Surface delivery of a single nanoparticle under moving evanescent standing-wave illumination

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Abstract. We study the delivery of a submicrometre-sized spherical dielectric particle suspended in water and confined in an evanescent field in the proximity of a glass–water interface. When illuminated by a single evanescent wave, the particle is propelled along the glass surface by the radiation pressure. Illumination by two counter-propagating and coherent evanescent waves leads to the formation of a surface-bound evanescent standing wave serving as a one-dimensional array of optical traps for the stable confinement of the particle. These traps can be translated simultaneously along the surface by shifting the phase of one of the two interfering evanescent waves, carrying the confined particle along in an optical conveyor belt (OCB). However, due to the thermal activation, the particle jumps between neighboring optical traps, and its delivery conditions in the OCB are thus more complex than in the case of the single evanescent wave propulsion. We analyze the delivery speed of a single particle confined in the OCB moving with different speeds and formed by optical traps of different depths. We present a theoretical description of the particle delivery speed in the OCB and compare it with the delivery speed in the single evanescent wave. We support our theoretical conclusions by experimental observations and demonstrate that especially particles having diameters smaller than $\sim 220$ nm are delivered faster in the OCB using the same total optical power.

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1. Introduction

Controlled delivery of micro- and nano-particles is an issue encountered in many areas of research, starting with the delivery and acceleration of single atoms [1, 2] up to the guiding of cells or cell ensembles with sizes of tens of micrometres [3]. When colloidal particles or cells are to be delivered, microfluidic systems are the most frequently used option. Except for external mechanical pumps, the motion of a colloidal solution in such systems can be driven by electrophoresis [4], dielectrophoresis [5], optically induced dielectrophoresis [6], electro-osmosis [7] or light-controlled electro-osmosis [8]. Alternatively, the light itself can also be used to deliver microparticles suspended in a fluid [9]. The classical method uses single or multiple optical tweezers to trap and transport a particle in the fluid [10, 11]. However, the manipulation range of optical tweezers is restricted to an area of the optical microscope’s field of view. Therefore, novel methods of long-range optical particle delivery in space or along a surface have been developed. Guiding of particles along the propagation direction of a single Gaussian beam was first demonstrated by A Ashkin in his early paper [9] and later employed in the optical sorting system [12] or direct guiding of living cells toward a surface [3]. Long-range particle guiding over the 3 mm range by a single continuous wave or fs-pulsed Bessel beam has been reported, too [13, 14]. Another possibility is to couple the laser beam into hollow fibers or waveguides [15, 16] or photonic crystal fibers [17] and guide the particle inside the fiber. Guiding of particles in the evanescent field outside the optical fiber was demonstrated by Brambilla et al [18].

The evanescent field generated by the total internal reflection at dielectric interfaces was first used to guide particles along a flat surface by Kawata et al [19]. The use of evanescent waves for particle manipulation brings several advantages over the free space systems such as easy sample access, background signal reduction, easy integration into the opto-fluidic systems, and large-scale manipulation with up to thousands of particles in parallel [20]. Guiding of dielectric [21]–[24] and metallic [25]–[27] nano- and micro-particles along planar optical waveguides appears to be promising due to the possible integration into real opto-fluidic circuits suitable for lab-on-a-chip applications.

An alternative approach to the controlled particle delivery uses the geometry of two counter-propagating beams. If these beams are evanescent and incoherent they just compensate the radiation pressures of each other and provide large-scale surface particle organization and/or delivery [28]–[31]. However, if the two beams interfere, they form a standing wave capable of...
stable spatial confinement of illuminated particles. A particle placed into the standing wave is confined in the high- or low-intensity regions (so-called optical traps) according to its size and refractive index [32]. In this way, many particles can be simultaneously confined and precisely moved if the phase of one of the interfering beams is changed in a controlled way. A movable array of optical traps forms the basis of the optical conveyor belt (OCB), which can deliver bi-directionally micrometre- and sub-micrometre-sized particles. Up to now, this principle has been employed for particle delivery in the traveling Gaussian standing wave [1], the Bessel standing wave [2, 33, 34] and the evanescent standing wave [35, 36].

Standing-wave particle delivery utilizes steep intensity gradients between the standing-wave nodes and antinodes that confine the particles along the standing-wave axis due to the so-called gradient force. In the evanescent field configuration, the gradient force also pulls the objects toward the surface. In contrast, single beam delivery is based on the so-called scattering force associated with the radiation pressure. It has been shown that for smaller particles the gradient force in the standing wave can be several orders of magnitude larger than the scattering force in a single beam of the corresponding total power [37]. Therefore, especially the particles of sizes in the range of hundreds of nanometres should be delivered faster by the OCB. However, due to thermal excitations from the liquid bath, the trapped particle jumps between the neighboring optical traps (potential minima) during the OCB delivery [38, 39]. Consequently, the position of the particle relative to the moving OCB changes. Since the jumps occur more frequently in the direction opposite to the OCB motion, the particle will always move slower than the OCB. In this article, we provide a theoretical description of the particle delivery speed in the OCB and its comparison with experimental measurements. We also compare experimentally and theoretically the particle delivery speeds in the single evanescent wave and the evanescent OCB. We find that for sufficiently small particles, the particle delivery is indeed faster in the OCB in comparison with the single evanescent wave of the same total power.

2. Brownian particle in a moving periodic potential

In this section, we will describe the one-dimensional (1D) theoretical model of the behavior of a particle confined in one of many identical optical traps created in the optical standing-wave moving with a constant velocity \( u \). If we focus only on the particle behavior along the propagation axes of both counter-propagating beams and neglect the lateral motion of the particle, the problem can be treated as 1D. Therefore, the optical forces, generally non-conservative in 3D, can be assumed conservative and having periodic potential. It has been shown [40, 41] that the configuration with a particle placed into a periodic potential \( U(x) \) traveling with a constant velocity \( u \) (the potential is therefore also time-dependent) is equivalent to the static but tilted effective potential of the following form (see figure 1):

\[
U_{\text{eff}}(x) \equiv U(x) + x \gamma u,
\]

where \( x(t) \) is the particle coordinate, \( u \) is the velocity of the traveling periodic potential, and

\[
\gamma = \gamma_F \gamma_0 = \frac{3\pi}{8\nu} d \gamma_F
\]

is the Stokes viscous drag coefficient (\( d \), \( \nu \), \( \gamma_F \) and \( \gamma_0 \) denote the diameter of the spherical microparticle, the viscosity of the surrounding medium, the correction factor for surface proximity [42] and the bulk drag coefficient at 20 °C, respectively). In the case of the evanescent standing wave, \( U(x) \) is the periodic potential with a period \( L \) and height of the potential

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Figure 1. Particle delivery in 1D traveling potential. The periodic potential $U(x)$ that travels with the constant speed $u$ (left) is equivalent to the static but tilted effective potential $U_{\text{eff}}(x)$ (right). The particle is originally settled in one potential minimum; however, due to the thermal activation it can jump to both neighboring minima (shown by green arrows). Jumps down the potential tilt (to the left here) are more probable and cause the mean particle current $\langle dx/dt \rangle$ to be smaller than $u$.

The effective potential $U_{\text{eff}}$ can be inserted into the overdamped Fokker–Planck (Smoluchowski) equation describing the time evolution of probability density $P(x,t)$ of the particle position in the potential landscape. In order to calculate the mean particle velocity and the steady-state probability density, it is useful to introduce the so-called reduced probability density $\hat{P}(x,t)$ that is periodical in the same way as the potential $U(x)$ and normalized over a period $L$:

$$\hat{P}(x,t) \equiv \sum_{n=-\infty}^{\infty} P(x+nL,t),$$

$$\int_{0}^{L} \hat{P}(x,t) \, dx = 1.$$  

In the long time limit $t \to \infty$, one obtains a steady-state reduced probability distribution $\hat{P}_{\text{ss}}(x)$ and particle current $\langle dx/dt \rangle$ along the x-axis:

$$\hat{P}_{\text{ss}}(x) = \mathcal{N} \cdot \frac{\gamma}{k_B T} \left[ \int_{0}^{L} \int_{y}^{y+L} \exp \left( \frac{U_{\text{eff}}(z) - U_{\text{eff}}(y)}{k_B T} \right) \, dz \, dy \right]^{-1},$$

$$\mathcal{N} = \frac{k_B T}{\gamma} \left[ \int_{0}^{L} \int_{y}^{y+L} \exp \left( \frac{U_{\text{eff}}(z) - U_{\text{eff}}(y)}{k_B T} \right) \, dz \, dy \right]^{-1},$$

$$v \equiv \left\langle \frac{dx}{dt} \right\rangle = u - \frac{L k_B T}{\gamma} \frac{\exp (\gamma u L / k_B T) - 1}{\int_{0}^{L} \int_{y}^{y+L} \exp ((U(z) - U(y) + (z - y) \gamma u) / k_B T) \, dz \, dy}.$$
Figure 2. Dependence of the mean velocity \( v \) of a nanoparticle located in the OCBs with various traveling speeds \( u \) and heights \( \Delta U_0 \) of the potential barriers. The particle (350 nm in diameter) is immersed in water (viscosity \( \nu = 0.001 \text{ Pa}\text{s} \)) and placed far from any solid surface (\( \gamma_F \approx 1 \)). The spatial period of the OCB potential \( (3) \) corresponding to the distance between the neighboring intensity maxima of the standing wave is \( L = 200 \text{ nm} \). The green curve denotes the maximal microparticle velocity \( v_{\text{max}} \) for each trap depth. Regions on the far left or the far right of the green curve correspond to the Brownian surfers or the Brownian swimmers, respectively. In the simulations throughout the article, we assume the refractive indices of the particle and water to be 1.59 and 1.334, respectively, the angle of incidence of the evanescent field-generating wave on the surface \( \theta_i = 62^\circ \), and the light wavelength in vacuum is equal to 532 nm.

Due to more frequent particle jumps to the neighboring lower potential minimum (against the direction of the OCB movement), the particle current (mean particle velocity \( v \) with respect to the surface) is always smaller than the speed of the potential movement \( u \) (speed of the OCB) but it always has the same sign as \( u \). The term

\[
-L k_B T \frac{\exp(\gamma u L / k_B T) - 1}{\int_0^L \int_{-y+L}^y \exp \left( (U(z) - U(y) + (z - y)\gamma u) / k_B T \right) \, dz \, dy}
\]

(10)
can then be associated with the force slowing down the particle current due to the stochastic jumps between the neighboring potential wells.

There exist two limiting modes of the OCB particle transport. For very low velocities \( u \) of the potential movement and sufficiently deep potential wells, the particle follows tightly the movement of a single potential minimum (optical trap); such a particle is called a Brownian surfer [43]. The fast-moving shallow potential wells represent the opposite case. The particle in such a potential does not feel its presence and behaves like a swimmer floating on the surface of the ocean; thus it is called a Brownian swimmer [41]. The particle speed \( v \) tends to zero for both very small and very large OCB speeds \( u \). Therefore, there has to be an optimal OCB velocity \( u_{\text{max}} \) providing the highest particle delivery speed \( v_{\text{max}} \). Figure 2 shows the mean velocity \( v \) of
Figure 3. The mean velocity $v$ of a polystyrene particle of varying diameter $d$ placed into the traveling OCB in the same configuration as in figure 2. The left part of the figure (red curve) shows the dependence of the trap depth $\Delta U_0(d)$ on the particle diameter. Both beams forming the OCB are approximated by evanescent plane waves. The intensity of the electric field $E_0 = 9.8 \times 10^5 \text{V m}^{-1}$ of each of the waves is chosen to give the trap depth $10 k_B T$ for the particle diameter 350 nm.

Let us focus in detail on the problem of a microparticle placed into the traveling evanescent OCB and let us consider the dependence of the potential depth $\Delta U_0$ on the particle size. We use our previously developed model [36] based on the Mie scattering theory [44] to calculate the optical force acting on a particle placed into the evanescent standing wave. The light reflection and re-scattering due to the proximity of the surface are neglected in the calculations. For all the studied particle sizes, we use the same total laser power $P$ of the two counter-propagating beams, which gives potential barrier height (trap depth) $\Delta U_0 = 10 k_B T$ for a polystyrene microparticle of diameter 350 nm. The results are presented in figure 3. The left part of the figure (red curve) shows the dependence of the optical trap depth $\Delta U_0$ on the particle diameter—the so-called ‘standing wave size effect’ [32, 33, 35, 36]—whereas the right part expresses how the particle speed $v$ depends on the OCB speed $u$ and the particle diameter $d$. It can be seen that the particles with standing-wave-insensitive sizes having negligible $\Delta U_0$ (zeros of the red curve) are not affected by the traveling potential and behave as Brownian swimmers for all OCB speeds. Particles of other sizes are carried by the traveling potential with speeds following equation (9). The left part of the figure also demonstrates the decrease of the envelope of the trap depth curve $\Delta U_0(d)$ for the larger particles having a majority of their volume outside of
Figure 4. Comparison of the particle delivery by the OCB and single evanescent wave. The blue curves show the maximal velocity of the particle in the OCB $v_{OCB}$ calculated from equation (9) for different particle diameters. The trap depth was set to $5k_B T$ (full curves) and $10k_B T$ (dashed curves) for the particle diameter 350 nm. For this particle size, the trap depth 5 or $10k_B T$ is obtained for the electric intensity in the single evanescent wave $E_0 = 6.9 \times 10^5 \text{ V m}^{-1}$ or $E_0 = 9.8 \times 10^5 \text{ V m}^{-1}$, respectively. The trap depths for the other particle diameters were obtained from the optical force calculations [36] using the above values of the electric intensity. The green curves show the velocity of the particle propelled by the single beam $v_{SB}$ (one of the beams forming the OCB is blocked). The inset shows the ratio of both velocities $\eta = v_{OCB}/v_{SB}$ as a function of the particle size.

In the following step, we compare the maximal particle delivery speed in the OCB $v_{OCB}$ with the particle speed $v_{SB}$ caused by a single evanescent beam propulsion. In the case of the single beam propulsion, we determine the microparticle speed from the balance between the optical force $F_{SB}$ and the Stokes viscous drag force as:

$$v_{SB} = \frac{F_{SB}}{\gamma}.$$  \hspace{1cm} (11)

We use the same theoretical model to express the optical forces in a single evanescent beam and traveling OCB [36]. Figure 4 compares $v_{SB}$ with the maximal particle delivery speeds in the OCB $v_{OCB}$, found from equation (9). The calculations have been carried out with the power of each of both OCB-forming beams equal to the power of the single illuminating beam; thus, in the case of the OCB delivery, the total power in the system is two times higher. The inset shows the ratio $\eta = v_{OCB}/v_{SB}$ of both delivery speeds as a function of the particle size.

Assuming that all the power divided into two beams in the OCB is redirected into one beam to propel the particle by radiation pressure, the ratio $\eta > 2$ indicates that the OCB transforms the laser power to the particle kinetic energy with higher efficiency. As has already been demonstrated in figure 3, the maximal particle speed in the OCB depends on the depth of the evanescent wave region. Consequently, with the combined effect of the larger viscous drag coefficient, their motion in the traveling OCB becomes slower.
Figure 5. The ratio of delivery speeds $\eta = \frac{v_{OCB}}{v_{SB}}$ calculated for different particle diameters and trap depths. The values of the trap depth $\Delta U_0$ on the vertical axis correspond only to the particle diameter 350 nm; they are achieved with a specific electric field intensity. For particles of other sizes the trap depths are determined by inserting these electric field intensity values and particle diameters into the exact force calculation formulas [36] (see the red curve in the left part of figure 3). Parameter combinations giving $\eta > 2$ ensure more efficient transfer of the light momentum to the speed of the particle delivered by the OCB in comparison with the single beam delivery.
3. Experimental procedures

For the experiments with the OCB nanoparticle delivery, we used an experimental setup based on the interference of two counter-propagating evanescent waves [35, 36]. In contrast with other methods of generation of a periodic near-field interference pattern by a retro-reflecting mirror [45, 46], we used a setup with two independent counter-propagating Gaussian beams that were focused on the top surface of a glass hemisphere under total internal reflection conditions. The scheme of the setup is depicted in figure 6. A linearly polarized laser beam (Coherent Verdi, 10 W, $\lambda_{\text{vac}} = 532 \text{ nm}$) passes through a half-wave plate at $\lambda/2$ that rotates its polarization so that the beam can be separated into two equal parts by a polarizing beam splitter (PBS). The polarization state of the beam reflected from the PBS is changed to circular polarization by a $\lambda/4$ plate. Subsequently, this beam is retro-reflected from a movable mirror, and its polarization is changed back to linear after passing again through the $\lambda/4$ plate. However, this polarization is now perpendicular to the original one so that the beam passes through the PBS and it is subsequently focused by a pair of cylindrical lenses L1 on the top planar surface of a glass hemisphere. The second beam transmitted through the PBS is focused by a pair of cylindrical lenses L2 and made to overlap on the top surface of the glass hemisphere with the first beam. Both beams are incident on the top surface of the glass hemisphere at an angle $\theta_i$ and their overlapping gives a spot 50–100 $\mu$m long and 10 $\mu$m wide with standing-wave fringes separated by 200 nm. The BK7 glass hemisphere (diameter 10 mm) is covered with a thin layer of refractive-index-matching immersion oil and a coverslip that forms the bottom of the sample. A piezo-driven movable mirror (PIFOC, Physik Instrumente) is used for changing the phase in one of the two interfering beams and thus translating the interference fringes precisely and quickly over 50 $\mu$m. Tuning the angle of incidence of both beams results in generation of either a surface-patterned evanescent field or a propagating interference light field just above the surface. The angle of incidence also slightly affects the distance between the interference fringes; however, its influence on the extent of the evanescent field from the surface is much
Figure 7. Detection of the particle location in the moving OCB. The position of the OCB is modulated with different speeds (see dashed lines indicating the OCB position as a function of time) and the positions of a transported polystyrene particle 350 nm in diameter are recorded and analyzed (solid lines). Different colors mark regions of different OCB translation speeds.

more dominant. A small increase of the angle of incidence by a few degrees causes a decrease of the optical forces acting on a particle by several orders of magnitude (see [36]). Therefore, in our experiments, we selected the angle of incidence $\approx 62^\circ$, which is just 0.5° larger than the critical angle. This ensured strong optical forces and also avoided the existence of propagating waves above the surface.

Based on the theoretical predictions (see figure 3), we performed the experiments with the polystyrene particles of diameters 200 and 350 nm that are sensitive to the standing-wave intensity modulation in order to obtain strong optical forces and deep traps in the OCB. The movement of a single confined polystyrene particle was recorded by a fast CCD camera (Optronics, CamRecord 600) providing a recording frame rate of 5000 fps for a time period of 25 s. Within this period, the piezoelectric actuator performed a sawtooth-like motion with different speeds resulting in the corresponding translation of the OCB. For each OCB speed, several periods of the OCB motion were recorded. The position of the particle center relative to the moving OCB and also to the fixed reference frame of the sample was evaluated with sub-pixel accuracy by a new particle tracking method giving resolution in nanometres [47]. Figure 7 shows both the analyzed motion of the particle (solid line) along the $x$-axis (the propagation axis of the evanescent waves and the OCB motion) as well as the displacement of the OCB (dashed line). It can be clearly seen that with increasing OCB translation speed, the lag of the particle motion with respect to the OCB translation grows as predicted by equation (9).

4. Data analyses

The procedure for recording and analyzing the experimental data on the OCB nanoparticle delivery was as follows. At the beginning of the experiment, the OCB was kept stationary ($u = 0$) while the particle position was recorded (initial blue stretch of the curves in figure 7). From equation (7), we obtain for this condition that $\hat{\mathcal{P}}_{\text{st}}(x)$ has the form of the Boltzmann distribution $\hat{\mathcal{P}}_{\text{st}}(x) \sim \exp \left[ -U(x)/k_B T \right]$. Experimentally, the reduced probability distribution $\hat{\mathcal{P}}_{\text{st}}(x)$ was obtained from the histogram of particle positions transposed to the interval $(-L/2, L/2)$. One-parametric fit of the Boltzmann distribution function to the experimental data then gave the trap depth $\Delta U_0$ (see figure 8). For the experimental data shown in figure 7, we obtained $\Delta U_0 = (6.2 \pm 0.5) k_B T$, assuming the temperature of the immersion fluid to be
Figure 8. The reduced probability density \( \hat{P}_s \) of finding a particle of diameter 350 nm at a distance \( x \) from its equilibrium position in the OCB for a stationary OCB \( (u = 0) \). The histogram is fitted by the Boltzmann distribution giving the trap depth \( \Delta U_0 \) as the only free fit parameter.

Figure 9. Measured and calculated mean speeds \( v \) of the polystyrene particle (diameter, 350 nm) as a function of the OCB speed \( u \). Experimental data (dots) are fitted by equation (9) using \( \gamma_F \) as the only free fit parameter (solid line).

\( T = 293 \text{ K.} \) Note that the error of the fitted parameter value above and later on in this section corresponds to the 95% confidence level. The agreement between the fit and the experimental data is very good as figure 8 shows.

The mean particle speed \( v \) and the OCB speed \( u \) were obtained from the data presented in figure 7 (full and dashed position records, respectively). Each color in the position traces corresponds to a particular OCB speed \( u \) and also to the corresponding mean particle speed \( v \). Both speeds were determined from line fits to the respective color-coded stretches of the position traces keeping the value of the fitted line slope constant for all position modulation periods belonging to a single OCB speed. Resulting velocities \( v \) and \( u \) are displayed in figure 9 as dots. The maximal errors of \( u \) and \( v \) obtained by the fit were \( \sim 230 \) and \( \sim 370 \text{ nm s}^{-1} \), respectively, which is less than the size of the markers used for displaying the data points in figure 9.

Subsequently, we used equation (9) to compare the experimental results with the theoretical predictions. Since we know the stationary depth of the trap \( \Delta U_0 \) from the stationary OCB
Figure 10. (a) The correction factor of the viscous drag coefficient $\gamma_F$ in the direction parallel to the surface given by the surface presence (see equation (7-4.27) in [42]). (b) The change of the water dynamical viscosity $\nu$ with increasing temperature. The circles represent data taken from [48] and the line is the spline interpolation.

Figure 10 illustrates both the effects (i.e. viscosity changes with temperature and surface proximity) and reveals that both strongly influence the behavior of the particle in the traveling OCB. For a particle in contact with the surface, one obtains $\gamma_F \approx 3$ and a temperature rise by $20^\circ C$ causes viscosity to decrease to $2/3$ of its value at $20^\circ C$. Without the measurement of the local temperature of the fluid surrounding the particle and the particle–surface distance, we are not able to determine experimentally the exact value of $\gamma_F$. However, if we assume a constant temperature during delivery equal to the room temperature of $20^\circ C$, we will obtain from equation (12) the distance $h$ between the particle center and the surface as 440 nm, which is a plausible value. The agreement between the experimental results and the theoretical fit illustrated in figure 9 persuades us to claim that the used transport model describes well the real particle behavior at this level of approximation.

5. Comparison of the nanoparticle delivery speed in the OCB and the single evanescent beam

In order to study the delivery speed of the particle pushed by the radiation pressure of a single evanescent wave and by the OCB under the same experimental conditions, we alternately
Figure 11. (a) Records of the particle positions during the single evanescent wave propulsion. The particle of diameter 350 nm was successively propelled by the first and the second beam coming from the left (green curve) and right (red curve), respectively. The tilt of the curves is caused by the variation of the evanescent wave intensity along its propagation (see text). (b) Records of the particle speed in single evanescent waves as a function of particle position $x$ (tilted green and red curves corresponding to the beams incident from the left and right, respectively). The particle speed was determined from the time differences of the smoothed particle position tracks presented in (a). The horizontal gray line shows the maximal delivery speed and the range of positions of the particle moving in the OCB (compare with figures 7 and 9). Dashed and dotted horizontal lines show the theoretical values of the maximal delivery speeds in the OCB and single evanescent wave, respectively (see text).
If, however, we consider only the particle motion around \( x = 1 \mu m \), where the OCB depth \( \Delta U_0 \) was obtained and where both counter-propagating beams have almost the same intensity, the experimental data agree quite well with the theoretical prediction of the delivery speed ratio. The difficulties with the axial beam intensity variations could be overcome if one employed the interference of non-diffracting Bessel beams \([33, 34]\) and delivered the particles far from the surface.

In order to validate the conclusions from figures 4 and 5, we have further studied the behavior of particles with diameter 200 nm (data not shown). Since 200 nm particles are too small for the above described particle position tracking method, we had to apply a different tracking algorithm based on the bright-field imaging of the particles \([49]\). We moved the OCB with three different speeds (40, 60 and 100 \( \mu m \text{s}^{-1} \)), and afterwards, we alternately blocked one of the OCB-forming beams. This time the beams were less tightly focused in the \( x \)-direction and, therefore, the axial intensity variations were smaller and we could neglect their influence on the particle delivery speed. We found that the particle moved with a maximal velocity 23 \( \mu m \text{s}^{-1} \) for the OCB velocity 60 \( \mu m \text{s}^{-1} \), whereas the average velocity with a single blocked beam was two times lower and was equal to 11.5 \( \mu m \text{s}^{-1} \). This proves that the OCB is indeed able to deliver tiny particles much faster than the single beam radiation pressure.

6. Conclusions

We have focused on the motion of a single nanoparticle in a traveling periodic potential (OCB) and studied theoretically and experimentally the mean particle delivery speed in this system. The delivery of a nanoparticle in the moving OCB is equivalent to the particle motion in a tilted but static periodic potential. Due to the thermal activation, the particle jumps between neighboring potential minima in both directions (up and down the potential landscape slope); however, the net motion of the particle is directed along the potential tilt (against the direction of the OCB motion). In the theoretical analysis we have employed the 1D Fokker–Planck equation to predict the mean velocity of a particle in this system \([41]\). For modeling, we have approximated the moving OCB by a 1D array of optical traps formed in the interference field of two counter-propagating coherent evanescent waves. The phase of one of the waves could be changed and therefore the whole structure of optical traps could be moved with a controlled rate.

We have studied theoretically the delivery speeds of a particle placed in the OCB under various conditions: different speeds of the OCB motion, and various particle sizes and depths of the optical traps. We have compared these results with the particle guiding speed in a single evanescent wave and found that the OCB should provide faster delivery of particles with diameters between 290 and 370 nm and smaller than about 220 nm with the same total used power. The existence of two discrete ranges of the favorable particle sizes is caused by the standing-wave size effect \([32]\). We have verified these conclusions experimentally with particles of diameters 350 and 200 nm and have obtained a very good agreement between the measurement and simulation. In the case of simultaneous delivery of many particles, the dynamics of the particle delivery is considerably more complex due to the optical and hydrodynamic interactions between the particles forming the delivered bound structure \([29, 31, 42, 46]\). The dependence of the particle delivery speed on the number of simultaneously confined particles is currently under investigation.

Even though we have dealt with a specific arrangement of two counter-propagating interfering evanescent waves, our results can be readily generalized to other configurations.
of the incident beams (e.g. Gaussian or Bessel beams). Our findings suggest that the OCB is an efficient and convenient tool for fast delivery of a single nanoparticle that can be easily integrated into lab-on-a-chip systems and combined with other particle micromanipulation and analytical techniques.

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