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Polarization and angle independent magneto-electric Fano resonance in multilayer hetero-nanoshells

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ABSTRACT

In this work, we have demonstrated that the Si–SiO_2 –Au multilayer hetero-nanoshells can support the polarization and angle independent magneto-electric Fano resonance. Such Fano resonance arises from the direct destructive interference between the orthogonal electric dipole mode of Au core and magnetic dipole mode of the Si shell and is independent of the angle due to the high structural symmetry. In contrast to metal particle arrays, here is a possibility to generate controllable interaction between the electric and magnetic dipole resonances of individual nanoshell with the structural features. The discrete magnetic responses provided directly by the Si shell pave the groundwork for designing the magnetic responses at optical frequencies and enable many fascinating applications in nanophotonics.

1. Introduction

Fano resonances arising from electric modes in metallic nanostructures were realized by using the near-field interaction between superradiant (bright) and subradiant (dark) modes or between superradiant and superradiant modes [1–3]. It is worth mentioning that, based the steep dispersion of Fano resonance, a scheme of Fano resonances was demonstrated spread rapidly from atomic physics [4,5], where it was first discovered, to plasmonic system [6–9]. Fano resonance has sparked the surging interest due to its observations and applications in different fields and a lot of progress has been made on Fano resonances in plasmonic nanostructures [10–13]. While Fano resonances of an isolated metal nanoparticle are still purely electric effects in the absence of natural magnetism [14,15], the properly tailored plasmonic nanoclusters in a planar ring geometry or a three-dimensional cluster have been designed recently to induce artificial optical magnetism and can support magnetic plasmonic Fano resonances [16–22], but such resonances in such plasmonic system still possess the prominent intrinsic losses.

Fano resonances arising from the interferences between magnetic and electric responses in all-dielectric nanoparticles with large permittivity values (such as Si and Ge nanospheres) have attracted considerable attention in recent years [23,24]. Fano resonances generated in dielectric nanoparticle or nanoclusters have been realized [25–28], where the strong magnetic responses are connected to the existence of hybrid modes for which the radial component of the magnetic field is not equal to zero and the magnetic Fano resonances can be employed for the realization of anomalous scattering signatures. However, the magnetic response at optical frequencies has so far mainly focused on purely metal or dielectric nanoparticles, little attention has been given to the magneto-electric Fano resonances in dielectric–metal hybridized nanoparticles, which are of significance to inquiry light matter interaction.

Symmetry breaking provides a particularly intriguing means to realize pronounced Fano resonances with strong modulation depths [29,30]. Fano resonance achieved in such broken structures also inevitably shows strong incident polarization-dependent optical responses due to the breaking structural symmetry. However, for many applications based on Fano resonances, such as optical switches [31,32], surface enhanced raman scattering (SERS) [33–35], and particularly for use in sensing applications that benefit from sharp spectral features and extreme field localization [36–39], polarization and angle independent magneto-electric Fano resonance is highly desirable but such resonance has rarely been reported.

Here we study the scattering properties of the Si–SiO_2 –Au (SSA) multilayer hetero-nanoshells (MNS) supporting the orthogonal electric dipole (ED) of gold (Au) core and magnetic dipole (MD) of the silicon (Si) shell simultaneously and reveal the existence of polarization and angle independent magneto-electric Fano resonance. Such Fano resonance occurs through the interference of a pair of orthogonal electric and magnetic dipole modes with the overlap spectrally, rather than electric–electric Fano resonance in metallic nanostructures with purely electric

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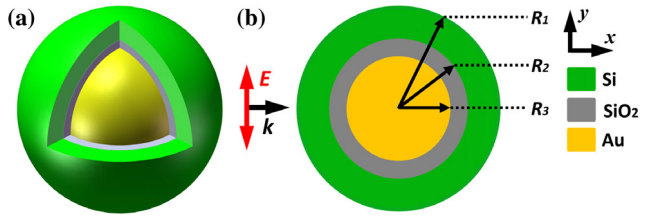

Fig. 1. (a) Schematic three-dimensional illustration of the SSA MNS. (b) Midsectional view of the SSA MNS with geometric parameters. The polarization (E) and propagation (k) directions of incident light are denoted.

effects in the absence of natural magnetism. With the high structural symmetry of the nanoshell may enable an excellent platform with much more flexibilities to study nonlinear and lasing effects when nonlinear and/or gain materials are incorporated.

2. Numerical methods

Fig. 1 illustrates the structure and corresponding geometrical parameters of the SSA MNS. The SSA MNS dimensions are denoted by the radius of each layer, R_1, R_2, and R_3, shown in Fig. 1(b). And the dielectric constant of the SiO_2 spacer layer is set as 2.04. The surrounding medium is air and the dielectric constant is set to 1. The dielectric constants for Si and Au are taken from Ref. [40] and Ref. [41], respectively. The far-field properties of MNS were simulated using a finite-difference time-domain (FDTD) method. In the calculation of FDTD, we assume a uniform grid, and the unit cell size is $1 \times 1 \times 1$ nm^3 to improve its precision of calculation.

3. Simulation results and discussions

The scattering of a spherical particle (single or multilayered) can be decomposed into a multipole series (that which is called Mie's expansion) characterized by electric $\{a_n\}$ and magnetic $\{b_n\}$ Mie coefficients. For an incident plane-wave illumination, the scattering expressed in the Mie coefficients,

$$Q_s = \frac{2}{k^2R^2}\sum_{n=1}^{\infty}(2n+1)\left\{|a_n|^2 + |b_n|^2\right\} \quad (1)$$

where k is the angular wave number in the otherwise uniform material (it is vacuum in our study); and R is outmost layer radius of the particle. The scattering by a small-size spherical particle, usually the excitation of higher order resonances can be neglected (a_n, $b_n \approx 0$ ($n > 1$)), that is, small-size particle can be treated as dipolar particle that only the dipolar terms of Eq. (1) contribute to the scattered field, and the scattering is completely determined by the first coefficients a_1 and b_1, i.e.

$$Q_s = \frac{6}{k^2R^2}\left\{|a_1|^2 + |b_1|^2\right\} \quad (2)$$

where a_1 and b_1 are the electric and magnetic dipolar Mie coefficients, respectively.

Fig. 2(a) shows the scattering spectra of single Au sphere (R_3 = 48 nm) and the Si nanoshell (inserting a SiO_2 core into Si sphere) with R_1 = 75 nm at different R_2. To identify the origin of each spectral feature, the spectral scattering of one single Si sphere is also shown (black dashed line) as a reference, there are apparently two observable resonances around 500 nm and 610 nm, representing the magnetic quadrupole and magnetic dipole (MD) resonances, while electric dipole (ED) resonance is suppressed and does not show a peak here. Although the ED and MD resonances coincide spectrally with the same strength, the ED and MD resonances are orthogonal and not coupled to each other due to the high symmetry of Si sphere. So the Si nanoshell supports electric/magnetic resonances just as single Si sphere does magnetic and electric responses. By inserting the SiO_2 core into the Si sphere, it can

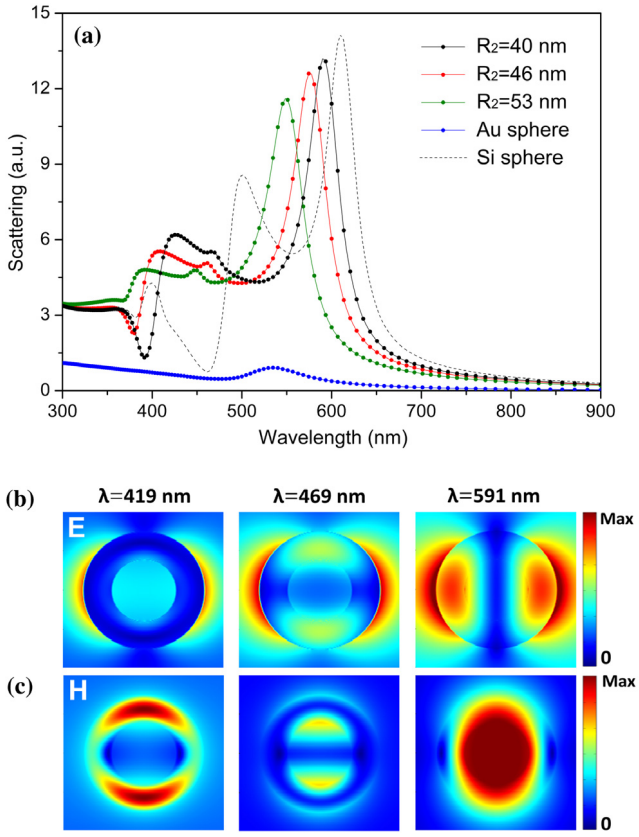

Fig. 2. (a) Scattering spectra of single Au sphere (R_3 = 48 nm) and the Si nanoshell (R_1 = 75 nm) at different R_2. (b) The electric and (c) magnetic near-field enhancements of the Si nanoshell with R_2 = 40 nm at the center cross section.

be seen that the scattering spectra all have blue shift and the degree of the shift is determined by the radius of the SiO_2 core, as shown in Fig. 2(a). Differing from the Si sphere, a weak resonance appears around 460 nm accompanied by two clearly developed resonances around 420 and 590 nm. And the intensity of resonances is weakened with increasing R_2, as shown in Fig. 2(a). In Fig. 2(b) and (c), we show the corresponding electric and magnetic near-field enhancements with R_2 = 40 nm at the center cross section. According to the Mie theory, the lowest-energy resonance at 591 nm in the Mie expansion is the MD (b_1) mode. Physically this mode corresponds to a situation where the electric field inside the shell creates a resonant circulating displacement current differing from the conduction current in plasmonics, which mimics the behavior of the MD mode. The resultant magnetic dipolar field distribution can be identified by observing the near-field maps at 591 nm in Fig. 2(c). And the magnetic field at 419 nm with a blank distribution is enhanced inside the Si shell, which is associated with the magnetic quadrupole mode (b_2). In addition, the depolarization field in the Si shell oscillates to the incident field and creates a dipolar electric field distribution as illustrated at 469 nm, which corresponds to the ED resonance (a_1). Interestingly, for wavelengths larger than $\lambda \approx 520$ nm, the scattering is completely determined by the first dipolar magnetic Mie coefficients b_1, where the Si shell can be approximated as a MD resonance. Compared to the Si shell, scattering of Au sphere exhibits a lower strength and is completely determined by the first dipolar electric Mie coefficient a_1.

Fig. 3(a) displays the scattering spectrum of the MNS with $R_1/R_2/R_3$ = 75/53/48 nm. By inserting an Au core into the Si-SiO_2 nanoshell, the scattering spectrum change a lot due to the hybridization between the electric and magnetic responses, distorting and producing new spectral features, which manifests itself by a pronounced