Probing of Magnetic and Electric Optical Responses of Silicon Nanoparticles

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Abstract

We experimentally study near- and far-field properties of the magnetic and electric dipole resonances of silicon nanospheres on a glass substrate for different polarisations. By employing scanning near-field optical microscopy we are able to verify the existence of the magnetic dipole resonance of such particles by direct measurements of the near-field distribution.

1. Introduction

Recently, several groups experimentally demonstrated that high-refractive index dielectric nanoparticles can exhibit both electric and magnetic scattering resonances in the visible range [1, 2]. The coexistence of both electric and magnetic responses offers new possibilities to control scattering patterns of subwavelength nanoparticles, including unidirectional emission [3, 4]. This property makes subwavelength dielectric nanoparticles the smallest and most efficient nanoantennas. But, up to now no direct verification of the existence of magnetic dipole resonance was demonstrated. In this study for the first time we perform near-field measurements of the light scattering by silicon nanoparticle by employing scanning near-field optical microscope (SNOM). We are able to identify the strong angular distribution corresponding the magnetic dipole response.

2. Experimental Approach

In this work we study optical properties of silicon nanoparticles deposited on a glass substrate. In order to characterize the optical responses of single nanoparticles we resorted to two different experimental techniques: polarized dark-field microscopy [5] and SNOM, Fig. 1.

The experimental setup shown in Fig. 1a for the dark-field measurements was similar to the one discussed in Ref. [5]. Polarized white light was mildly focused on the sample surface at grazing incidence. The light scattered by a particle was collected from the top by 50x objective and analyzed by a spectrometer in a confocal arrangement.

In the SNOM experiments (see Fig. 1b) the particle was exited by a laser beam focused to a spot of 25 μm in diameter (at $1/e^2$ intensity level). We used supercontinuum source with tunable filter which allowed us to vary the excitation wavelength within entire visible spectral range. The light was polarized along the x-axis. The electromagnetic fields were collected by an aperture fiber probe. The scanning was performed in a plane at $h = 175$ nm elevation over the surface.

3. Results and discussions

The main goal of this study was to distinguish experimentally magnetic dipole (MD) from electric dipole (ED) responses of silicon nanoparticles. To this end we resorted to a home-made dark-field microscope with two separate optical channels for excitation (side channel) and collection (upper channel), Fig. 1. There are two main features of such experimental geometry. First, the use of a relatively low numerical aperture objective (NA=0.55) in the upper channel allows one to collect dominantly radiation that corresponds to the lateral polarization components of dipole scatterer. Therefore, the main contribution to the signal observed in the experiments give lateral components of electric ($\mathbf{E}_{\|}$) and magnetic($\mathbf{H}_{\|}$) fields of incident wave. Second, due to the grazing incidence of the exciting beam, we obtain $\mathbf{E}_{\|} \gg \mathbf{H}_{\|}$ for the s-polarization and vice versa, $\mathbf{H}_{\|} \gg \mathbf{E}_{\|}$ for the p-polarization, see Fig. 2a.

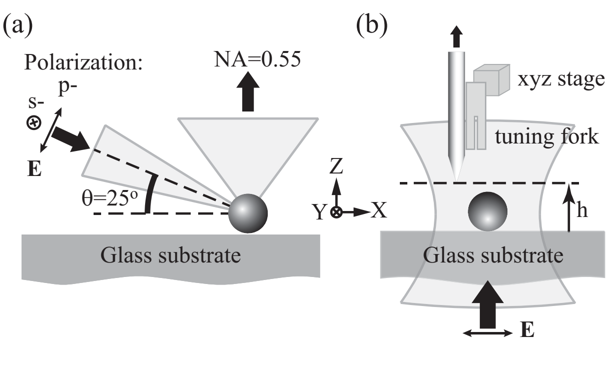

Figure 1: (a) Experimental setup for polarization-resolved dark field microscopy. The sample was excited by polarized light from the side at grazing incidence. The scattered light was collected from the top by the 50x objective. (b) Schematic of scanning near-field optical microscopy experiments. The silicon particle was excited from the bottom by focused laser beam. The scanning was performed at a predefined elevation h over the substrate surface. The excitation wavelength was tuned in the visible spectral range.

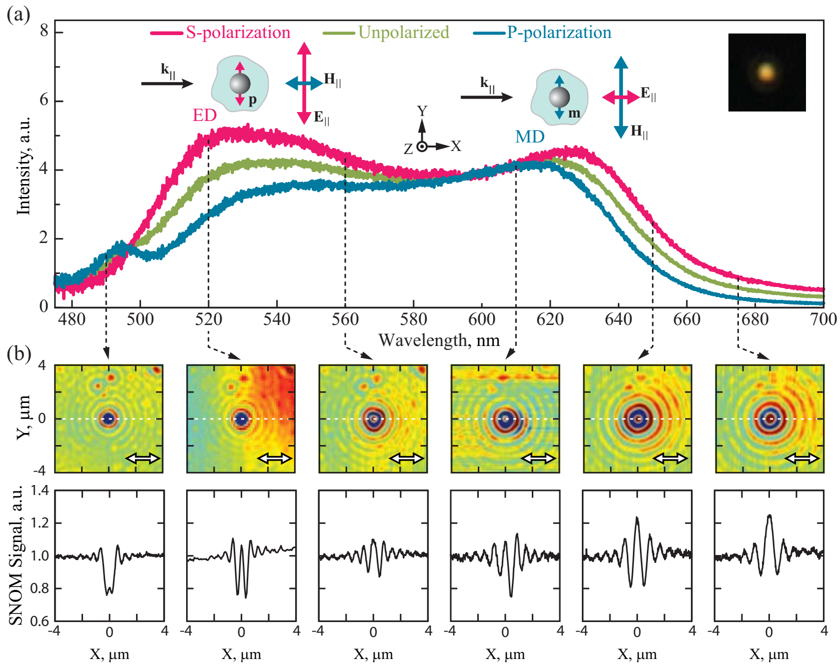

Figure 2: (a) The scattering spectra obtained from silicon nanoparticle with diameter $D = 140$ nm. The lateral components of electric and magnetic fields of incident wave with s- and p-polarization are schematically shown at the top. The optical dark-field image of the particle is given in the inset. (b) Near-field patterns in the vicinity of the particle obtained at the elevation $h = 175$ nm above the substrate. The polarization of the incident wave is directed along x-axis. Corresponding horizontal profiles of the patterns are shown at the bottom.

The polarization-resolved dark-field spectra obtained from a silicon particle with diameter of $D = 140$ nm are shown in Fig. 2a. All the three spectra possess two peaks. For the s-polarized incident wave, the short-wavelength peak is higher that the long-wavelength one. The fact that in this case the in-plane electric field is larger then the magnetic field allows us to conclude that the short-wavelength peak is concerned with ED resonance of the particle. Similarly, for the p-polarized light the long-wavelength peak is more pronounced and is likely concerned with MD resonance of the particle.

The near-field patterns in the vicinity of the particle are shown in Fig. 2b. The experimental data were normalized to the Gaussian beam background for convenience. The concentric circles on the images originate from the interference between the incident beam and the radiation scattered by the particle. The radial dependence of the magnitude of the intensity modulation demonstrates the magnitude of the waves irradiated by the particle. These data give information about both the amplitude and the phase of the scattered waves at different wavelengths.

The pattern obtained at $\lambda = 610$ nm possesses vivid polarization dependence: the particle scatters light mainly along the direction of polarization (perpendicular to the magnetic field of the exciting wave) of the incident beam. This gives additional experimental support to the fact that the particle acts mainly as a MD in this spectral region.

4. Conclusions

We have studied experimentally optical properties of silicon nanoparticles on a glass substrate. In the dark-field spectra we observed two resonant peaks. In our polarization-resolved experiments we have shown that the short-wavelength peak is more pronounced for s-polarized excitation, while for p-polarized incident light the long-wavelength is dominating. This result allows us to conclude that these peaks correspond to electric dipole and magnetic dipole resonances of the particle respectively.

In our SNOM measurements we obtained different maps of interference of incident beam with the radiation scattered by the silicon particle at different wavelengths. Strong angular dependence of the intensity modulation observed at $\lambda = 610$ nm indicates that the particle scatters light dominantly along the polarization of incident wave, i.e in the direction perpendicular to the magnetic field. This gives additional support to the fact that in this spectral region the silicon particle acts as an optical magnetic dipole.

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