Optical Magnetism without Metamaterials

Jinxiang Li[1], Nikitas Papasimakis[1], Kevin F. MacDonald[1], and Nikolay I. Zheludev[1, 3]

1. Optoelectronics Research Centre and Centre for Photonic Metamaterials, University of Southampton, Southampton, SO17 1BJ, UK

2. Centre for Disruptive Photonic Technologies, TPI, SPMS, Nanyang Technological University, Singapore 637371

We show that metamaterial structuring is not necessary for the manifestation of optical magnetism: a strong optical magnetic response is an essential characteristic feature of a thin layer of homogeneous dielectrics.

The development of structured matter exhibiting optical magnetism has been one of the main achievements of metamaterials research. Here we show that a much more common material structure - a thin homogeneous layer of dielectric - can exhibit a strong magnetic response at optical frequencies. Indeed, we show that the characteristic properties of thin films, such as Fabry–Pérot interference resonances, cannot be explained without optical magnetism. Strong magnetic and multipolar responses are a more common feature of the optical properties of matter than is generally appreciated, The complex structure of multipolar fields in a thin layer of dielectric may be exploited for the excitation of high-order multipole atomic transitions in the constituent atoms and therefore employed in spectroscopy, active laser media and quantum qubit applications.

The rapid rise of the electromagnetic metamaterials research field has historically been driven by the opportunity to develop materials with optical magnetism, which is absent in naturally occurring media: Optical magnetism is essential for negative refraction, and negative refraction is required for superlenses and some forms of “cloaking”. In metamaterials, this magnetic optical response is associated with light-induced oscillating displacement current loops in the constituent metallic or dielectric metamolecules. We show here that an optical magnetic response is a characteristic feature of a homogenous dielectric layer of sub-wavelength thickness $d < \lambda$ *without* any structuring of the layer.

For example, the vanishing reflectivity at the fundamental Fabry–Pérot resonance wavelength is a consequence of destructive interference among the electric dipole, magnetic dipole and electric quadrupole of the layer: The electric dipole induced by incident light arises from strong in-phase displacement fields throughout the volume of the dielectric film (black arrows in Fig. 1a), while the induced magnetic dipole emerges from ring-like displacement currents (white arrows in Fig. 1b). The radiated fields are in anti-phase and interfere destructively to negate reflection (Fig. 1c). The second order FP interference resonance is associated with higher order multipoles: The electric octupole, magnetic quadrupole and toroidal dipole contribute at this wavelength, while the electric dipole response is entirely absent.

These regimes of suppressed reflectivity may be compared with that of the optical anapole, in which destructive interference between electric and toroidal dipoles can suppress metamaterial reflectivity, and with Huygens metamaterial surfaces engineered to cancel reflection and enhance transmission through interference of electric and magnetic responses of the metamolecules. In the case of thin unstructured dielectric layers, reflectivity suppression is achieved without lateral structuring of the layer but is nonetheless related to interference among different multipoles.

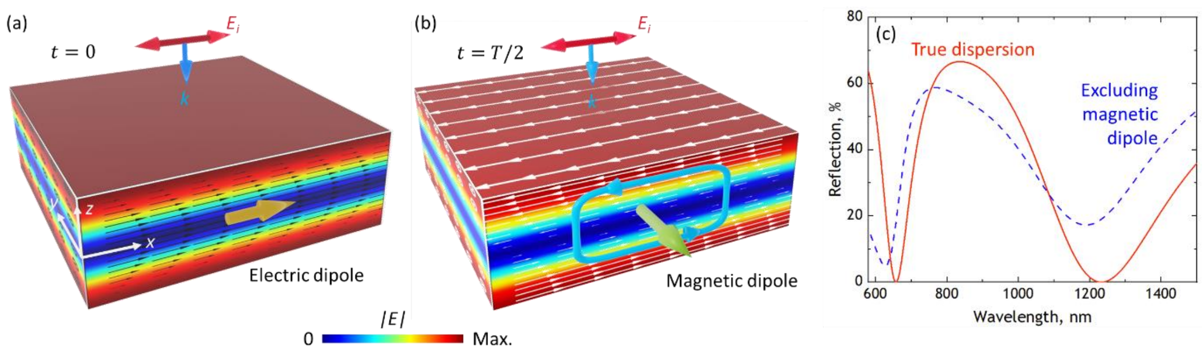

Fig 1 (a, b) Electromagnetic multipoles induced in a thin dielectric layer (200 nm of gallium phosphide) by a normally incident light wave at the fundamental Fabry Pérot resonance wavelength (1232 nm) at two moments of time separated by half of the period *T*. Black vector arrows in (a) relate to electric displacement field amplitude and direction; white arrows in (b) depict displacement current. Overlaid 3D block arrows illustrate the significant multipoles in each case: (a) the electric dipole and (b) the magnetic dipole [arising from the current loops annotated in blue]. (c) Spectral dispersion of the GaP film’s reflectivity. Solid lines are obtained by numerically solving Maxwell’s equations. The dashed line is derived from multipole scattering reconstructions *excluding* the magnetic dipole contribution, i.e. illustrating its importance by the magnitude of deviation from the correct [numerical] result that arises from its omission.