ECIO'05: 12th EUROPEAN CONFERENCE ON INTEGRATED OPTICS
- ABSTRACT -

Microsphere Chain Formation in the Evanescent Field of an Optical Waveguide

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SUMMARY

Dielectric microparticle guiding in the evanescent field of an optical waveguide is described. Chains of two or more particles are formed and propelled along the waveguide, and their behaviour is compared with hydrodynamic coupling theory.

KEYWORDS

optical trapping, optical waveguides, integrated optics, microsystems

INTRODUCTION

Lab-on-a-Chip or Micro Total Analysis Systems (μTAS) offer substantial advantages for biological and chemical assays and analytical methods [1, 2, 3]. They introduce the ability to work rapidly with small sample sizes, within closed and possibly complete analytical systems. One important function within such a system would be particle trapping and sorting. To achieve this, one may employ mechanical [4] or electrical [4, 5] methods, hydrodynamic flow [3, 6] and more recently proposed optical methods [7, 8]. In the early 1990's optical particle manipulation using an evanescent field was demonstrated [9]. The evanescent field was generated by illuminating a prism with a laser beam under total internal reflection condition. Subsequently, the evanescent field of a channel waveguide was employed [10]. Particles were confined in two dimensions in the waveguide cover region while at the same time being propelled in the direction of light. Subsequently, propulsion of dielectric microparticles and metallic nanoparticles in the evanescent field of single mode and multimode waveguides was investigated [11, 12]. In a recent paper we have demonstrated how a Y-branched optical waveguide can be used for microparticle sorting [13]. The sorting was accomplished by simply changing the power distribution between the branches. Such a structure could be incorporated as part of μTAS for manipulation of biological particles. Larger particles could be manipulated directly, provided that their refractive index is sufficiently high compared with that of the surrounding medium. Small biological molecules could be linked to latex spheres and thus manipulated by the optical field.

We have recently investigated propulsion of dielectric microspheres along a channel waveguide produced by Cs^+ ion-exchange in glass [14]. Such a waveguide has higher refractive index increase with respect to the substrate compared to the K^+ ion-exchanged waveguides used previously. The field is more confined which leads to more stable particle guiding and higher propulsion speeds. Formation of collections of particles on top of the waveguide was observed. Such "chains" were seen to move faster than single particles under the same input power condition. In this work we will present a quantitative characterization of chain propulsion. We compare the results of our measurements to predictions given by the hydrodynamic coupling of spheres to a planar surface [15].

EXPERIMENTAL CONFIGURATION AND RESULTS

Fig. 1 depicts the experimental configuration. Channel waveguides were formed in soda-lime glass, using an Al mask with 2.5 μm wide openings, by Cs^+ ion-exchange in a molten $CsNO_3$ salt at 450°C for a duration of 21 hours. The resultant waveguides were monomode at 1082 nm which is the wavelength of the laser used. The light was coupled from the fibre to the waveguide by direct butting. The laser light was linearly polarized and the TE polarization was selected. Polystyrene beads (n=1.59) of 3, 7 and 10 μm diameter were used. The microspheres were diluted in de-ionized water (n=1.33). The particle solution was confined on top of the waveguide in a volume (20mm × 30mm × 0.1mm) defined by spacers and a glass cover slip on top. Particles were observed with an optical microscope with dark field illumination and a ×50 microscope objective. A CCD camera was mounted on top of the microscope, and images were recorded with a VCR and later converted to a digital format.

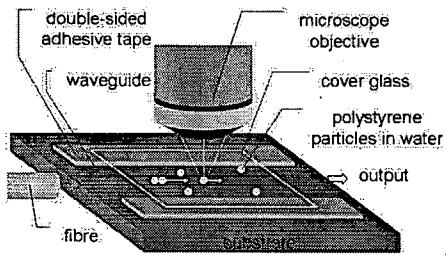

Figure 1. Experimental setup.

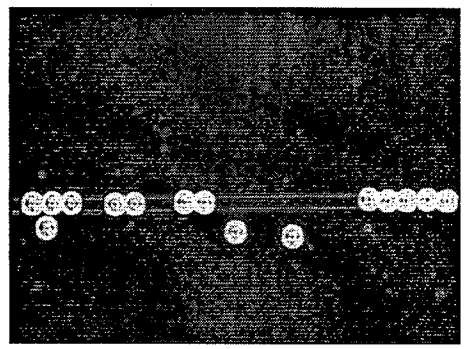

Figure 2. Chains of 10 μm diameter particles.

Once a waveguide was illuminated, the particles on top of it were stably propelled in the direction of light propagation unless they hit an obstacle. Propulsion speeds varied from about 1 μm/s up to 33 μm/s, depending on particle size and input power. Due to heating of the waveguide, small convective currents formed in the cell bringing more particles toward the waveguide. Thus, more and more particles were confined and guided along the waveguide. We observed the formation of particle chains as shown in Fig.2. Particle speed was calculated by measuring the time they needed to travel a 100μm distance along the waveguide. All the measurements were made at the same position on top of the waveguide. To determine the behaviour of the chains compared with individual particles, the difference in speed between single particles and particle chains was calculated. However, this was done only if a chain was immediately preceded by or followed by a single particle, and if these were not more than 60 s temporally and at least 100μm spatially apart. The reason for this is as follows. The situation on top of the waveguide was changing continuously as more particles were trapped, causing changes in the power in the waveguide at the observation point as particles scattered light from the waveguide. Furthermore, there exist optical and hydrodynamic interactions between particles [15, 16], so a particle was considered 'single' only if the distance to the next particle along the waveguide was greater than 100μm.

We measured the velocities of chains of particles and of individual particles for diameters of 3, 7 and 10μm with fibre output powers (incident upon the waveguide input) between 300mW and 750mW. Chains were typically two or three particles long. Results for 7μm diameter particles are shown in Fig. 3. 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 and the waveguide propagation loss up to the point of measurement.

All the differences in speed in Fig. 3 are positive, implying that a chain is always faster than the corresponding single particle. In order to explain this we have investigated the possibility of hydrodynamic coupling for particles travelling in chains near a planar surface. Particle motion is hindered near a surface. However, particles moving through a fluid excite flows through the no-slip boundary condition at their surfaces [15]. These flows couple distant particles' motions, so that each particle's dynamics depends on the particular configuration of the entire collection. Collective diffusion coefficients are thus enhanced by hydrodynamic coupling because fluid displaced by one sphere entrains the other. We have used the following expression for the collective diffusion coefficient along the propulsion direction [15], $D_{\parallel}^{C}(r,h)$:

$$\frac{D_{\parallel}^{C}(r,h)}{2D_0} = 1 - \frac{9}{16}\frac{a}{h} + \frac{3}{2}\frac{a}{r}\left[1 - \frac{1+\xi+\frac{3}{2}\xi^2}{(1+\xi)^{5/2}}\right] \quad (1)$$

where D_0 is the individual spheres' free self-diffusion coefficient, a is spheres' radius, h is the distance from the spheres' centre to the surface, r is the center-to-center separation and $\xi = 4h^2/r^2$. For two adjacent particles on the waveguide surface ($a = h = r/2$), this calculation yields a chain velocity which is 1.65 times larger than a single particle velocity.

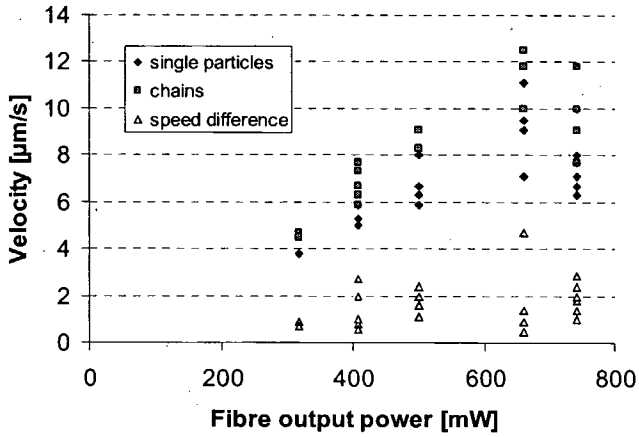

Figure 3. Chain and single particle velocities as function of fibre output power for 7 µm diameter spheres. The difference between the chain velocity and the corresponding single particle velocity is calculated for each pair.

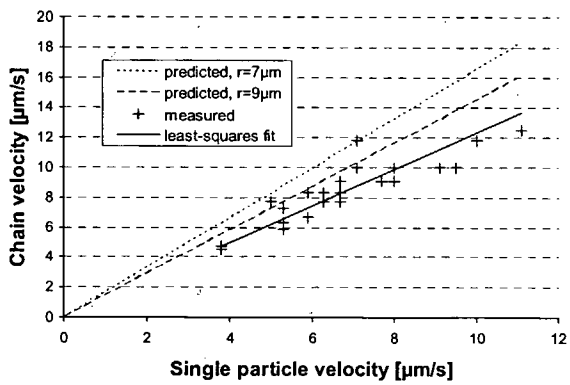

Figure 4. Measured chain velocity as function of the corresponding single particle velocity. The values predicted by hydrodynamic model are given for $a = 3.5$ µm, $h = 3.5$ µm for $r = 7$ µm and $r = 9$ µm with the line slope being 1.65 and 1.43, respectively. A line through the origin is fitted to the data with a slope of 1.24.

The resulting dependence between the chain velocity and its respective single particle velocity for 7µm diameter particles is given in Fig.4 with the dependence predicted by the hydrodynamic coupling model. There may be a small separation between the particles in the chains, so we have included the predicted values for zero separation ($r = 7$ µm) and 2 µm separation ($r = 9$ µm). The measurements agree with the predicted values to a reasonable extent. There might be several reasons for the residual discrepancy. We have combined measurements for chains made up of two and three particles, whereas Eq. 1 applies to two particles. Possible unwanted bulk flows were not taken into account. Such flows might be created by fluid evaporation since the cell was open at two ends. Besides, small convective currents certainly exist due to the heating of the

waveguide. Particles' distances from the surface may also vary. The optical interaction between particles may play a role as well. We have experimentally observed the existence of such and interaction for polystyrene particles of 5μm diameter on top of a K^+ ion-exchanged waveguide. They were weakly propelled forward and formed an almost stationary chain, more than 10 particles long and 2 particles wide.

The results for 3 μm particles were similar to those observed for 7μm particles. Straight lines through the origin were fitted to the data, with resulting slopes of 1.28 for 3μm particles and 1.24 for 7μm particles. However, the situation was not as clear for particles of 10μm diameter. A possible explanation may be that these larger particles scatter light more and also give rise to greater hydrodynamic effects. Therefore, the interaction between particles might be more pronounced and more significant at larger particle separations thus yielding a more complicated situation.

CONCLUSION

We have characterised the propulsion of dielectric microspheres in the evanescent field formed in the waveguide cover region. The waveguides were produced by Cs^+ ion-exchange in glass and excited with 1082nm laser light. Polystyrene particles of 3, 7 and 10 μm diameter were stably guided along the waveguide, with propulsion speeds between about 1 μm/s and 33 μm/s, depending upon particle size and input power. They were observed to form chains which had significantly higher propulsion velocities than single particles. We compared the measured velocities to the theoretical predictions given by the hydrodynamic coupling of the spheres to a planar surface, and found reasonable agreement. The residual discrepancy may have several explanations, e.g. differences between chains consisting of 2 and 3 particles, bulk fluid flow and optical interaction between the particles.

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