Direct observation of optical trapping of a single quantum dot with an all-silicon nanoantenna

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Abstract: Silicon nanoantennas are used to optically trap individual streptavidin-coated CdSe/ZnS quantum dots (QDs) with minimal thermal effects. Using fluorescence microscopy, we track the position and light emission from optically-trapped QDs as a function of time.

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1. Introduction

We demonstrate the optical trapping of single quantum dots (Life Technologies, Qdot 655 Streptavidin Conjugate, Q10121MP) with all-silicon (Si) nanoantennas, using illumination from a continuous wave (CW) trapping laser ($\lambda=1064$ nm). Interest in the optical trapping of QDs [1-4] has been motivated by the promise that QDs offer for applications in biomolecule labeling. Unlike previous reports, our all-Si nanoantennas present the opportunity for enhanced optical forces without deleterious thermal effects and complicated experimental set-ups. We furthermore directly observe the optical trapping of single quantum dots in vicinity of a nanoantenna, i.e. tracking their position vs time, for the first time to our knowledge. The CdSe/ZnS core-shell QD is coated with a polymer and streptavidin, and has an overall diameter of ~15-20 nm (Fig.1c). We present simulations of the optical forces, field distributions, and temperature rise occurring in optical trapping. We present experiments in which fluorescence microscopy is used to directly observe the trapping of individual QDs, enabling simultaneous monitoring of position and emission intensity vs time. We discuss the contributions of one- and two-photon absorption (TPA) to the emission.

Fig.1. (a) SEM 45°-view image of Si nanoantenna. Each nanoantenna consists of two identical Si cylinders with diameters of 200 nm, heights of 200 nm and a 50 nm gap in between, surrounded by an Si ring, all on an Si wafer substrate. Ring has inner and outer radii of 0.525 and 0.725 µm, respectively, and height 200 nm. (b) Simulation of electric field (|E|) distribution in the $yz$- and $xz$- plane, for 1064 nm plane wave illumination ($\lambda=1064$ nm) traveling in $+z$ direction. Orange dots indicate coordinate system origin. Scale bar: 200 nm. (c) Schematic illustration of QD structure [5]. (d) Model of QD used in optical force simulations. (e) Peak and gap center temperature increases ($\Delta T$) vs trapping laser intensity. (f) Optical forces as a function of position ($F_{x}$ at $x_{QD}=0$; $F_{y}=F_{z}$=0). QD: $r_{1}=5$nm, $r_{2}=7$nm, $r_{3}=10$nm; Small QD: $r_{1}=3$nm, $r_{2}=4$nm, $r_{3}=5$nm. QD trapping forces are determined on polymer surface. (h) Zoom-in of |E| distribution with a QD trapped in the gap.

2. Numerical simulations

Our nanoantenna comprises a pair of Si cylinders surrounded by an Si ring, all on an Si substrate (Fig.1a). The gap width (50 nm) is much larger than the QD diameter. We use a commercial finite element package (COMSOL) for the simulations. Illumination is from a plane wave ($x$-polarized, $\lambda=1064$ nm) incident from the water side. In Fig.1b, we show the electric fields in two orthogonal cross sections. Three field maxima and trapping regions occur: a main
maximum in the gap region, and two secondary maxima at the outer extremities of cylinders. In Fig.1e, we plot the simulated temperature increase as a function of trapping laser intensity. It can be seen that both the peak temperature rise and the temperature rise in the gap center are both very small. In Fig.1f, we plot the vertical (i.e. into substrate) force $F_z$ on the QD as a function of its position in the vertical direction, found using the Maxwell stress tensor (MST) method. The particle is centered over the gap ($x_{\text{center}}=y_{\text{center}}=0$). For comparison, calculations are included of the forces on a polystyrene nanoparticle (NP) and on a smaller QD. It can be seen that for $z_{\text{center}}<-140$ nm, each particle is attracted toward the antenna. The strongest forces are near the antenna edge ($z_{\text{center}}=-200$ nm). In Fig.1g, we plot $F_x$ and $F_z$ as functions of QD position along the x-axis ($y_{\text{center}}=0$, $z_{\text{center}}=-215$ nm). In Fig.1h, we show the electric field distribution ($xz$-plane, $y=0$) when a QD is located at the vertical position ($z$) for which $F_z=0$ (Fig.1f).

3. Experimental results: optical trapping and two-photon excitation of individual QDs

The QDs are suspended in phosphate-buffered saline solution (1X PBS, pH 7.4) with surfactant added (Tween 20, 0.05% (v/v)) to prevent aggregation. The QD concentration is $\sim 10^{-8}$ mol/L. Our experimental set-up comprises an inverted optical microscope fitted with an oil immersion objective (NA 1.3), green (532 nm, for fluorescence excitation) and infrared (1064 nm, for trapping) lasers, filters, an electron-multiplying CCD (EM-CCD) camera and a spectrometer. In Fig.2a-c and Fig.2d-f, we present the results of two QD trapping experiments. We confirm that the QDs are not being stuck to the Si surface solely by some non-optical means by turning off the trapping laser and observing the QDs being released. In Fig.2a and 2d, we plot the fluorescence intensity counts integrated over a 30×30 pixel cross section centered over the Si nanoantenna of each EM-CCD frame as a function of time. A clear blinking behavior is observed during the period over which the QD is trapped (~4-47s and ~49-51s in Fig.2a and ~0-68s in Fig.2d). Fig.2b shows an intensity count histogram of blinking trace (4-45s) in Fig.2a. A selection of four EM-CCD images of a trapped QD is shown as Fig.2c. Emission spectra of a single QD before and after switching off the green laser are also measured (Fig.2e). In Fig.2f, we present scatter plots of the positions of a trapped QD, for data sets obtained with both lasers and with trapping laser only. These are collected at a frame rate of 30 fps and with ~1000 points per data set. These are from the same experiment as Fig.2d. In the experiments, due to the high TPA cross section ($\sigma_{\text{TPA}}$), QDs can be excited by one-photon absorption from the green laser and/or TPA from the infrared laser. We confirm this via our EM-CCD images and from measured spectra (Fig.2e). We note however that at the (relatively weak) illumination level employed (~16.1 mW/µm²) and considering the intensity enhancement expected of our antenna (~4.91²), the nonlinear refractive index ($\gamma I$) of CdSe is $\sim -5.7 \times 10^{-7}$ ($<< n_0 = 2.54$), suggesting insignificant modification to the optical trapping force (Fig.1f&g).

4. References

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