Assembly of microsphere chains by counter-propagating, guided waves

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Abstract: Microspheres can be trapped in the evanescent field of an optical waveguide and guided along it. In this work we show how counter-propagating waves in the waveguide can be used to assemble chains of microspheres of arbitrary length.

Introduction
For light propagating in a dielectric waveguide, a part of the field extends into the cover medium. This evanescent tail can be used to manipulate microparticles suspended in water, provided that the refractive index of the particle is higher than that of the cover medium and the size of the particle is less than about 15 µm [1]. The optical forces due to the evanescent field act to guide the particle along the waveguide. The use of waveguides to trap particles combines the possibilities of optical tweezers with the techniques employed in integrated optics. This technique can be used to make a Lab-on-a-Chip for manipulation and sorting of nano- and microparticles [2,3]. We have previously shown that chains of two and more particles are readily formed, and that these chains travel faster than single particles [4]. In this work we have used counter-propagating waves from a high-power laser to move particles both ways and hold it at a fixed position on the waveguide surface. We will show how counter-propagating waves can be used to form chains of arbitrary length in a controlled way.

Experimental configuration and procedure
Channel waveguides were formed in soda-lime glass, using an Al mask with 4 µm wide openings, by Cs⁺ ion-exchange in a molten CsNO₃ salt at 450 ºC for a duration of 24 hours. The resultant waveguides were monomode at 1083 nm, which is the wavelength of the laser used. The output power from the laser was in the range 0.5 to 1 W. A directional coupler was used to split the light from the laser 50:50 in two fibres. Light was coupled from the fibres to each end of the waveguide by direct butting. Polystyrene beads (n=1.59) of 7 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 (usually 20 mm × 20 mm × 0.1 mm) defined by spacers made of PDMS and a glass cover slip on top. Particles were observed with an optical microscope with bright field illumination and a ×50 microscope objective. A digital CCD camera was mounted on top of the microscope, and images were recorded on a computer.

Particles migrate onto the waveguide due to Brownian motion, get trapped in the evanescent field of the waveguide and are guided along it when only one fibre is present. With two fibres and equal power going both ways in the waveguide, the particles should stop. In this work, the fibres were positioned laterally to adjust the power injected into the waveguide. By doing so, particles could be moved both ways along the waveguide, and also stopped at a given location. However, there is some propagation loss in the waveguide, and the power in the two directions will thus be equal over a limited length of the waveguide. Particles moved towards this section from both sides and chains are thus formed. The process is speeded up by adjusting the power in the fibres and moving the growing chain back and forth to sweep up single particles. It also helps that chains tend to move faster than single particles [4] so that the chain will catch up with single particles.

Results
In order to show that chains of arbitrary length can be formed, we started by making a chain of only two particles. For this we used a relatively low particle concentration and a short PDMS-cell. A single particle migrated onto the waveguide by Brownian motion and was trapped on the waveguide. It was moved back and forth on the waveguide until a second particle was trapped on the waveguide and eventually was caught up by the first due to a difference in velocity. A single chain of two particles was thus formed, as
shown in fig. 2.

By using a higher concentration and a longer PDMS-cell, many particles can be trapped along the waveguide. Some of the particles will form chains at random. By starting out with such a chain and move it back and forth, it will catch up with other particles and thus grow into a long chain. Some images of this sequence are shown in fig. 3. As explained previously, the formation of a chain in this way is both due to chains travelling faster than single chains and due to particles moving from both sides towards the point of equal intensity. Figure 4 gives the velocity of particles at different points along the waveguide. The velocity decreases and eventually changes sign, meaning that the particles move in the opposite direction. This shows that the particles are moving from both sides towards the point of equal intensity. For this measurement, input power was not adjusted, while the microscope was moved along the waveguide.

The velocity of the particle should be approximately proportional to the difference in intensity impinging on the particle from the left versus from the right. The amount of light scattered by the particle is also linear with the incident intensity. The velocity should thus be linearly related to the difference in scattered light on the two sides of the particle, and figure 5 shows this relationship. The intensity of the scattered light was measured by summing up the intensity in an area on each side of the particle, from images like no. 2 in figure 3. This measurement was done for a single particle while adjusting the power in one direction. It is close to a linear relationship between velocity and difference in intensity, as anticipated. The laser was linearly polarised, but we did not adjust the fibre output to any particular polarisation. Interference effects were not observed, possibly due to different polarisation for the two beams and also due to the large size of the spheres.

Conclusions
We have shown how counter-propagating waves in an optical waveguide can be used to assemble chains of microspheres. Chains consisting of any number of spheres, from just two up to more than 50, can be assembled in this way. We have also shown that the velocity of the microspheres depends on the position

Fig. 4: Velocity of particles vs. relative position along the waveguide.

Fig. 5: Difference in intensity of scattered light on two sides of particle, versus velocity of particle.
along the waveguide due to propagation losses, and again that the velocity is linearly dependent on the amount of light scattered by the particle.

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References
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