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Large-angular separation of particles induced by cascaded deflection angles in optical sorting

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Abstract

A composite microlens array (MLA) with two cascaded guiding axes has been fabricated to achieve a large lateral separation of an object with different refractive indices or sizes. The MLA projects a composite pattern formed by its focal spots into a microchamber for optical sorting in a microscopic system. This approach enables passive, high power, efficient, and continuous microfluidic sorting without requiring complicated optical assembly. Separation of particles with different refractive indices to a lateral angle of 40° is experimentally demonstrated with moderate laser power.

Optical tweezers that were invented by Ashkin *et al.*¹ are able to trap and manipulate colloidal particles or biological cells with a gradient force generated by a highly focused laser beam. In the development of optical trapping technology itself, it has been matured for applications ranging from simple trapping and manipulation to more sophisticated areas such as optical vortices,² optical actuator,³ three-dimensional (3D) optical tweezers,⁴ laser guidance,⁵ creation of two-dimensional (2D)/3D colloidal crystals, and structures.⁶ Among the applications, optical actuator and optical sorting are two key components that might give rise to all optical laboratory-on-a-chip and optofluidic devices. An all-optical sorting was reported that was based on an optical lattice created by multibeam interference particles that can be sorted by sizes or by refractive indices.⁷ Unlike those approaches using fluorescence as labels for sorting,^{8,9} the all-optical sorting method makes use of the natural physical attributes of particles, such as size or refractive index as a label for sorting; hence, it has the advantages of being continuous, noninteractive, and minimally invasive. In addition to the multi-interference, computer generated holograms^{10,11} and phase contrast¹² are also used to generate optical lattice for sorting.

The principle of all-optical sorting lies in the fact that the trajectories of particles may deviate when they pass through an optical potential landscape, and the trajectories of the particles are strongly dependent on their sizes and refractive indices. If relevant parameters and conditions are selected properly, the group of particles mixed with different sizes or refractive indices will be separated laterally. The lateral angle of the separation is a key

parameter that evaluates the performance of a sorting system. When the optical pattern is generated with a tailored degree of interconnectedness, it has been reported that particles may be deflected to an angle of 45° from the original flowing direction. The multi-interference and phase contrast approach to generate the required interconnected optical lattice in references has experimentally been demonstrated.^{7,12} Recently it has also been proven that discrete optical spots array is capable of realizing a deflection angle of 45° but it requires laser power higher than 1 W.¹³ In order to realize large deflection angles but with moderate laser power, we propose a composite optical lattice pattern with two cascaded deflection axes to realize optical separation with a larger deflection angle. The composite spots pattern is enabled by a composite microlens array (MLA) fabricated in melted positive photoresist, which is employed efficiently to project the optical pattern into the microchamber on a sample stage. It has been proven experimentally that a group of microparticles with same size but different refractive indices are separated laterally with a greater deflection angle.

In a microchamber with a very low Reynolds number, diffusion works as a dominant factor. As diffusion is fairly slow, how to separate objects efficiently is a problem. In the all-optical sorting method, optical force is introduced to determine varied trajectories for objects of different characteristics. The principle of the optical sorting technique is based on the resultant deflection that is induced by optical gradient forces competing with an external driving force in the laminar flow. The direction of driving force has an angle with regard to the guiding axis of the optical lattice. When a mixture of different groups of objects are translated through the optical potential landscape, the condition of whether the particles will be deflected or not is dependent on a series of parameters, especially the particles' sizes and refractive indices. Sorting a mixture of particles can be implemented and realized following particles trajectories at different angles. The details of sorting principle were introduced in our previous paper.¹⁴ It has been proven theoretically that the optical sorting condition depends exponentially on the sizes and refractive indices of the particles algebraically. As long as the relevant parameters are set appropriately, the objects with larger sizes or higher refractive indices will deviate with an angle from the previous driving direction and become locked-in to the guiding axis of the optical lattice. The principle of sorting on discrete 2D optical lattice is based on the locked-in transport theory, which has a limit angle (much smaller than 45°) only if the laser power reaches 1 W or more. In order to solve this limit, we modify the optical lattice to composite optical lattice with two cascaded guiding axes, as it is shown in Fig. 1. The angles between two axes of lattice and the direction of horizontal flow are θ_1 and $(\theta_1 + \theta_2)$, respectively, and both θ_1 and θ_2 are designed not to exceed the limit of the lock-in theory. When the mixed objects with different refractive indices pass through the optical lattice, those with higher refractive indices will deviate from the original horizontal driving direction and are locked into the first guiding axis. Subsequently, those deflected objects encounter the second part of the lattice. As the angle between flow direction and second guiding axis still does not exceed the limit, they will be further deflected to follow the second guiding axis. Accordingly, the two groups of particles are laterally separated with a larger angle of $(\theta_1 + \theta_2)$.

Reflow technique is employed for the fabrication of refractive MLA.¹⁵ Figure 2(a) shows a micrograph of the fabricated MLA in photoresist. The diameter of the individual microlens was $180\ \mu\text{m}$. Figure 2(b) shows the surface profile of MLA measured by surface profiler (Veeco Metrology). It is revealed that the smoothness and uniformity of MLA is satisfied.

In optical trapping and sorting experiments, microbeads are held in a microchamber with a sandwiched structure, which is composed of two parallel glass coverslips separated with a spacer of $70\ \mu\text{m}$. The fabricated composite MLA is employed to project a 2D optical lattice with two guiding axes, and the scope of the optical pattern is approximately $30 \times 30\ \mu\text{m}^2$.

When the laser output power is set at 400 mW, the particles are trapped in an array with regard to the distribution geometry of fabricated composite MLA, as shown in Fig. 3. In order to separate particles continuously, the particles are required to pass through the optical landscape at a constant speed. In our experiment, an upright microscope with a motorized stage is employed to translate samples in the microchamber stably, and the minimum of translation velocity is 1.2 $\mu\text{m/s}$. Two groups of microbeads with the same diameter size (3 μm) but different refractive indices are selected for separation in microchamber; one is a polymer bead ($n=1.59$), and the other is a silica sphere ($n=1.42$). The mixture of particles is driven by the motorized stage at a speed of 15 $\mu\text{m/s}$. The angles between driving force and two guiding axes are 20° and 40°, respectively. When the samples are uniformly translated into the optical lattice, it is found that most of the polymer beads are first deflected to follow about 20° following the direction of first guiding axis, subsequently further deflected to the direction of second lineage axis with an angle of 40° to the original direction. However, most of those silica spheres escaped from the optical landscape without obvious changes in the trajectories. Consequently, two groups of particles have been laterally separated. As it is shown in Fig. 4, those marked in square are the silica particles; while in circle are the polymer particles. The three micrographs are consecutive snapshots of objects' motions with 1 s intervals.

In order to characterize the influence of laser power on the sorting efficiency, we repeated the optical sorting experiments with different laser power while keeping other parameters including flowing speed (15 $\mu\text{m/s}$) unchanged. The sorting efficiency is defined as the proportion of larger particles with obvious trajectory change minus the proportion of smaller particles being significantly changed in motion trajectories (only particles passing through the optical landscape were involved). In experiments, it is found that no obvious sorting phenomenon can be observed until the laser power is increased to 200 mW and above. It is noted in Fig. 5 that the sorting efficiency can be plotted as a function of laser power, which is in agreement with the theoretical analysis. The sorting efficiency can be achieved higher than 80% when the laser power of 500 mW is employed. It is also seen in the figure that sorting efficiency reaches the maximum when laser power is 600 mW. This is due to the fact that once the laser power is higher than 600 mW it results in a larger deflecting proportion of the smaller particles but without deflecting more particles with a larger diameter.

The presented optical sorting system makes use of composite MLA with two cascaded deflection angles to provide an approach to a large separation angle without additional cost of laser power applied to the sorting system. This provides an advantage to the optical sorting system when laser power versus deflection angle optimized for sorting efficiency.

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FIG. 1.
(Color online) Principle of optical sorting induced by cascaded deflection angles.

FIG. 2.
(a) Micrograph of the fabricated MLA with reflow technique (b) surface profile of the MLA.

FIG. 3.
(Color online) Micrograph of trapped microbeads.

FIG. 4.
(Color online) Consecutive snapshots of optical sorting by refractive index.

FIG. 5.
Relationship between separation efficiency and output power of laser.