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Colloidal sorting in dynamic optical lattices

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Abstract
Passive microfluidic sorting techniques based upon the interaction of particles with an optically defined potential energy landscape have possible advantages over active sorting techniques such as microfluorescence activated cell sorting (FACS), including ease of integration into lab-on-a-chip systems, reconfigurability, and scalability. Rather than analysing and deflecting a single-file stream of particles one by one, a passive approach intrinsically aimed at parallel processing may, ultimately, offer greater potential for high throughput. However attempts to sort many particles simultaneously in high density suspensions are inevitably limited by particle–particle interactions, which lead to a reduction in the efficiency of the sorting. In this paper we describe two different approaches aimed at reducing colloidal traffic flow problems. We find that continuous translation of the sorting lattice helps to reduce nearest neighbour particle spacing, providing promise for efficiency improvements in future high throughput applications, and that a flashing lattice yields a reduction in unwanted pile-up and spillover effects which otherwise limit the efficiency of sorting.

Keywords: optical tweezers, cell sorting, transport, optical lattice, angular Doppler effect, ratchet

(Some figures in this article are in colour only in the electronic version)

1. Introduction

While the current ‘gold standard’ for cell sorting is FACS, that technology is complex, expensive, and requires the development of fluorescent tags. Several geometries have recently been demonstrated for utilizing *optical forces alone* to sort materials entrained in microfluidic flows [1, 2]. All-optical chromatography has now been used to sort designed proxies for anthrax spores and other bioterrorism agents from a background of pollen and other species [3]. Elsewhere, the response to optical forces has been used to separate metastatic cancer cells from less aggressive cancer cells and from normal cells [4] as well as sorting stem cells out from a background of differentiated cells [5]. These new approaches have been incorporated into lab-on-a-chip technology for clinical trials that are currently underway.

To zeroth order the strength of a particle’s interaction with an optical lattice depends on a Clausius–Mossotti factor,

$$\alpha_0 = \frac{3n_{\mathrm{medium}}}{2c}\left(\frac{n^2_{\mathrm{sphere}} - n^2_{\mathrm{medium}}}{n^2_{\mathrm{sphere}} + 2n^2_{\mathrm{medium}}}\right)$$

which determines the relative polarizability of a particle, and also upon an integral of the optical intensity gradients over the volume of the particle,

$$\int_{\mathrm{Vol}} \nabla I(r)\,\mathrm{d}V$$

which shows that the optical force depends upon particle size, location, and, for shaped particles, upon orientation (or, to put it another way, how the particle samples the optical gradients). It is particularly difficult to go further in modelling dense, dynamic flows. Nevertheless, the zeroth-order model provides

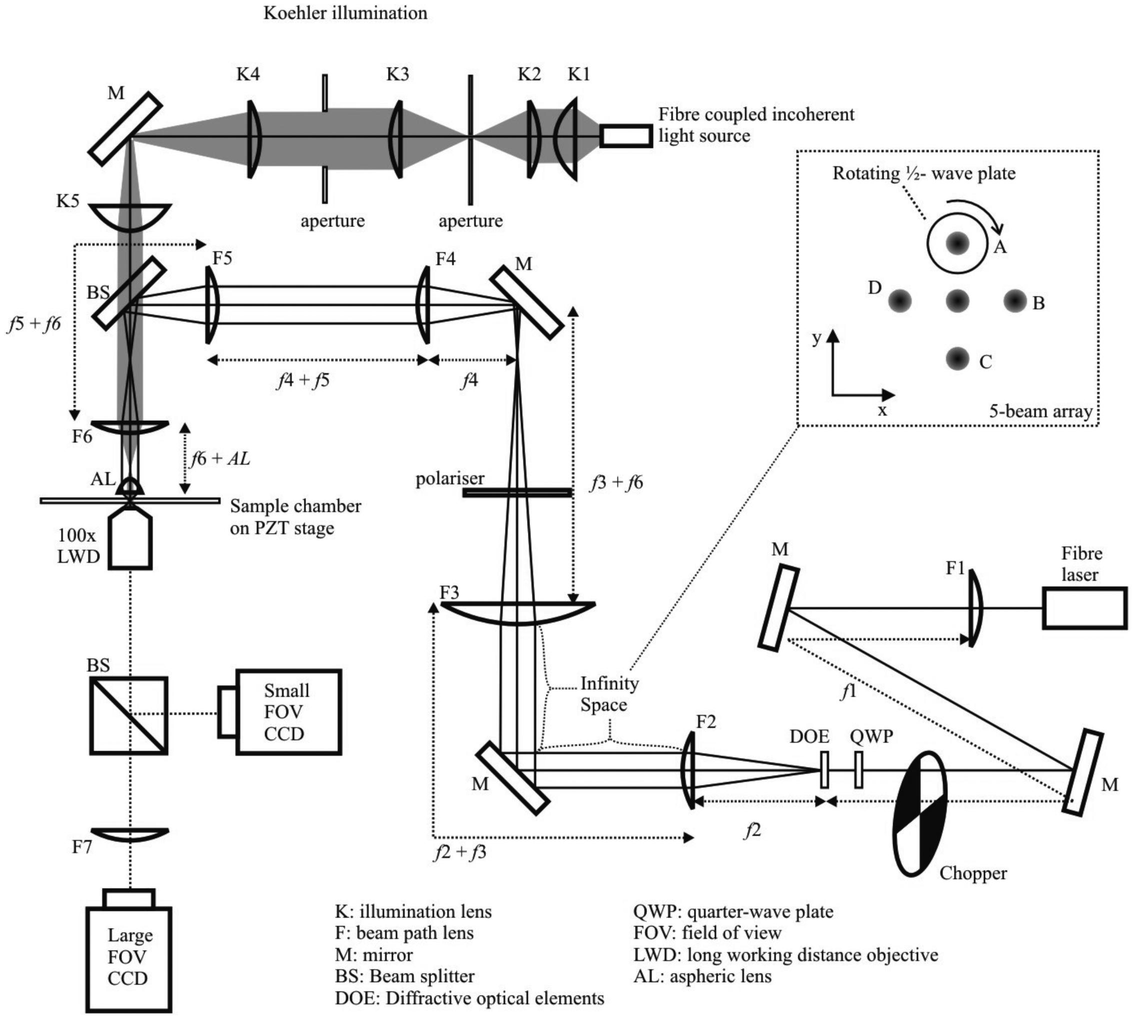

Figure 1. Schematic of our set-up, including the quarter- and rotating half-wave plates used for the angular Doppler effect, and the optical chopper and PZT stage used for the ratcheting sorter.

a guide to the intuition which often matches experimental results to a surprising degree.

Some methods that have been proposed utilize *active* intervention, one particle at a time, for sorting micrometre-scale particulate matter suspended in microfluidic channels, where an external decision-making process controls the deflection of particles into separate channels [6]. However, a *passive* approach involving flow through an extended optical lattice may ultimately offer greater potential for high throughput, due to its intrinsic ability to process particles in parallel without the need for any external decision-making. While passive techniques often offer greater throughput than active techniques, efficient throughput is eventually limited by particle–particle interactions and colloidal jamming.

As a basic transport problem, we have here an interesting model system. Since the particles are small enough to exhibit Brownian motion, we have a true thermal system (unlike shaken granular systems); yet, because the particles are large enough to be studied with conventional video microscopy, we can move beyond the ensemble-averaged measurements available in atomic and molecular studies. Indeed, simulations of colloidal transport across potential energy landscapes have begun to reveal a number of surprising features.

2. Experimental set-up: generating optical lattices

Large arrays of optical traps can be generated in several ways. Acousto-optic deflectors (AODs) can raster a single trap beam on a timescale much faster than the response time of the particles to be trapped, yielding a ‘time-shared’ array. Alternatively, one may physically split the input beam using, for example, the methods of holographic optical tweezers (HOTs) [7, 8] or generalized phase contrast (GPC) [9]. While each of those methods allow for real-time reconfigurations and optimization, another, less complex method appropriate for generating *symmetric* lattices relies simply upon the interference between multiple beams. The optical landscape and lattice properties can be finely tuned based on parameters such as laser wavelength and angle of orientation of the interfering beams. Here we use an inexpensive diffractive optical element (DOE) as a beam splitter, and then generate an extended lattice via multi-beam interference. We utilized a 1070 nm wavelength laser (IPG Photonics) to provide a maximum power of 3 mW $\mu\mathrm{m}^{-2}$. In our set-up, shown in figure 1, five beams were created by the DOE. By changing the number, relative strength, and phase of the interfering beams we can obtain a range of interferograms that can be used in optical sorting. Interfering two beams of equal strength will yield a 1D periodic lattice; interfering three yields a 2D periodicity; interfering all five creates a 3D body centred tetragonal lattice; varying the relative strength of the beams allows us to continuously tune between these limits, creating a tailored degree of interconnectivity along channelling directions [10].

There are two senses in which we can convert these static optical lattices into dynamic lattices, we can either modulate amplitude or we can modulate phase. The former, which yields a 'flashing lattice,' we have achieved either by direct laser modulation or, here, through the use of an optical chopper. The latter, implemented here via the angular Doppler effect [11], generates a *translating* lattice.

3. Translating optical lattices

In order to generate the translating lattice we continuously modulate the phase of one of our five interfering beams. Through the use of a quarter-wave plate, all five beams are circularly polarized. Subsequently, a single one of these beams is passed through a rotating half-wave plate. The effect of the wave plate can be described in terms of a continuously evolving phase shift or more simply as an angular Doppler shift in the frequency of the beam. When this 'angular Doppler shifted' beam is interfered with the four other unmodified beams, the resulting interferogram is no longer static and translates at a rate proportional to the half-wave plate rate of rotation.

The direction in which the lattice translates is determined by the choice of which of the five interfering beams is frequency shifted and whether the frequency of this beam is shifted up or down. If the central beam is frequency shifted then the lattice is effectively scanned in the z-direction (direction of light propagation) and we progressively move through the vertical planes of the body centred tetragonal optical lattice. On the other hand, in order to achieve the sort of lateral scanning that adds to the usual deflections associated with optical sorting, we choose to frequency shift one of the peripheral beams, labelled A to D in figure 1. Shifting the frequency of beams A or C scans the lattice along the y-axis. If beams B or D are frequency shifted then scanning is along the x-axis.

4. Results: translating optical lattices

Our previous work has shown that particles with different size/geometry or index of refraction experience *different* potential energy landscapes as they traverse an optical lattice [12]. Critically, we have cleanly demonstrated that the same particle can be made to either strongly or weakly interact with the optical lattice: e.g., by suitably selecting the standing wave spacing, the deflecting force on a given particle type, which is quite significant for some optical lattice constants, can be adjusted to *nearly vanish* [13]. By tuning the flow velocity (as in figure 2), lattice constant, or incident power it is possible to obtain a highly selective lateral deflection of one particle species with respect to another while minimizing flow-speed dependent particle–particle interactions. Exploiting this effect, we have presented passive, all-optical (non-invasive) methods for microfluidic sorting of colloidal or biological matter. Yet because accurate particle tracking of polydisperse ensembles remains a significant challenge, we here use 1 μm silica and polymer spheres as a model system for a more systematic exploration of some of the basic issues involved in multi-species colloidal traffic through optical lattices.

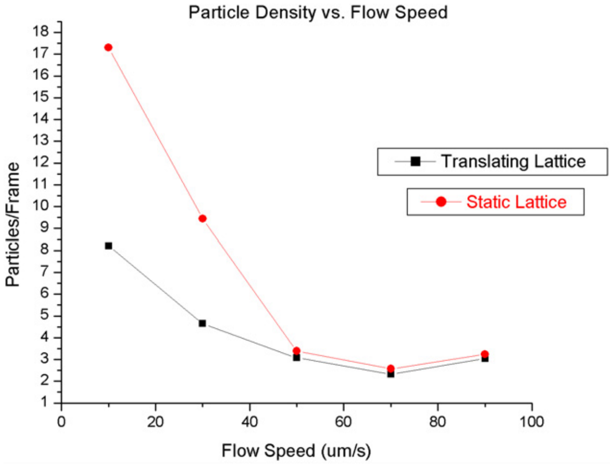

Figure 2. Dynamically translating lattices reduce traffic 'pile-ups'. The resulting efficiency of sorting increases by 10–20% for optimal injection channels. This happens as a result of the larger nearest neighbour spacing seen here. At the highest flow speeds particle activation due to viscous drag dominates for both static and translating lattices. This study was carried out for particles of 1 μm in diameter with a lattice constant of 3 μm.

These explorations have revealed two main forms of *particle–particle interactions* that limit the degree of sorting that occurs in these traffic flows. The first is where a weakly deflected species knocks a strongly deflected species in the direction of flow, reducing its net deflection angle and reducing the overall efficiency of the sorting process. Yet, as shown in figure 2, by adding a DC translation to the optical lattice, we are able to reduce, significantly, the particle density within the sorting region (figure 2). This reduction, in turn, decreases the frequency of particle–particle interactions, thereby allowing an increase in efficiency when working with crowded particle suspensions. Our results are that this reduction in particle density leads to an increase of up to 20% in routing efficiency for optimal injection channels.

The second form of particle–particle interaction occurs when strongly deflected particles form, collectively, physical barriers that can cause particles which would *normally* be weakly deflected to spill over into the uptake stream, reducing the efficiency of sorting. We have found that it is possible to overcome this problem either by utilizing a translating optical lattice (for the reasons noted above) or by using a flashing substrate where the sorting comes about as a result of a novel, selective ratcheting effect.

5. Flashing optical lattices

Rather than using phase modulation, as we did to create the translating optical lattice, we can create an alternative form of dynamic lattice via amplitude modulation of the laser. This system is similar to that described by Libal *et al* who predicted new forms of ratcheting in colloidal particles travelling over

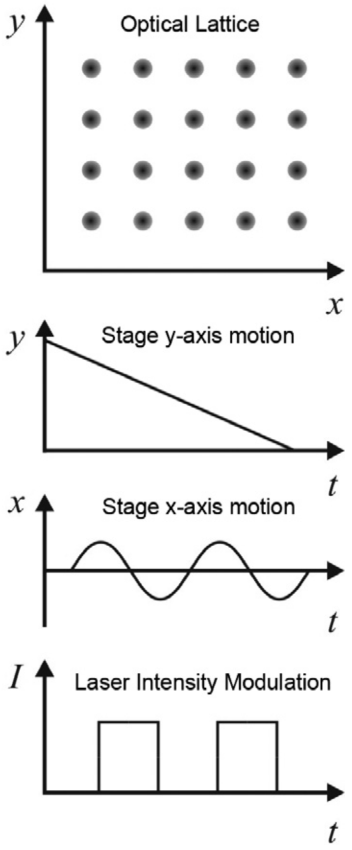

Figure 3. Driving scheme for the synchronization of the fluid drive and the flashing of the optical lattice. By setting the correct frequency, phase and amplitude relationships for each driving signal, a ratcheting effect occurs.

flashing substrates [14]. In our 'flashing' lattices the optical potential was chopped at a frequency matched to that driving a piezoelectric sample stage back and forth along one axis in the sample plane. The amplitude of the stage oscillation was slightly higher than spacing between intensity minima in the optical lattice, and the resulting maximum stage velocity was consistent with trapping. This scheme is represented in figure 3, which schematically shows the lattice, its intensity signal and the drive in the x- and y-directions

In figure 3 we can see that during positive x-motion of the stage, the lattice is switched off and the motion of the particles is unhindered. However when the direction of motion of the sample switches, the lattice is turned on and the particles are locked in place as long as the trapping force of a local intensity maximum in the lattice is greater than the fluid drag exerted by the AC drive. This results in a ratcheting effect leading to a net motion of particles in the x-direction.

The strength of the ratcheting effect depends upon the relative strength of the interaction each particle experiences with the underlying optical lattice, the frequency of the stage oscillation, the lattice constant, and the phase relationship between the stage and lattice driving signals. By tuning parameters such as the depth of modulation of the optical lattice or fluid drag based on maximum velocity of the AC drive, it is possible to arrive at a situation whereby a weakly interacting species is no longer locked into the lattice but a strongly interactive species continues to ratchet. For our system, a sinusoidal velocity profile with a peak-to-peak amplitude of 3.3 μm was used for our AC ratchet. With these parameters, the maximum drag of approximately 180 pN can be obtained for an isolated sphere through calibration against Stokes drag. Note, however, that it is not possible to calibrate the optical forces in the many-body limit, where hydrodynamic coupling and the collective effects of light scattering (e.g., optical binding) add enormous complexity. Just as statistical mechanics cannot be derived from Newton's laws, many-body colloidal systems must be treated via formalisms that *differ in type* from the approaches used to analyse single-particle systems.

It is useful, however, to note that our *maximum* laser power density was found to be 3 mW μm^{-2}. In many cases, sorting occurs for power densities that are *significantly less* than those used for experiments using conventional optical tweezers. With these low power densities, figures 4 and 5 show a significant selectivity of particles: thus, the ratcheting effect can be used to sort particles according to their size, shape or refractive index.

6. Results: flashing optical lattices

As outlined by figure 3, we have studied transport when an orthogonal DC flow is superimposed on the AC flow created

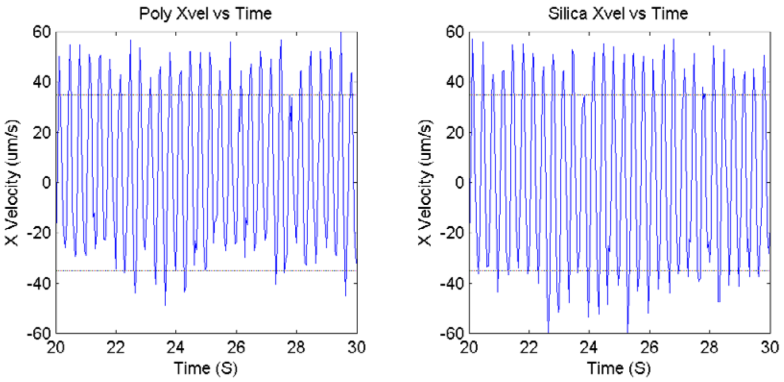

Figure 4. Polymer x-velocity versus time (at left), showing an offset not seen for the silica (at right). Increase in x-velocity indicates effective routing for the strongly interacting species (polymer).

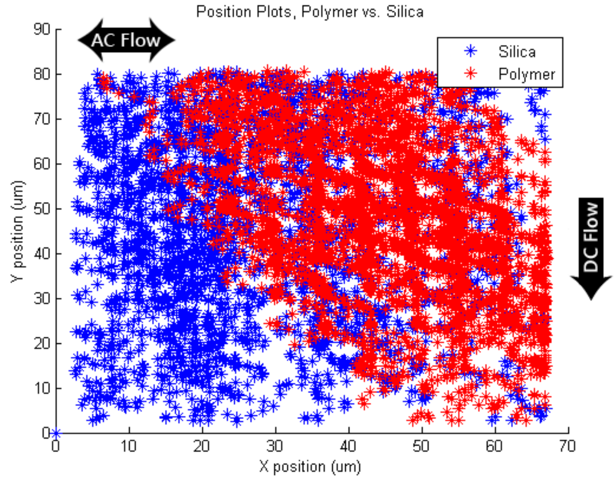

Figure 5. Particle trajectories: while silica particles flow directly through the flashing lattice, the polymer spheres are efficiently ejected to the right.

by the stage oscillation. Figures 4 and 5 illustrate a particular run in which the DC flow was created by translating the stage at 10 μm s^{-1} in the negative y-direction (normal to the ratcheting direction). The ratchet rate was 3 Hz with an amplitude of stage motion slightly larger than the optical lattice constant (3 μm). The sample consisted of a model *bidisperse* ensemble of 1 μm silica and same-sized polymer spheres. The figures clearly indicate selective sorting by index of refraction. For example, the mean x-velocity (lateral deflection) for polymer spheres was 5.17 μm s^{-1}, while for silica it was only 1.41 μm s^{-1}, while the y-velocities of the two species were quite similar (polymer $= -3.26$ μm s^{-1}, silica $= -3.12$ μm s^{-1}).

Assuming that the external force from the flashing optical landscape is large enough to overcome particle–particle interactions (namely non-interacting particles trying to 'bump' strongly interacting particles from their locked positions) this methodology can also be used to reduce improper routing as a result of many-body effects. Additionally the flashing of the optical landscape offers a mechanism for particles to escape the landscape when they reach the far side. This means that there are minimal pile-up problems and the associated problem of the spill over of weakly interacting particles is ameliorated.

7. Conclusions

To minimize the limitations associated with particle–particle interactions we introduced a novel method utilizing the angular Doppler effect to create a dynamic lattice. The resulting, continuously translating lattice helps to reduce the density of colloidal traffic *within* the lattice and so may be of relevance to future, high throughput applications.

An alternative approach, involving a ratcheting mechanism, was also found to result in sorting of multi-species ensembles. In the version that includes AC + DC flow, the flashing of the optical substrate ejects the particles downstream at the side of the lattice, continuously removing any pile-ups from the input particle stream.

Acknowledgments

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