Optical manipulation of gold nanoparticles using an optical nanofiber

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Gold nanoparticles are gaining increasing attention due to their biological and medical applications. In this letter, we experimentally demonstrate the optical manipulation of 250-nm-diameter gold nanoparticles along an optical nanofiber (550 nm in diameter) injected by an 808-nm laser light. The nanoparticles situated in the evanescent optical field are trapped by optical gradient force and move along the direction of light propagation due to optical scattering force. The velocities reach as high as 132 μm/s at an optical power of 80 mW.

Keywords: optical manipulation, gold nanoparticles, nanofiber

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1. Introduction

Optical manipulation has paved the way to applications in the development of physics, chemistry, and biology.[1–5] The optical tweezer[6–11] is a contactless and nondestructive tool, which can localize particles to a focal spot with high precision. However, a major obstacle of this conventional technique is the diffraction limit. Alternately, there is a growing interest in using an evanescent field based on the strong confinement of the electromagnetic field, which can be utilized to trap and move the particles with the help of optical gradient force and scattering force. The evanescent fields around some devices, such as total reflection prisms,[12] planar waveguides,[13–15] and photonic resonators,[16,17] enable strong optical gradient and scattering forces to be exerted on particles. Recently, optical nanofibers were also used to manipulate polystyrene submicro particles.[18–20] Compared with planar waveguides, nanofibers require no substrate, and maximize the fraction of the mode outside the nanofibers. Moreover, optical manipulation of gold nanoparticles using optical nanofibers has not yet been reported. Here we investigate optical trapping and transportation of gold nanoparticles along an optical nanofiber using an 808-nm laser light. Because the chemical properties of gold nanoparticles allow for multifarious types of custom functionalization, the stable manipulation of gold nanoparticles can open broad applications in chemistry, biology, and medicine.

2. Theoretical analysis

To obtain a suitable diameter of nanofiber for optical manipulation of gold nanoparticles, we simulated electric (E)-field distribution of the 808-nm laser light at the interface between the nanofibers and surrounding water based on a three-dimensional finite-difference time-domain method. The refractive index of the nanofiber and water were assumed to be 1.45 and 1.33, respectively, and the E-field was normalized per unit power. Figure 1 shows the dependence of the normalized E-field on the nanofiber diameter. It can be seen that the maximum E-field at the interface of the nanofiber and water exists for a diameter of 550 nm. Due to the mode confined within the nanofiber, the E-field at the surface is small at relatively big diameters, while at small diameters the evanescent wave scatters into the water. Therefore, nanofiber with a diameter of 550 nm was used in the experiment.

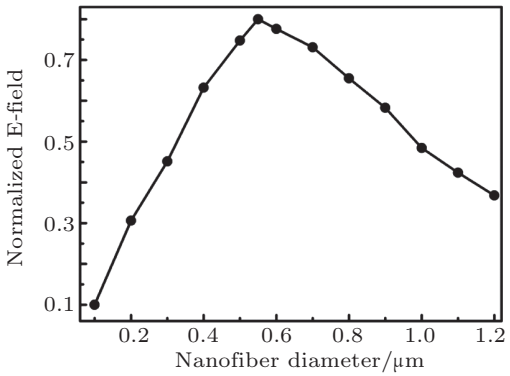


Fig. 1. Simulated relation between the normalized E-field distribution of the 808-nm laser light and the nanofiber diameter.

3. Experiment and discussion

Figure 2 schematically indicates the experimental apparatus. The nanofiber was fabricated as the minimum waist of a tapered optical fiber (TOF) through a flame-heated method by drawing a standard telecommunication single-mode optical fiber (SWF-28, Coring Inc.). The diameter and length of the waist are 550 nm and 5 mm, respectively, and the length of the tapered region at both sides of the waist is 20 mm. In the experiment, the nanofiber was positioned on a microslide substrate, and fastened by two microstages. One pigtail of the

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nanofiber was linked to an 808-nm laser source, which denotes extremely low insertion loss. The optical power was measured at the output of the laser source using an optical power meter. The 250-nm gold nanoparticles were dispersed in the water (volume ratio of particle to water is about 1:1000). To avoid aggregation of the gold nanoparticles, the suspension was assisted by ultrasonic wave vibration for 20 min before the experiment.[21] Drops of the nanoparticle suspension were laid on the microslide substrate with a pipette, and used to surround the nanofiber. A computer-connected camera and microscope with optional magnifying objective lens (5×, 20×, 40×, and 100×) were used for real-time monitoring.

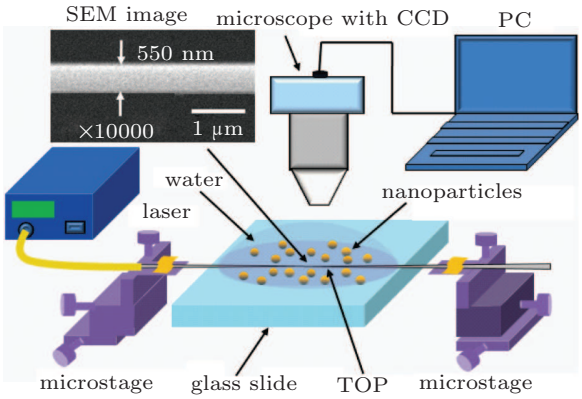


Fig. 2. (color online) Schematic of the experimental apparatus. TOF denotes tapered optical fiber.

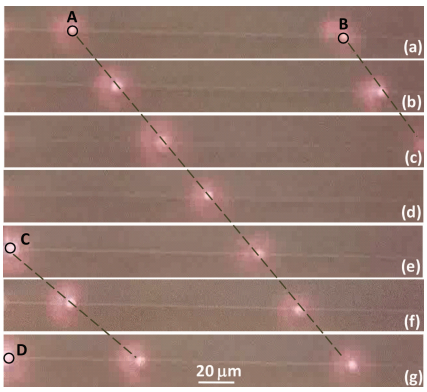


Fig. 3. (color online) Seven consecutive microscope images of 250-nm gold nanoparticles A, B, C, and D transported along a 550-nm nanofiber at an optical power of 15 mW. Images were taken with an interval of 3 s.

Once the injected optical power of the 808-nm laser source increases to 10 mW, gold nanoparticles near the nanofiber are trapped by optical gradient force, and stably transported along the direction of light propagation owing to the scattering force.[22] Because the viscous drag force balances scattering force on the particles, the gold nanoparticles swiftly arrive at a constant transport velocity. Figure 3 shows seven sequential pictures taken by the CCD within an interval of 3 s at an optical power of 15 mW, and the particles are displayed as bright spots due to scattering of the strong evanescent wave. As the manufacturer specifies, the variation of nanoparticle size is $\sim 5\%$, particles with different diameters have different velocities at the same evanescent field distribution area. For example, particle A moves a distance of 155.88 μm in the period of 18 s, and the velocity was estimated to be 8.66 μm/s. The propulsion velocities of the particles B and C were measured to be 7.30 and 11.85 μm/s, respectively.

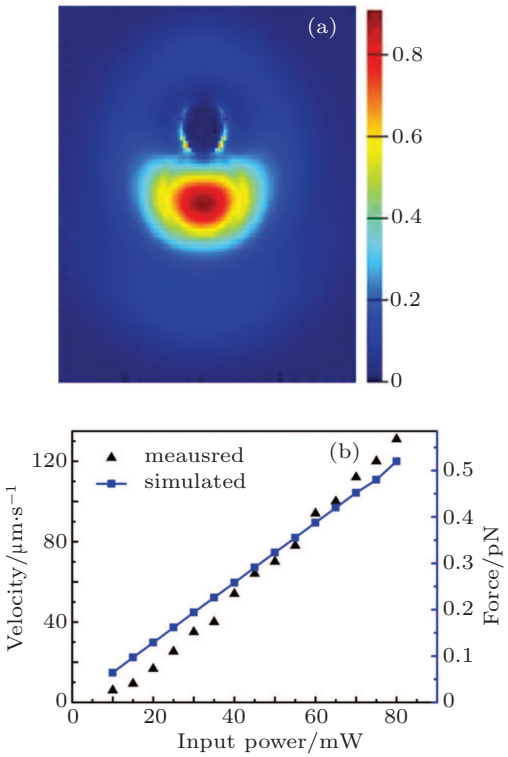


Fig. 4. (color online) (a) The transversal cross-section view of the simulated electric field amplitude distribution of a gold nanoparticle placed on the 550-nm-diameter nanofiber. (b) Plot of measured average velocity (left axis) and optical scattering force (right axis) versus input power. The blue line with square symbols corresponds to simulation data, and triangles correspond to the measured data. Each measured data point represents the average value of many particles at the same evanescent field distribution.

The simulated force is computed by the integral of the Maxwell stress tensor along the total external surface of the particle based on three-dimensional finite-difference time-domain (3D-FDTD) simulation. Figure 4(a) shows the transversal cross-section view of the simulated electric-field amplitude distribution of a gold nanoparticle placed on the 550-nm-diameter nanofiber. Figure 4(b) shows the simulated and measured optical scattering force dependence of the input power. Using the Stokes' drag formula $F = 6\pi r\eta v$, we can obtain the measured optical scattering force exerted on the nanoparticles along the nanofiber. Here F is the viscous force, and is equal to the optical scattering force along the propagation direction of the laser light, r is the radius of the gold nanoparticle, v is the average velocity of nanoparticles. We make use of the room-temperature viscosity of water ($\eta = 8.9 \times 10^{-4}$ Pa·s) is that no obvious temperature change

emerged in the process of the measurement. To ensure identical evanescent field distribution at the same input power, all particle velocity measurements were performed along a 230-μm-long nanofiber. It can be observed that the transportation velocity is linearly fitted with the input power. Average velocities of particles as high as 132 μm/s were obtained at an input power of 80 mW.

4. Conclusion

In summary, we have demonstrated optical trapping and transportation of 250-nm gold nanoparticles using a 550-nm-diameter nanofiber. Velocities of the particles increase with increasing input power, and the maximum average velocities reach 132 μm/s at an input power of 80 mW. This technique may be of wide interest for applications in chemistry, biology, and medicine.

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