Resonant Directional Scattering and Light Extraction with Silicon Nanodisks

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Abstract

Subwavelength silicon nanodisks support electric and magnetic Mie-type resonances which can be tuned independently *via* the nanodisk geometry. Here we employ arrays of silicon nanodisks with engineered resonances to demonstrate directional far-field scattering as well as shaping of the emission spectra of semiconductor quantum dots. Our results suggest a novel approach for utilizing controlled interference of different Mie-type modes of all-dielectric nanoparticles for functional metasurfaces and highly directional nanoantennas.

1. Introduction

Driven by the huge promises for applications based on plasmonic metamaterials and nanoantennas, metallic nanostructures have been extensively studied in the last decade and still remain an active field of research. However, plasmonic nanostructures inherently suffer from strong dissipative losses of metallic components at optical frequencies, thereby hampering both performance and practical benefit of most of their potential applications in nanophotonics. A new route to overcome this problem is opened up by the recent experimental observations of electric and magnetic Mie-type resonances in high-permittivity all-dielectric nanoparticles [1-3]. While such all-dielectric nanoparticles exhibit very low losses at optical frequencies, their resonances can be utilized in direct analogy to plasmonic resonances of metallic nanoparticles.

Of particular interest for all-dielectric optical nanoantennas is the interplay of electric and magnetic modes supported by high-refractive-index nanoparticles. Tailored mode interference offers unique opportunities for directional scattering [4-7], including the suppression of resonant backward scattering in the case of spectral mode overlap [6] and reversal of the scattering direction depending on the incident wavelength [7]. However, to date most experiments on scattering by high-refractive-index all-dielectric nanoparticles have been focused on such simple geometries as spheres or cubes, which do not allow for spectral tuning of the magnetic and electric resonances with respect to each other [8]. Here, we overcome this limitation and demonstrate experimentally that all-dielectric silicon nanodisks enable spectral control over the induced electric and magnetic resonances of the nanoparticles, including a spectral mode overlap [9].

2. Results and Discussions

In experiment, we fabricate silicon nanodisk arrays on a low-refractive-index substrate using electron-beam lithography on silicon-on-insulator wafers in combination with reactive ion etching. A scanning electron micrograph of a typical fabricated sample is shown in Fig. 1a. Next, the silicon nanodisks are embedded into a low-refractive index matrix using low-pressure chemical vapor deposition of

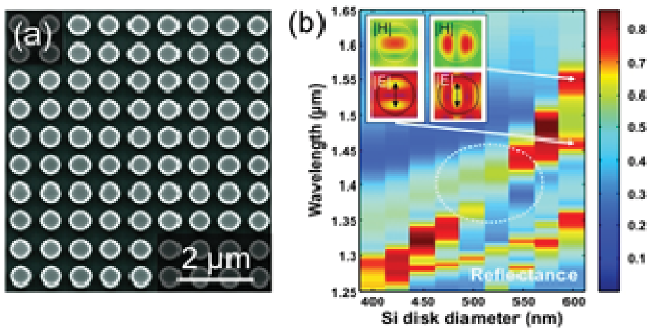

Figure 1: (a) Scanning electron micrograph of a typical fabricated array of silicon nanodisks. (b) Experimentally measured reflectance spectra for silicon nanodisks featuring a systematic diameter variation [9]. The white ellipse indicates the position where resonant backscattering is suppressed due to a spectral overlap of the electric and magnetic resonances. Insets show the calculated mode profiles.

silicon oxide and spin-on dielectric in order to create a homogenous dielectric environment. A systematic variation of the nanodisk diameter at constant nanodisk height allows us to tune the spectral positions of the nanodisks' electric and magnetic resonances with respect to each other and to bring them into spectral overlap [9]. Near-normal-incidence linear-optical transmittance and reflectance spectra of the fabricated nanodisk arrays are measured using a home-built white-light spectroscopy setup (see Fig. 1b for reflectance spectra). For the largest nanodisk diameter two clearly separate resonances are observed (see arrows in Fig. 1b), which are characterized by high reflectance and low transmittance levels and correspond to the fundamental electric and magnetic dipolar resonances in the nanodisks. As the diameter is reduced, the two resonances move closer together until they overlap spectrally, before they start separating again. Importantly, the interference of electric and magnetic modes in the individual subwavelength silicon nanodisks leads to the suppression of resonant backward scattering of light (see white ellipse in Fig. 1b), resulting in higher transmittance and lower reflectance levels for overlapping than for isolated resonances.

In order to obtain a deeper understanding of our experimental results we also calculate corresponding normal-incidence transmittance and reflectance for experimental sample parameters using CST Microwave Studio. We obtain a very good agreement with experimental data. Our calculations furthermore reveal that near-unity transmittance is obtained for a perfect mode-overlap in the absence of Fabry-Perot resonances that originate from the layered silicon-on-insulator wafer structure.

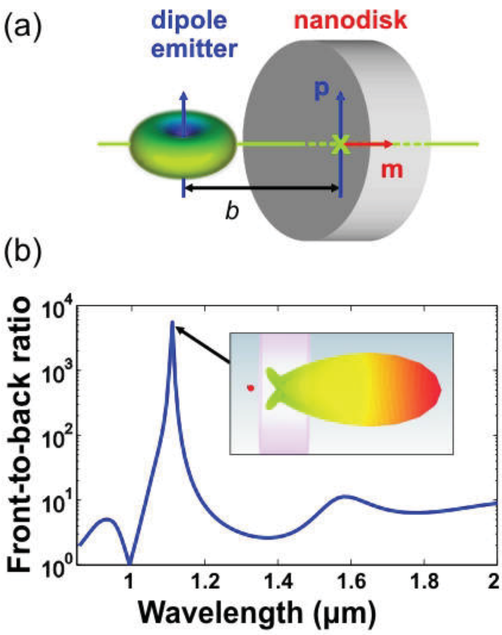

Figure 2: (a) Sketch and (b) numerically calculated front-to-back ratio for a tailored silicon nanodisk antenna excited by a point-like dipole source [9].

Next, we extend our study on the directional scattering properties of silicon nanodisks under excitation by a localized dipole source. Experimentally such a source could, *e.g.*, be implemented by a quantum dot (QD) or a nanocrystal containing a color center. We numerically calculate the front-to-back ratio for an all-dielectric nanoantenna consisting of a single nanodisk with d=620 nm, which is excited by an electric dipole source, located 40 nm away from its surface as illustrated in Fig. 2a. Our results are shown in Fig. 2b, indicating that highly directional scattering with an ultra-high front-to-back ratio of more than 5500 and a directivity of about 6 is achieved at 1.11 µm wavelength, thereby demonstrating the great potential of silicon nanodisk resonators for the use as director elements of optical nanoantennas [9].

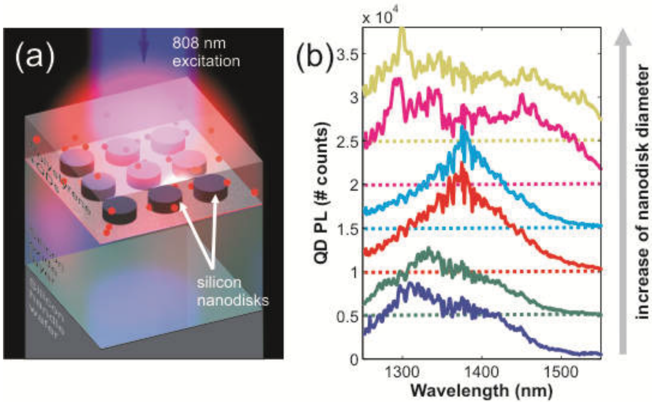

Figure 3: (a) Sketch and (b) experimentally measured micro-photoluminescence spectra for PbS quantum dots coupled to silicon nanodisks with various diameters.

However, it remains an open question if silicon nanodisk resonators can also facilitate the second key functionality of optical nanoantennas, namely energy extraction from an excited emitter. In order to gain an insight into the interplay of nanoemitters and silicon nanodisk resonators, in the following we investigate experimentally how the spontaneous emission properties of near-infrared PbS QDs are influenced by coupling to the nanodisks' spectrally matched electric and magnetic Mie-type modes. To this end, instead of embedding the nanodisks into a low-refractive index medium, we cover them with a thin polymer layer containing spectrally matched PbS QDs as schematically illustrated in Fig. 3a. We then perform micro-photoluminescence (PL) spectroscopy measurements of the coupled system for various nanodisk diameters.

These results are shown in Fig. 3b. Clearly, the spectral QD PL line shape is strongly dependent on the nanodisk aspect ratio. In particular, the spectral positions of the local maxima correlate with the electric and magnetic mode frequencies in the different structures, clearly indicating that the QDs couple to the Mie-type modes of the silicon nanodisk resonators.

This correlation is preserved for the case of overlapping electric and magnetic modes. This indicates that a high photonic local density of states exists in the structure despite the lack of a pronounced resonance signature in the transmittance/reflectance spectra due to suppression of backward scattering and predominant forward scattering. Such a behavior cannot be obtained by any isolated optical resonances in any type of nanoparticle arrays.

3. Conclusion

Our results demonstrate that high-index all-dielectric nanodisks are not only suitable for tailoring directional far-field scattering, but that they also have a high potential for extracting energy from localized emitters and redirecting this emission into a given direction. Based on these key functionalities we expect that silicon nanodisks will play an important role in future all-dielectric nanophotonics, including directional nanoantennas, functional all-dielectric metasurfaces, and nonlinear-optical applications of all-dielectric subwavelength resonators.

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