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Optical propulsion of microspheres along a channel waveguide produced by Cs^+ ion-exchange in glass

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Abstract

Experimental results on optical propulsion of polystyrene microspheres are presented. Particles of 3, 7 and 10 μm diameter were stably trapped and propelled on top of a waveguide. The waveguides were made by Cs^+ ion-exchange in glass for singlemode operation at 1082 nm. The highest average velocity for single particles was about 33 $\mu m/s$, achieved for 10 μm diameter particles and a fibre output power of 870 mW. Particle velocity was measured as a function of the fibre output power for the three different particle sizes. Under the same input conditions, it was observed that collections of particles move faster than single particles and that the velocity increases with particle size. The formation of several hundred micrometer long chains of particles and some evidence of particle binding is reported.

Key words:
Optical trapping, Optical propulsion, Optical binding, Evanescent field, Optical waveguide, Ion-exchange, Polystyrene spheres, Mie particles, Microspheres
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1 Introduction

Optical trapping of particles by an evanescent field in the cover region of a channel waveguide was first experimentally demonstrated in 1996, by Kawata and Tani [1]. Particles which are optically more dense than the surrounding

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medium are attracted to the high intensity region by the gradient force and propelled in the direction of the propagation of light by the radiation pressure [2–5]. This technique combines the possibilities of conventional optical tweezers [6–9] with the techniques employed in integrated optics and can be applied over a range of particle types. Optical manipulation of living cells provides advantages such as reduced sample size, high positional accuracy and a sterile, non-invasive procedure [9–11]. In combination with various integrated optics structures, such as branching waveguides, optical switching devices, optical modulators and so on, this technique may find applications in cell sorting, transporting and mixing devices [12]. In addition, different molecules of interest can be linked to microspheres and thus manipulated by means of optical trapping and propulsion [13,14]. Experimental investigation of particle propulsion has been reported for dielectric microparticles and metallic nanoparticles in the evanescent field of singlemode, as well as multimode channel waveguides [1,12,15,16].

In this paper, we characterize the optical propulsion of dielectric microparticles on a Cs^+ ion-exchanged channel waveguide formed in glass. To our knowledge this kind of waveguide has not been used previously for particle manipulation. Relatively high refractive index increase gives a more confined field which leads to advantages such as more stable trapping at higher propulsion speeds than reported in [1,12]. However, compared to previously used K^+ ion-exchanged channel waveguides, Cs^+ ion-exchanged waveguides have higher losses. Particle velocity is measured as a function of the input power for three different particle sizes. Under the same input conditions, the dependence of the particle velocity on the particle size is investigated. We also observe chains formed of particles of different sizes, and witness the formation of several hundred micrometers long chains formed of identical particles.

In the next section the experimental procedures are described. The results are presented in Section 3 and discussed in Section 4. Concluding remarks are given in Section 5.

2 Experimental procedures

The experimental setup is shown in Figure 1. Channel waveguides, about 4 cm long, were formed in a sodá lime glass by Cs^+ ion-exchange. The substrate was coated with an aluminium mask which was photolithographically patterned with 2.5 μm wide stripe openings. Ion-exchange was performed in molten $CsNO_3$ salt at 450°C. A diffusion duration of 21h resulted in single mode waveguides at 1082 nm, which is the wavelength of the Ytterbium fibre laser used as the light source in our experiments. The refractive index profile was estimated by prism coupling and the fitting of a theoretical curve (Fermi function). The surface index increase was found to be approximately 0.03. The

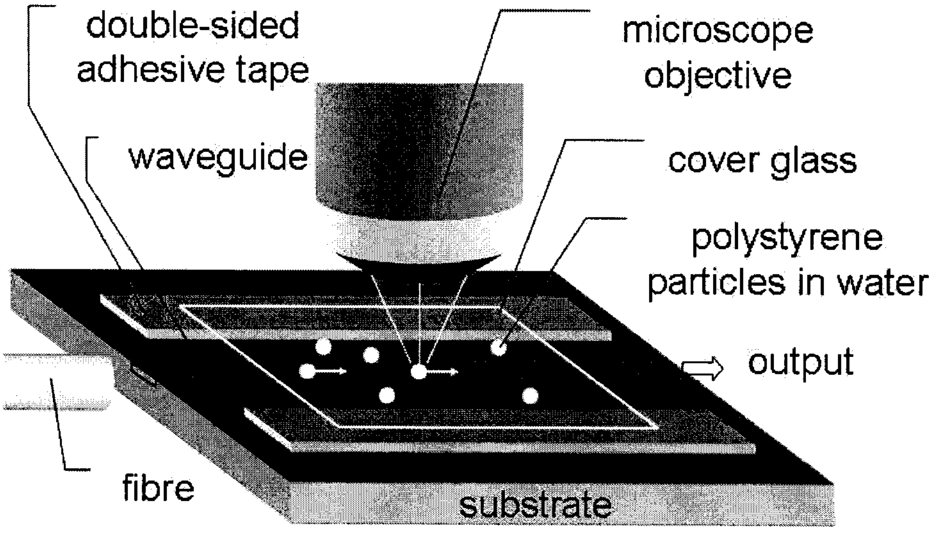

Fig. 1. Experimental setup for motion tracking of latex microspheres.

light was coupled from the fibre to the waveguide by direct butting. The measured overall loss of the waveguide used for our experiments was 8 dB. This loss incorporates loss due to the coupling of the fibre to the waveguide and the waveguide propagation loss. The laser light was linearly polarized and the polarization set to TE with a rotational fibre holder. We used polystyrene beads of 1, 3, 7 and 10 μm diameter. Standard deviations for the given diameters were 0.056 μm and 0.11 μm for 7 and 10 μm diameter particles, respectively. For 1 and 3 μm diameter particles, standard deviations were not given. The refractive index of these particles is $n = 1.59$ and the specific gravity is 1.05 g/cm^3. Microspheres were diluted in de-ionized water ($n = 1.33$). The particle solution was pippetted on the top of the waveguide and confined in a very shallow volume defined by spacers (made of double-sided adhesive tape) and a glass cover slip on top. An optical microscope with a 50 times microscope objective was used to observe the particles with dark field illumination from above. A bandpass filter which transmitts light in the wavelength range 350 to 650 nm was used to cut off the scattered laser light from the microscope image. A CCD camera was mounted on top of the microscope. The image obtained was monitored, recorded with a VCR and forwarded to a computer for conversion to a digital format.

Particles were observed through the microscope and the time needed for them to travel a 100 μm distance along the waveguide was recorded, so the velocity could be calculated. All particle velocity measurements were made at the same, convenient spot on top of the waveguide, 12 mm away from the input facet of the waveguide.

3 Results

We found that particles of 1 μm diameter could not be trapped at all using our setup, while the trapping was successful for larger particles. Once trapped, particles would be stably propelled in the direction of the radiation unless they hit an obstacle. When the laser was switched off, particles would stop their forward progress immediately and randomly wander away from one another and the waveguide.

The measured waveguide output power was observed to drop considerably with the number of particles trapped on top of the waveguide. Therefore, it was more convenient to plot the particle velocities against the fibre output power incident upon the waveguide rather than against the waveguide output power. The power reaching the particles was some 3 to 6 dB lower than the fibre output power due to the coupling loss and the waveguide propagation and scattering losses. The particle velocity decreased both along the waveguide and as the number of trapped particles increased.

Two different types of experiments were conducted. Firstly, the particle velocity dependence on the fibre output power was measured for each of the three different particle sizes in turn. The results of these measurements are presented in subsection 3.1. Secondly, in order to investigate the particle velocity dependence on the particle size, another type of experiment was performed. Particles of different sizes were mixed and their velocity was measured for the same input power. The results of these measurements are presented in subsection 3.2.

3.1 One-size particle experiments

In this subsection we present the results of the experiments where only one size of particles was present in the cell at a time. Particles were observed to form chains of different lengths. We use the word "chain" to describe the collective motion of two or more particles travelling together. Under the same input power, the collections of particles were observed to move faster than single particles. The formation of one such chain is illustrated in Figure 2. Note that light is launched from the right hand side in this and subsequent figures. The collection of particles B and C is propelled faster than a single particle A, which results in the formation of a three-particle chain, as seen in the fourth image. These chains could reach several hundred micrometers in length, as illustrated in Figure 3.

Due to the favoured collective particle motion, single particles were very difficult to observe. Therefore, we measured the velocities of particles in chains,

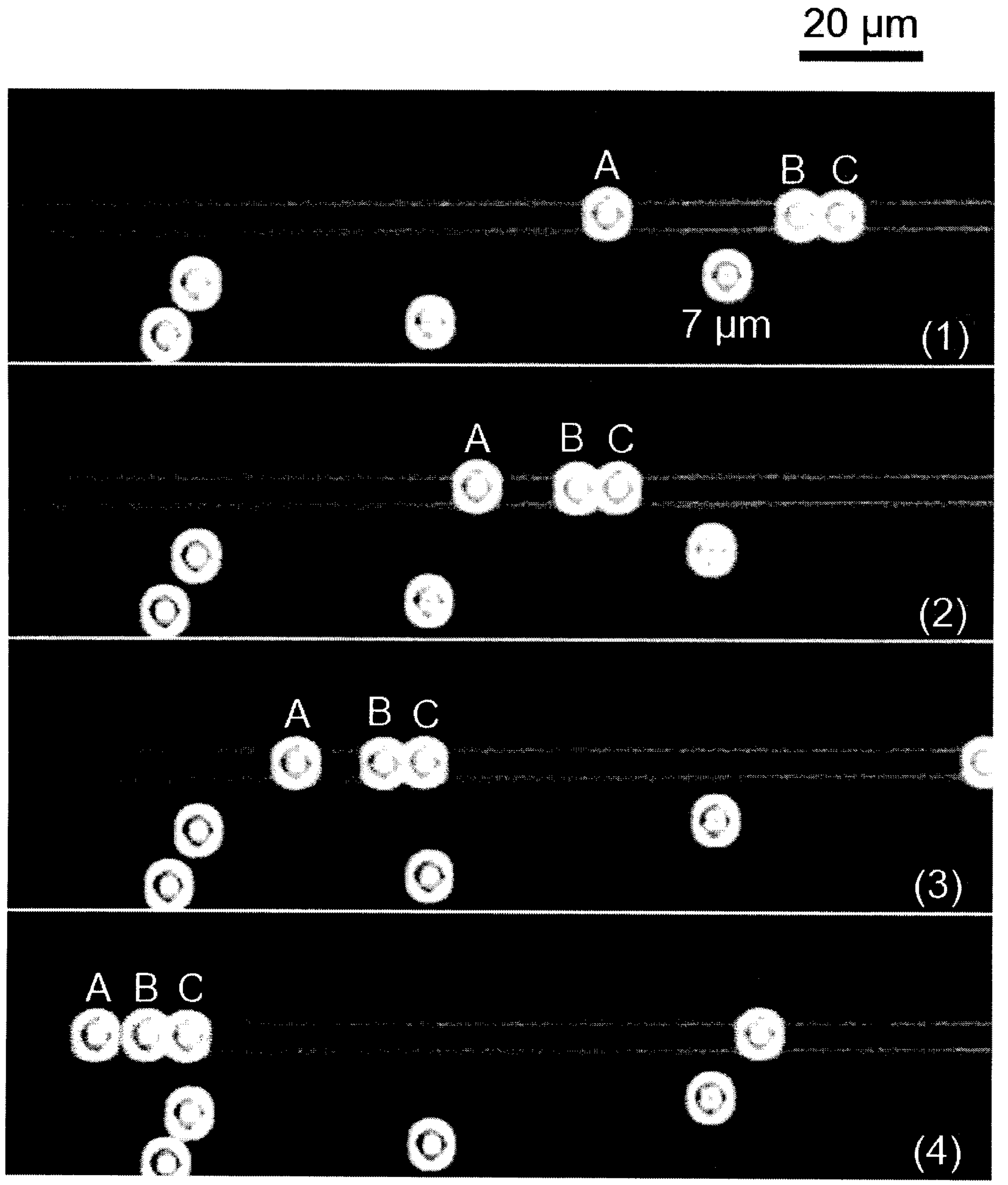

Fig. 2. Images showing the formation of a chain of 7 μm sized particles, taken with a 2 s interval. Light is launched from the right hand side.

rather than as single particles. Figures 4, 5 and 6 show the experimentally obtained dependence of the particle velocity on the fibre output power for particles with diameters of 3, 7 and 10 μm , respectively. Vertical bars represent standard deviation. The particle concentration for a given particle size was constant for each of these graphs, as the same cell was used throughout the measurements. However, the particle concentrations were not identical for the different particle sizes and the fibre-to-waveguide coupling loss may also have been different. In addition, the loss imposed by particle scattering depends on the particle size and the number of particles on top of the waveguide. There-

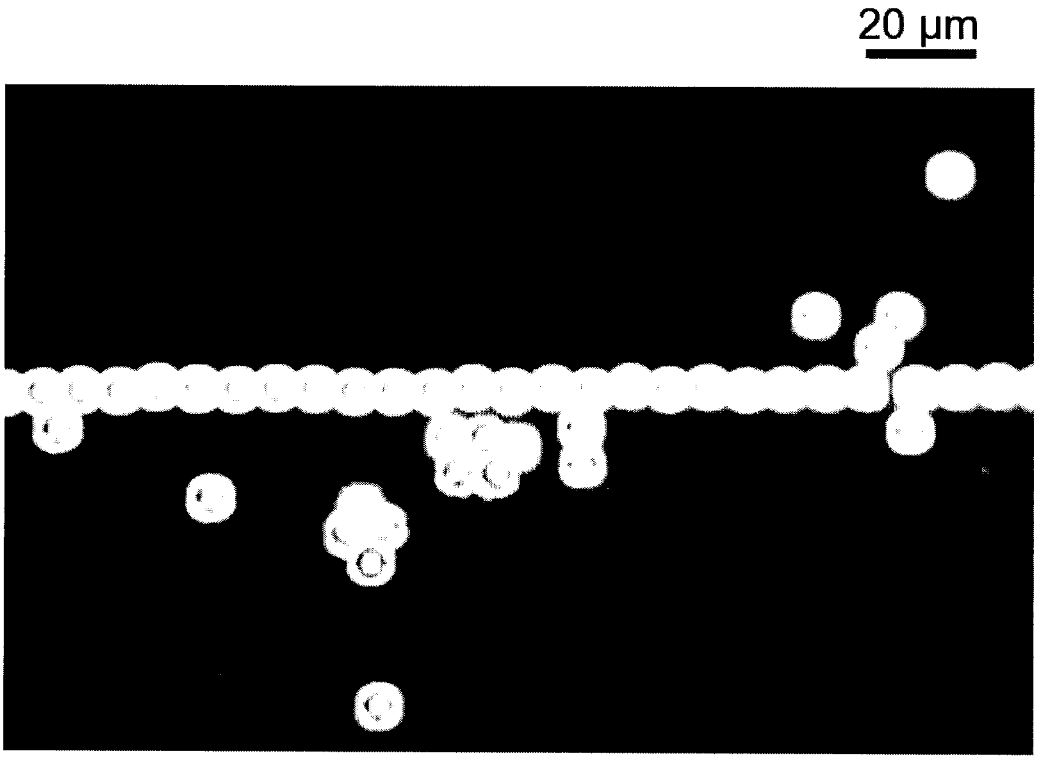

Fig. 3. A long chain of 7 μm particles formed about 25 mm from the waveguide input facet.

fore, the power delivered to the particles may not have been the same in the three cases and the comparison of particle velocities for different particle sizes must be made with caution. We observe that the velocity does not linearly increase with the input power. The curves consistently display a local minimum for a fibre output power of about 830 mW for all three sizes, while there is no corresponding dip in the measured waveguide output power. The waveguide output power increased linearly with the input power which confirms that the power reaching the particles was indeed increased compared to the previous point of measurement and one would expect the measured particle velocity to increase.

3.2 Experiments with mixed particle sizes

In this subsection we present the results of the experiments where the cell contained a mixture of particles of all three different sizes. This was done in order to investigate more closely the influence of the particle size on the particle velocity. The particle concentration was suitably reduced to avoid the formation of long chains. All velocity measurements were taken for single particles only and 550 mW fibre output power. Figure 7 shows the results quantitatively. We observe that the velocity increases with the particle size

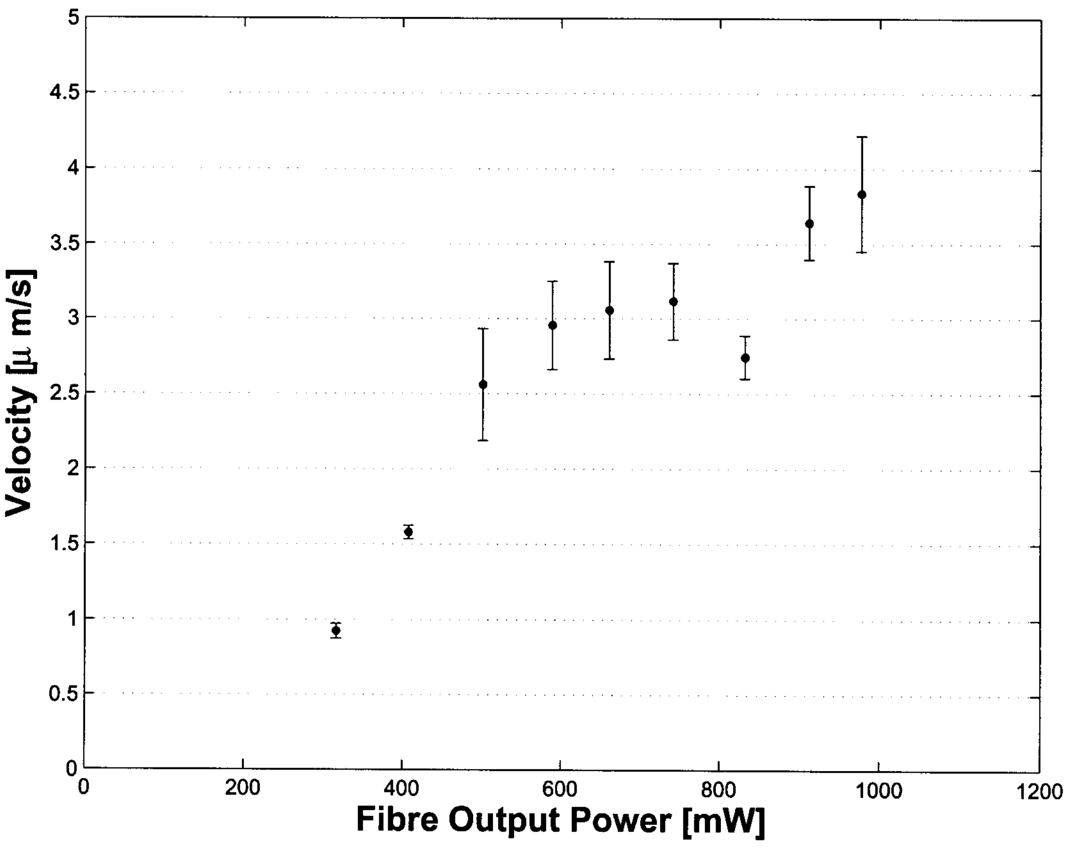

Fig. 4. Velocity of 3 μm diameter particle chains as a function of the fibre output power.

which is in agreement with theoretical prediction [3]. Two sets of images, taken at 10 s intervals, illustrate this. Figure 8 shows a waveguide with particles of 7 μm and 3 μm diameter trapped and propelled on top of it. It is obvious that the larger particle is propelled faster, eventually catching up with the smaller particle. Figure 9 shows a similar situation, only with 7 μm and 10 μm diameter particles. The maximum single particle velocity measured was about 33 μm/s for 10 μm diameter particles and fibre output power of 870 mW.

Figure 10 shows a 7 μm diameter particle propelled together with and, therefore, at the same speed as two 10 μm diameter particles ahead of it. Knowing that independently smaller particles move with less speed than bigger ones for the same input power conditions, this situation is highly unexpected. This implies that these particles are bound in some way and the smaller particle is somehow allowed to move faster when travelling shortly behind another particle. Once the laser was switched off, particles on top of the waveguide separated, unlike particle clusters residing outside the waveguide region. This demonstrated that particle collections on top of the waveguide were not a result of mechanical binding, while clusters on the side were indeed mechanically bound particles. Hence, the particles were not observed to systematically flock

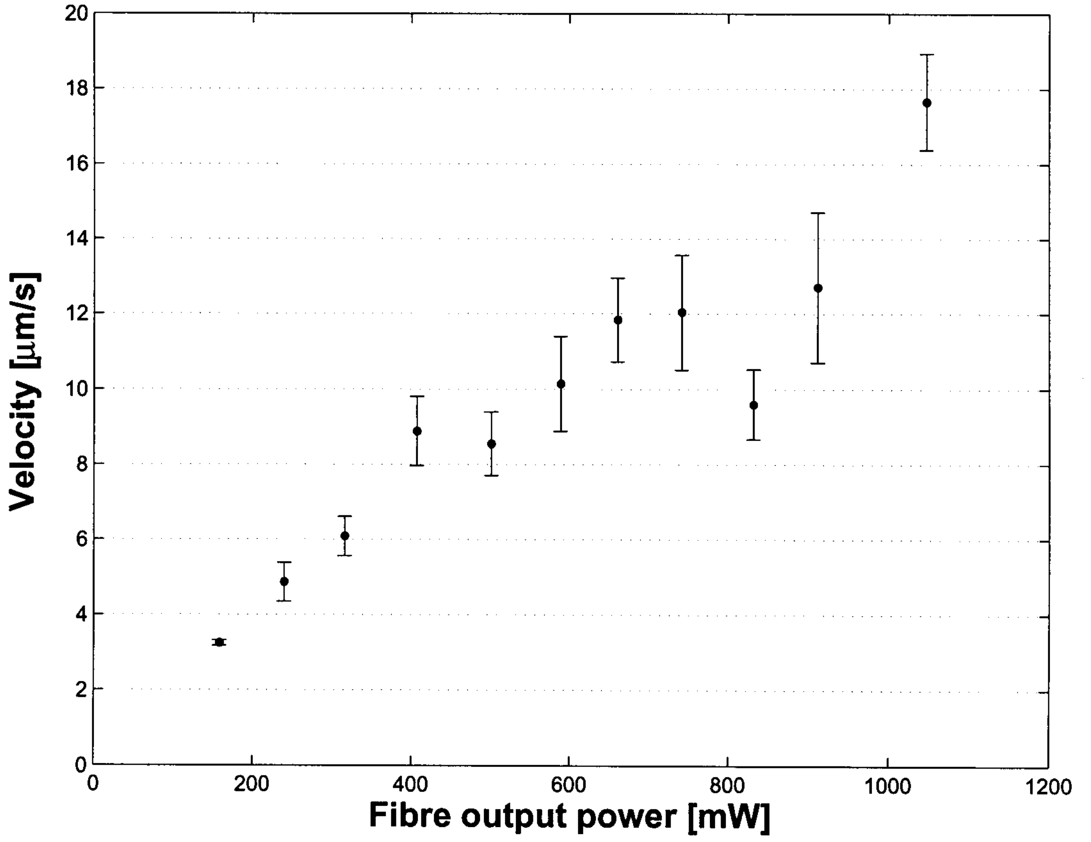

Fig. 5. Velocity of 7 μm diameter particle chains as a function of the fibre output power.

together anywhere else but on top of the waveguide.

4 Discussion

In this section, we will discuss the various parameters which were observed to affect the trapping of particles. As the fibre output power was increased, particles initially found on top of the waveguide were trapped and propelled. Particles residing at the side of the waveguide, even partially on top of it, were not observed to be attracted to the waveguide laterally (as seen in Figure 8). However, a certain lateral attraction to the waveguide is expected according to the theory. In the particular case of Cs^+ ion-exchanged channel waveguides, the mode field is very confined so the lateral attractive force is expected to be of limited extent. The Brownian motion of our particles and a possible random flow in the cell would easily overcome it and make the lateral force difficult to observe.

The measured waveguide output power was observed to drop during the mea-

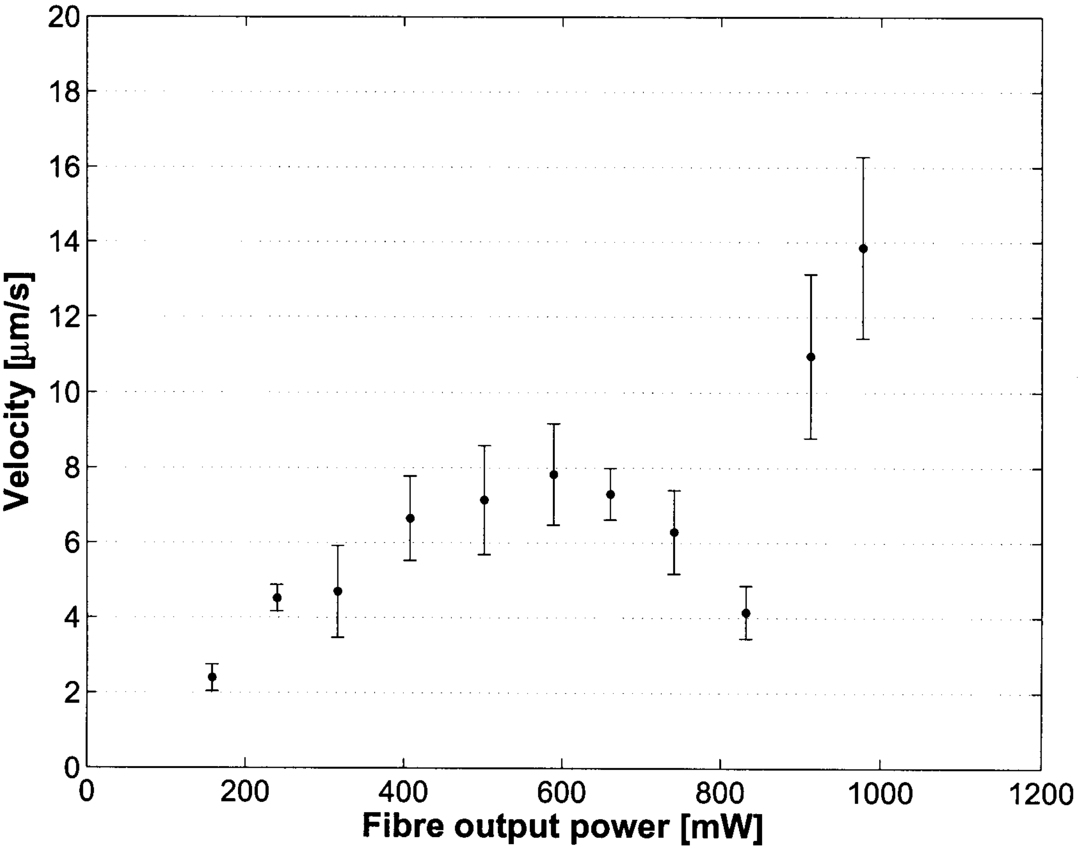

Fig. 6. Velocity of 10 μm diameter particle chains as a function of the fibre output power.

surement. This can be explained by the increased scattering losses as the number of trapped particles on top of the waveguide increases with time. It was also observed that the particle velocity was dropping along the waveguide length. This can be readily explained through the two-way loss of power reaching the particles. Firstly, the power drops along the waveguide as a result of the waveguide propagation losses. Further to this, additional losses are imposed by scattering of the trapped particles. This also implies that the particle velocity is dependent on the concentration of the particle solution. Therefore, all the measurements were made on the same spot on top of the waveguide, and the velocity was plotted against the fibre output power.

The results presented in Figures 4, 5 and 6, show rather large standard deviations for the measured particle chain velocity. According to theory, resonance effects assume an important role leading to rapidly varying particle velocity dependence on particle size [3]. Thus, variations in particle diameter, as given by the standard deviation, could provide an explanation for the observed particle velocity standard deviations. In addition, the separation between the particle and the surface also affects the velocity. The fact that the speed was measured in chains of different lengths may also play a role. A certain local

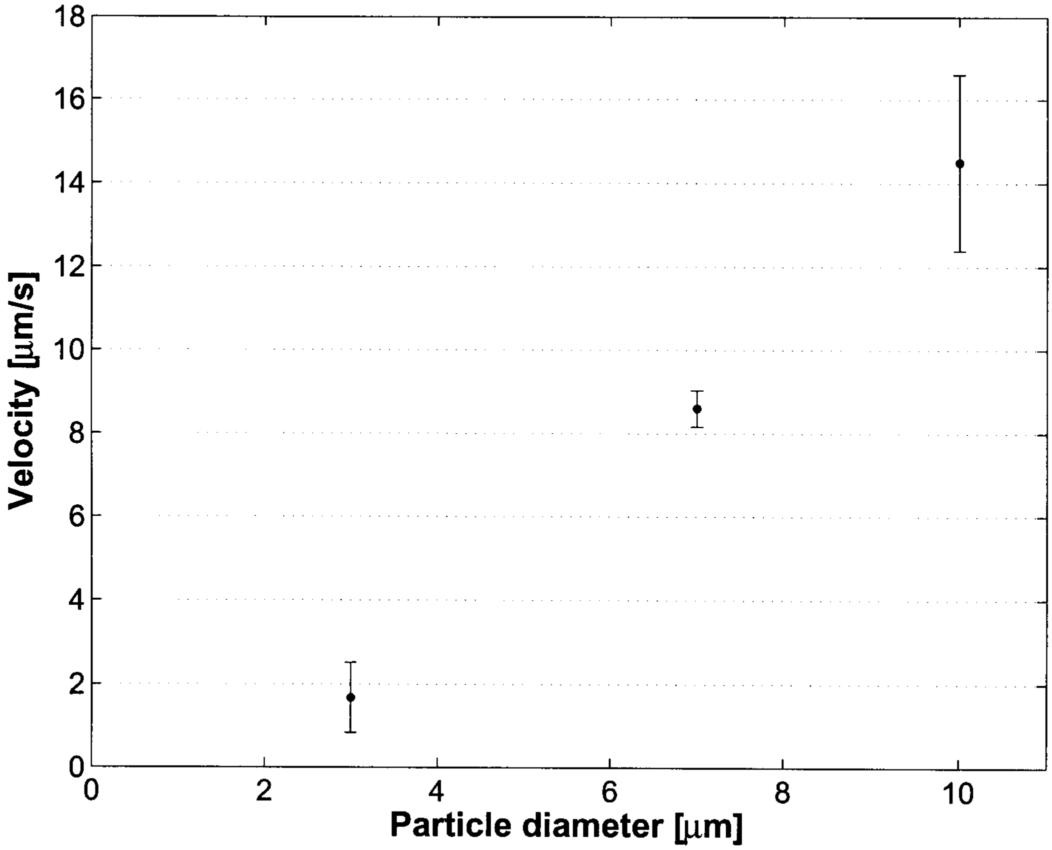

Fig. 7. Velocity versus particle size for a fibre output power of 550 mW, measured for single particles.

minimum in the particle velocity was observed for all three particle sizes for the fibre output power of 830 mW. The origin of this local minimum remains unexplained and may very well be a peculiarity of the waveguide used.

One may compare the results in Figures 4, 5 and 6 with the results presented in Figure 7. The velocity of 10 μm diameter single particles is obviously higher than the velocity for the same particles in chains. This may seem to be in disagreement with the statement in subsection 3.1. It was stated that the collections of particles were observed to move faster than single particles. However, it was emphasized that this is true if the observed chains and single particles are under the same input power conditions. This is by no means satisfied for the chains of Figures 4, 5 and 6 and the single particles of Figure 7. Even if the coupling loss was the same in the two experiments, the scattering losses imposed by the trapped particles were not the same.

The fact that chains of particles move faster than single particles under the same input conditions, as well as the binding phenomena presented in Figure 10 in subsection 3.2, may be explained as follows. Hydrodynamic coupling as a kinematic effect, inevitably exists between the propelled particles and the

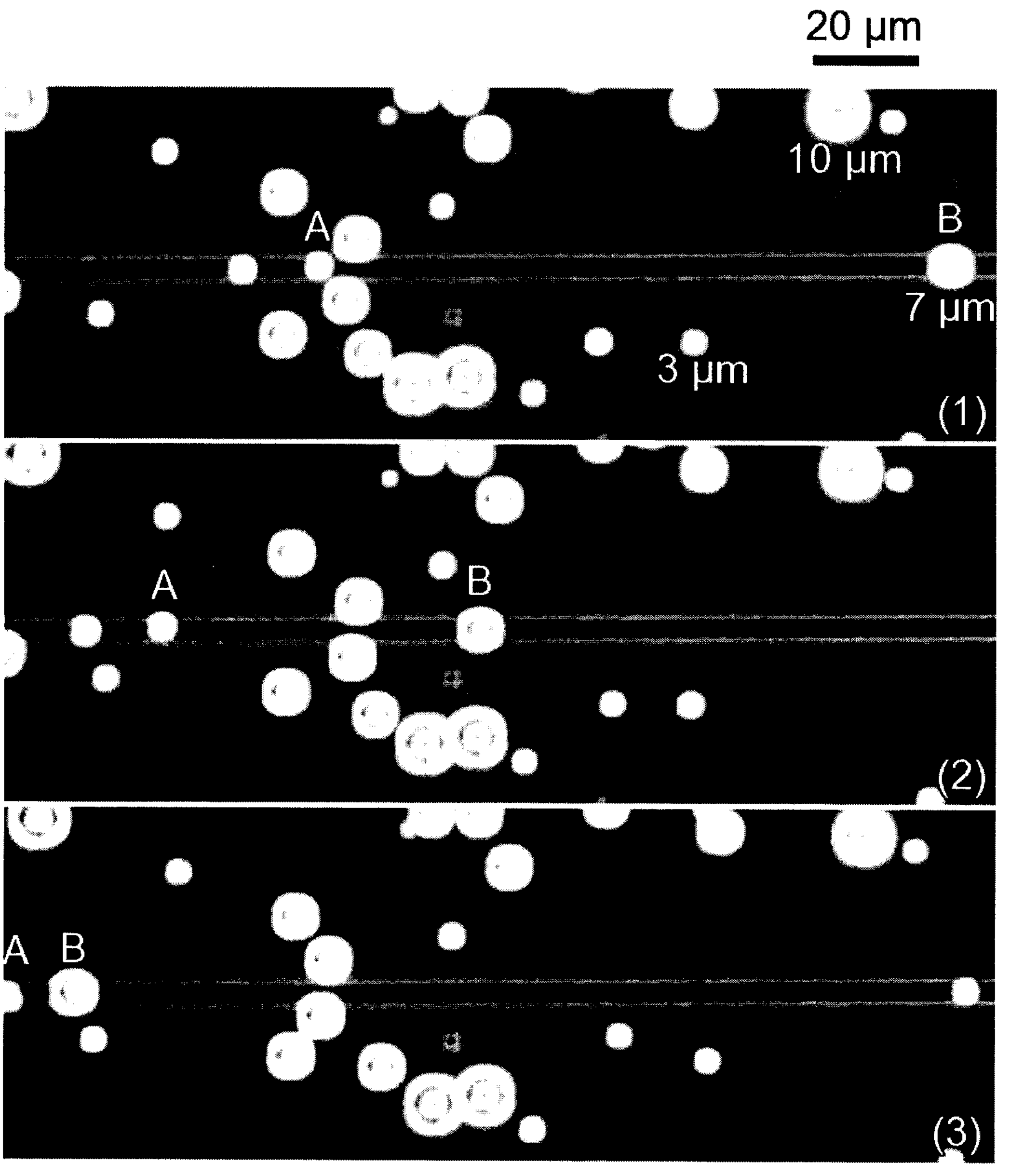

Fig. 8. Images showing a particle with 7 μm diameter (B) moving faster than particles with 3 μm diameter (A) for the same input conditions, taken with a 10 s interval.

substrate plate, as well as between the particles themselves [19–21]. Recent articles that address this problem show that the particle motion is hindered near a planar surface [19–21]. However, the collective diffusion coefficients are enhanced by hydrodynamic coupling because fluid displaced by one sphere entrains the other. Therefore, the commonly used Stokes law needs to be corrected for the case of particles near a surface and in particular for chains of particles. Also, the influence of optical interaction between particles can be taken into account. Theoretical investigation of optical binding of two particles in water on a dielectric flat surface illuminated by total internal reflection was

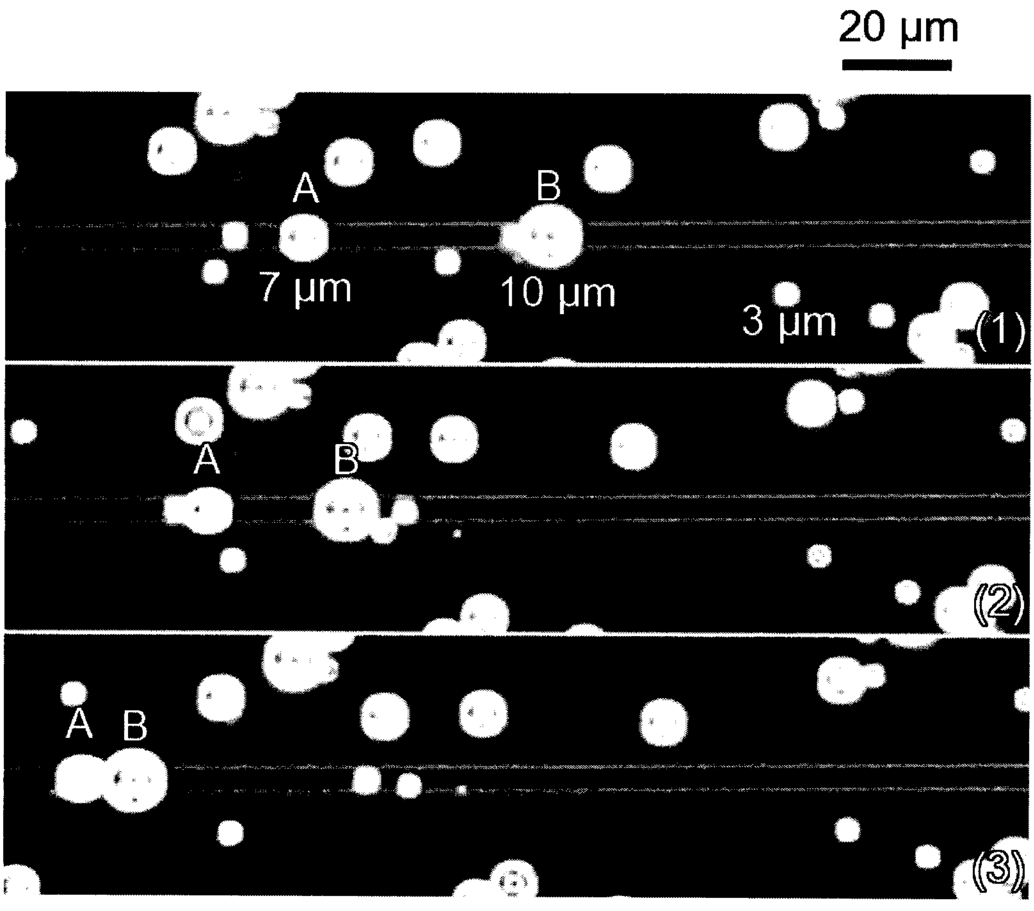

Fig. 9. Images showing a particle with 10 μm diameter (B) moving faster than a particle with 7 μm diameter (A) for the same input conditions, taken with a 10 s interval.

reported in [22]. According to this work, when two spheres are impelled by an evanescent wave propagating along a surface, the distance between them keeps some particular values given by the positions of the minima of the potential of interaction between them, the deepest one corresponding to zero separation. For a more profound explanation of the observed binding phenomena a more quantitative characterization of the collective particle motion is needed.

Along with optical and hydrodynamic effects, thermal effects might prove important since the waveguide region is heated through the absorption of guided light. This creates a thermal gradient around the waveguide region which exherts force on the trapped particles through the phenomenon of thermophoresis. It has been shown that a variety of particles, including polystyrene particles, exposed to a temperature gradient, experience a force directed toward the low temperature region, depending on the particle and suspension liquid properties [17,18].

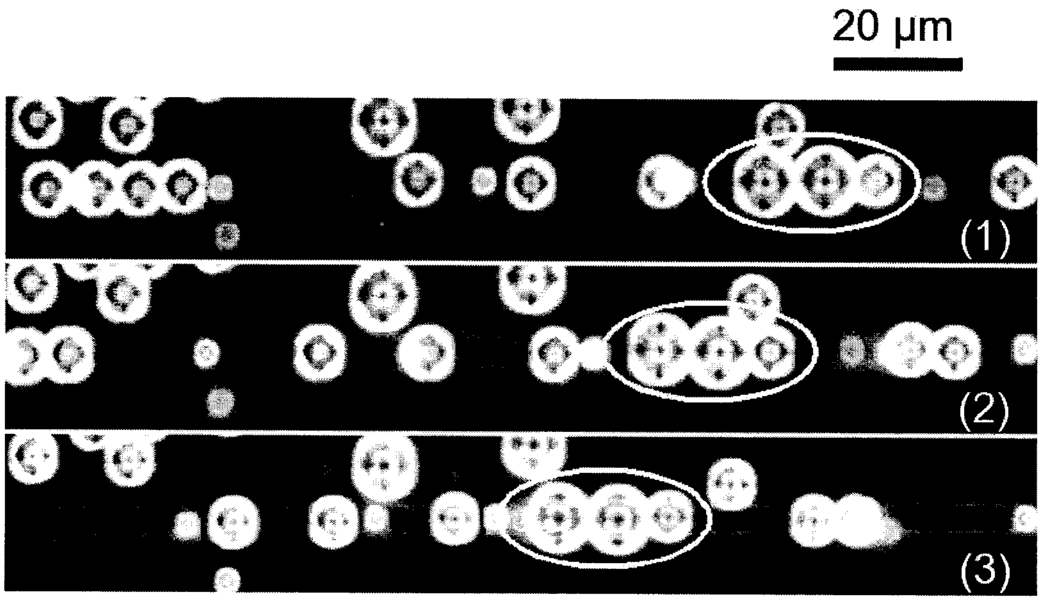

Fig. 10. Illustration of the binding effect. Images showing the propulsion of a collection of two 10 μm and one 7 μm sized particle, taken with a 4 s interval.

5 Conclusion

We have demonstrated that the evanescent field formed in the cover region of a singlemode waveguide formed by Cs^+ ion-exchange in glass can trap and propel polystyrene dielectric microspheres of different sizes. To the best of our knowledge, this kind of waveguide was used for this purpose for the first time. The trapping was more stable and considerably higher propulsion speeds were obtained than previously reported. Propulsion of 3, 7 and 10 μm diameter spheres was characterized with respect to the fibre output power at 1082 nm wavelength and for TE polarization. Particle velocity was reported to increase with the fibre output power displaying a local minimum for 830 mW for all three particle sizes. The origin of this local minimum remains unexplained. Dependence of the particle velocity on particle size for the same input power condition was also studied. The velocity was reported to increase with particle diameter which is in agreement with theoretical predictions. Further study and careful characterization of the particle velocity dependence on particle diameter will provide means for separation of particles of different sizes according to speed. The maximum single particle velocity measured was about 33 $\mu m/s$ for the case of 10 μm diameter spheres and 870 mW fibre output power. Under the same input power conditions, collections of particles (chains) were observed to move faster than single particles. Particles were observed to form chains which could reach several hundred micrometers in length. As a possible explanation of the reported particle binding, combined hydrodynamic and optical effects were suggested.

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