Optical tracking of a nanoparticle trapped by a double nanohole aperture

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Abstract: A double nanohole aperture in a gold film is used to trap a polystyrene nanosphere with a diameter of 20 nm. Fluorescence microscopy is used to track the position of the trapped nanosphere.

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1. Introduction

Conventional optical tweezers trap particles using the forces exerted by laser beams focused with lenses. They face challenges for the trapping of very small particles however because the forces are roughly proportional to particle volume. This means that the field intensity must be increased to maintain trap stability, but this can lead to deleterious thermal effects. In addition, diffraction sets a lower bound on the focal spot size, thereby determining the precision with which an object can be trapped. This has motivated interest in optical traps based on plasmonics [1]. Of note has been the ‘self-induced back action’ (SIBA) effect, in which the position of a trapped particle alters the resonance of a nanophotonic structure such as a nanoaperture [2]. It has been argued that using the SIBA effect, nanoparticles (NPs) can be stably trapped with laser powers and local intensities much smaller than what would be required using conventional tweezers [2] and experimental demonstrations have been made [3]. Recent theoretical analysis [4] has furthermore suggested that SIBA could enable a remarkable range of optical manipulation capabilities beyond those already demonstrated. The understanding and further development of the SIBA effect would be greatly facilitated by direct observation of the dynamics of trapped nanoparticles, i.e. position as a function of time. To the best of our knowledge, however, this has not been demonstrated in previous reports (e.g. [3]). In these reports, the trapping process was monitored by measuring the optical transmission (of trapping laser or of fluorescence from the trapped object) through the nanoaperture as a function of time, with step-like increases in transmission indicating the trapping of a nanoparticle. Here, we employ fluorescence microscopy to track the position of a polystyrene nanosphere (20 nm diameter) trapped via the SIBA effect by a double nanohole (DNH) aperture in a gold film. We anticipate that our method will be a valuable tool for the development of the SIBA effect.

2. Electromagnetic simulations

We first present electromagnetic simulations of the force exerted on a nanoparticle near a DNH aperture (Figure 1).

Fig.1. (a) DNH aperture in Au film: LEFT-scanning electron micrograph (SEM), RIGHT-simulated structure, comprising two holes (diameter $D = 100$ nm) separated by 140 nm (center-to-center). (b),(c) Simulation electric field ($|E|$) distribution, for plane wave illumination from water side (traveling in $+z$ direction, intensity $I = 6.67$ mW/ μm^2). Black dot indicates coordinate system origin. (b) $x = 0$ cross section (c) $z = -50$ nm cross section. (d),(e),(f),(g) Force exerted on particle ($n = 1.6$) as a function of particle diameter d and position. For intensity $I = 6.67$ mW/ μm^2 .

We use COMSOL to simulate our DNH (Fig.1a), formed in a gold film (100 nm thick) on a glass substrate covered with water. Plane wave illumination (x -polarized, $\lambda=1064$ nm) is incident from the water side, resulting in highly confined electric fields in the DNH (Fig.1b-c, no NP present). We next introduce our NP, compute the electric and magnetic fields on a surface that surrounds it, and determine the force using the Maxwell stress tensor (MST). In Fig.1d, we plot the peak force in the z -direction F_z as a function of NP diameter, assuming that the NP center is at $(x_{center}, y_{center}, z_{center})=(0,0,-102$ nm). It can be seen that force increases with diameter d . In Fig.1e, we plot F_z as a function of NP position along the z -axis, for $(x_{center}, y_{center})=(0,0)$. It can be seen that the NP is pulled into the DNH (F_z is positive). In Fig.1f, we plot F_x and F_z as functions of NP position along the x -axis, with $y_{center}=0$ nm, and $z_{center}=-50$ or -100 nm. The positive values of F_z confirm that the NP is pulled into the DNH. It can also be seen that F_x is positive (negative) when x_{center} is positive (negative). This indicates that the NP is pulled to the sides of the DNH gap (30 nm wide), to the positions denoted by red dots in Fig.1a. In Fig.1g, we plot F_y and F_z as functions of NP position along the y -axis, with $x_{center}=0$ nm, and $z_{center}=-50$ or -100 nm. The positive values of F_z again confirm that the NP is pulled into the DNH. It can also be seen that F_y is positive (negative) when y_{center} is negative (positive). This indicates that the NP experiences a restoring force for excursions in the y -direction from the DNH center ($y=0$).

3. Experimental results: dynamics of a trapped nanoparticle

Fig. 2a schematically illustrates our set-up. An x -polarized laser beam ($\lambda=1064$ nm) is focused by an oil immersion objective (100 $\times$, NA 1.3) into a sample chamber containing water, polystyrene NPs (FluoSpheres, 20 nm diameter, carboxylate-modified, Nile Red, Life Technologies) and a trace amount of surfactant (Tween 20) to prevent aggregation. A green laser ($\lambda=532$ nm) excites fluorescence, which is imaged onto an electron multiplying camera (EM-CCD) operated at 30 fps. Several EM-CCD frames are shown as Fig. 2b-d. At time t_0 , the NP moves randomly and is $\sim 2.8\mu\text{m}$ from the DNH. From time t_1 , the NP is stably trapped for ~ 34 seconds. At time t_2 , it is no longer trapped. We verify that blocking the laser results in quick release of the NP from the trap. We also verify that the NP is less strongly trapped (larger positional fluctuations) when the laser power is reduced or the polarization is rotated. To illustrate the trapping process, we plot the fluorescence intensity integrated over a 30×30 pixel cross section centered over the DNH vs time. At $t\sim 6$ s, the NP enters the DNH vicinity and becomes trapped, resulting in an abrupt jump in fluorescence. At $t\sim 49$ s, the trapping laser is turned off and the NP is released. Turning the laser on at $t\sim 55$ s results in the NP being trapped again. To assess the trapping more quantitatively, we determine the NP center positions from 1000 EM-CCD frames using a radial-symmetry-based particle localization algorithm [5] over an interval of 33s (Fig.2f). In Fig.2g-h, we plot the positions (x_c and y_c) as histograms. The full-widths-at-half maximum (FWHMs) of fitted Gaussian distributions are 59 and 190 nm along the x - and y -directions, respectively.

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Fig.2. (a) Experimental set-up. (b)-(d) EM-CCD frames showing trapping of NP by DNH (approx. position: yellow dot) and brightness scale bar. $P=38\text{mW}$ (before objective). (e) Fluorescence intensity vs time. $P=51\text{mW}$ (before objective). (f) Scatter plots of NP center locations. $P=15\text{mW}$ (before objective). (g),(h) Position histograms along x - and y -axes, extracted from data of panel f).

4. References

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