{T}_{-+} - \vec{T}_{+-}$. Second, the metamaterial has the same transmission properties for circularly polarized waves of opposite handedness propagating in opposite directions, i.e., $\vec{T}_{+} = \overleftarrow{T}_{-}$ and $\vec{T}_{-} = \overleftarrow{T}_{+}$.

Figure 4 shows the total transmission asymmetry for circularly polarized terahertz waves incident on the structure's front and back directly. Experimental and numerical results are generally in good agreement and show that asymmetric transmission takes place over the entire studied spectral range from 0.25 to 2.5 THz. The largest asymmetry of total transmission occurs around 0.47 THz, where the structure is measured to be 6% (simulation: 8%) more transparent for RCP than LCP terahertz waves incident on its front. For waves incident on the metamaterial's back the situation is reversed with larger total transmission for LCP than RCP by the same amount.

The resonant character of asymmetric transmission at 0.47 THz is linked to the excitation of enantiomerically sensitive plasmons, these are induced charge-field excitations that depend on the mutual handedness of the wave and the metamaterial pattern.[2,5] Indeed, numerical simulations show radically different patterns of currents when the metamaterial structure is excited by left or right circularly polarized

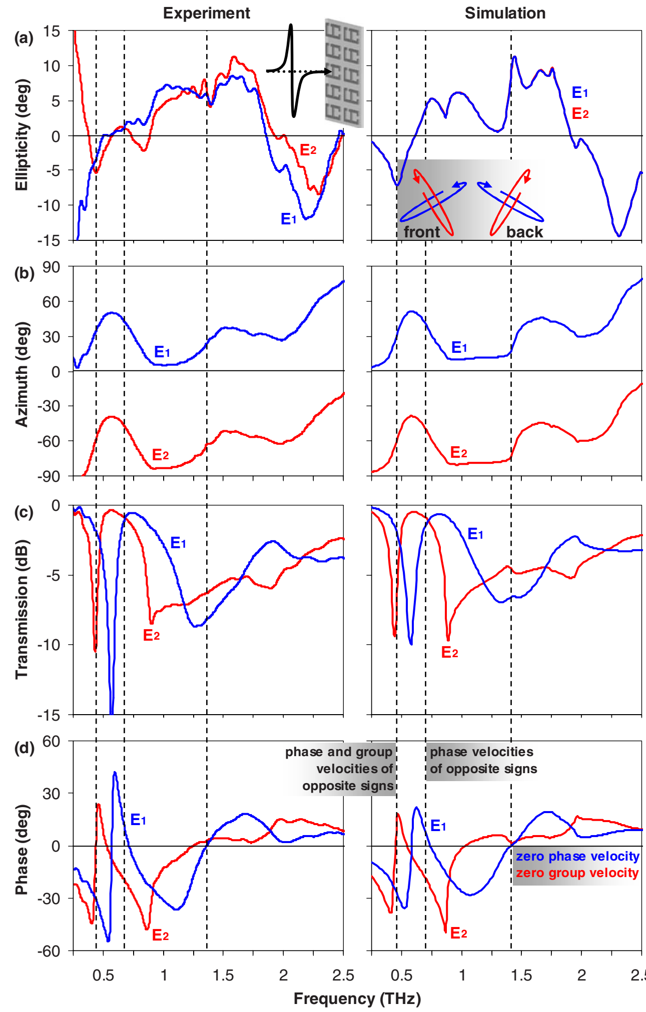

FIG. 6. (Color online) Transmission eigenstates E_1 and E_2 for forward propagation in terms of (a) ellipticity angle and (b) azimuth. (c) Transmission level and (d) phase delay for these eigenpolarizations.

waves: a RCP wave entering the metamaterial from the front side induces a strongly anisotropic electric dipole current oscillation d along the long side of the unit cell that is responsible for the efficient circular polarization conversion, see Fig. 5(a). On the contrary, the current mode excited by a LCP wave propagating in the same direction is dominated by high Q-factor antisymmetric current oscillations, which correspond to magnetic moments m oscillating normal to the metamaterial plane, see Fig. 5(b). As the magnetic components cannot interact with the incident and scattered fields (which propagate parallel to m), this current configuration is weakly coupled to free space. These high Q-factor currents, known as trapped or closed modes[2,25] are responsible for the smaller level of circular polarization conversion resulting in lower resonant total transmission.

Although the metamaterial shows strong circular polarization conversion, certain polarization states remain unchanged on transmission. Ellipticity and azimuth of the transmission eigenstates for waves incident on the structure's front are shown in Figs. 6(a) and 6(b), respectively. In contrast to optical activity, or the Faraday effect, asymmetric transmission is associated with corotating elliptical eigenstates. The eigenpolarizations have orthogonal orientations and their handedness is reversed for the opposite propagation direction, see inset to Fig. 6(a). Figures 6(c) and 6(d) illustrate the metamaterial's transmission properties for its eigenpolarizations in terms of transmission levels and phase delay. Intriguingly, the metamaterial pattern can introduce positive as well as negative phase delays, indicating that positive and negative phase velocities should be expected in a bulk material based on the structure. The group velocity, which is proportional to the slope of the phase dispersion, can only be discussed for stable eigenstates. However, eigenstate stability in a finite medium may be achieved for any frequency by limiting the pulse spectrum. Therefore, in principle, also the group velocity may be defined even if the eigenstates depend on frequency. Various bands of positive and negative phase dispersion indicate that in 2D-chiral bulk metamaterials group velocities of either sign may be possible. For example at 0.45 THz the eigenstates appear to have both opposite phase velocities and opposite group velocities, while at 0.95 THz their group velocities are almost identical, but their phase velocities have opposite signs. Finally at 1.41 THz the phase velocity of eigenstate E_1 and the group velocity of E_2 are zero. As group and phase velocities of opposite sign are a signature of negative refraction,[26] these results indicate an opportunity to develop both polarization sensitive negative index and slow light media for elliptically polarized waves on the basis of bulk 2D-chiral anisotropic metamaterials.

In conclusion, we present experimental and numerical evidence of asymmetric transmission of circularly polarized terahertz waves through a planar chiral metamaterial. The observed effect is due to different levels of circular polarization conversion for waves incident on the planar structure's front and back and may lead to a novel class of polarization sensitive terahertz devices such as polarization and direction sensitive beam splitters, circulators and sensor components.

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