Particle sorting by optical pattern of line shapes

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ABSTRACT

In this paper, we propose an optical method for sorting micro-particles with holographic optical tweezers. By projecting an optical pattern onto the sample plane of a microscope via its objective, we can separate the sample particles of different sizes flowing to different directions.

Keywords: sorting, holographic optical tweezers, optical tweezers

1. INTRODUCTION

In 1986, Ashkin [1] developed the first optical tweezers system, which provided a non-contact method to manipulate micro-particles by changing the position of the focal point of trapping laser with movement of optical component. Then, Reicherter [2] and Curtis [3] used a spatial light modulator to modulate the laser beam and developed the dynamic holographic optical tweezers (HOT) system. The HOT system is a combination of a computer generated hologram and an optical tweezers system. Based on this new system, it is capable of creating a large number of optical traps in any arbitrary three-dimensional configuration and any distributions of the light intensity. Moreover, there is a great opportunity to generate a certain light intensity distribution which provides the ability of manipulation of micro-particles without any movement of the optical component. With the benefits described above, we propose a new method of sorting micro-particle based on the HOT system.

The main idea of our sorting method is described as below. When a micro-particle in a flowing solution is illuminated by an optical pattern, the particles will encounter an optical gradient force associated with the optical pattern and a water-driven force simultaneously. It can be shown that for those particles with diameter D less than or equal to the wavelength λ of the optical pattern, the gradient force on them is size-dependent. In other words, the particles of different sizes experience different gradient forces, and a larger particle experiences a larger force. When the gradient force on a larger particle is large enough to compete with the water-driven force against the particle, the larger particle will be deflected by the optical pattern. On the contrary, the smaller particle will not be deflected.

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In section 2, we first simulate the trajectories of the flowing particles with different sizes under the illumination of laser. Then in section 3, we will describe the setup of our HOT system and the sorting holographic optical pattern. The experimental result is shown in section 4. And section 5 is a discussion and summary of our work.

2. THEORY

As described above, when the flowing particles are illuminated by the optical pattern, there will be two kinds of forces exerted on them. One is the dragging force due to the flowing fluid and the other is the gradient force due to the optical pattern, as show in Fig. 1. We followed Yasuhiro Harada's [3] model to calculate the optical gradient force exerted on the particles of different sizes by the HOT system. The gradient force of laser shows as below,

$$F_g(\vec{r}) = \frac{2\pi n_2 a^3}{c}\left(\frac{(\frac{n_1}{n_2})^2 - 1}{(\frac{n_1}{n_2})^2 + 2}\right)\nabla I(\vec{r}), \qquad (1)$$

where *c* is the speed of the light in vacuum, n_1, which equals to 1.59, is the refractive index of the particle, n_2, which is 1.33 for water, is the refractive index of the solution, *a* is the radius of the particle and *I(r)* is the intensity distribution of the laser. From equation (1), it can be shown that a larger particle experiences a larger optical gradient force and a smaller one experiences a smaller gradient force. In Fig. 1, when the gradient force exerted on the particle is large enough to balance the force $f_{//}$, which is the force component of the dragging force along the direction of the gradient force. The particle will move along the optical pattern of the line shape. Thus the particle is guided by the optical pattern. But when the particle is small, the optical gradient force exerted on it may not be able to balance the force $f_{//}$. Thus the small particle will be deflected a little bit and then go through the optical pattern of the line shape. So we utilize this principle to separate particles of different sizes.

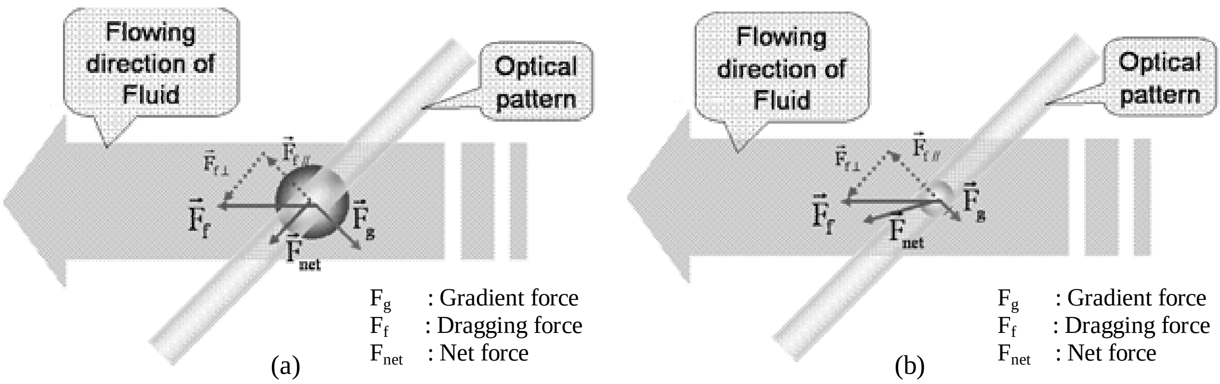


Fig. 1 Force diagrams of the flowing particles with different sizes under the illumination of an optical pattern. (a) Large particle. (b) Small particle.

In our simulation, we neglect the axial force generated by the optical tweezers and the Brownian motion of the micro-particles. We use the finite difference method to obtain the numerical results for the motion equations of the particles as given by:

$$M\frac{d^2\vec{r}}{dt^2} = -\sigma\left(\frac{d\vec{r}}{dt} - V_f\right) + F_g(\vec{r}) \ , \qquad (2)$$

in which M is the mass of the particle, V_f is the flowing speed of the fluid, and σ is the dragging coefficient of the particle. For a given optical pattern, we solve for the trajectories of the particles of different sizes. Fig. 2 illustrates the simulated trajectories of two beads of 1 μm and 0.5 μm in diameter, separately, after the beads flow through the optical line pattern.

In this simulation, we assume that the flowing speed of the beads is 15 μm/sec, and the laser power of the line pattern is 500 mW. The range of each figure is 60 μm X 60 μm and the time interval of the simulated trajectory is 4 sec. The dash line in Fig. 2 represents the trajectory of the particle and the background image represents the intensity distribution of laser. The highest intensity corresponds to white and the zero intensity corresponds to black. Fig. 2 (a) shows that large bead will be guided and move along the line. On the contrary, Fig. 2 (b) shows that the small bead still flows through the line. From the simulation, we find that it is feasible to separate the sample particles of different sizes flowing to different direction in a micro-channel.

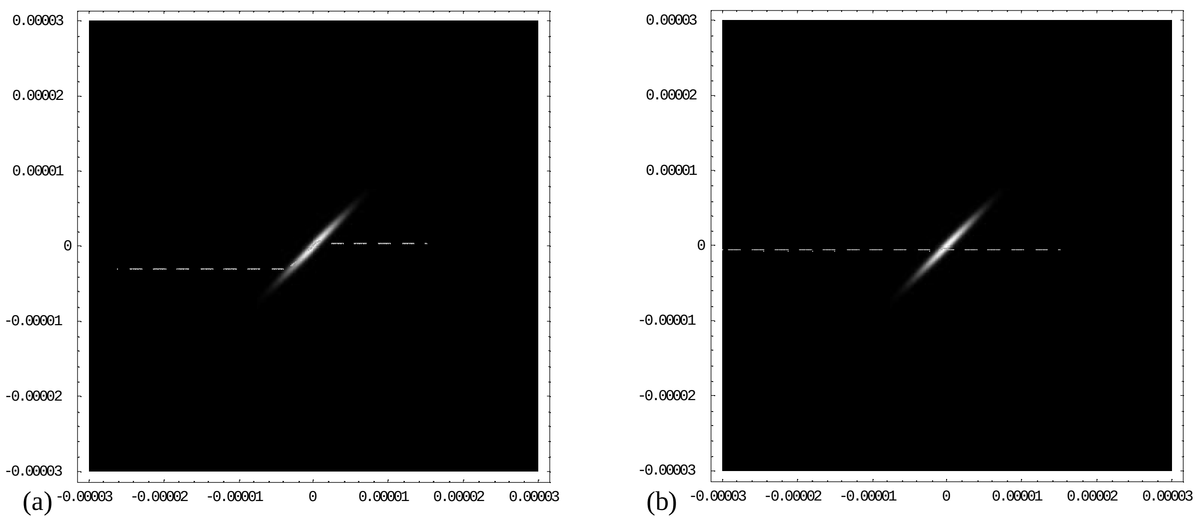


Fig. 2 The simulated trajectories of two beads of (a) 1 μm and (b) 0.5 μm in diameter, separately, after the beads flow through the line pattern.

3. Method

3.1 holographic optical tweezers (HOT) system

As shown in Fig. 3, the setup of our HOT system basically consists of an optical tweezers system and a computer-controlled phase-only spatial light modulator based on a Hamamatsu X8267 programmable phase modulator (PPM). The Nd:YVO_4 laser beam with 1064 nm in wavelength is first expanded by a beam expander, and then reaches the PPM through a beam splitter. The PPM will shape the expanded beam into a desired pattern and reflect the modulated beam into a 100X oil-immersion objective (NA 1.25) through the beam splitter, a relay lens system and a hot mirror. Finally the modulated beam is focused on the sample plane and forms a desired optical pattern. The image of the sample particles is real time monitored by a CCD camera via the objective, the hot mirror, and an imaging lens.

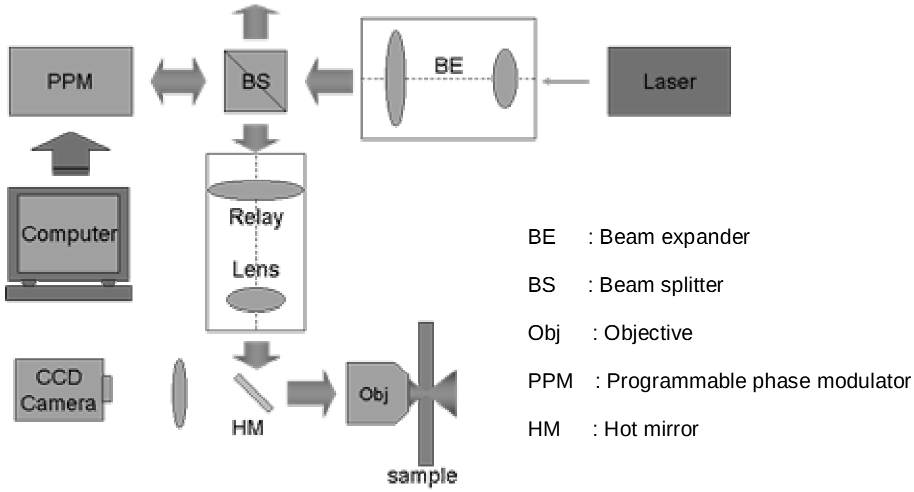


Fig. 3 Setup of our holographic optical tweezers (HOT) system

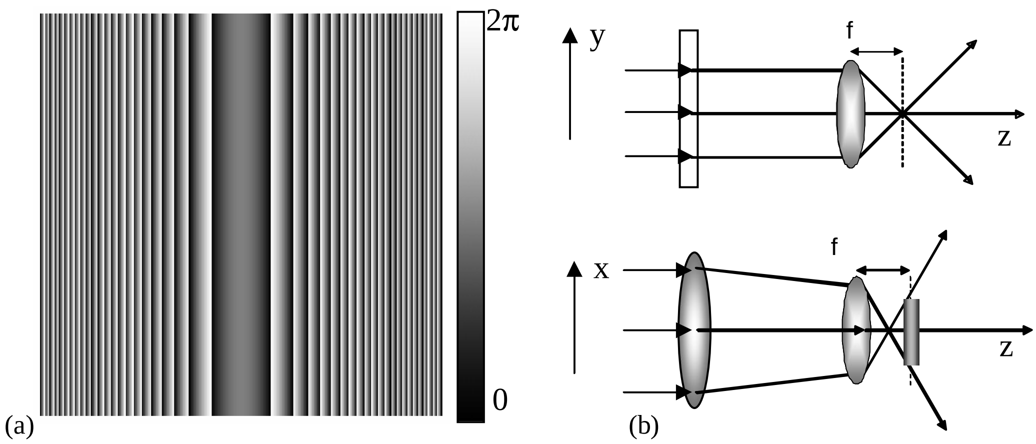


Fig. 4 Principle of line segment generation (a) Input phase pattern of PPM. (b) Geometric view of line segment generation.

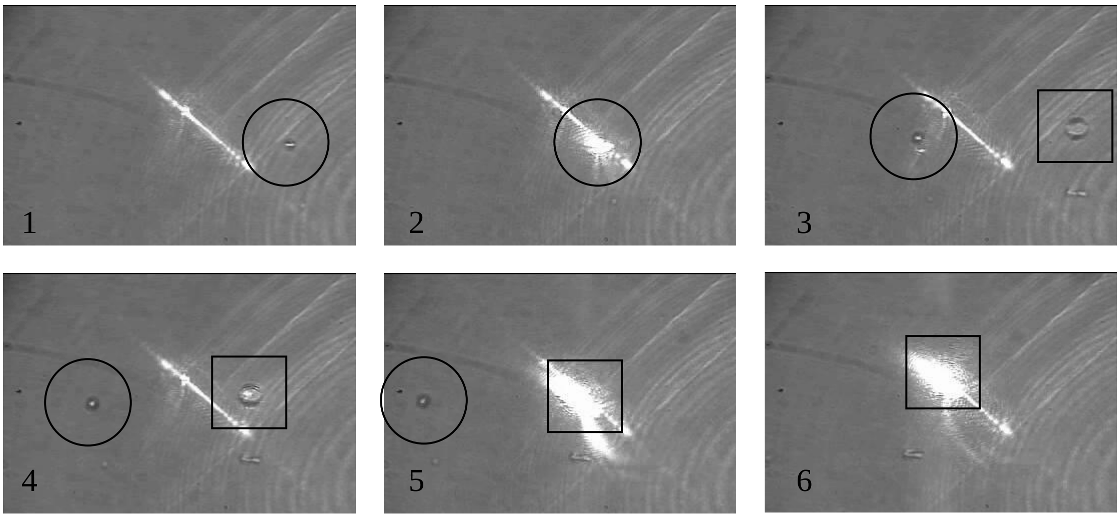
3.2 Sorting holographic optical pattern

We used PPM to simulate the phase distribution of a cylindrical lens, as shown in Fig. 4 (a). For a cylindrical lens, it can make the laser beam converge or diverge in one direction while leave the other direction unchanged. Thus it made the laser intensity distribution on the original focal plane to be a line segment, as shown in Fig. 4 (b). If we want to change the orientation of the line segment in the sample plane, we can just change the orientation of the input phase distribution on PPM with computer. In our experiment, we rotated the line segment 45 degrees with respect to the flowing direction of the fluid for convenience.

3.3 Sample preparation and particle flow creation

In order to make particle flow, we tried two methods. In the first method, the sample solution, which contained 6 μm and 3 μm beads, was dropped on a slide and covered with a cover slip. Then we moved the stage that held this slide. In the second method, we used a slide and a cover slip to form a flowing chamber and used the micro-pump to drive the fluid. The depth of flowing chamber is approximately 50 μm. In the fluid, there was a mixture of 6 μm beads and 1 μm beads. In both methods, we used a CCD camera to record the trajectories of the particles with different sizes, after they went through the optical pattern.

The advantages of the first method are that we can control the flowing speed of particles easily and the particles would usually stay at the bottom of the slide. Thus it is close to our conditions of simulation, two-dimensional motion of the particles. But the disadvantage of it is that sometimes the particles would attach to the slide and the optical gradient force has no effects on them. The advantage of the second method is that we can prevent the particles from sticking on the slide. But the control of the flowing speed would be harder and the motion of the particles is three-dimensional. This three-dimensional motion of the particles would cause some unwanted deflections.



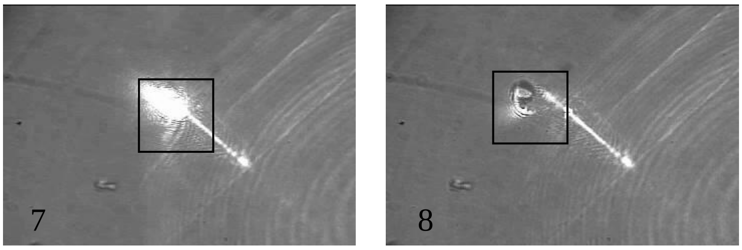
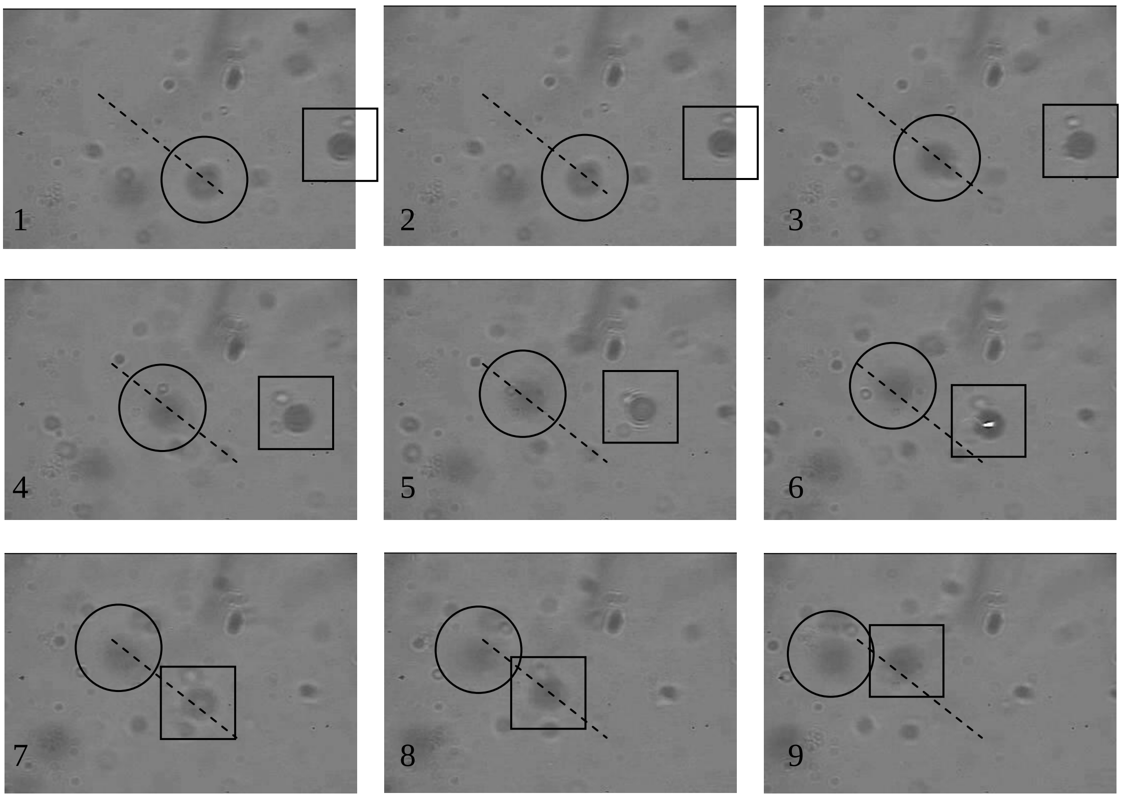


Fig. 5 Sequential snap shots of particles sorting by the optical pattern of the line shape using first method. The time interval between each image is 1/3 sec. The particle in the circle is a 3 μm bead and the particle in the square is a 6 μm bead.

4. RESULTS

As we moved the sample stage, the sequential snap shots of the motion of the particles are shown as Fig. 5. The time interval between each image is 1/3 second. The image range is about 75 μm X 45 μm. In Fig. 5, the particle in the circle is a 3 μm bead and the particle in the square is a 6 μm bead. In our experiment, we first checked if the particles attach to the slide. If the particles are free to move, we move the stage to make the particles go through the optical pattern. From Fig. 5 we can see that the 3 μm bead go through the optical pattern without deflection, but the 6 μm bead is deflected by the optical pattern. This is the same result as the computer simulation.



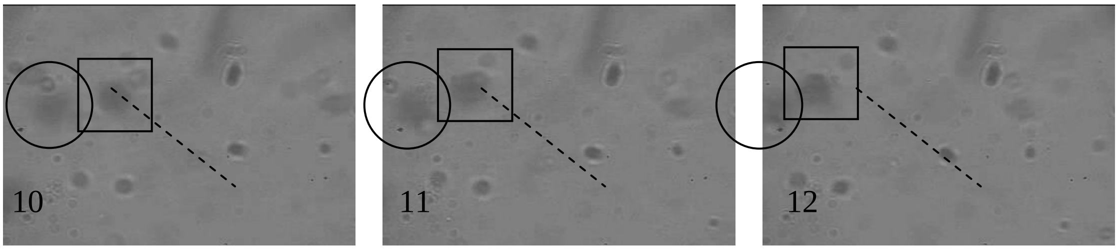
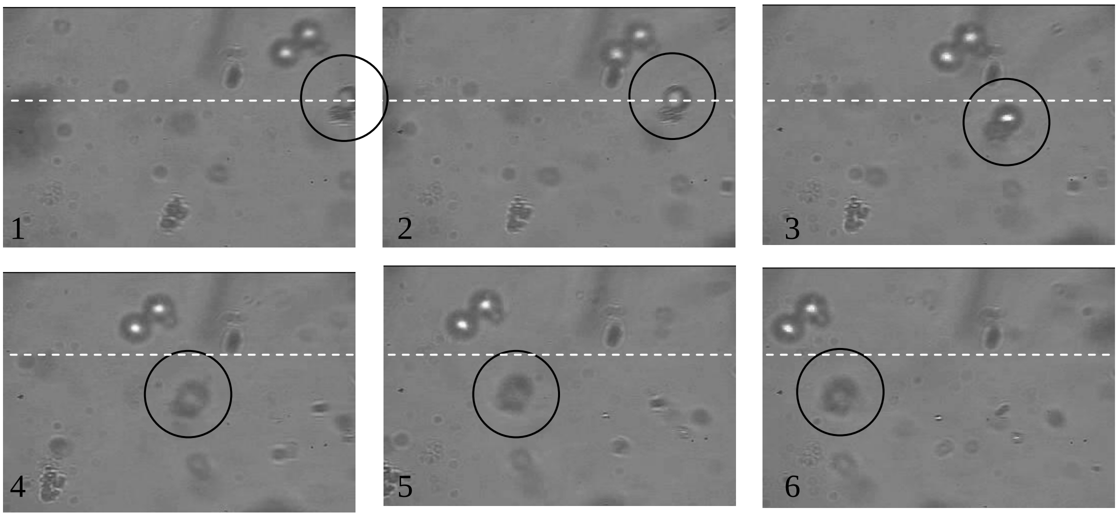


Fig. 6 Sequential snap shots of particles sorting by the optical pattern of the line shape using the second method. The time interval between each image is 1/3 sec. The particles in the circle and in the square are 6 μm beads and other small dots are 1μm beads. The dash line is the location of the optical pattern.

When we used micro-pump to make fluid flow, Fig. 6 shows the sequential snap shots of the motion of the particles. The time interval between each image is 1/3 second. The dash line is the location of the optical pattern. In Fig. 6, the particles in the circle and in the square are 6 μm beads, but they are at different depth of the flowing chamber. The particle in the circle is at the bottom layer and the particle in the square is above the one in the circle. The other small dots in each image are 1 μm beads. From Fig. 6, we can see that the 1 μm beads are not deflected by the optical pattern but the 6 μm beads are. This is the same result as the previous experiment. But there are some differences between these two methods. In Fig. 6 the large particle at higher layer was pushed down to the bottom. And sometimes, particles which are at a different depth of the flowing chamber would be deflected to a different direction, as shown in Fig. 7.



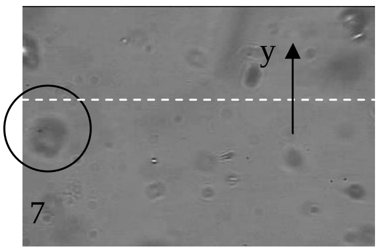


Fig. 7 Sequential snap shots of the motion of the particle which is at a higher layer of the flowing chamber. The dash line is the initial y position of the particle in the circle. The time interval between each image is 1/3 second.

The particle in the circle in Fig. 7 is a 6 μm bead, which is at a higher layer of the flowing chamber than the previous one. From it, we can notice that the direction of the deflection of the particle is different from the previous one as shown in Fig. 6. In Fig.6 the deflected particles moved toward the top of the image, but in Fig. 7 the particle moved toward the bottom of the image. The origin for this phenomenon is that the intensity distribution at different depth of the flowing chamber is different. Because from Fig. 4 (b), we can see that light intensity distribution changes with z position, the depth of the flowing chamber. Thus the particles which are at different depth of the flowing chamber encountered different intensity distribution and were deflected to a different direction.

5. CONCLUSION

In this paper, we propose a new particle-sorting method by optical pattern, which is generated by a HOT system. We have demonstrated the feasibility of separating the sample particles of different sizes flowing to different directions theoretically and experimentally. In addition to the predicted results, we also observed some unwanted deflections of particles. These deflections are caused by the changes of the laser intensity distribution along z axis and decrease the efficiency of the sorting. Those unwanted deflections can be avoided by reducing the depth of the flowing chamber or using the PPM to control the laser intensity distribution along the depth of the flowing chamber. But with proper design of the flowing chamber, it may be possible to utilize this feature of light to sort particles with different sizes three-dimensionally. In this way, a more efficient particles-sorting with light can be achieved.

6. REFERENCE

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