Dielectric microsphere manipulation and chain assembly by counter-propagating waves in a channel waveguide

Katarina Grujic and Olav Gaute Hellesø

Department of Physics and Technology, University of Tromsø, 9037 Tromsø, Norway

katarina@phys.uit.no, ogh@phys.uit.no

http://uit.no/fysikk/mikroelektronikk/9

Abstract: We study the formation and the propulsion properties of chains of dielectric microspheres in the evanescent field of a channel waveguide made by Cs^+ ion-exchange. Particle chains are shown to move faster than single particles. We exploit counter-propagating waves for axial positioning of single and chains of microspheres. The particles can be propelled back and forth at will, and trapped at a given point for several minutes. We demonstrate that this technique can also be used to assemble a long, one-particle wide, chain.

OCIS codes: (170.4520) Optical confinement and manipulation; (140.7010) Trapping; (230.7380) Waveguides, channeled.

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1. Introduction

Recently, micromanipulation has emerged as a tool for studying colloidal dispersions of various types of micro- and nanometer sized particles. It is of particular interest for cellomics, as a tool for manipulation of cells within Micro Total Analysis Systems (μTAS) or Lab-on-a-Chip [1]. The aim here is to work within complete analytical systems with the possibility to study a single cell and control interactions between particular cells. These systems would normally incorporate particle trapping and sorting. These functions can be accomplished by various methods [1], including optical methods [2, 3]. Optical trapping by means of a tightly focused laser beam has already proven to be a valuable research tool for biomanipulation [4]. However, the use of near-field optical micromanipulation would introduce further enhancements. Using the evanescent field of a waveguide as a manipulation tool allows us to exploit a variety of integrated optics structures. One example is using Y-branched waveguides to sort microparticles, as demonstrated earlier [5]. When a particle solution is introduced in the waveguide cover region, particles interact with the waveguide's evanescent field. This interaction is such that the particles are drawn towards the waveguide and propelled in the direction of light propagation. Effectively, the particles are guided along the waveguide as first demonstrated in 1996 [6]. Along with the study of single particles, the study of particle collections is of interest and relevant for coupled resonator optical waveguides (CROW) and high order optical filters [7]. The study of light induced self-assembly and optical binding interactions between particles has also attracted attention lately [8, 9]. Optical waveguides are suitable to study these effects, as their width is comparable to that of microparticles. It thus becomes easy to assemble and study microsphere chains that are one particle wide, as we will show.

In this work, we investigate the propulsion properties of dielectric microsphere chains on top of a channel waveguide made by Cs^+ ion-exchange in glass. We also present a technique for the assembly of long chains, based on the use of counter-propagating waves. It will be demonstrated how this techique offers a precise axial control of microparticle propulsion with the ability of trapping the particle at any given point along the waveguide. Firstly, we shall give a quantitative characterization of the chain propulsion, as it was observed that, under the same input power, collections of particles move faster than single particles [10]. For simplicity, we limit our study to the propulsion of two particle chains (bi-spheres). We present an experimental study of the motion of particles in fluid at very small separations, both to one another and to a wall. This condition is relevant for optical particle manipulation systems and also applies to microfluidic devices. In this case both hydrodynamical and optical coupling may be acting on bi-spheres. Secondly, we shall demonstrate axial control of microparticles by means of counter-propagating evanescent waves. Counter-propagating waves have previously been used for particle manipulation on a prism surface [11]. Their use with optical waveguides is a natural extension of the particle guiding setup we used in our previous publications [10]. Depending on the difference in the power of light sent in each direction, the particles can be propelled back and forth along the waveguide, and trapped at any given location, for several minutes. Finally, we will show how this technique leads to the self-assembly of a microparticle chain of arbitrary length. This chain can then be manipulated by the same means of counter-propagating waves.

2. Experimental procedures

The experimental apparatus is shown in Fig. 1. Straight channel waveguides were formed by Cs^+ ion-exchange in soda lime glass [10]. The diffusion duration was adjusted so that the waveguides were single mode at 1083 nm, which is the wavelength of the 2W Ytterbium linearly polarised fibre laser used as the trapping light source in our experiments. When neccessary, the light of this laser could be split by using a 2×2 fibre-coupler and almost equally devided between the two output fibres. The fibre holders were mounted on micropositioning

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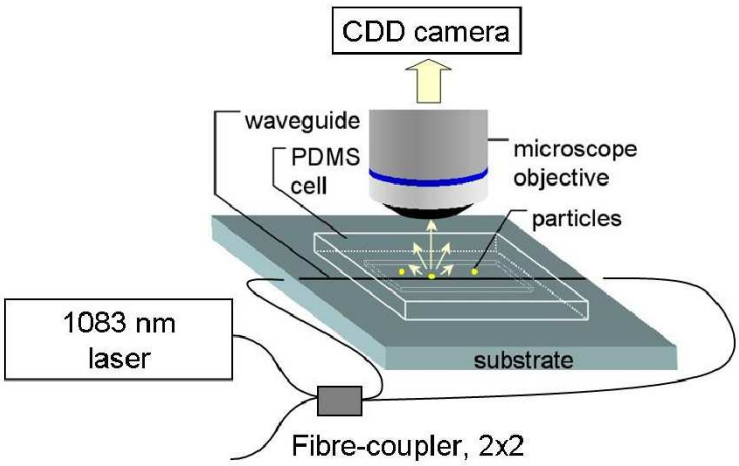

Fig. 1. Experimental setup.

stages. The light was injected by direct butting to one or both ends of the waveguide. In the latter case, a counter-propagating evanescent wave was formed in the waveguide cover region. By moving the fibres, we controlled the fibre-to-waveguide coupling loss, and thus the optical power through the waveguide in each direction.

A dielectric microparticle solution was confined on top of the waveguide in a cell ($10 \times 10 \times 0.5\ mm^3$) formed either between double-sided tape spacers or in moulded polydimethylsiloxane (PDMS) elastomer, with a glass cover slip on top. We used polystyrene microspheres (Duke Scientific, from 3 to 12 μm in diameter, $n = 1.59$, specific gravity $1.05\ g/cm^3$) suspended in de-ionized water. An optical microscope with the illumination from above and a $50\times$ objective lens was used to observe the particles and the laser light scattered by the particles. A short wave pass filter (Andover Corporation, 50% transmission at 1011.35 nm) was used to suppress the 1083 nm scattered light when neccessary. A CCD camera was mounted on top of the microscope and the images were recorded on a computer.

3. Results

The modal effective refractive indices of our waveguide were approximately 1.54. Thus, the illuminated waveguide has an evanescent field depth of about 0.3 μm into the cover region filled with water-particle solution. The light was, therefore, only coupled to the polystyrene microspheres settled in the close vicinity of the waveguide surface. These particles were stably guided along the waveguide.

3.1. Characterisation of the bi-sphere velocity

In the first set of experiments we set out to explore the velocity of bi-spheres with respect to single particles. In these measurements, we required only one fibre coupled to the waveguide. The light was TE polarised. 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. A particle was considered to be single if it was separated at least 100 μm from the neighboring particles on the waveguide. In order to compare the velocities of single particles and particles travelling as bi-spheres we had to make sure that the same power was driving both the single microspheres and the corresponding bi-spheres. Namely, the power in the waveguide fluctuates

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with the number of particles trapped on it due to scattering losses. Monitoring the waveguide output power revealed that, within a 60 s time span, there was very little change in the observed output power value. Therefore, we inferred that approximately the same power was reaching both a single particle and a chain if these were not more than 60 s temporally apart. It should be noted that the power reaching the particles was lower than the fibre output power due to the fibre-to-waveguide coupling loss, the waveguide propagation loss up to the point of measurement and the scattering losses from particles on the waveguide.

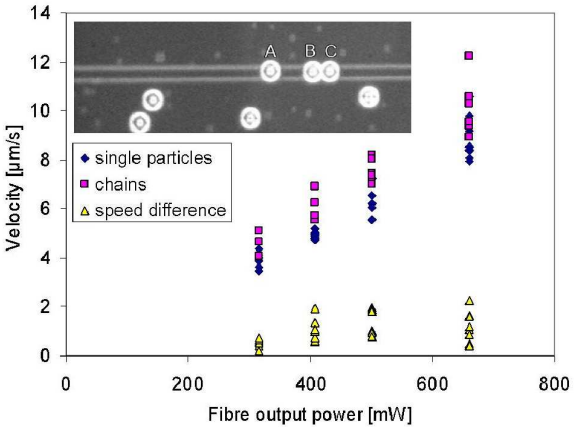

Fig. 2. Bi-sphere and single particle velocities as function of fibre output power for 7 μm diameter spheres. The difference between the bi-sphere velocity and the corresponding single particle velocity is calculated for each pair. The inset shows a single microsphere A and a bi-sphere BC on top of the waveguide (dark field illumination mode of the microscope).

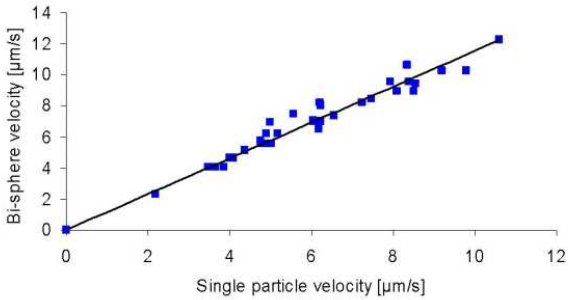

Fig. 3. Measured bi-sphere velocity as function of the corresponding single particle velocity for 7 μm diameter spheres. The given line has a slope of 1.15.

The results of these experiments are shown in Fig. 2. Here we plotted the measured single particle velocities and the corresponding bi-sphere velocities against the fibre output power. We have also included the differences between the bi-sphere velocities and their corresponding single particle velocities. Note that these were always positive. In the plot given in Fig. 3 we considered the bi-sphere velocity versus the corresponding single particle velocity. A linear fit through these measurement points, $v_{bi} = a v_{single} + b$, yields $a = 1.11 \pm 0.04$ and $b = 0.28 \pm 0.25$. If we assume that $v_{bi} = 0$ when $v_{single} = 0$ and fit a line through the ori-

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gin to these results, we determine the average chain versus single particle velocity ratio to be 1.15 ± 0.01. We obtained similar results for 3 μm diameter particles with a slope of 1.18 ± 0.03 for a line fitted through the origin.

3.2. Axial positioning of microspheres

In order to gain better control over the microparticles, we illuminated the waveguide with two counter-propagating waves. We have not observed any interference effects. The large size of the spheres (7 μm) compared to the wavelength of light in the material (about 0.7 μm) might have concealed such effects. However, limited coherence and differences in polarisation of the beams could have eliminated interference.

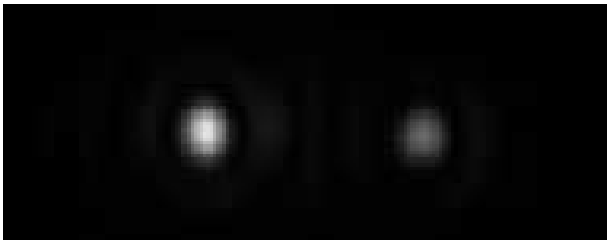

Fig. 4. Light scattered by a particle on a waveguide illuminated by counter-propagating waves. The two hotspots are the light scattered from the front and rear of the particle due to the propagating and counterpropagating waves, respectively. The white light illumination of the microscope was turned off, so the particle is not visible.

In Fig. 4 we can see the typical scattering pattern from a particle on top of the waveguide. It constists of two ”hotspots” on either side of the particle, each due to scattering from the exit face of the sphere, corresponding to the respective counter-propagating wave. We observe that the intensities of these hotspots serve as an approximate measure of the optical power in the waveguide modes in each direction at a given point. By manipulating the fibres, that is the fibre-to-waveguide coupling loss, we could control the optical power in each direction and thus control the movement of the particle.

This is illustrated in the movie shown in Fig. 5. The filter used to cut off the laser light scattered by the particle is occasionally taken out to allow visualisation of the counter-propagating waves and their mutual power difference. One can see that the particle is moving in the direction of the stronger beam. When the power of the two beams is roughly equated, the particle remains trapped at the desired position.

Figure 6 shows the particle velocity as a function of the intensity difference of the hotspots. The intensity of the scattered light was measured by summing up the intensities of all pixels constituting a given hotspot, from images like that in Fig. 4. This measurement was done for a single particle and differing power in the counter-propagating waves. At each point, images were taken every second for 20 seconds. From these, the distance travelled by the particle and thus the velocity was calculated. The plotted intensity difference is calculated as the average of the intensity differences of all the 20 images. Similar results were obtained also with other particle diameters.

3.3. Assembly of a long microsphere chain

We have observed the formation of a long particle chain, as illustrated in Fig. 7. One can clearly see the waveguide with the particles on top. The waveguide was illuminated with counter-propagating waves. We used the filter to remove laser light scattered from the particles. However, some traces of it are still visible due to the limited attenuation of the filter. The images

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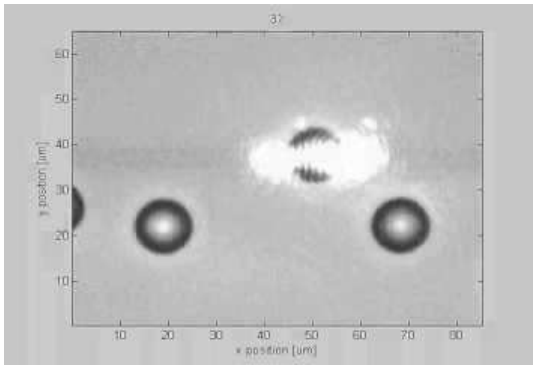

Fig. 5. Movie (2.5 MB) of a 12 μm diameter particle on top of a Cs^+ ion-exchanged waveguide illuminated by counter-propagating evanescent waves. We used bright field illumination mode of the microscope. The light scattered from the front and rear of the particle is due to the propagating and counterpropagating waves, respectively. A filter inserted to cut off the scattered laser light is taken out occasionally, to allow visualisation of the counter-propagating waves and their mutual power ratio. The movie was sped up 9 times for convenience.

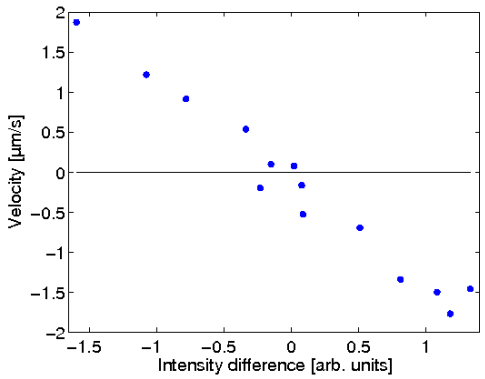

Fig. 6. Particle velocity versus the intensity difference of the scattered light in the front and rear of the 7 μm diameter sphere.

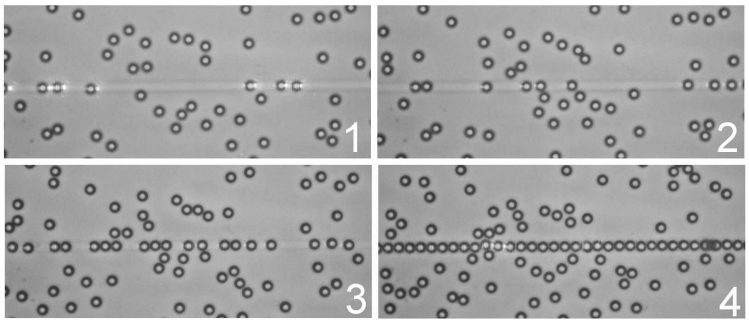

Fig. 7. Formation of a long chain of 7 μm diameter spheres. The images are taken over the same region of the waveguide, ca. every 3 minutes.

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were taken every three minutes and show the section of the waveguide where the counter-propagating waves were of approximately equal power. Namely, the optical power changes along the waveguide due to propagation and scattering losses as will be discussed in the next section. It was observed that particles at the opposite ends of the cell travelled in opposite directions. With time, the number of particles on top of the waveguide increased and particles formed short chains. After ca. 10 minutes a long chain was formed. Eventually, the chain itself could be manipulated by adjusting the optical power in each direction in very much the same way as for the manipulation of single particles.

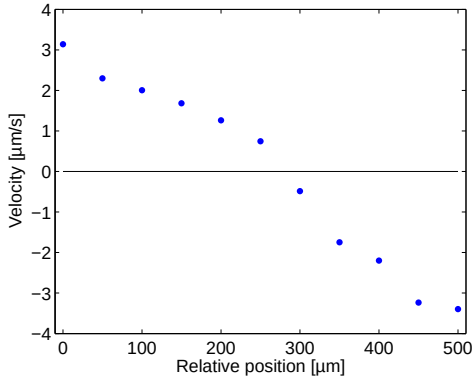

Fig. 8. Velocity versus relative particle position along the waveguide.

In order to get a better insight in the mechanism behind the chain assembly, we measured the particle velocity at different points along the waveguide. The measurements were taken for single particles, every 50 μm along the waveguide. Both fibres were kept fixed at such positions that the optical power difference in the counter-propagating waves dropped to zero at a point within the cell. The results are given in Fig. 8. Obviously, the particles from the opposite ends do move towards each other and come to a stop in the central region.

4. Discussion

As presented previously, bi-spheres always move faster than single particles. To explain this phenomenon, we need to consider both hydrodynamical and optical effects. Particles moving through a fluid excite flows through the no-slip boundary condition at their surfaces. These flows couple particles' motions. This hydrodynamic coupling enhances the collective particle velocity because fluid displaced by one sphere entrains the other [12]. On the other hand, the influence of a nearby wall hinders the particles' motion. To treat this precisely, the influence of the wall and the second particle should be taken into account simultaneously [12]. Further to this, the optical effects such as optical particle coupling must be taken into consideration [8, 9]. The effect of this is by no means obvious. For a quantitative explanation Maxwell's equations must be solved for an array of particles in an evanescent field. This is outside the scope of the present paper.

The axial control of microspheres by means of counter-propagating waves proves to be a very straightforward and effective method for particle manipulation. Figure 6 shows that the velocity of the particles is proportional to the hotspots' intensity difference, that is the difference in power of the two counter-propagating waves, as expected. By equating the power in the two waves, we could keep a particle trapped at a given point. Except for the observed Brownian motion, the particle trapping was stable. The particle could be kept at the given location for

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several minutes with our setup. The limit is due to experimental conditions, such as liquid evaporation and mechanical vibrations of the fibres.

We thus have two effects at disposal for the formation of microsphere chains. Firstly, the bi-spheres catch up with the single particles, thus forming three-particle and longer chains. We can possibly speed up this process by manipulating the fibres, that is the powers in the counter-propagating waves. Thus, we can move a chain back and forth in order to add single particles to it. Secondly, just keeping the fibres fixed and counter-propagating waves' power difference constant and equated somewhere within the cell leads to the formation of a long microsphere chain. As seen in Fig. 8, particles at opposite ends of the waveguide travel towards each other. This is due to the waveguide propagation loss which accounts for the power change along the waveguide, even though the fibres are fixed. Thus, the optical power difference of the counter-propagating waves is highest and of opposite sign at the ends of the cell, and decreases towards the middle. Being proportional to the optical power difference, the particle velocity changes similarly. One may notice the change in the slope of the measurement points around zero velocity. This is due to chain formation in the central region and thus an increased number of particles. This results in higher scattering losses, decreasing the power reaching the particles and thereby the measured particle velocity. In effect, all this results in the formation of a long particle chain in the central region. The final length of the chain is, for our setup, limited only by the length of the cell. It is possible to improve the assembly of particle chains by the addition of larger spheres. Larger spheres move faster for a given power [10] and catch up with smaller ones, thereby forming a chain.

5. Conclusion

In this work, we have studied the formation and the propulsion properties of dielectric microsphere chains on top of a channel waveguide made by Cs^+ ion-exchange in glass. We have measured that bi-spheres move faster than single particles for a given power. For 7 μm diameter particles, they are, on average, 15% faster. We have also shown how counter-propagating beams in an optical waveguide can be used to manipulate these microspheres. The particle's velocity is shown to be proportional to the difference in power of the two beams. They can thus be propelled back and forth and trapped at a desired location for several minutes. Based on this, we have presented a technique for the formation of a long, one-particle wide, chain.

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