Metamaterials: Demonstrating Toroidal Moment in the Frame of Classical Electrodynamics

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Abstract: We present electromagnetic metamaterials the resonant response of which cannot be attributed to the excitation of conventional magnetic or charge multipoles and can only be explained by the existence of the induced toroidal dipole.

Toroidal moments are fundamental electromagnetic excitations that cannot be represented in terms of the standard multipole expansion [1]. They were first considered by Zel'dovich back in 1957 [2], but only recently have become the subject of growing interest owing to their peculiar electromagnetic properties. Electromagnetic interactions with toroidal currents were predicted to disobey such widely accepted principle as the action-reaction equality. Toroidal currents can also form charge-current configurations generating vector potential fields in the absence of radiated electromagnetic waves. Although toroidal moments are held responsible for parity violation in nuclear and particle physics, no direct evidence of their importance for classical electrodynamics has been reported so far. This is because effects associated with toroidal moments in naturally available materials are extremely weak and usually masked by much stronger effects due to conventional electric and magnetic dipole and quadrupole moments.

Here we demonstrate for the first time a classical system the electromagnetic response of which is directly related to the resonant excitation of the toroidal dipole moment. The resonant toroidal response has been observed in a 'metamaterial slab', a two-dimensional array of artificially engineered electromagnetic scatterers (metamolecules) of toroidal symmetry. To emphasize the toroidal response we came up with a design of a metamolecule where both electric and magnetic dipole moments induced by an incident electromagnetic wave (as well as higher multipoles) are substantially suppressed, while the toroidal response is spectrally isolated and resonantly enhanced to a detectable level.

Since toroidal excitation is routinely neglected in the constitutive relations, boundary conditions, electromagnetic forces and in the calculation of momentum loss and radiation intensity of charge-current configurations, we believe that our results indicate a need for the revision of some aspects of electrodynamics involving structures of toroidal symmetry. Furthermore, given that many biologically important molecules have elements of toroidal symmetry and may support toroidal moments such a revision could unveil new mechanism of intra-molecular interactions and genetic information transfer.

[1] V. M. Dubovik, V. V. Tugushev "Toroid moments in electrodynamics and solid-state physics", Phys. Rep. **187**, 145-202 (1990).
[2] Ia .B. Zel'dovich "Electromagnetic interaction with parity violation", Sov. Phys. JETP **6**, 1184-1186 (1958).