Delivery of multi-particle chains by an optical conveyor belt

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ABSTRACT

A motional array of optical traps created by interference of two counter-propagating waves can be used for particle delivery. The mean particle speed is affected by jumps between neighboring traps and is always lower than the velocity of the trap array. We show that a significant enhancement of the delivery speed can be obtained if several particles are delivered simultaneously. We speculate that optical binding between particles and hydrodynamical drafting cause this speed enhancement.

Keywords: optical trapping, Brownian motion, standing wave

1. INTRODUCTION

Micro- and nano-particle delivery is an issue encountered in many areas of research – starting at the delivery and acceleration of single atoms [1] up to the cells or cell ensembles with sizes in tens of micrometers. Microfluidics is a typical delivery method in colloidal systems consisting of particles of different shapes and sizes or living cells. Except the external pumps the colloidal suspensions can be moved by e.g. electrophoresis, dielectrophoresis [2] or electroosmosis [3]. In certain situations when one has to deliver the particles across the flow or in a stationary fluid, micromanipulation by light is one of the possibilities. The single beam optical trap, holographic optical tweezers, or acousto-optical deflectors have been used to either precisely deliver a single particle into desired area or to rectify the motion of huge amounts of particles. Often arrays of optical traps are created. The motional arrays [4, 5] have been used for direct and precise delivery while stationary structures [6] often rectify the random motion in preferred directions and therefore deliver particles. Another option for particle delivery by optical means is a ratchet that is created by optical pattern asymmetric in time or space [7, 8]. Furthermore particles have been delivered along the planar waveguides over long distances by the evanescent field leaking to the environment [9, 10].

Interactions between many colloidal particles placed simultaneously into the laser beams cause principal deviations in their behavior comparing to the single particle placed in laser beams. The best known phenomenon is self-organization of colloidal particles into various one- or two-dimensional structures without the necessity to create optical trap for each particle (so-called optical binding) [11–14]. Apart from the optical forces many particle systems are influenced by hydrodynamical interactions between individual particles. Mechanical constraints [15] as well as optical tweezers [16–18] were used to confine colloidal particles in linear or ring-like structures and the hydrodynamical interactions were studied. However these works either neglected the light interactions between particles or these interactions were not present at all. Grujic et al. [9] showed that a pair of particles, so called bi-particle, moving along planar waveguide moves 15 % faster than single particles.

In our paper we focus on a behavior of more particles delivered in the traveling standing wave, also called optical conveyor belt (OCB) [4, 19], and we show that with the same velocity of the traveling wave more particles are delivered faster.

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2. OPTICAL CONVEYOR BELT

The interference of two counter-propagating waves creates an array of optical traps that can be described by a periodic potential with cosine profile, i.e. \( U(z) = -\Delta U / 2 \cos(2\pi z / L) \), where \( \Delta U \) is a height of potential barrier and \( L \) is the distance between two neighboring minima. The random motion of a particle in such a potential traveling with speed \( u \) (optical conveyor belt) was studied [20, 21] and an average velocity of bead was found as follows:

\[
\langle x \rangle = u - \frac{L k_B T \left[ \exp(yuL / k_B T) - 1 \right]}{\gamma \int_0^L dx \int_{x+L} dy \exp \left[ \frac{U(y) - U(x) + (y-x)yu}{k_B T} \right]},
\]

where \( \gamma \) is Stokes' drag coefficient, \( k_B \) Boltzmann constant and \( T \) temperature. The formula above suggests that the colloidal particle follows the movement of the traveling potential, however, its mean velocity is lower comparing to \( u \). This is caused by the particle jumps over the potential barrier between neighboring optical traps. When the OCB velocity is small, the confined particle follows the motion of the OCB. As the OCB velocity increases the jumps between neighboring traps happen more frequently. These jumps are in the direction opposite to the OCB motion and consequently the average bead speed decreases. The limiting case is that the particle jumps so often that it remains stationary. There exists an optimal velocity of the OCB that gives maximal delivery speed of the trapped particle. However, even if the OCB moves with the high velocity and the speed of the single confined particle is low, the delivery speed can be significantly enhanced if more than one particle are transported together.

We used interference of two counter-propagating evanescent waves and created an array of optical traps near the surface [5, 19], see Fig. 1 for the details. Two independent counter-propagating Gaussian beams were focused on the top surface of a prism. The beams overlapped there and created a spot 100 \( \mu \)m long and 10 \( \mu \)m wide with the standing wave fringes separated by 200 nm. Tuning the incident angle results in either a surface patterned evanescent fields or a propagating light field just above the surface. This set-up enables to alter the relative phase between the two beams in a controlled way by a movable mirror. Its movement results not only in the motion of the standing wave but also in motion of objects confined in this standing wave.

![Fig. 1. Experimental setup. Laser light (Coherent Verdi, 10 W, \( \lambda_{\text{ex}} = 532 \text{ nm} \)) is separated into two beams by a polarizing beam splitter (PBS). One beam is reflected on the movable mirror and returns to the PBS. Since the beam has passed twice through the quarter-wave plate \( \lambda/4 \) its polarization is now perpendicular to the original one and it passes directly through the PBS. Both beams behind PBS have the same polarization. They pass through two pairs of cylindrical lenses L1, L2 that focus the beams to the upper surface of the prism. The prism consists of a BK7 half-sphere lens (diameter \( \frac{1}{2} \)) covered with a thin layer of immersion oil and a cover slip. Movable mirror was controlled by a PIFOC (Physik Instrumente) which provided precise and fast movement over 50 \( \mu \)m with velocity up to 200 \( \mu \)ms\(^{-1} \).]
3. RESULTS AND DISCUSSION

The height of the potential barrier between two neighboring optical traps, i.e. the trap depth $\Delta U/\gamma$, depends not only on the incident laser power but it is also strongly dependent on the size of the bead due to so-called “size effect” [5, 19]. This is caused by the fact that the light scattering causing the optical forces strongly depends on both the size of particle and the distance of interference fringes. Based on our previous results we used polystyrene beads of diameter 520 nm in the experiments since these beads interact strongly with the incident light. The movement of the particles was recorded by a fast CCD camera (Optronics, CamRecord 600) recording 250 fps for approximately 4 minutes. During this period a piezoelectric actuator (PIFOC) performed a saw tooth like motion with velocity either 76 $\mu$m$^3$ or 100 $\mu$m$^3$. This is approximately twice the velocity of OCB motion that causes maximal delivery speed of single confined particle. Consequently, the trapped particle was bi-directionally moved by the standing wave. Because of the random motion other particles diffused to the area of the OCB and they joined the motion forming a particle chain. Within the recorded interval the chains of up to the 18 particles were formed. Also the particles usually joined chain in such a way that the chain of certain length performed at least 3 periods of saw tooth motion before another particle was confined. However in certain cases two particles joined the chain almost at the same moment. Figure 2 compares the motion of particle chains formed by one to 15 beads and taken at four different times. Each horizontal stripe in the figure shows a chain formed by a constant number of particles that existed over a period 2 – 50 seconds.

![Fig. 2. Images of chains of 1 – 15 polystyrene beads of diameter 520 nm placed in water and confined in the OCB. The images compare chain positions and particles locations inside each chain at four different moments. For clarity the positions of the center of the mass at $\gamma = 0$ were vertically aligned. The positions of the centers of the mass are indicated by the vertical bars and the horizontal scale bar in top-right corner shows distance of 2.5 $\mu$m. Note that the chain of 10 particles is missing because 10th and 11th particle joined the chain at almost the same moment.](image-url)
The positions of the bead centers were evaluated with our modification of the particle tracking method [22]. Afterwards we performed a calibration measurement with only one bead confined in the OCB. We used detection method [23] that enables to detect the position of bead with respect to the standing wave fringes and also the motion of the fringes (the light scattered by the particle was observed with camera frame rate 5000 fps). We obtained the velocity of OCB motion as 76 µms⁻¹ and we also obtained the resolution of the camera as 50.7 nm per pixel.

If the OCB does not move the particles in the chain self-arrange in the interference field along the propagation axis of evanescent fields – in an analogy with longitudinal optical binding [11–14]. On the contrary to these works the interference optical traps are also present in our system. The final equilibrium positions are therefore given by both the original optical traps and by the optical binding. Once the OCB starts to move the chain also moves. A single trapped particle moves over only a very small distance due to frequent jumps between neighboring traps. As the chain length increases the distance traveled by particles in the given amount of time also increases leading to the higher speed. Figure 2 shows that – as the chain moves in one direction – the particles in the center of the chain catch up with the leading particles and leave the tail particles behind. When the direction of the OCB motion is reversed central particles again move faster and catch up with the leading ones. However the particles never touch or collide with each other. Happel [24] discussed similar case from the point of hydrodynamics and considered three in-line sedimenting spheres. In that case the spheres never form a stable three-body configuration. Imagine two spheres that are close together at the end of the chain and a leading sphere that is far from them. These two spheres form a bi-particle that moves faster and catches up a leading particle. When the distance between all particles is the same, the middle particle forms a bi-particle with the first one and the two leading particles move away form the last one. Periodic limit cycle of the same type was described [17] where three particles move along a circular fringe of high order Bessel beam. We observed a similar behavior in the sense that particles in the middle of the chain leave tail particles behind and they catch up with the leading ones.

In order to determine the velocity of individual particles, the record of the positions of i-th particle in the chain was fitted by

\[ z_i(t) = A_i \left( \frac{t - \phi_i}{T_i} \right) + D_i, \]

where \( S(x) \) is a symmetric saw-tooth function having values in the range \([-1;1]\) with period \(2\pi\). \( A_i, \phi_i, T_i, \) and \( D_i \) are fitted parameters. Figure 3 shows an example of positions of 8 particles (each in different color) in the chain compared with the fit of Eq. (2).

![Fig. 3. Positions of 8 particles in the chain – colored lines – and fit by (2) – dashed black lines.](image)

Using the fitted parameters we obtain the velocity of i-th particle in the chain as \( v_i = \left(2A_i\right)/(\pi T_i) \) and the results are shown in Fig. 4. We have found that the speed of a single delivered particle is 12.5 µms⁻¹ while the speed of the fastest particle in 15–particle chain is 71 µms⁻¹. That is an almost 6 times enhancement of the original speed. The average speed of the whole chain (calculated as the velocity of the center of mass of the chain) is increasing as well. The average velocity enhancement is lower but the 15–particle chain still moves almost 5 times faster than the single particle. The increase of average speed is linear with the slope \((4.1 \pm 0.3) \text{ µms}^{-1}\) per particle up to 11–particles chain. As the speed of particles approaches the speed of OCB one can observe saturation. We performed further experiments with OCB...
velocity of 100 μm s⁻¹ and we observed formation of chains up to 18 particles long. However we observed no saturation of velocity in these measurements and the slopes of velocity increase with the number of particles in the chain varied between 1 and 4.7 μm s⁻¹ per particle.

The velocity profile of particles in the chain of certain length resembles parabolic profile. It means that particles in the center of the chain move faster than the particles at the edges. The observed velocity of the edge particles was 50% or even more low than the velocity of the particles in the center of the chain. This is caused by two reasons. The hydrodynamical drafting causes that particles packed together move faster. However even more important is the intensity profile of beams forming the OCB. The intensity of beams changes significantly over 50 μm – which is the length of the longest chain. Therefore the trap depth ΔU decreases towards the chain edges and it further decreases the velocity.

4. CONCLUSIONS

An array of the optical traps forms a device called an optical conveyor belt (OCB) that ensures bi-directional delivery of sub-micrometer particles immersed in fluid. Experimentally, the OCB was obtained by an interference of two counter-propagating evanescent waves. We changed the phase of one beam in a saw tooth manner to generate bi-directional movement of the optical traps with constant absolute velocity. However single confined particle moves much more slowly compared to the traps velocity (OCB velocity) because it jumps between neighboring optical traps. If more particles are confined in OCB, such a chain moves faster compared to single delivered particle. Velocity increase is linear up to certain amount of particles and exceeding this number it saturates.

Based on our measurement we found that the central particles in the chain move almost twice as fast as the particles at the chain edges and also travel longer distance. The particles velocity profile is influenced both by intensity profile of incident beams but also by the hydrodynamical drafting effect.

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