# OPTICAL MANIPULATION OF MICRO-OBJECTS BY RESULTANT FORCE INDUCED BY ARRAY SOURCES

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## 1 Introduction

Ashkin *et al.* firstly demonstrated three-dimensional trapping of a microscopic object by means of a single focused laser beam.[1] The technique is called optical trap (or optical tweezers) and is used as a noncontact manipulation method for microscopic objects. The applications are listed as manipulation of biological particles[2], measurement of pico-newton force[3], and so on. Modulation of the illumination beam is an effective method to extend various manipulations. For example, rotation of a micro-particle is implemented by a particular hologram.[4]

A vertical-cavity surface-emitting laser (VCSEL) array is composed of many laser sources whose emission intensities can be controlled independently and modulated over 100MHz. We take an interest in the notable properties of the VCSEL array sources and applied it to an optical manipulation method.[5] The technique is called VCSEL array trapping. A major advantage of usage of the VCSEL array sources is flexibility in generation of spatial and temporal emission patterns. The feature enables us to implement wide variety of manipulations with a compact hardware configuration. We reported non-mechanical translation of an object and simultaneous translation of multiple objects by the VCSEL array trapping.[5] However, satisfactory translation velocity was not obtained because the maximum emission intensities of the individual pixels of the VCSEL array is smaller than that of the light sources generally used for optical trapping.

To overcome the problem, a manipulation method for microscopic objects by simultaneous illumination with multiple sources is studied. Dependence of the resultant force by multiple sources on the illumination distribution is clarified by computer simulations. Applicability of the VCSEL array trapping is discussed.

## 2 Performance of current VCSEL array trapping system[5]

Performance of the VCSEL array trapping is measured by the experimental system shown in Fig. 1. The VCSEL array used (NTT Photonics Laboratory; wavelength of 854nm±5nm, maximum output of more than 3mW, aperture of 15$\mu$m$\phi$, and pixel period of 250$\mu$m) has $8 \times 8$ pixels, whose emission intensities are controlled by the driver circuits of our own composition and the personal computer. The target objects are polystyrene spheres of 6$\mu$m and 10$\mu$m in diameter, which are dispersed in water. (Polysciences, Inc., Polybead Polystyrene Microspheres; refractive index of 1.60, density of 1.05g/ml) The spacing period and the intensity of the VCSEL array imaged on the sample plane are 3.75$\mu$m and 1.1mW/pixel, respectively. Simultaneous translation of two objects with different size and non-mechanical translation of an object by switching of the emitting pixels are performed by the system. The translation velocities were measured as 0.48$\mu$m/sec and 0.45$\mu$m/sec, respectively. The translation velocity may not be high enough for practical applications. We recognized that the main reasons are shortage of the intensity and large spacing period of the imaged VCSEL's.

## 3 Resultant force from multiple sources

In order to achieve fast manipulation, strong force must be applied to the object. Assigning multiple VCSEL's to individual objects seems to be effective to solve the problem because total power of illumination is increased. To analyze the resultant force by the illumination with multiple VCSEL's, computer simulations

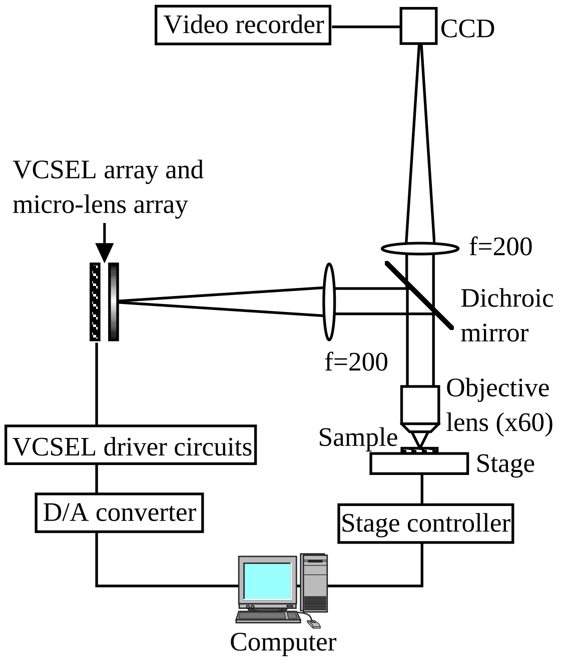


Figure 1: Experimental system of VCSEL array trapping.

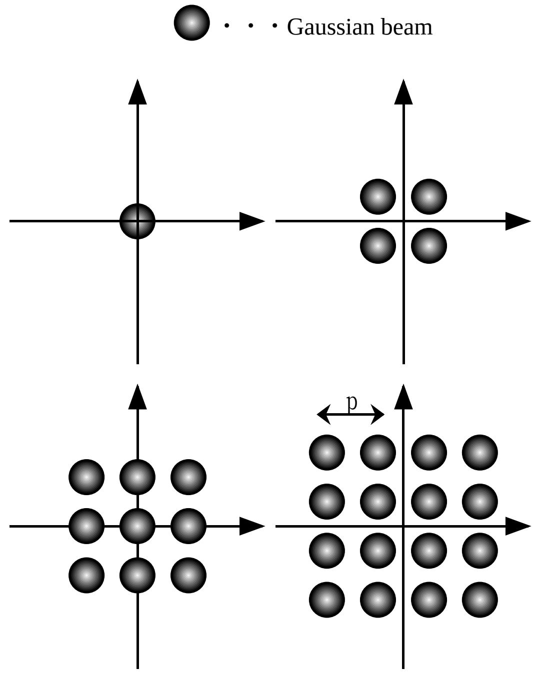


Figure 2: Illuminating distribution assumed in computer simulation. Upper left; 1VCSEL, upper right; $2 \times 2$ VCSEL's, lower left; $3 \times 3$ VCSEL's, lower right; $4 \times 4$ VCSEL's.

are employed. The calculation is based on the ray-optic model developed by Gauthier *et al.* Figure 2 shows the illuminating distribution on the object plane assumed in the simulations. The numbers of the emitting VCSEL's are changed as 1 (current system), $2\times2$, $3\times3$, and $4\times4$. Parameters of the sources and the object are assumed as follows: the beam profile of each VCSEL pixel is a gaussian beam whose waist is $2.6\mu$m (measured value of the experimental system), the VCSEL's are imaged with spacing period $p$ ($p = 0.5, 1.0, 1.5, 2.0\mu$m), the intensity is 1.1mW/pixel, and the target object is a sphere of $6\mu$m in diameter. The resultant force is resolved into three components; horizontal ($x$, $y$) and vertical ($z$) directions. Note that the components of the $x$ and $y$ directions are equivalent owing to the symmetry of the illuminating distribution.

Dependence of the horizontal force on the spacing period of the VCSEL's is shown in Fig. 3. Different symbols correspond to the number of the emitting VCSEL's. The horizontal component of the resultant force is almost in proportion to the number of the VCSEL's for $p = 0.5\mu$m. For the other cases, the larger is the period $p$, the lower is the horizontal force. One reason is that some of the elemental forces which the target object receives from the individual VCSEL's interfere each other. It is shown that simultaneous illumination with multiple VCSEL's is effective to increase the translation velocity.

Dependence of the vertical force on the spacing period of the VCSEL's is shown in Fig. 4. For $p = 0.5\mu$m, the vertical component of the resultant force is in proportion to the number of the VCSEL's as with the horizontal component. Note that the vertical force increases with spreading the VCSEL's contrary to the horizontal case. When the object is illuminated by the $4 \times 4$ VCSEL's with $p = 1.5\mu$m, the vertical force is larger than that obtained by a single source illumination with intensity as 16 times strong as a single VCSEL. This fact suggests that the strong force can be obtained by illuminating the object with the optimal pattern even if the total power of illumination beams is small. Therefore, the VCSEL array trapping has capability to implement three-dimensional trapping with low total power.

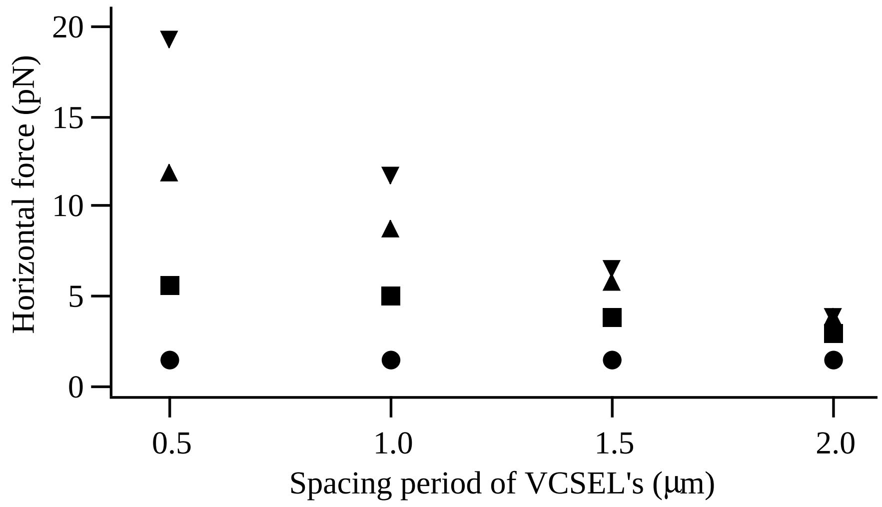


Figure 3: Dependence of horizontal component of resultant force on spacing period of VCSEL's. ●; 1VCSEL, ■; 2 × 2 VCSEL's, ▲; 3 × 3 VCSEL's, ▼; 4 × 4 VCSEL's.

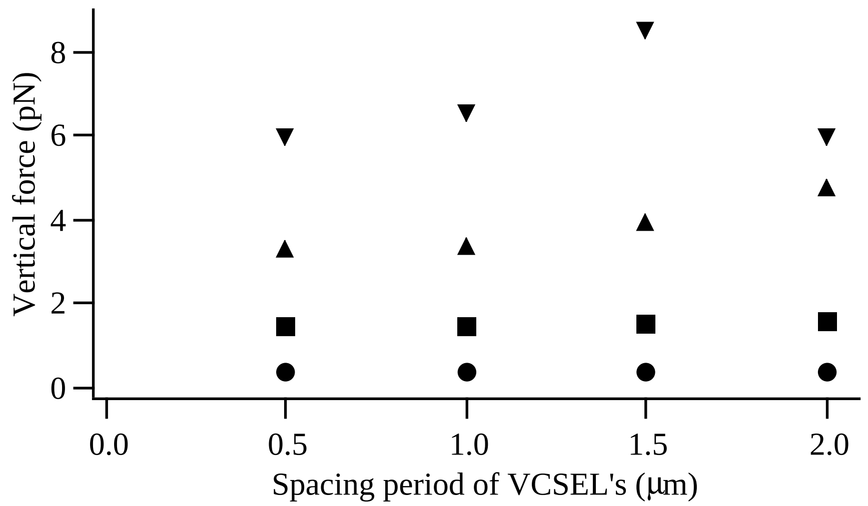


Figure 4: Dependence of vertical component of resultant force on spacing period of VCSEL's. ●; 1VCSEL, ■; 2 × 2 VCSEL's, ▲; 3 × 3 VCSEL's, ▼; 4 × 4 VCSEL's.

## 4 Applications

In previous section, effectiveness of simultaneous illumination with the multiple VCSEL's is clarified for capture and translation of the target object. The advantages of the method are not limited in simple manipulation. The advanced manipulations such as translation of cylindrical objects and rotation of object with complicated-shape can be considered.

The resultant force by multiple light sources depends on parameters such as the spacing period of the spot array. Namely, the force the object receives is high sensitive to the illumination distribution. This means that the VCSEL array trapping has a capability for minute manipulation with control of the emission pattern. In addition, various manipulation modes can be achieved by a compact hardware configuration. From these points of view, the biological fields which cover DNAs or proteins are interesting as an application of the VCSEL array trapping. DNA molecules are attached to a micro-bead and manipulated. In the field, the target itself is small, so that miniaturization of the processing system is an important issue. Capabilities of the VCSEL array trapping in parallel manipulation and complicated manipulation also suggest applicability to on-chip chemical systems what is called Lab-On-A-Chip[6], molecular computing[7], and so on.

## 5 Conclusion

A manipulation method for microscopic objects by simultaneous illumination with multiple VCSEL sources is studied. The computer simulation shows that the resultant force largely depends on the light pattern. The force for manipulation is possible by the current VCSEL array trapping efficiently when the optimal illumination distribution is selected. Use of the multiple sources provides flexible manipulation like a human's hand which is more convenient than tweezers.

## Acknowledgment

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