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Retardation-effect-induced plasmon modes in a silica-core gold-shell nanocylinder pair

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ABSTRACT

The retardation-effect-induced plasmon modes in a silica-core gold-shell nanocylinder pair is investigated by the two-dimension finite difference time domain method. We show that for light polarized perpendicular to the axis connecting the pair, the spectrum depends sensitively on the size of nanocylinder pair. As the size increases, several retardation-induced non-dipolar plasmon modes including multipolar modes appear in the spectrum and the resonance wavelength and strength of its plasmon modes can be tuned by changing separation width between the nanocylinder pair. Both extinction spectra as a function of size of the core-shell nanocylinder and near-field intensity associated with the coupling resonance modes are reported.

1. Introduction

The optical properties of metallic nanostructures are attractive because of their ability to enhance, emit, and modify the optical field. The dependence of their optical properties on the size, shape, and surrounding medium is an active subject of research, and recent advances in nanofabrication have enabled us to design the nanostructures with different shapes and functionalities, such as nanorices [1], nanorings [2], and nanoshells [3]. Compared to solid metallic particles, these core-shell nanostructures exhibit highly tunable plasmon modes that can be tuned over an extended wavelength range between visible and near infrared regions and the variation of the plasmon resonance wavelength is interpreted as originating from coupling of localized surface plasmon modes at the inner and outer surfaces of the core-shell structure [2,4].

For small nanoparticles where the quasi-static approximation is valid, only plasmon resonance modes containing dipole moments can be excited by the external light. Several recent studies have shown that by breaking the symmetry of a nanostructure, non-dipolar plasmon modes can be excited [5,6]. Another mechanism for exciting non-dipolar plasmon modes is phase retardation effect [7]. When the size of the nanostructures is larger than a quarter of the wavelength of the incident wave, the spatial retardation effect over the volume of the nanostructure should be considered. In this work, we use the 2-D finite different time domain method [8] to study the optical properties of a pair of silica-core gold-shell nanocylinders. The extinction spectra for the nanocylinder pair with different sizes and separation widths are studied in details to understand the effect of the phase retardation effect on the plasmon oscillation in a nanocylinder pair.

2. Calculation methods

Our FDTD simulation domain is separated into three regions from outside to inside: absorbing boundary, scattered field region, and the total field region. The perfectly matched layers are used as absorption boundary to prevent reflections of scattered waves back into the simulation domain. The FDTD calculations were done accurately using a mesh size of 0.25 nm, a time step of 4.16666e−19 s, and a Courant number of 0.5. The program codes have been checked with the analytical theory [9], for a single silica-core gold-shell nanocylinder, as shown in the inset of Fig. 1. The permittivity of silica is taken as 2.1. The optical response of gold is modeled using the three critical point pole pairs (CP3) model [10], which provides a good fit to tabulated experimental data [11]. The CP3 model can be expressed as

$$\varepsilon(\omega)=\varepsilon_{\infty}+\frac{\sigma/\varepsilon_0}{i\omega}+\sum_{p=1}^{3}\left(\frac{A_p\Omega_p e^{i\phi_p}}{\Omega_p-\omega-i\Gamma_p}+\frac{A_p\Omega_p e^{-i\phi_p}}{\Omega_p+\omega+i\Gamma_p}\right) \quad (1)$$

The value of the parameters can be found in [10]. The geometrical arrangement of the nanocylinder pair and the incident wave is shown in Fig. 1. The propagating direction of the incident wave is along the

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axis that connects the nanocylinder pair, and the electric field of the incident wave is perpendicular to this axis.

3. Results and discussion

3.1. Phase-retardation-induced dipole and quadrupole plasmon modes

We first investigate the spectral characteristics of the silica-core gold-shell nanocylinder pair by fixing the ratio of the outer radius to inner radius at 6:5 and the ratio of the outer radius to the inter-nanocylinders spacing at 5:1, and by changing the outer radius from 15 to 135 nm with a 15 nm interval. In Fig. 2 the simulation results show that for outer radius of 15 nm, only plasmon modes containing electric dipole moments can be induced by incident light. This is because in this case the quasi-static approximation is valid, so that the electromagnetic field across the extent of the nanocylinder pair can be assumed to be uniform. This plasmon mode, near 720 nm, corresponds to in-phase symmetric dipole–dipole interaction mode, and the symmetric dipole mode is a result of the electrons at the inner surface of the core-shell nanocylinder aligned symmetrically with the electrons at the outer surface [4]. For outer radius of 30 nm, the out-of-phase symmetric dipole–dipole interaction mode, near 790 nm, appears in the spectrum. This out-of-phase plasmon

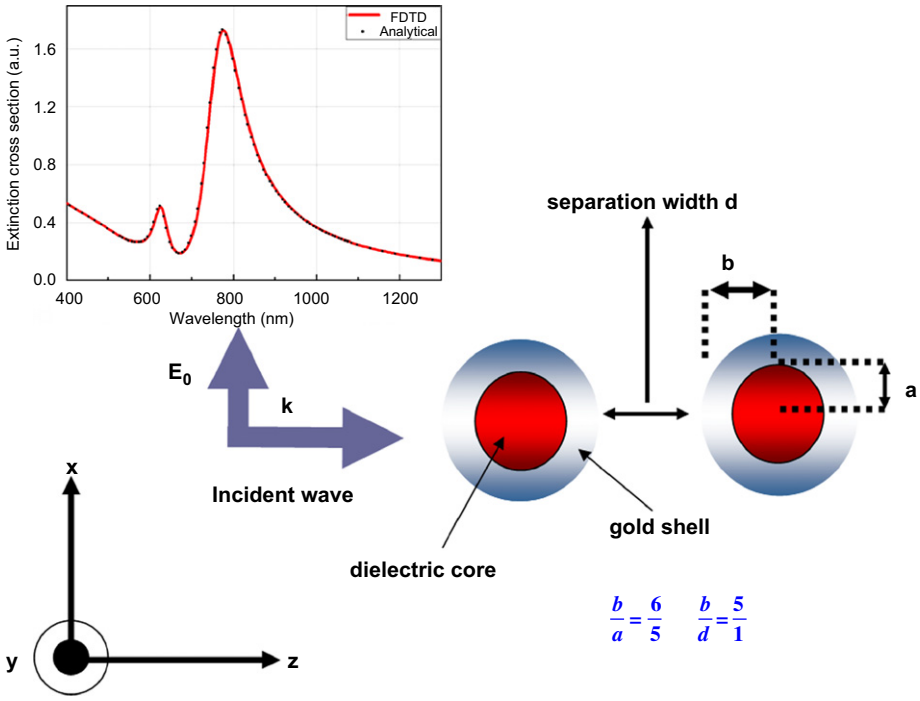

Fig. 1. Schematic diagram of the geometrical arrangement of the silica-core gold-shell nanocylinder pair. Inset: the extinction spectra of a silica-core gold-shell nanocylinder with outer radius 90 nm and inner radius 75 nm obtained from the analytical theory (dots) and FDTD method (red lines) with the CP3 model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

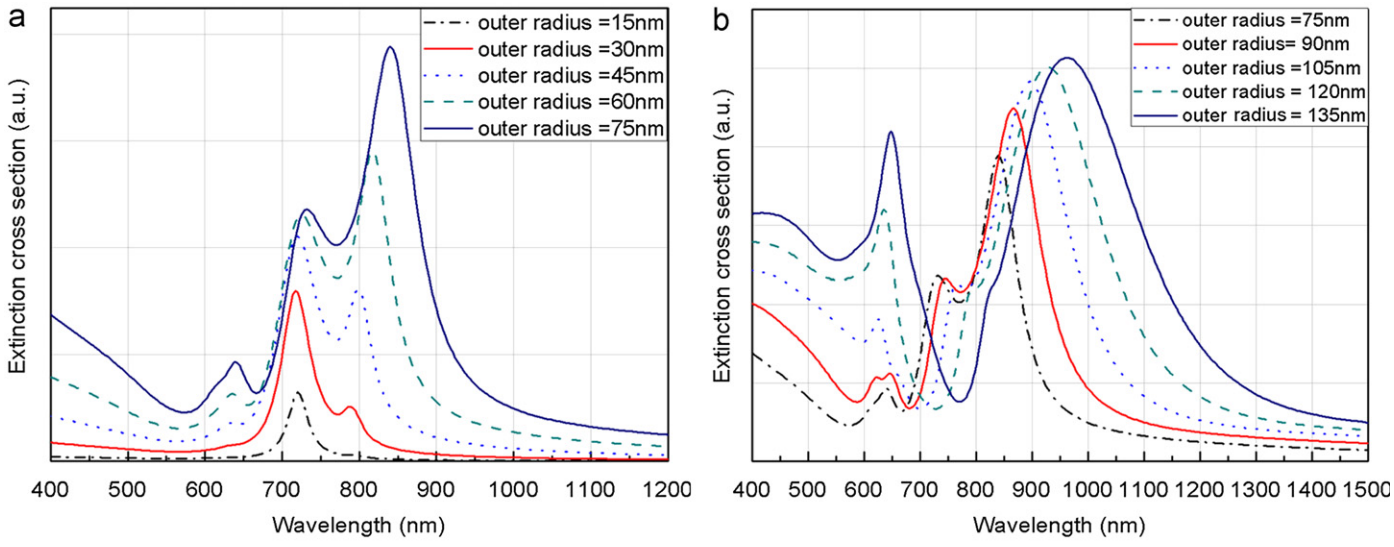

Fig. 2. The extinction spectra as a function of size of the silica-core gold-shell nanocylinder pair from the outer radius of 15 to 135 nm. The ratio of the outer radius to inner radius is fixed at 6:5 and the ratio of the outer radius to the inter-nanocylinders spacing at 5:1.