Size-dependent trapping and delivery of submicro-spheres using a submicrofibre

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Abstract. We report size-dependent trapping and delivery of polystyrene submicro-spheres using a 600 nm diameter fibre. Theoretical results show that both gradient and scattering forces exerted on polystyrene submicro-spheres by the evanescent wave field around the submicrofibre increase with an increase in the sphere diameter, and the delivery velocity of the bigger spheres is also higher than that of smaller spheres. To support the theoretical predictions, experiments were performed using polystyrene spheres with diameters of 230, 400, 530 and 700 nm by injecting a 532 nm green laser into the fibre. The results demonstrate that spheres with larger diameter can be more easily trapped to the surface of the fibre and delivered in the propagation direction of the laser at a low input laser power.

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1. Introduction

Size-dependent trapping and delivery/guiding of particles are important issues in particle micromanipulation or sorting applications, concerning the toxic potential in particles with sizes of tens of nanometres [1]. With methods such as chromatography [2], gel electrophoresis [3] and microfluidic technology [4, 5] being continually refined, there is a growing trend toward size-dependent trapping and delivery of particles using the optical method due to its non-contact nature and simple geometry. Classical optical methods use one or multiple Gaussian beams to achieve trapping and delivery of particles [6–8]. Periodic optical landscape methods have also been presented to be used for large-scale particle trapping [9–11]. In addition, due to strong field confinement, non-diffracting beams, such as Bessel beams [12], Airy beams [13] and Vortex beams [14], have been applied for large-scale optical trapping and delivery of particles. In recent years, with their features of powerful trapping and delivery, evanescent waves at surfaces have also been proposed for use in large-scale organization [15, 16], long-range delivery [17–20], self-organization [21] and so on. In particular, in trapping and delivery of micro/nanoparticles [22–26], the evanescent wave around subwavelength diameter optical fibre exhibits some unique capabilities such as considerable power leakage outside the fibre, enhanced evanescent wave field, extremely low coupling and transmission loss, and flexibility in three-dimensional (3D) geometry [27]. Therefore, subwavelength-diameter optical fibre would be a preferable candidate for size-dependent trapping and delivery of submicro-spheres. To verify this idea, in this paper, we first do a theoretical analysis and prediction based on simulations. We then perform experiments to confirm the prediction via polystyrene submicro-spheres using a single submicrofibre by injecting a 532 nm green laser.

2. Theoretical analysis

To find a suitable fibre diameter, 3D simulation was performed using a finite-difference time-domain (FDTD) method. Figures 1(a)–(f) show the transversal cross-section view of the simulated electric-field (E-field) distributions by injecting a 532 nm green laser into different diameter fibres. The input optical power, i.e. the power injected into the front face of the submicrofibre, is normalized to be 1 W. The use of 532 nm green laser is made because this wavelength exhibits a very low absorptivity for water. The refractive indices of fibre (silica) and environment (water) at 532 nm wavelength are 1.46 and 1.33, respectively. According to the simulations, we know that when the fibre diameter ($D_{\text{fibre}}$) is increased from 200 nm (figure 1(a)) to 250 (figure 1(b)), 300 (figure 1(c)), 400 (figure 1(d)), 600 (figure 1(e)) and 800 nm (figure 1(f)), the calculated optical power leakage decreases from 96% to 85, 76, 55, 22 and 8%, respectively. Fibre with a smaller diameter provides higher optical power leakage than that with a larger diameter. Figure 1(g) shows the normalized E-field at the surface of the fibre and the power leakage as a function of fibre diameter. From figure 1(g), it can be seen that the normalized E-field reaches a maximum value of 69% at the fibre diameter of 350 nm. The fibres with diameters of about 300 nm are suitable for particle trapping and delivery because of high power leakage and normalized E-field. However, concerning the mechanical properties, a fibre with smaller diameter is more fragile than a fibre with larger diameter. Since the normalized surface E-fields (55%) and the power leakage (22%) of fibre with diameter of 600 nm are adequate to trap and deliver the particles, the fibre with 600 nm diameter is chosen as an example in our experiments.
Figure 1. (a)–(f) Transversal cross-section view of simulated E-field distributions with a 532 nm green laser injected in fibres with diameters ($D_{\text{fibre}}$) of (a) 200 nm, (b) 250 nm, (c) 300 nm, (d) 400 nm, (e) 600 nm and (f) 800 nm. (g) Normalized E-field at the surface of the fibre and optical power leakage versus fibre diameter.

To theoretically investigate size-dependent trapping and delivery of particles using a 600 nm diameter submicrofibre, we use polystyrene spheres with diameters ($D_{\text{sphere}}$) of several hundreds of nanometres. The refractive index of the polystyrene spheres is 1.6 at 532 nm wavelength. Figures 2(a)–(d) show the longitudinal views of the simulated E-field distributions with different diameter spheres trapped at a position of 20 nm from the fibre surface. The input power is also normalized to be 1 W. The optical force $F$ exerted on the sphere by the evanescent wave field around the fibre is calculated using $F = (n/c) \int \int \Delta S dA$ [28], where $n$ is the refractive index of the surround medium (water), $c$ is the speed of light in vacuum and $\Delta S$ is the difference between the energy density flux through the unit area travelling into and coming out of the sphere. The force $F$ consists of two components. One is the gradient force $F_g$ that attracts the spheres toward the surface of the fibre, and the other is the scattering force $F_s$ that propels the trapped sphere to move along the fibre in the propagation direction of laser. The $F_g$ and $F_s$ can be expressed as $F_g = (n/c) \int \int \Delta S \perp dA$ and $F_s = (n/c) \int \int \Delta S \parallel dA$, respectively, where $\Delta S \perp$ is the component of $\Delta S$ in a direction perpendicular to the fibre, and $\Delta S \parallel$ is the component in a direction parallel to the fibre. The forces are calculated 10 $\mu$m from the front face of the fibre, where a spatial steady state is established. Figure 2(e) shows the calculated $F_g$ and $F_s$ exerted on different diameter spheres. When the sphere diameter increases from 200 nm to 400, 600 and 800 nm, the calculated $F_g$ increases from 1.9 to 7.8, 17 and 31 pN, while $F_s$ increases from 4.7 to 20, 39 and 60 pN. Figure 2(f) shows the calculated delivery velocities ($V$)
Figure 2. (a)–(d) Longitudinal cross-section view of simulated E-field distribution along a 600 nm diameter fibre with sphere diameters ($D_{\text{sphere}}$) of (a) 200 nm, (b) 400 nm, (c) 600 nm and (d) 800 nm trapped at a position 20 nm from the fibre surface. (e) Calculated optical forces exerted on the different diameter spheres. (f) Calculated delivery velocities for different diameter spheres. The input power is normalized to be 1 W.

for different diameter spheres, which were calculated according to $V = F_v / 3\pi D_{\text{sphere}} \eta$ by Stokes’ drag formula [29], where $F_v$ is the viscous force which is equal to the scattering force ($F_s$), and $\eta$ is the room temperature dynamic viscosity of water ($\eta = 9.144 \times 10^{-4}$ Pa s). It can be seen that a hump appears for sphere diameters around the laser wavelength (532 nm). This is because the increase of optical force with increasing of sphere diameter becomes slower when the sphere diameter exceeds the laser wavelength [30]. Since spheres with larger diameters have much higher delivery velocities, different size spheres can be delivered with different velocities. For the particle trapping and delivering method based on a planar waveguide [20], under the same input optical power, the calculated scattering force exerted on the spheres trapped to the surface of the waveguide also increases with increasing sphere diameter. However, the magnitude of the calculated scattering force at unit power in the present work is one order larger than that in the case of a planar waveguide, indicating that the submicrofibre can be more efficient in delivery of particles.

3. Experiments

To verify the theoretical prediction, experiments were performed using the setup schematically shown in figure 3. We used 600 nm diameter fibre that was drawn from a telecom single-mode silica fibre using a flame-heating technique [25]. The measured optical loss of the fabricated fibre is about 0.2 dB. The diameters of the polystyrene spheres are 230, 400, 530 and 700 nm.
During the experiment, a drop of aqueous solution of polystyrene spheres was placed on a slide with the 600 nm diameter fibre immersed in it. One pigtail of the fibre is connected to a 532 nm wavelength laser for optical power supply. Real-time monitoring was performed using a computer-interfaced charge-coupled device (CCD) camera mounted on top of the optical microscope.

We first observed the trapping and delivery of polystyrene spheres with diameters of 400 and 700 nm. Figure 4(a) shows the optical microscope image of the 600 nm diameter fibre, which was immersed in the aqueous solution of spheres without optical power launched into the fibre. Note that spheres of both diameters were randomly distributed in water and no trapping and delivery were observed. The inset of figure 4(a) shows an SEM image of the fibre. With an optical power from 0 to 2 mW launched into the fibre, no trapping of spheres was observed and only a very short delivery distance (<10 µm) for the spheres occurred close to the fibre surface. The reason is that the $F_g$ exerted on the spheres is too weak to trap them to the fibre surface. However, as the magnitude of $F_s$ is 2.1–2.6 times that of $F_g$, propulsion of the sphere along the fibre occurs once it approaches the fibre surface. As the input power was gradually increased over 2 mW but less than 10 mW, the 700 nm diameter spheres near the fibre were stably trapped and delivered along the fibre, while the 400 nm diameter spheres still cannot be trapped. The reason is that, at the same input power, the $F_g$ and $F_s$ exerted on 700 nm diameter spheres are 2.9 and 2.4 times larger than those exerted on 400 nm diameter spheres as predicted by the theoretical calculations. Figures 4(b)–(f) show five consecutive images of the delivered spheres taken by the CCD with 1 s intervals at an input power of 3.5 mW, in which only 700 nm diameter spheres were stably trapped and delivered along the fibre. The measured average delivery velocity is 23 µm s$^{-1}$ for spheres A$_1$, A$_2$ and A$_3$ in figure 4. Each bright spot represents a sphere. Because the optical fields outside the fibre decrease with increasing distance to the fibre [22], the bright spots of spheres B$_1$ and B$_2$ are much weaker and smaller. When the input power was increased to 10 mW, stable trapping and delivery of 400 nm diameter spheres occurred. Figure 5 shows five consecutive images of
Figure 4. Optical microscope images. (a) 600 nm diameter fibre immersed in an aqueous solution of submicro-spheres. The inset is a scanning electron microscope (SEM) image of the fibre. (b)–(f) Delivery of 700 nm diameter spheres with an input power of 3.5 mW.

Figure 5. Optical microscope images of delivered 400 nm (indicated by $B_3$) and 700 nm (indicated by $A_4$) diameter spheres with an input power of 10 mW.
both the 400 nm (indicated by B) and 700 nm (indicated by A) diameter spheres trapped and delivered, which were taken by the CCD with 1 s intervals at an input optical power of 10 mW. Under this condition, the measured average delivery velocity for the 400 nm diameter spheres is 24 µm s⁻¹, while that for the 700 nm diameter spheres is 63 µm s⁻¹.

Figure 6(a) shows the measured delivery velocities (v) of four different diameter spheres versus input power. It can be seen that the minimum input powers for stable trapping and delivery of 230, 400, 530 and 700 nm diameter spheres are 21, 10, 3.5 and 2 mW, respectively. This indicates that larger spheres are more easily trapped to the surface of the fibre at a low input power, which is attributed to stronger $F_g$ exerted on larger spheres as shown by figure 2(e). For comparison, theoretical calculated velocities ($V$) are shown in figure 6(b). It can be seen that in both experimental and theoretical results, the delivery velocities for larger spheres are higher than those for smaller spheres at the same input power. For a specific sphere diameter, the delivery velocities of the spheres are proportional to the input power, which coincides with the case of the planar waveguide [20]. Besides, according to the experimental results shown in figure 6(a), the average sphere delivery velocities at unit power can be calculated and the results are larger than those obtained using a planar waveguide for the same sphere size. For example, for a 700 nm diameter sphere, the calculated average sphere delivery velocity is 7084 µm s⁻¹ W⁻¹, which is about 44 times that using a planar waveguide (about 160 µm s⁻¹ W⁻¹). The results confirm that the submicrofibre used in our experiment is more efficient in delivery of submicro-spheres.

4. Conclusions

In summary, size-dependent trapping and delivery of submicro-spheres has been presented by injecting a 532 nm wavelength laser into a 600 nm diameter fibre. 3D FDTD simulation-based theoretical calculations show that the gradient and scattering forces exerted on the spheres induced by evanescent waves around the fibre increase with increasing sphere diameter, predicting that large-size spheres can be trapped more easily and delivered much faster than small ones. Experiment performed on 230, 400, 530 and 700 nm diameter spheres has confirmed the theoretical calculations. We believe that the size-dependent trapping and delivery using a submicrofibre will find potential applications in organic submicro/nano-systems, especially synthetic and biological polymers.
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