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Nanofiber-excited plasmonic manipulation of polystyrene nanospheres

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This paper reports optical nanofiber-excited plasmonic manipulation of polystyrene nanospheres. Gold nanoparticles (200 nm in diameter) are deposited on the surface of a nanofiber, and their local surface plasmon resonance (LSPR) is excited by the evanescent wave around the nanofiber. Theoretical results indicates that, the field enhancement resulting from the LSPR excitation can generate enhanced gradient and scattering forces acting on the spheres, and the accelerated propulsion occurred. To verify the prediction, experiments were performed to trap and transport polystyrene nanospheres along a 500 nm diameter fiber decorated with gold nanoparticles, the average enhancement factor of the velocity of spheres for the LSPR case is founded to be about 5 times with respect to the nanofiber case.

Introduction

Since the first demonstrated in 1970[1], optical tweezers have proven to be a powerful technique due to its successful implementation in the fields of physics, chemistry and biology[2-6]. This success largely lies in the noninvasive nature of optical forces, which can be acted on micro-/nano- particles without disturbing the environment. Despite these advance, optical tweezers are fundamentally limited by the natural diffraction of light, prevents direct manipulation of particles much smaller compared to the incident wavelength. One solution to the challenge is employing evanescent field around planar waveguides[7-9] and nanofibers[10-12], particles can be trapped by the gradient force that points along the gradient of the field, and transported along the wave propagation direction by the scattering force. Recently, it has been suggested to make use of surface plasmon resonance structures to trap and manipulate particles by their potential for considerably enhanced optical forces[13-16], For example, R. Quidant et al. report on novel 2D SP-based optical tweezers formed by finite gold areas fabricated at a glass surface.[17] Using a periodic array of gold disks, efficient trapping of micro-objects under reduced laser intensity compared with conventional optical tweezers have been reported[18]. Wang et al. demonstrated plasmonic trapping employing a thin micrometer scale gold stripe[19]. However, these plasmonic devices are largely limited by complex nanofabrication method and sophisticated optical structures. To resolve these problems, the incorporation of nanoparticles on nanofibers has recently received intensive attention due to their advantages such as flexibility, small size and low cost[20-22]. Since the evanescent wave from the nanofiber can excite the localized surface plasmon resonance (LSPR) of gold nanoparticles, in this paper, we demonstrated plasmonic manipulation of polystyrene nanospheres using an optical nanofiber decorated with gold nanoparticles. First, a theoretical analysis and prediction is presented based on three-dimensional finite difference time domain (3D FDTD) simulation. Then, experiments were performed to confirm the prediction by using a 500 nm diameter optical fiber decorated with gold nanoparticles to accelerate the PS spheres.

Theoretical analysis

When gold nanoparticles are deposited on the surface of a nanofiber, the LSPR of which can be excited by the evanescent wave from the nanofiber. To numerically investigate the plasmonic trapping and manipulation of nanospheres using an optical nanofiber

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decorated with gold nanoparticles, 3D simulation was performed using a finite difference time domain method. In the simulations, the refractive indices of nanofiber, polystyrene nanosphere and water were set to be 1.45, 1.58 and 1.33, respectively. The gold nanoparticle is modeled as a sphere, and the dielectric constant of which at a wavelength of 808 nm is taken as $-27.0 + 1.90i$. The distance between the nanofiber and the PS sphere is assumed to be 10 nm, equal to the Debye length estimated for the experimental parameters used. The optical power, i. e. the power launched into the front face of the nanofiber, is normalized to be 1 W. Fig. 1a shows the transversal cross-section view of the electric-field (E-field) distributions of an 500 nm fiber at an wavelength of 808 nm. It can be seen that, a proportion of the beam propagates outside the fiber as evanescent wave. Fig. 1b shows the transversal cross-section view of the E-field distributions of a 500 nm diameter nanofiber decorated with a gold nanoparticle for LSPR excitation. The result shows that, a larger enhancement was observed around the gold nanoparticle owing to the excited LSPR mode, the largest enhancement occurred at the gap between the gold nanoparticle and the nanofiber surface. The E-field magnitudes are much higher in the LSPR case than the nanofiber case, which is due to the enhanced fields resulting from LSPR excitation.

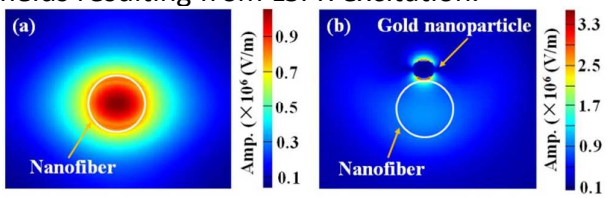

Fig. 1 (a) and (b). 3D FDTD transversal cross-section view of simulated E-field for nanofiber case and LSPR case, respectively. For the LSPR case, there is a gold nanoparticle deposited on the surface of the nanofiber.

The total optical force (F) exerted on the spheres consists of two orthogonal components, i. e. the gradient force (Fg) and the scattering force (Fs), which can be calculated by integrating the time-independent Maxwell stress tensor ($\langle T_M \rangle$) along the external surface of the sphere. $\langle T_M \rangle$ is described by

$$\langle \mathbf{T}_M \rangle = \mathbf{D}\mathbf{E}^* + \mathbf{H}\mathbf{B}^* - \tfrac{1}{2}\left(\mathbf{D}\cdot\mathbf{E}^* + \mathbf{H}\cdot\mathbf{B}^*\right)\mathbf{I}, \quad (1)$$

where D is the electric displacement, H is the magnetic field, E is the electric field, B is the magnetic flux field, and I is the isotropic tensor. The optical force F can be obtained by

$$\mathbf{F} = \oint_S (\langle \mathbf{T}_M \rangle \cdot \mathbf{n}) ds, \quad (2)$$

where $\mathbf{n}$ is the normal vector pointing outward from the surface S of the sphere.

Fig. 2 shows the gradient force and scattering force exerted on a 200 nm PS sphere under the action of conventional evanescent field of nanofiber as a function of fiber diameter, both forces reach the maximum values at the fiber diameter of 500 nm and 400 nm, respectively. For a large fiber diameter, most of the guided power is confined within the fiber, the decrease of forces is owing to the evanescent field around the fiber surface is relatively weak. Moreover, when the fiber diameter is below these values, a larger proportion of the energy penetrates into the surrounding medium resulting in a decrease of the optical gradient and scattering forces. Therefore, in this paper, the diameter of nanofiber was chosen to be 500 nm.

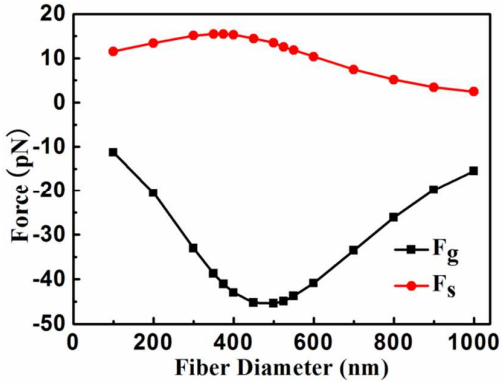

Fig. 2 Calculated optical gradient and scattering forces exerted on a 200 nm PS sphere versus fiber diameter.

To further understand the enhanced optical force of PS spheres at LSPR excitation, simulation was performed by calculating the optical gradient and scattering force acting on a 200 nm PS sphere ,which was placed on the surface of a gold nanoparticle deposited on the nanofiber. The calculated optical force as a function of gold nanoparticle size is shown in Fig. 3a.It can be seen that, the maximum value occurs for a size of 150 nm, the sizes of the gold nanoparticles for high efficiency trapping and manipulation of nanospheres are 125–200 nm. Fig. 3b shows the dependence of the magnification times (M) of optical force on the gold nanoparticle size, M was obtained by calculating ratio of optical force acted on the PS sphere for LSPR case by comparison to the nanofiber case.

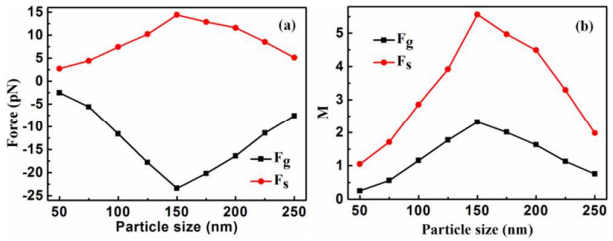

Fig. 3 (a) For the position decorated with a gold nanoparticle, optical gradient and scattering forces acted on a 200 nm PS sphere as a function of gold nanoparicle size. (b) The magnification times (M) of optical force on a 200 nm PS sphere as a function of gold nanoparticle size.

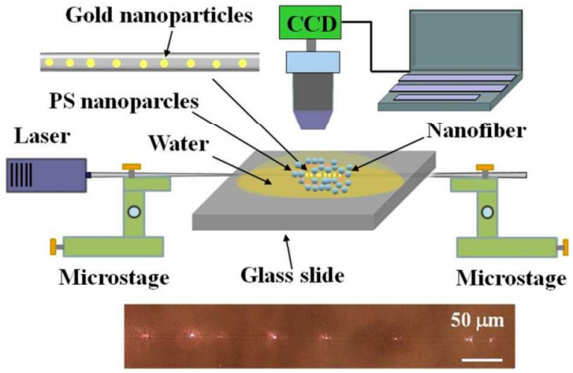

Fig. 4 Schematic of the experimental setup.

Experimental setup

To verify the theoretical prediction, experiments were performed using a 500 nm fiber decorated with gold nanoparticles (200 nm in diameter), the experimental setup is schematically shown in Fig. 4. A computer interfaced optical microscope with a CCD camera mounted on the top is used for real-time monitoring. The nanofiber (500 nm in diameter) was draw from a standard telecommunication single mode optical fiber (SMF-28, Corning, Inc.) by a flame-heated method. A solution was adjusted at a *p*H of 3 by adding HCL solution to facilitate the deposition of gold nanoparticles onto the nanofiber, which was prepared by diluting 200 nm gold nanoparticles (purchased from Nanoseedz, Ltd) into deionized water (volume ratio of particles to water is 1:3,000) with the assistance of the ultrasonic wave vibration for 40 minutes. The nanofiber was immersed into the solution for 60 s and thereafter rinsing with deionized water, some gold nanoparticles deposited onto the surface of the nanofiber are well separated from each other without aggregation, as shown in Fig. 4. In the experiment, the nanofiber decorated with gold nanoparticles was immersed in a 200 nm PS sphere solution (volume ratio of spheres to water is 1:1,000) with two ends fixed by two tunable microstages. The 808 nm laser source was connected to the one end of the nanofiber, the evanescent wave of which was used to excite the LSPR modes of gold nanoparticles.

Results and discussion

Gold nanoparticles were purchased from the supplier, and the LSPR wavelength is 808 nm. When the laser beam was injected into the nanofiber, the PS nanospheres (200 nm in diameter) will be trapped by optical gradient force and transported along the direction of light propagation owing to scattering force induced by the evanescent field. The injected power was measured at the output of the laser source using an optical power meter. When the PS spheres moves along the nanofiber decorated with gold nanoparticles, due to enhanced optical force acted on the spheres provided by the LSPR excitation of gold nanoparticles, the accelerated propulsion occurred. A sequence of optical microscope images of a PS sphere at an optical power of 100 mV is shown in Fig. 5, which were recorded by the CCD camera at a rate of 15 frames per second. The PS sphere moved along the fiber at a distance of 160 μm in the period of first 0.3 s, and the estimated transportation velocity is 533 μm/s. In the next 0.3 s, the transported distance is 179 μm, and the velocity of the sphere is estimated to be 599 μm/s, therefore, the average velocity of the sphere is estimated to be 565 μm/s. For comparison, the velocity of a 200 nm PS sphere delivered along the conventional evanescent field of the nanofiber is measured to be 110 μm/s, the enhanced factor of the velocity is estimated to be of about 5 times.

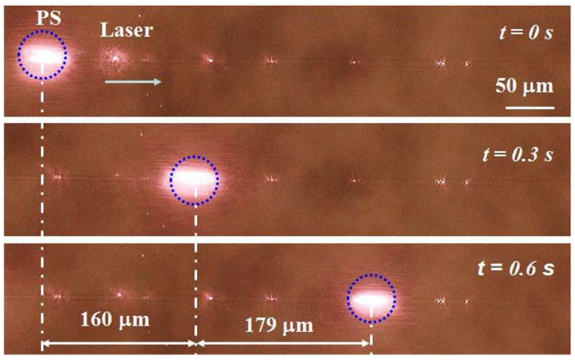

Fig. 5 Consecutive optical microscope images of a PS nanosphere transported along the 500 nm fiber decorated with gold nanoparticles at an optical power of 100 mW.

Fig. 6 shows the measured average velocities of nanospheres transported by optical forces versus the optical power. Each point of the experimental data represents the average velocity of the 20 spheres. The result shows that, the measured velocity increases with the input power for both cases. For example, at an optical power of 20 mW, the average velocity of spheres moved along the conventional evanescent field of the nanofiber is estimated to be 13 μm/s, however, when spheres delivered along the nanofiber decorated with gold nanoparticles, the average velocity enhanced to be 54 μm/s. When the optical power increases to be 110 mV, the average velocity of spheres reached to be 119 μm/s for the evanescent field of the nanofiber and 656 μm/s for the LSPR mode, respectively. The average velocity is about 5 times larger for the LSPR case than the nanofiber case, the result of the experiment is in good agreement with the theoretical prediction.

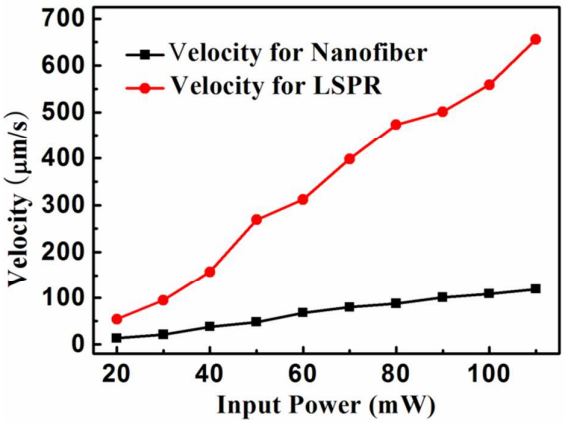

Fig. 6 Measured average velocity for nanofiber case and LSPR case as a function of input optical power.

Conclusions

In conclusion, we theoretically and experimentally demonstrated the enhanced propulsion of 200 nm PS spheres using a 500 nm nanofiber decorated with gold nanoparticles by launching into the 808 nm laser beam. From 3D FDTD simulations, we attribute the enhanced optical force exerted on spheres to field enhancement provided by LSPR excitation of gold nanoparticles. Experiment was performed to confirm the theoretical calculation. The use of LSPR of gold nanoparticles deposited on the nanofiber in optical manipulation opens new perspectives by addressing the current main limitations of conventional optical nanofiber. This work would be advantages for nanoparticle trapping and manipulation.

Acknowledgements

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Notes and references

‡ Footnotes relating to the main text should appear here. These might include comments relevant to but not central to the matter under discussion, limited experimental and spectral data, and crystallographic data.

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