array of asymmetrically split wire rings from $\alpha = +45°$ to $-45°$. Similarly, using the metamaterial array of asymmetrically split ring apertures, polarization rotation can be tuned continuously from $\Delta\Phi^t = -28°$ to $+28°$. In case of the asymmetric aperture array, it is particularly useful, that the maximum of circular birefringence coincides with absence of circular dichroism and negligible linear dichroism/birefringence [T_{-+}, T_{+-}, see Fig. 3(d)]. Thus, at the maximum of polarization rotation, the metamaterial exhibits pure circular birefringence and behaves like an ideal tunable polarization rotator. This behavior is opposite to the effect seen in most optically active molecular systems, where characteristically strong resonant polarization rotation of initially linearly polarized radiation is accompanied by substantial circular dichroism resulting in an elliptical polarization state.

Comparing the optical activity for both asymmetric split ring metamaterials, we find that the aperture array shows about 3.5 times larger polarization rotation, see Fig. 4(b). On the other hand, circular dichroism is about 3.5 times larger for the wire structure, see Fig. 4(a). Overall, the spectral and angular dependence of polarization rotation and circular dichroism, each, is similar, but of reversed sign, for the positive and negative metamaterial structures.

Neglecting the presence of the substrate, the positive and negative metamaterials are complementary structures in the sense of Babinet's principle [33–35]. Babinet complementary planar metamaterials exhibit interchanged optical activity in transmission and reflection [36]. Thus it may be expected that both arrays of asymmetrically split rings exhibit substantial polarization rotation and circular dichroism also for reflected waves.

Similarly to optical activity in conventional 3D-chiral molecules, optical activity due to extrinsic 3D chirality has been linked to electric and magnetic responses of the meta-molecules [6]. In a wire split ring, which essentially consists of a pair of electric dipole antennas, in-phase current oscillations correspond to an electric dipole oscillating in the metamaterial plane. On the other hand, the asymmetric splitting also allows the currents in both wires to oscillate in anti-phase, giving rise to a magnetic dipole oscillating perpendicular to the metamaterial plane. Only the magnetic dipole component perpendicular to the propagation direction can contribute to the scattered field and this radiating magnetic component is zero at normal incidence and has opposite signs for opposite angles of incidence. Therefore optical activity can only be observed at oblique incidence onto the asymmetrically split ring arrays and reverses sign for opposite angles of incidence.

In summary, we demonstrate strong and tunable resonant polarization rotation and circular dichroism in achiral planar terahertz metamaterials. The effects are due to extrinsic 3D chirality arising from the mutual orientation of a metamaterial lacking twofold rotational symmetry and the incident terahertz beam. Due to (i) the large magnitude of the observed optical activity, (ii) the huge tunable range of the effect and (iii) the simplicity of suitable planar metamaterials, such structures are ideal functional elements for novel, highly efficient terahertz polarization rotators, circular polarizers, modulators and vibration sensors.

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