Fractionation of polydisperse colloid with acousto-optically generated potential energy landscapes

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The motion of colloidal particles on a periodic optical potential energy landscape in the presence of an external driving force may result in particle separation. In contrast to recent methods of holographic or interferometric generation of such landscapes, we use an acousto-optic deflector to create two-dimensional landscapes. We present what is believed to be the first experimental realization of fractionation with simultaneous sorting of four different sizes of colloidal microparticle into laterally separated parallel laminar streams. © 2007 Optical Society of America

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Recent years have witnessed a major growth in the exploration of microparticle motion on optical potential energy landscapes.[1–3] The nature of the interaction between a particle and the light field depends on the particle's size, shape, and composition. Particle and cell motion through an optical landscape may therefore lead to the spatial separation of different particle species and ultimately to methods for passive particle sorting.

In the absence of fluid flow one may use periodic patterns such as Bessel beams[4] or motional light patterns[5,6] to enable optical sorting. In the presence of fluid flow, optical chromatography may be realized with a light field propagating against the direction of flow.[6] An alternative and very powerful form of sorting can be established through the motion of particles across 2D or 3D optical patterns, where the particles follow statistical trajectories across the associated potential energy landscapes.[1–3,8–10] These methods, however, have so far been restricted to sorting bidisperse samples, with preferential deflection of one of the two particle species. Simultaneous fractionation of multiple species has been predicted[2] but perhaps surprisingly not yet seen experimentally. Such a development would open up such passive optical sorting to multiple-particle colloidal systems and would be a step toward, for example, the sorting of whole blood, where several different types of cell may be present. Two key issues must be addressed. First, the optical pattern must deflect the different particle species into distinct, parallel, but laterally displaced laminar streams. Second, the method should allow arbitrary optical landscapes to be created over large areas with sufficient beam powers.

In this Letter we describe how to generate spatially *continuous* time-shared optical landscapes for passive optical sorting. We present examples of novel patterns for optical sorting and report experimental results of the first successful simultaneous fractionation of four species of colloid. While the acousto-optic deflector has already been used extensively in optical trapping to generate 2D arrays of discrete optical traps, it has never, to our knowledge, been employed to create such complex landscapes. We discuss how we obviate the temporal issues associated with using a scanning device for creating such landscapes. Acousto-optic devices offer rapid and controllable scan rates. Furthermore, they offer efficiency similar to that available from spatial light modulators but with far larger power handling capability.

The experimental arrangement consisted of a standard optical tweezers set-up (see Fig. 1). A dual-axis acousto-optic deflector (AOD) system (NEOS Technologies) was placed at a point conjugate to the back aperture of a 100× NA=1.25 oil immersion microscope objective. The dual-axis system had an efficiency of approximately 25% and was operated by using a custom-made LabVIEW program. To create the optical landscapes we used a 1070 nm yttrium fiber laser (IPG Laser, 10 W) with an output beam diameter of 5 mm and bandwidth of 5 GHz. For this work the power at the back aperture of the objective was measured to be 400 mW. The NEOS 45035-3 AOD was controlled by two variable applied DC voltages. These were generated by a National Instruments data acquisition (DAQ) card (PCI-6221). Our program took as an input a standard 256-level grayscale bitmap representation of the desired optical distribution. The 2D image was then processed into two

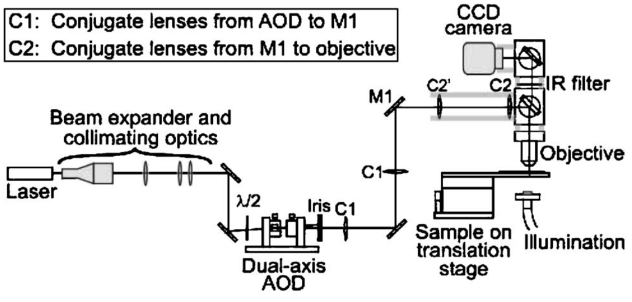

Fig. 1. Diagram of setup. An AOD was incorporated into a standard optical tweezers system. A pair of lenses, C1 ($f=150$ mm), allowed conjugate mirror (M1) beam steering. Lenses C2′ ($f=250$ mm) and C2 ($f=75$ mm) increased the angle of the deflection of the beam in the sample plane, enabling manipulation over a larger area.

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waveforms that were fed to the DAQ device. These waveforms contained the x and y components of the beam's target position and were received simultaneously by the AOD.

To generate the effect of multiple gray-scale levels in the raster-scanned laser image, the laser was paused at each optical pixel for a period of time determined by the brightness of the corresponding pixel in the original input image. It should be noted that intensity levels could in principle be controlled by the inclusion of a high-speed amplitude modulator such as a Pockels cell in the optical train, programmed to work in synchronization with the AOD. Some AOD systems can modulate transmitted beam power, yet we were able to demonstrate that, should that functionality be absent, holding the beam position at a given location for a determined period can act as a suitable alternative. The spatial scaling of the image in the sample plane was chosen so that the displacement of adjacent pixels was smaller than the diameter of the scanning beam (2.5 μm). This enabled the generation of an effectively continuous time-integrated optical landscape rather than an array of discrete trapping sites.

An important consideration is a temporal effect due to the action of the raster scan on the particle. High-index particles were observed to move along the direction of the scan. In a 2D raster scan, we observed them to move along a diagonal in the plane of the applied image. In general, we found that particle drift due to this scanning effect could dominate the behavior generated by the local intensity gradient of the applied pattern. As a consequence, to study particle behavior in the applied landscape free from such time varying effects, we isolated this scanning artifact for the present study.

Since the scanning effect arises because of the sequential and directional nature of the raster scan, a possible method to counter the effect would be to randomize the order in which the pixels are drawn out by the laser. This works in principle; however, in reality it results in too many large, rapid changes in the AOD driver signal, which seriously impedes performance owing to the finite rise time of various components of the system. In practice we found it was better to apply small sequential changes to the AOD driver signal. This can be achieved by running the raster scan in reverse every second frame. This process was observed to suppress particle behavior associated with the scanning and left us free to study particle behavior due to the applied time-integrated optical landscape. For the work presented in this Letter, we scanned the image at 100 Hz.

For our samples, we used two different polydisperse mixtures of silica spheres (Bangs Laboratories) suspended in deionized water. The first contained three different sphere sizes: 2.47, 3.01, and 5.08 μm. The second mixture contained four sphere sizes: 2.3, 3.0, 5.17, and 6.84 μm. Observations of the colloidal dynamics in this system were performed through the same objective as used for focusing the beam. Illumination light was introduced from below by using a high-power white-light source (Thorlabs OSL1-EC).

Particles were tracked at standard video frame rates (25 Hz), and center-of-mass trajectories were mapped with custom-written LabVIEW software using a proprietary (NI IMAQ Vision) feature-matching algorithm. This approach was used because it enabled us to distinguish between different species of particle in the same video sequence.

We present two examples in this Letter that demonstrate that we were able to achieve multispecies fractionation. Both examples contain a uniform bright diagonal line to the right of the pattern that acts as an optical funnel, channeling the polydisperse colloidal mixture into a single particle stream a few micrometers in width. To the left of the optical funnel is an exit ramp of decreasing intensity, which guides the particle stream back across the flow. The experimental data presented in this Letter were taken with a flow velocity of 30 μm/s. We managed to successfully fractionate particles at flow rates up to 100 μm/s.

While traversing the exit ramp, the spheres experience a hydrodynamic drag force pulling them to the left. To a reasonable approximation, this force scales linearly with the particle radius. In the pattern, the spheres experience an optical trapping force that scales as the cube of the particle radius. As a result, smaller particles are likely to be drawn out of the optical landscape first. A more detailed theoretical study of particles in such landscapes is typically described by a Langevin equation. This has been performed elsewhere.[2,3]

Figure 2 shows the first example, where the exit ramp has distinct zones of decreasing intensity along its length. The smallest particles (2.47 μm) exit first, while larger particles continue further along the ramp. With a continuous ramp, the exit ports are not particularly well defined. We experimented with different configurations and found that inserting discrete gaps of increasing size between the regions of constant intensity produced highly localized laminar particle exit streams (Fig. 3). It should be noted that the scanning Gaussian spot size is such that these gaps do not necessarily constitute complete intensity nulls. Nevertheless, they still provide potential en-

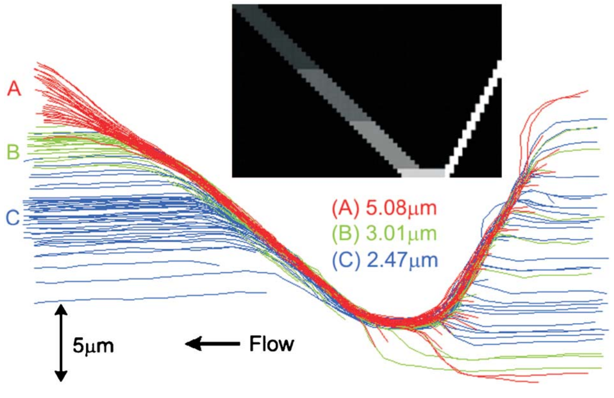

Fig. 2. (Color online) Plotted trajectories of (C) 46 2.47 μm, (B) 18 3.01 μm, and (A) 32 5.08 μm silica spheres flowing from right to left across an optical pattern (inset) with exit ramp made of adjacent regions of decreasing intensity (75%, 45%, 30%, and 15% of funnel intensity).

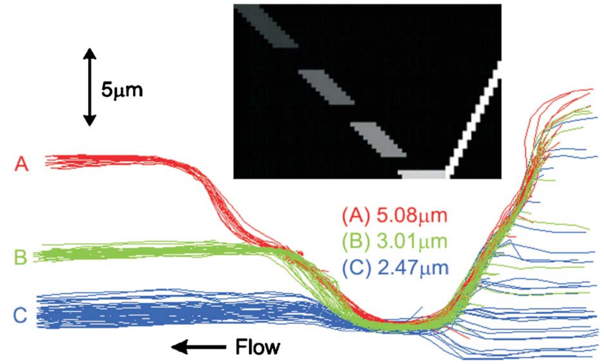

Fig. 3. (Color online) Plotted trajectories of (C) 58 2.47 μm, (B) 13 3.01 μm, and (A) 33 5.08 μm silica spheres. The system is similar to that in Fig. 2 except here gaps of 3, 4, and 5 pixels (inset) have been introduced between regions of constant intensity to improve sorting resolution.

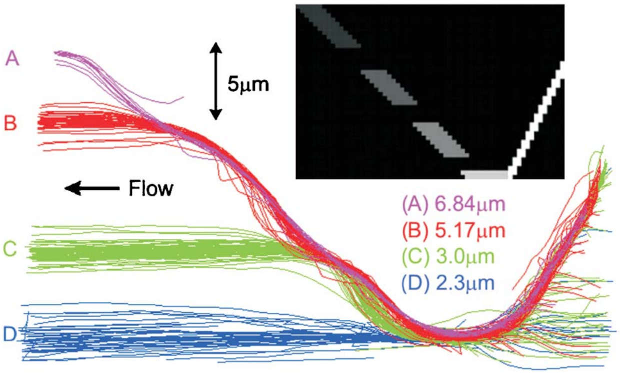

Fig. 4. (Color online) Plotted trajectories of (D) 38 2.3 μm, (C) 78 3.0 μm, (B) 47 5.17 μm, and (A) 11 6.84 μm silica spheres flowing through the same optical landscape as in Fig. 3.

ergy barriers along the exit ramp that define the location of the output streams. If particle–particle collisions and interactions are avoided, which can be achieved by keeping the density of particles sufficiently low, near-100% sorting efficiency can be achieved, since the sorting is deterministic. Figure 4 shows results obtained by using a different mixture, containing four different sizes of silica microsphere. The pattern used was the same as that used in Fig. 3.

A key restricting factor in this approach is the spatial resolution of the applied image. The principle limitation is the rate at which the computer can produce the analog signal required to send to the AOD. With faster electronics, larger, more complex patterns could be realized, and in principle it should be possible to fractionate more than four species at once. The method presented in this Letter requires the particle stream to be reduced to single file after passing through the optical funnel. This limits the throughput to around 40 particles/s (for 2.3 μm particles); however, there is potential for scaling up the system to process larger areas.

In conclusion, our data show what is to our knowledge the first fractionation of a polydisperse mixture of particles in an externally driven flow over an optical potential energy landscape. This was created by using a dual-axis acousto-optic modulator. We note that the use of a reconfigurable device such as an AOD allows fast and easy modification of the landscape, with the possibility for dynamic optical sorting landscapes rather than the static patterns presented here. We have shown that the inclusion of discrete tailored gaps in the exit ramp leads to highly localized parallel laminar exit streams for different particle sizes.

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