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Spatial Arrangement of Small Particles by Imaging Laser Trapping System

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We describe spatial arrangement of polystyrene latex using a microscopic imaging system. A reduced photomask pattern is imaged on the particles in a water-filled cell so that polystyrene spheres align in a two-dimensional pattern. Calculating the forces exerted on the spheres by isolated line pattern, we investigated an optimum size for sphere diameter and the line width of the patterns. We are able to align spheres in real-time by this technique.

Key words: laser trapping, particle alignment, micro-manipulation, interferometer

1. Introduction

The technique of micro-manipulation has received attention recently and has been developed in biology, chemistry, physics and other fields. Optical trapping is one of the most promising techniques for this purpose, because of its essentially non-contact and remote controlled features of light. Ashkin showed that spheres were trapped three-dimensionally by a focusing laser beam,[1-3] while Burns *et al.* demonstrated that three-dimensional arrays of latex particles could be constructed by interfering with 2-5 trapping laser beams.[4]

Optical trapping is currently of interest in the micromachine field. Fabrication of micro-machines demands a control technique that can move micro particles or parts to an arbitrary position and assemble them. In the field of biology this technique is expected for micro-sagely to handle a single cell.[5] Masuhara and his colleagues performed three-dimensional spatial patterning of small spheres using a laser-scanning micro-manipulation technique in which a focused laser beam was scanned three-dimensionally with computer-controlled galvano mirrors.[6-8] Scanning of the laser beam requires switching the beam or changing the scan speed and direction to make patterns.

We propose a new technique to pattern small polystyrene latex spheres with a diameter of 4.23 μm using an imaging system with photomasks. We can align spheres on the photomask image at the same time. We have also moved the sphere patterns to shift the photomask and/or to control the phase of the source light with an interferometric technique. Compared with our proposed technique, the experimental system of laser beam scanning is complicated since it requires advanced programming. Using interferometric fringes it is difficult to make an arbitrary pattern. Our technique is easy to expand to a large area patterning, and performs with high energy efficiency.

2. Trapping Force for Particle Arrangement

Optical trapping is performed by forces induced by a momentum change of photons caused by reflection and refraction of light. When a ray is incident on a sphere and exits from the sphere, it reflects and/or refracts. The change in photon momentum induces forces at the boundary of the sphere to preserve momentum, so that force F works on the sphere consequently. The magnitude of the forces due to reflection (F_r) and refraction (F_d) are given by,

$$F_r = \frac{2n_1PR}{c}\cos\alpha_1\,, \tag{1}$$

$$F_d = \frac{PT}{c}(n_2\cos\alpha_2 - n_1\cos\alpha_1)\,, \tag{2}$$

where R and T denote the reflectance and the transmittance at the boundary, n_1 and n_2 the refractive indices of the environment and the sphere, respectively, α_1 and α_2 the incident and transmitted angles, P the power of incident beam, and c the velocity of light.

We calculated the force exerted on a small particle in an isolated single belt pattern using a geometrical optics approach. Figure 1 shows a schematic diagram of re-

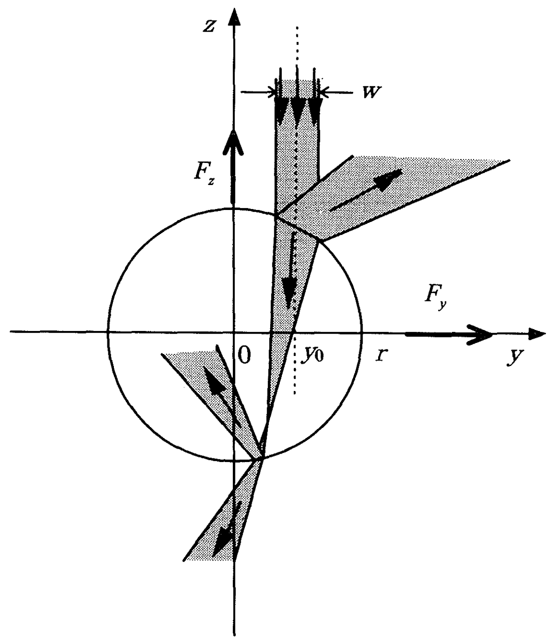

Fig. 1. Schematic diagram of the relations of the single line pattern width w and the sphere which has radius r. Offset between the center of line and the center of sphere is y_0.

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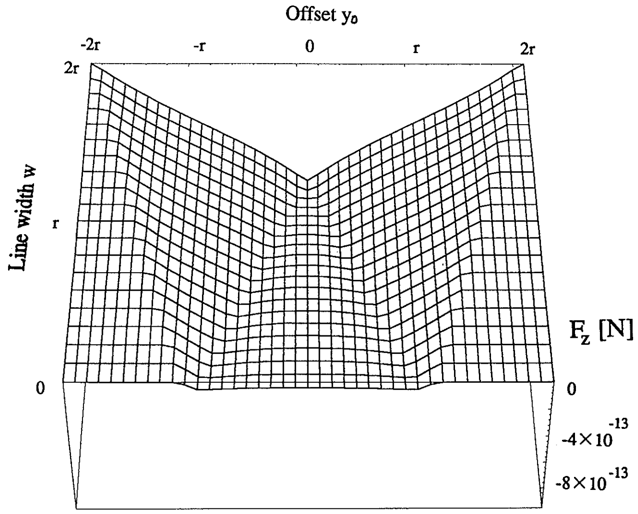

Fig. 2. Axial trapping force F_z as a function of light line width w and offset y_0.

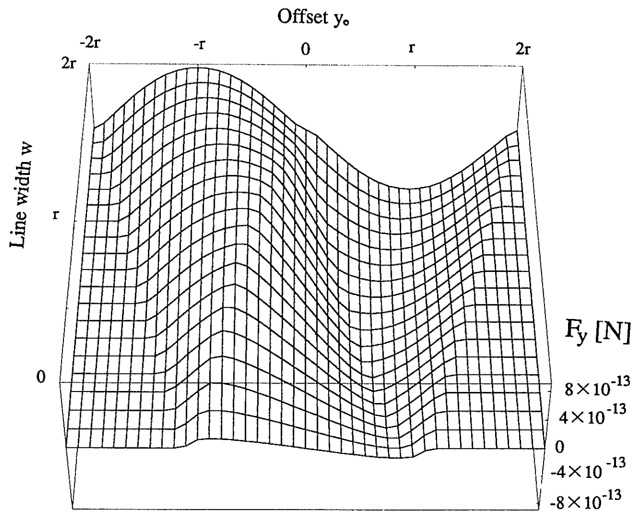

Fig. 3. Transverse trapping force F_y as a function of light line width w and offset y_0.

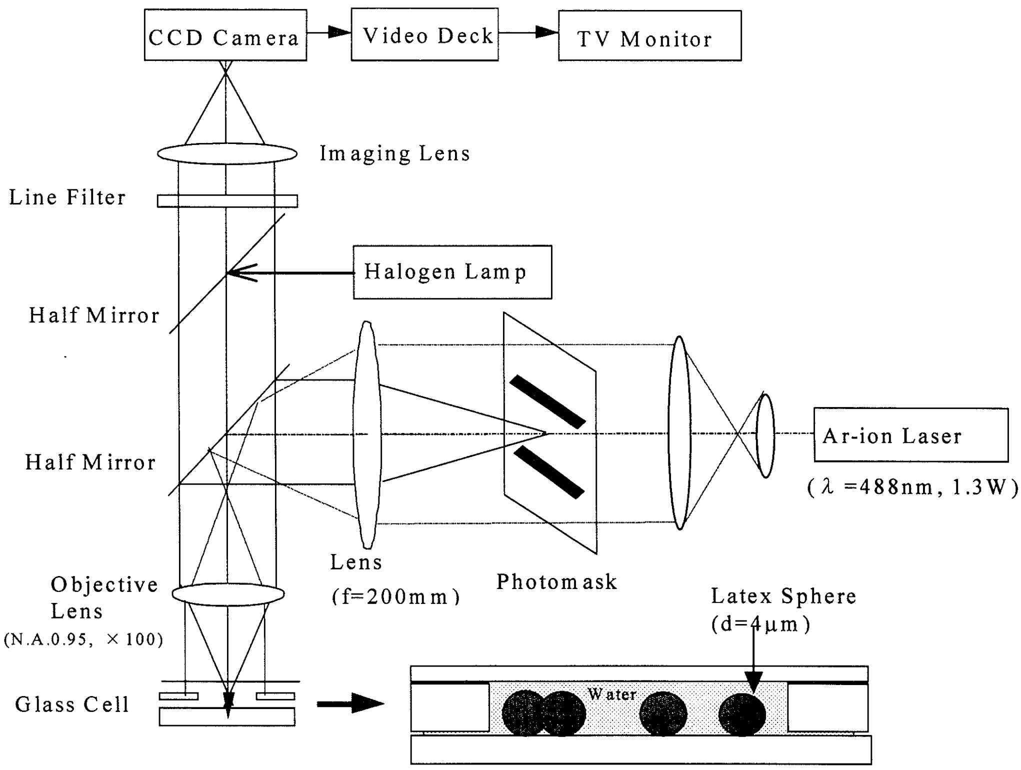

Fig. 4. Experimental setup with the reduction optics of a photomask.

flection and refraction of the belt-like light pattern, when the particle radius is r, where w represents width of the bright pattern and y_0 is an offset between centers of the sphere and the pattern. Two components of the horizontal force (F_y) and vertical force (F_z) are also shown in Fig. 1. Let us call the F_y component a recovery force that attracts the sphere to the center of the pattern. The negative value of F_z adds a friction force to the above motion.

We consider an afocal illumination system so that a parallel component of light falls perpendicularly on both the photomask and the sample. We found that line width plays an important role in patterning spheres. There are two ways to change the line width of the image pattern. One is to change the width of line pattern of the photomask and the other is to change the reduction ratio of the optical system. We scanned line widths from zero to the diameter of a sphere using the former technique.

We simulate trapping force under the following conditions. A trapped sphere in the water (n_1=1.33) has a radius of 2 μm and a refractive index (n_2) of 1.60. Total laser beam power is 6 mW. These conditions are similar to the experiments. Figure 2 shows the F_z component corresponding to the offset y_0 and width of the pattern w with the parameter of r. The sphere always feels a downward force because F_z, which is proportional to w, is negative in all y and w.

In Fig. 3 we plotted F_y corresponding to y and w with the parameter of r. The force F_y has the same maximum value in a range where w is from r to $2r$. When the beam width w is the same as the sphere radius r, F_y can achieve the maximum at the smallest input power. When w is between r and $2r$, the force F_y retains a maximum value. The vertical force F_z is always negative which results in a fractional force. This downward force increases as the width of pattern w expands. Considering both F_y and F_z, the width w of the pattern has an optimum value of r.

3. Experiments and Discussions

The experimental setup is shown in Fig. 4. We used an argon ion laser (Spectra-Physics Stabilite 2017) as light source of the patterning with a maximum output of 1.3 W (λ=488 nm). A laser beam was collimated and illuminated a photomask pattern, which image fell on a water-filled cell by using a lens L_1 and an objective lens L_2 (Olympus, MS-Plan 100, N.A. 0.95) with a reduction of one hundred. We made a cell whose wall was of aluminum foil sandwiched between a cover glass and a slide glass. The dimensions of the cell were 1 cm by 1 cm with a depth of 30 μm. A polystyrene latex sphere 4.25 μm in diameter was used whose refractive index was 1.6 and relative density was 1.06 to the water.

The image was projected onto a CCD camera (SONY DC-37) through a microscope (Olympus BHM). A color filter (Newport FSQ-OG515) was placed in front of the CCD camera to block the argon laser beam.

The photomask patterns were fabricated by aluminum foil. We prepared four types of mask: a single line pattern, a two parallel lines pattern, a rectangular pattern and gratings with 0.5–1.0 mm pitch.

Spatial patterning was performed the spheres of 4.25 μm in diameter. Input power of the laser was about 260 mW on a photomask, i.e., about 1.2×10^6 mW/cm^2 on the sample. Figures 5 (a), (b) and (c) are photographs aligned on a pair of parallel line image patterns, a rectangular line image pattern and periodic image pattern, respectively. The first spheres contacting the image pattern were aligned within a few seconds. Within several ten seconds the other spheres were aligned on the pattern. When a photomask was used, the spheres finally aligned on the pattern in 1 or 2 min. Spheres in contact with the pattern were aligned by the force we calculated previously.

Each line in Fig. 5 (a) and (b) corresponds to the image pattern which is about $2r$ in width. This means that the pattern of $2r$ is available for patterning of spheres using a photomask. In this experiment, the pattern with a width between r and $2r$ aligned the spheres on the pattern, whereas the pattern with a width more than $2r$ filled the pattern with the spheres. The pattern with a width less than r is hard to make a photomask and does not have sufficient light intensity to make a pattern because of the effect of diffraction.

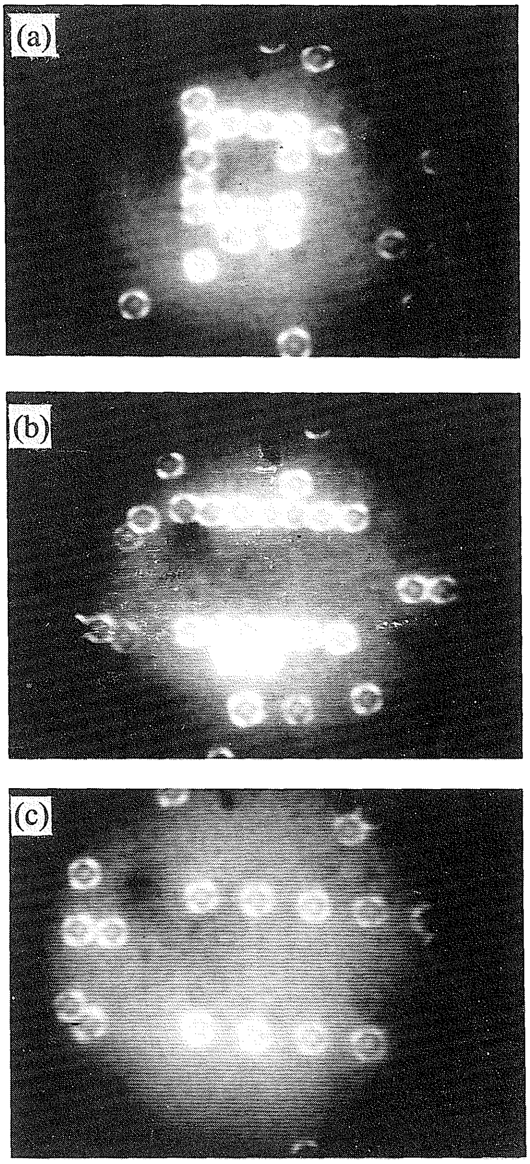

Fig. 5. Particles arranged by the reduced projection of mask patterns. Diameter of the particles is 4 μm. (a) Rectangular pattern. (b) Two parallel lines. (c) Two parallel lines with crossed gratings.

Periodic patterning was performed as shown in Fig. 5(c). In this case the periodic image pattern was two parallel dashed lines and it was formed by combination of a two parallel line photomask and grating at normal. Intervals of the dashes were determined by period of the grating on the photomask. While positions of the spheres were arbitrary on lines in the line pattern, they were restricted to the positions of dashes, and each dash had one sphere.

4. Conclusions

In conclusion, we have proposed a new technique of arranging small particles by the spatial trapping technique using imaging optics. We calculated the force exerted on the sphere by single line pattern to study the characteristics of the light force caused by the change in photon momentum. For arranging particles, we found that the line pattern has an optimum width which coincides with the radius of a trapped sphere (r). Spatial patterning was performed using an image projection system of the photomasks. This system enabled us to align the spheres on arbitrary patterns without any mechanical motion or switching of the laser beam. Compared with other techniques our system easily arranges a large area directly. If we use a phase-only diffractive spatial light modulator, we can use total energy from the light source. We are able to fabricate highly accurate micro-machines with this technique, and it will also be useful for developing new optical devices such as photonic crystals which can take advantage of its periodic characteristics.

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