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# Chiral phenomena in toroidal metamaterials

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***Abstract* – We present the first observation of circular dichroism due to a combination of resonant toroidal dipole and electric quadrupole excitations in a toroidal metamaterial.**

## I. INTRODUCTION

Optical activity (OA) is a well-established manifestation of chirality i.e. the property by which a pattern or structure cannot be mapped onto its mirror image, resulting in two distinct enantiomers. Such enantiomeric forms are ubiquitous across both natural and artificial structures. The interaction of enantiomeric media with light results in observable effects: rotation of linearly polarised light (circular birefringence) and differential absorption of circular polarisations (circular dichroism). Microscopically, these phenomena are typically described within the dipole approximation of the electromagnetic multipole expansion, with electric and magnetic dipoles induced in the media being the primary contributors to OA [1]. Interactions with higher-order multipoles are generally considered negligible, particularly in isotropic media. However, metamaterial engineering allows for designs where more exotic excitations dominate the OA response, including the toroidal dipole.

First identified by Zel'dovich in 1958 [2], the toroidal dipole is an elusive part of the dynamic multipole response that has recently been identified as an essential contributor to the microscopic response of certain metamaterials [3]. It has been suggested that, owing to its parity and angular momentum properties [4], the toroidal dipole could result in optical activity in the absence of an electric dipole response [5]. With the ubiquity of toroidal geometry across nature [5], it is anticipated that a wide range of optically active structures could be understood in terms of this microscopic response.

Here, we observe experimentally and confirm numerically the dominant contribution of the toroidal dipole to the OA of a metamaterial structure (toroidal optical activity).

## II. EXPERIMENT & SIMULATIONS

To demonstrate toroidal optical activity, we design and fabricate a metamaterial unit cell consisting of four split ring resonators embedded in a low loss dielectric slab [Fig. 1 (a-c)]. The arrangement of the unit cells gives rise to structural chirality in the resultant metamaterial array. Experiments in the microwave regime reveal two bands of resonant circular dichroism in the metamaterial's transmission spectrum at $\nu_1$ and $\nu_2$ [Fig. 1(d)]. This is found to be in good agreement with simulation results from a commercial 3D Maxwell's equations solver (COMSOL 3.5a).

In order to determine the microscopic origin of OA at these resonant bands, the charge current multipoles excited within the structure are extracted from the simulations, following the methodology from [3,6]. From this, we identify that the optical activity exhibited at $\nu_1$ can be understood in terms of the excitation of collinear electric and magnetic dipoles, corresponding to textbook optical activity. However, at $\nu_2$ the electric and magnetic dipole contributions to the optical activity become secondary, with the circular dichroism being underpinned by the previously unexplored and intriguing combination of an electric quadrupole and a non-negligible toroidal dipole. This is illustrated by the simulated electric and magnetic field distributions within the metamolecule, which reveal typical electric quadrupole and toroidal dipole field patterns [Fig. 2 (a-b)].

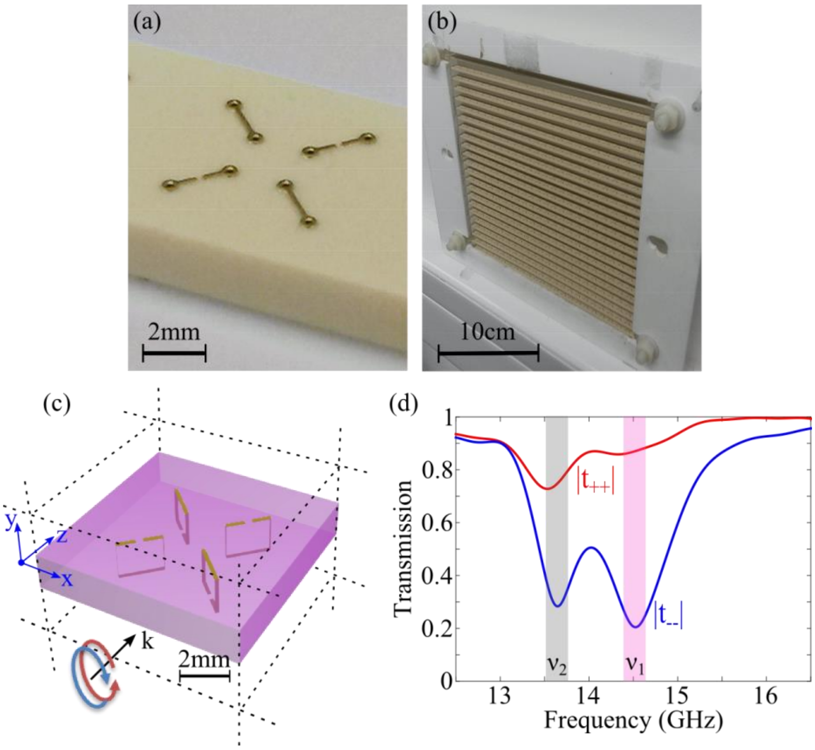


Fig. 1. Panel (a) shows a close-up photograph of a fabricated unit cell. The full metamaterial array after assembly is shown in (b). Panel (c) shows a schematic of the metamaterial unit cell with right (red) and left (blue) handed circularly polarised light incident along the *z*-axis. The unit cell is translated and repeated along the *x* and *y* axes to form the full metamaterial array. Panel (d) gives the experimentally-obtained metamaterial transmission spectrum for RCP(+) and LCP(-). The location of the two bands of resonant circular dichroism is indicated by $\nu_1$ and $\nu_2$ .

We reinforce this conclusion through an examination of the polarisation eigenstates of the metamaterial structure, and by explicitly demonstrating the roles of the aforementioned multipole pairs in shaping these eigenstates. It is shown that upon removal of the corresponding multipole pairs from the metamaterial response at $\nu_1$ and $\nu_2$, the polarisation eigenstates change from elliptically polarized to almost linear states, corresponding to an optically inactive, anisotropic material [Fig. 2(c)]. This confirms the dominant role of the electric quadrupole and toroidal dipole excitations in the observed optical activity.

## III. CONCLUSION

We have introduced a toroidal metamaterial system in which the observed OA cannot be described within the dipole approximation. Analysis of the structure's response reveals the necessity of higher order multipoles in the microscopic description, including the toroidal dipole excitation, in order to explain the resonant circular dichroism. This indicates that OA can occur even in the absence of an electric dipole, with the toroidal dipole taking its place in the microscopic mechanism. Such an exotic multipole combination is expected to be present across the fields of biology and chemistry, where toroidal topology is a common feature.

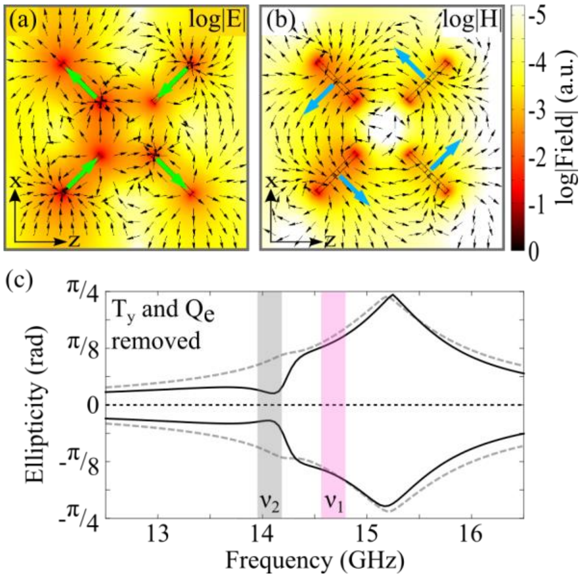


Fig. 2. Panels (a) and (b) show the normalised absolute value (log scale) of the electric and magnetic fields respectively and the associated vector arrows around a simulated unit cell under excitation from LCP at ν2. The electric field shows an electric quadrupole distribution, whilst the magnetic field shows a toroidal dipole distribution, as indicated by the electric dipole (green arrows) and magnetic dipole (blue arrows) orientations. Panel (c) shows the ellipticity of the two polarisation eigenstates of the metamaterial structure in two cases – when the full multipole response of the system is evaluated (dashed lines), and when the electric quadrupole and toroidal dipole excitations are removed (full black lines). It is clear that the ellipticity tends to linear polarisation when the electric quadrupole and toroidal dipole are removed.

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