Extraordinary transparent metasurfaces composed of transverse scatterers

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Abstract – **We present a novel optical effect where the scattered light on dielectric particles is suppressed simultaneously in the forward and backward directions. In contrary to the quadrupolar generalized Kerker conditions, this effect requires the coherent dipoles to be with** pi **phase with their quadruple counterparts. Electric dipole Fano profile and quadruples long-wavelength characteristics together set the physical environment to satisfy these conditions at a certain spectral position. The metasurface constructed from transverse scatterers is extraordinary transparent for the incident light where neither the phase nor the amplitude is perturbed.**

I. Introduction

Optical properties of high-refractive-index dielectric nanoparticles are attracting a great scientific interest nowadays [1]-[3]. These subwavelength scatterers can support the excitation of electric and magnetic multipolar resonances which allow the control over the electric and magnetic components of a light by changing the nanoparticles size, geometry, and material [4]-[6]. Desirable overlapping of certain multipole resonances of dielectric nanoparticles can be employed for the configuration of the scattered radiation. This, in its turn, could be useful for different applications, including nanoantennas [1], metadevices [7], multifunctional metasurfaces [8]-[13] etc. For example, directional light scattering due to the resonant Kerker effect in dielectric nanodiscs is used for the realization of Huygens nanoantennae and fully transparent metasurfaces [8].

In contrast to the previous works, where the directional backward or forward scattering is considered, here we pay attention to the transverse scattering pattern configuration and the corresponding requirements for multipole contributions of an individual scatter. We study the collective reflection from an infinite array of such scatters. The calculated numerical simulation is based on the finite element method implemented in COMSOL Multiphysics, and on the semianalytical multipole decomposition method [1].

II. Transparent metasurfaces

The total field radiated by an infinitely large lattice of identical multipole scatterers can be calculated by summing the contributions of all multipoles at any point in the space. If the lattice spacing of subwavelength size and the observation point in space is set to be sufficiently far away from the lattice plane, then each individual scatterer contribute to one point in the far field wavefront [14]. This approximation allowed us to conclude that the conditions that govern the directive scattering of a standalone scatterer are related to the reflection and transmission fields of a periodic lattice consisted of such scatterers. We find in terms of Cartesian multipoles the conditions at which the lattice is fully transparent; or the forward and backward scattering of a standalone scatterer are nearly-suppressed simultaneously if shined with x-polarized light [15, 16]

$$p_x = \frac{m_y}{c};\ \frac{Q_{xz}}{3} = \frac{M_{yz}}{c};\ p_x = -\frac{kM_{yz}}{2ic}. \tag{1}$$

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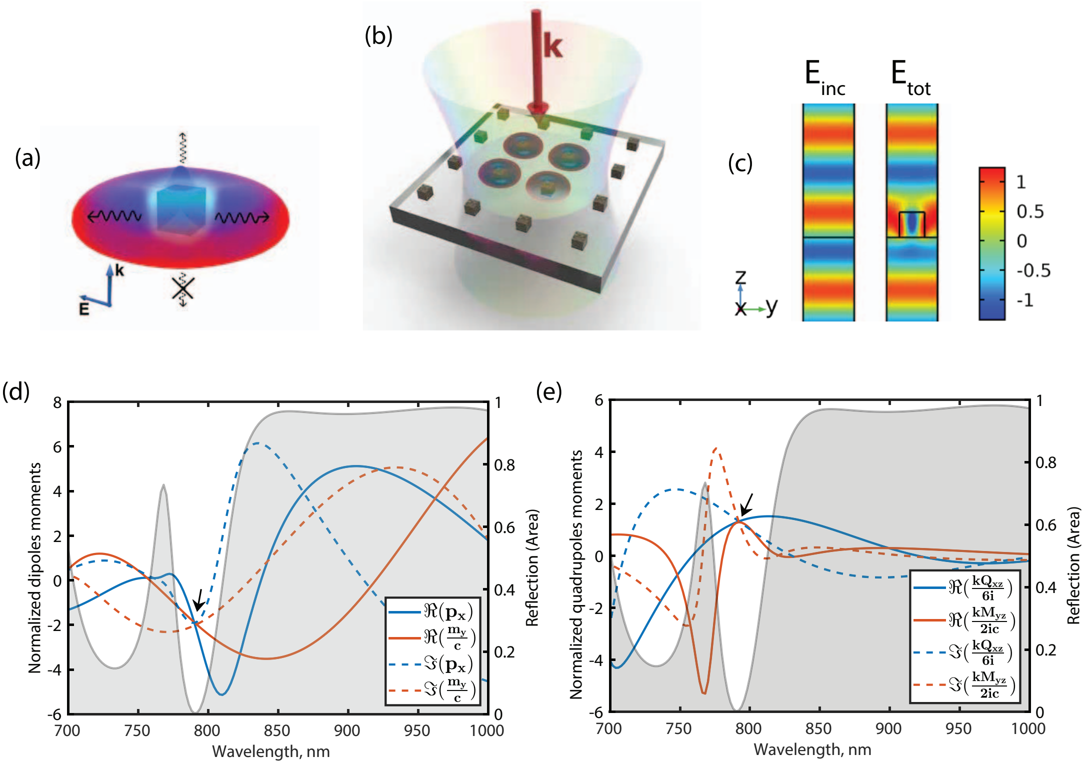

Fig. 1: (a) Transverse scattering pattern for a cubic nanoparticle with side 250 nm at wavelength λ=788 nm. (b) Artistic assembling of the cubic transverse scatterers into a square periodic lattice. (c) Fragment of the incident electric field (E_{inc}) and its total distribution (E_{tot}) with lattice present at the transverse scattering wavelength. Normalized real and imaginary parts of the dipoles (d) and the quadrupoles (e) contributions to the reflected field (Eq.1) of the lattice with spacing equal to 500 nm. The background gray area refers to the lattice reflection, and the arrows mark the wavelength corresponding to the transverse scattering wavelength and the near-zero reflection.

where k is the wavenumber of the incident light and c is the speed of light in vacuum. p_x, m_y, Q_{xz}, and M_{yz} are the non-zero complex components of the electric dipole, magnetic dipole, electric quadrupole, and the magnetic quadrupole, respectively. We assume the scattering is fully characterized by multipole contributions up to the magnetic quadruples , however conditions of Eq.1 can be developed to include higher order multipoles. The first term of Eq.1 is the well-known Kerker condition for dipoles and the second term is Kerker-like condition for quadrupoles. The last term is interesting, since it suggests that the coherent dipoles are in π phase with the coherent quadrupoles or the anti-Kerker condition of the dipole-quadrupolar scatterers. Simultaneously satisfying of Kerker and anti-Kerker conditions leads to the redirection of the scattered power to the lateral directions and suppression in the forward and backward directions [15].

We test conditions (1) and show the result in Fig.1. The scatterer is Si cubic nanoparticle with edge length 250nm situated in free space. Fig.1(a) shows the transverse scattering pattern of the cube at wavelength λ=788nm of the incident light. We construct an infinite square lattice of the cubic particles with spacing 500 nm. The lattice plane is aligned with the xy Cartesian plane and the incident light is x-polarized and propagates along the z axis (see Fig.1(b)). We plot the multipole contributions to the reflected field of the lattice (the scattered field in case of a standalone scatterer) in Figs.1 (d,e). At wavelength λ=788 nm, conditions (1) are nearly satisfied and result in zero reflection. Inspections of the plotted multipole contributions shows that the zero reflection spectrum is a shared point between the electric dipole Fano resonance profile and the quadrupoles long wavelength off-resonance region[15]. The inter-scatterer interactions within the lattice are weak providing conditions (1) hold for the standalone scatterer as well as within the lattice system [15].

In Fig.1(c), we compare a fragment of the incident field with the total field in the lattice at wavelength $\lambda = 788$ nm. The transmitted light goes through the resonant multipoles without perturbation of amplitude and phase, therefore displaying lattice invisibility effect, that can also be interpreted as full transmission of light through the photonic structure. It means that electromagnetic energy is localized inside and close to the metamolecules, but the wavefront of the incident field is barely affected by the presence of the scatterers [16]. We call such behavior "lattice anapole effect" because this effect is similar to light scattering by single particles in resonant anapole states.

III. Conclusion

To conclude, we explained physically and revealed the conditions to suppress the forward and backward scattering of a dielectric particle simultaneously. This unusual scattering signature take place when coherent dipoles and coherent quadrupoles satisfy Kerker conditions; and have π phase relation to each others. We generalized these conditions to obtain zero reflection from a metasurface consisting of transverse scatterers. The incident wave amplitude and phase are completely unaffected. We find such exotic optical behaviour is a result of the coincidence of the electric dipole Fano profile and quadrupoles in the long-wavelength region.

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