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Spatial Pattern Formation, Size Selection, and Directional Flow of Polymer Latex Particles by Laser Trapping Technique

Hiroaki MISAWA,* Masanori KOSHIOKA, Keiji SASAKI, Noboru KITAMURA,*
and Hiroshi MASUHARA*†
Microphotoconversion Project, ERATO, Research Development Corporation of Japan,
15 Morimoto-cho, Shimogamo, Sakyo-ku, Kyoto 606

Polystyrene latex particles with the diameter of ≈1 µm in water were laser trapped in spatial images of a laser beam. For a mixture of latex particles with different diameters, delicate tuning of the images resulted in size selection of the particles. Directional flow of the particles in water was also achieved by laser irradiation.

We recently reported that a single micrometer-order particle dispersed in solution could be easily tweezered three dimensionally by laser trapping technique and, spectroscopic characterization and laser ablation of an trapped particle were also shown to be possible.[1,2] Such new technique of laser trapping-spectroscopy-ablation is clearly indispensable to study chemical and physical properties of an individual small particle in solution. In addition to laser manipulation of an individual small particle, simultaneous laser trapping of plural small particles can be also achieved if the condition of $n_P > n_M$ is satisfied,[3] where n_P and n_M are the refractive indices of particles and the surrounding medium, respectively. Furthermore, since a laser beam intensity can be spatially patterned by appropriate choice of optical alignment, particles will be trapped in the laser beam images if the laser beam intensity is high enough for laser trapping. Quite recently, indeed, Burns et al. reported that laser trapping could create three-dimensional arrays of latex particles in interference patterns of trapping laser beams.[4] Besides periodical alignment of particles by Burns et al., the laser trapping technique involves versatile scientific and industrial applications. In the followings, we report laser trapping of latex particles in spatially-imaged laser patterns and discuss on future aspects of the technique.

Figure 1 shows spatially-patterned laser trapping of polystyrene (PSt) latex particles (diameter, d≈1 µm, n_P=1.59[5]) in water (n_M=1.33[6]). The laser trapping system has been reported elsewhere.[1,2] Upon irradiation of a 1064 nm laser beam (≈4 W), latex particles were trapped in the high laser intensity regions of the interference pattern (Fig. 1a), which was produced by spatial filters. Prolonged irradiation led to laser trapping of further numbers of latex particles and after several minutes, spatially-patterned laser trapping of PSt particles along concentric circles was achieved as shown in Fig. 1b. The spatial pattern of the particles disappeared immediately after switching off the laser (Fig. 1c).

Characteristic features of the phenomenon are summarized below.

1. According to the critical condition of the trapping, $U/kT \geq 10$, where U, k, and T are the potential energy of the trapping, Boltzmann constant, and temperature, respectively,[7] the high temperature limit of the

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† Permanent address: Kyoto Institute of Technology, Matsugasaki, Sakyo-ku, Kyoto 606.

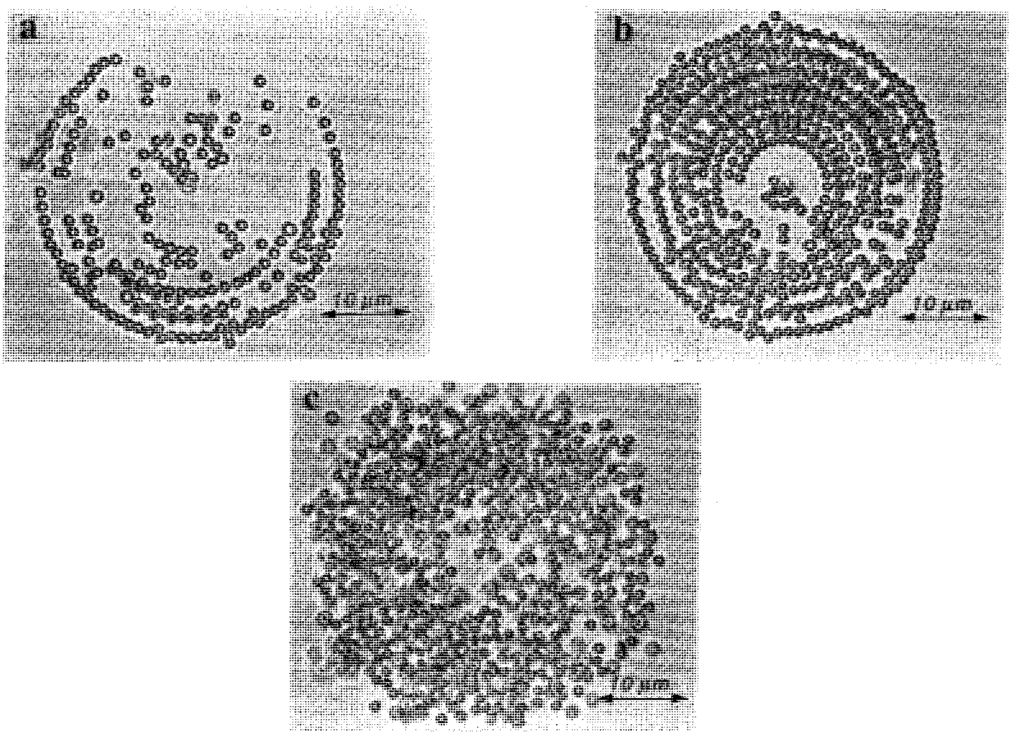

Fig. 1. Spatialy-patterned laser trapping of PSt particles in water at room temperature. a) and b) laser beam (1064 nm, ≈4 W) was irradiated. c) laser beam was turned off.

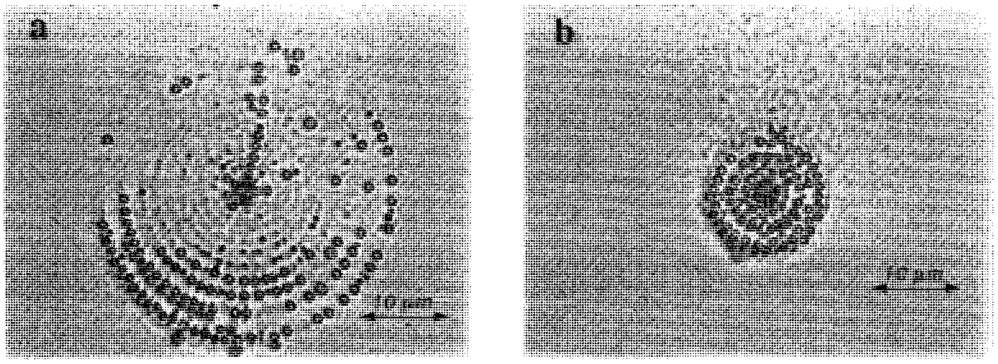

Fig. 2. Size-selective laser trapping of PSt particles (d≈1 and 0.25 μm) in water at room temperature (see text).

trapping is calculated to be ≈7500 K assuming the laser trapping forces exerted to a particle (d≈1 μm) to be 1 pN.[8)] At room temperature, laser trapping forces are strong enough to suppress thermal motion of each particle and to align the particles regularly in solution.

2. The spatial pattern of the laser beam almost coincides with that of the latex particles. Therefore, modulation of the laser beam diameter renders the change in the diameter of the spatial pattern of the particles. In the present experiments, we succeeded to control the diameter of the pattern in Fig. 1b from 20 to 60 μm by changing optical alignment of the system; focal point of the laser beam in a sample cell.

3. Similar spatial patterns of the particles can be produced at lower laser intensity. Upon irradiation of laser at ≈1 W, however, the spatial pattern formation required longer time as compared with the time necessary for the pattern formation on ≈4 W irradiation owing to weaker laser trapping forces at ≈1 W.

4. When we use a mixture of PSt with $d \approx 1$ and 0.25 µm, spatially-patterned laser trapping of the latex results in particle size selection. Namely, although the particles with $d \approx 1$ and 0.25 µm in the vicinity of the laser beam are trapped to form a spatial pattern, laser trapping is more favorable for the larger size of the particle (i.e., ≈1 µm) at given laser power.8) Upon prolonged irradiation of the laser (≈4 W), therefore, the number of ≈1 µm latex particles increases along concentric circles (Fig. 2a). When the diameter of the spatial pattern is reduced, the smaller particles are pushed out into water phase as shown in Fig. 2b. Size-selective laser trapping of particles in solution is demonstrated for the first time.

We describe here another important aspects of the present technique and discuss on some possible chemical applications. In a given medium, laser trapping is more feasible for the particle with higher refractive index under the condition of $n_P > n_M$.3) The present size selection experiment implies a future possibility of selection/concentration of higher refractive index particles from a mixture of particles with various n_P by a laser beam. It is worth noting that fixation of micrometer-order particle in any spatial patterns will open a new field of micropatterning of materials. This will be realized when dye-doped latex particles are laser trapped in a polymerizable monomer solution and dye-sensitized photopolymerization of the monomer is conducted. The present technique may also contribute for advances in colloidal chemistry. Ise and his co-workers have reported that latex particles in water align periodically in three dimensional space to keep the balance of electrostatic interactions between adjacent particles.9) If a laser beam is irradiated on such spatial patterns, non-equilibrium conditions of electrostatic interactions between the particles will be produced. Since laser trapping forces exerted to a single particle can be determined separately,8,10) electrostatic forces operating between the particles will be estimated.

Besides laser trapping of small particles along concentric circles, particles can be trapped in any desired laser beam images. An example is as follows. A laser beam was passed through two closely positioned pinholes before introducing the beam into the optical microscope. Interference of two beams from these

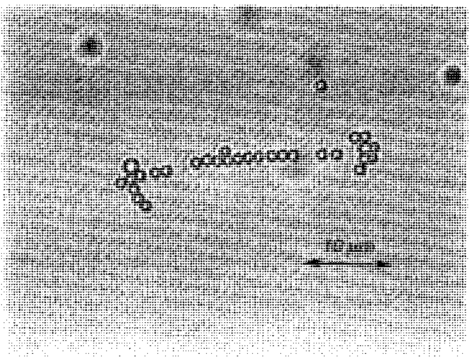

Fig. 3. Laser trapping of PSt latex particles ($d \approx 1$ µm) in water at room temperature along a line image of the laser beam.

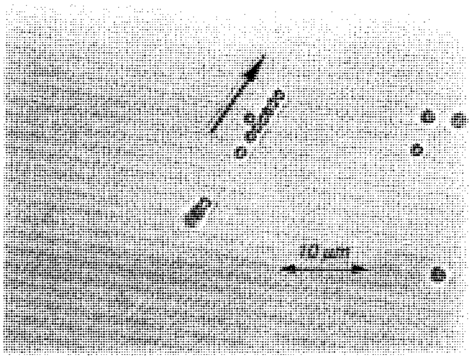

Fig. 4. Directional flow of PSt latex particles ($d \approx 1$ µm) by laser trapping in water at room temperature (see text).

pinholes produces line images in a sample solution. PSt latex particles in water were laser trapped along this line image of the laser beam as demonstrated in Fig. 3. Furthermore, it is very interesting to note that, when the gradient of the laser power in the image is produced through the pinholes, latex particles can be transferred from the lower laser power region to the higher power region. Namely, in Fig. 4, the particles were not fixed on the single line, but moved from the center to the upper-right of the photograph. Small particles in solution can be transferred to any directions by appropriate adjustment of the laser beam and optics.

Focusing of a laser beam into a wavelength-order spot (≈1 µm) is not a critical condition for laser trapping as demonstrated in the present study. Although laser trapping is dependent on particle size, laser intensity, and refractive indices of particles and medium,[3,8] various kinds of micrometer-order particles will be trapped in any laser beam images in the spatial range of several tens micrometer. Furthermore, each particle in laser trapped, spatially-patterned latex particles can be characterized and fabricated by our laser trapping-spectroscopy-ablation system.[1,2] Clearly, chemical applications of laser trapping technique will open a new field of micrometer chemistry and the studies along the strategy is now in progress in our project.

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References

1) H. Misawa, M. Koshioka, K. Sasaki, N. Kitamura, and H. Masuhara, Chem. Lett., 1990, 1479.
2) H. Misawa, M. Koshioka, K. Sasaki, N. Kitamura, and H. Masuhara, XVII International Quantum Electronics Conference, Anaheim (1990), Technical Digest p.170.
3) A. Ashkin, Phys. Rev. Lett., 24, 156 (1970); Science, 210, 1081 (1980).
4) M. Burns, J.M. Fournier, and J.A. Golvchenko, Science, 249, 749 (1990).
5) "Polymer Handbook," 2nd ed, ed by J. Brandiup and E.H. Immergut, John-Wiley, New York (1975).
6) "Organic Solvent," Technique of Chemistry Vol. II, ed by J.A. Riddick and W.B. Bunger, Wiley-Interscience, New York (1970).
7) A. Ashkin, J.M. Dziedzic, J.E. Bjorkholm, and S. Chu, Opt. Lett., 11, 288 (1986).
8) For poly(methyl methacrylate) particles in ethylene glycol, it was experimentally shown that the laser trapping forces exerted to a particle with d≈11 µm under laser irradiation were ≈6 pN and were ≈3 times larger than those with d≈3 µm at given laser power (200 mW).
9) K. Ito, H. Nakamura, H. Yoshida, and N. Ise, J. Am. Chem. Soc., 110, 6955 (1988).
10) H. Misawa, M. Koshioka, K. Sasaki, N. Kitamura, and H. Masuhara, Manuscript in preparation.

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