Optical manipulation of microscopic objects by means of vertical-cavity surface-emitting laser array sources

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We report on experimental verification of optical trapping using multiple beams generated by a vertical-cavity surface-emitting laser (VCSEL) array. Control of the spatial and temporal emission of a VCSEL array provides flexibility for manipulation of microscopic objects with compact hardware. Simultaneous capture of multiple objects and translation of an object without mechanical movement are demonstrated by an experimental system equipped with 8×8 VCSEL array sources. Features and applicability of the method are also discussed. © 2001 Optical Society of America

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1. Introduction

Since Ashkin *et al.* demonstrated trapping a microscopic dielectric particle by a three-dimensional optical gradient force in 1986,[1] optical beam trapping has been used for a wide range of applications, such as manipulation of biological particles,[2,3] measurement of piconewton force produced by a single kinesin molecule,[4] breakage of an actin filament,[5] alignment and spin of a birefringent object,[6] and an optical spin micromotor.[7] The optical trap technique is useful as a noncontact manipulation method for microscopic objects, and its importance is unquestionable. In addition, by introducing beam modulation, we can extend the variety of manipulations. The examples are trapping and translation of an object by use of two-beam interferometric fringes,[8] arrangement of microparticles according to intensity distribution by multiple-beam interference,[9] rotation by a beam with a helical wave-front structure,[10] and manipulation of low-index particles by a single dark optical vortex laser beam.[11]

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In conventional systems, including the above examples, optical manipulation is usually performed with a single light source. Optical components to generate desired light patterns for a specific manipulation are incorporated into the system with the light source and a reduction imaging system. When passive devices are used, complex manipulation is difficult because of poor flexibility in pattern generation. On the other hand, modulation of the light distribution by a rewritable spatial light modulator is an alternative method for flexible pattern generation.[12] However, high computational cost is required to calculate proper display patterns on the spatial light modulator, and unavoidable errors in the design and in the displayed pattern often disturb delicate manipulation for multiple objects. As a result, to achieve the desired function, the system tends to be complex and difficult to control. To overcome these problems, we present an optical manipulation method for microscopic objects that uses a vertical-cavity surface-emitting laser (VCSEL) array, which we refer to as VCSEL array trapping.

Emission intensities of individual VCSELs can be controlled independently with high frequency. Therefore, flexible manipulation for micro-objects is achieved by control of the spatial and temporal intensity distribution generated by the VCSEL array sources. VCSEL array trapping has many advantages. The VCSEL array can be easily combined with micro-optics. For example, a board-to-board free-space optical interconnect is implemented by the VCSEL array and microlenses without external relay optics.[13,14] These facts indicate that VCSEL array

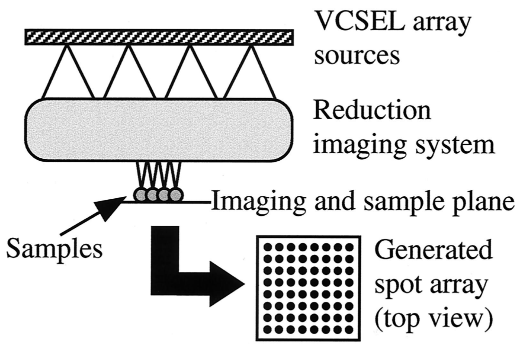

Fig. 1. Schematic diagram of VCSEL array trapping.

trapping has sufficient capability to reduce hardware complexity. Because no controls other than switching of the VCSEL array are required, additional devices for a specific function are not necessary and a troublesome control method is avoided. Various kinds of manipulation can be implemented by the same system configuration. Therefore, we expect to explore new applications for VCSEL array trapping.

The purpose of our study was to verify the capabilities of VCSEL array trapping and to clarify its features. In Section 2 we describe the procedure and the experimental system of VCSEL array trapping. In Section 3 we use VCSEL array trapping to demonstrate simultaneous manipulation of multiple particles, translation of a particle without mechanical movement, and position control of a particle by changing the emission intensities of multiple-beam trapping. In Section 4 we discuss the capability and applicability of the method for practical applications, and we provide our conclusions in Section 5.

2. Vertical-Cavity Surface-Emitting Laser Array Trapping

A tightly focused laser beam on a microscopic particle can be used to trap an object optically.[15] The particle receives a piconewton force induced by interaction with light such as absorption, reflection, and refraction. When the refractive index of the target particle is higher than that of the surrounding medium, the force pushes the particle toward the brighter illuminated region. As a result, the particle is drawn to the focused spot and can be translated if the spot is moved.

The trapping force depends on the illumination distribution on the particle. An example of the trapping capability enhancement is achieved by use of the Laguerre–Gaussian laser mode for axial trapping.[16] Another example is a single dark optical vortex laser beam to capture low-index particles.[11] As reported in these papers, flexibility in light pattern generation is an important requirement to enhance the performance and the functionality of the optical trap technique.

Use of parallel controllable beams is also effective as another solution for this problem. A schematic diagram of VCSEL array trapping is shown in Fig. 1. The VCSEL array is an array of semiconductor laser sources arranged with high density on a substrate. Emission intensities of the individual pixels can be independently controlled by electronics. The maximum intensity of each pixel is several milliwatts. With the VCSEL array one can achieve a faster than megahertz intensity modulation. Therefore, in terms of scanning rate, enough performance can be obtained that is comparable with that from a galvanomirror or an acousto-optic deflector.

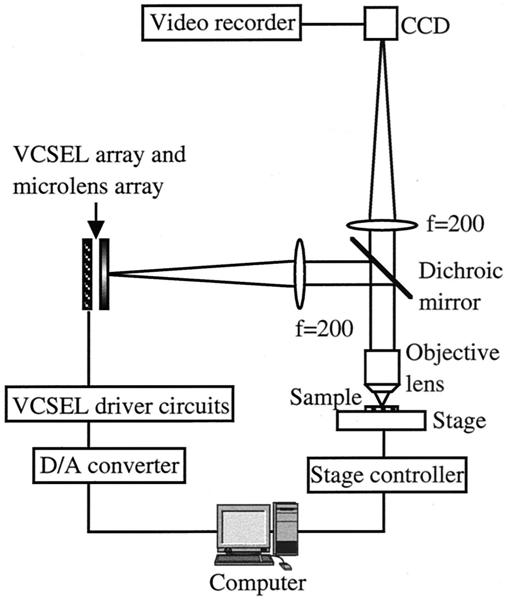

Fig. 2. Experimental setup of VCSEL array trapping. D/A, digital-to-analog.

The VCSEL array sources are useful for the manipulation of multiple microscopic objects and are effective for function extension and simple system configuration, because special devices are not required to generate arbitrary spot array patterns, and the pattern can be switched by control of the emission intensities of the individual VCSELs.

Figure 2 illustrates the experimental setup of the VCSEL array trapping system. Because we aim to verify the basic capability of VCSEL array trapping, we used bulk lenses instead of micro-optics. Emission distribution of the VCSEL array and the position of the sample stage are controlled with a personal computer (Dell 800-MHz PentiumIII processor). The VCSEL array from NTT Photonics Laboratory has 8×8 pixels, an 854- $\pm$ 5-nm wavelength, greater than 3-mW maximum output, a 15-μm ϕ aperture, and a 250-μm pixel pitch. The micro lens array of the system has a 720-μm focal length and a 250-μm lens pitch and was set to increase the light efficiency. Each VCSEL is modulated independently with an analog signal by the driver circuit of our own composition. A simple voltage-to-current conversion circuit was used to drive the VCSEL. The voltage signal input to the driver circuit was generated by a digital-to-analog converter. The emission intensity can be modulated to 100 kHz by the circuit. The VCSEL is driven by a 500-Hz rectangular wave sig-

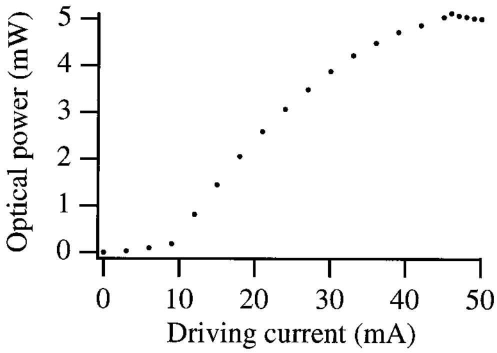

Fig. 3. Dependence of the emission intensity of the VCSEL on the driving current.

nal to prevent system overload. Dependence of the emission intensity measured by a photodetector placed close to the VCSEL on the driving current is shown in Fig. 3. The threshold current was approximately 10 mA, and the emission intensity increased to 5.1 mW with a driving current of 46 mA.

We used an immersible, long-distance objective lens (Olympus LUMPlan) with 60× focal length infrared radiation and 0.90 NA as the focusing lens. The VCSEL pixels were imaged onto the sample plane with a magnification of 1/67. Thus the optical spot pitch on the sample plane is 3.75 μm, and the maximum light intensity is approximately 1.1 mW. The sample plane was observed and recorded by an 8-mm video recorder. The sample objects were 6- and 10-μm-diameter polystyrene particles (Polysciences, Inc., Polybead Polystyrene Microspheres) with 1.60 refractive index and 1.05-g/ml density that were mixed and dispersed in water. The sample was positioned on the sample stage that was controlled in 1-μm steps by a simple control method.

3. Experimental Results

The desired spot array patterns were generated by a combination of emitting pixels of the VCSEL array. When different pixels of the VCSEL array were assigned to individual objects, multiple objects were captured and translated simultaneously by control of the spot pattern. Two kinds of particle were two-dimensionally captured with two VCSEL pixels. Unfortunately, with this experimental configuration, we cannot observe three-dimensional trapping. We translated the particles by moving the stage. A series of six pictures at 10-s interval is shown in Fig. 4. The target objects were polystyrene particles, 6 μm (lower right) and 10 μm (upper left) in diameter, as indicated by circles. The ● designates the origin of the stage. The stage was moved to the left and then upward. Since the observation field is stationary, the trapped particles remain at the same position while the other particles move with the stage. The result indicates that the multiple objects are translated, with an average of 0.48-μm/s velocity for simultaneous translation.

One can achieve various kinds of manipulation by switching the emission pattern of the VCSEL array. As an example, the translation and the position of a stationary object are verified experimentally. Seven VCSEL pixels arranged in an L shape on the 8 × 8 VCSEL array were used for nonmechanical transla-

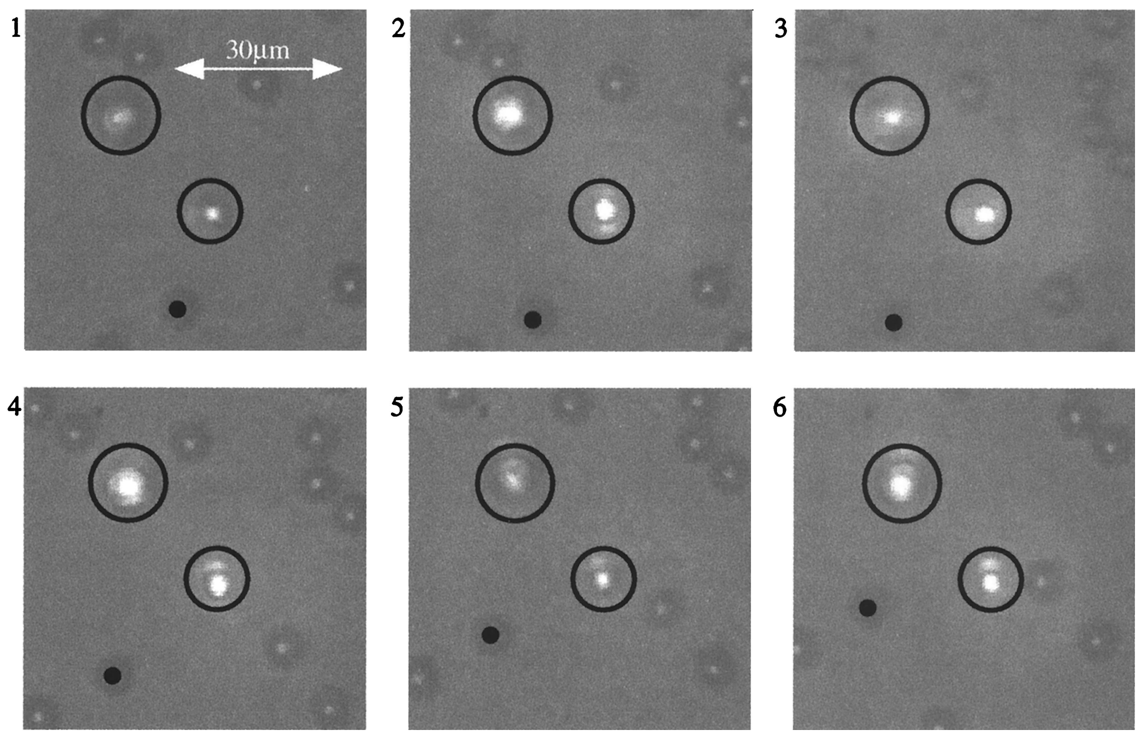

Fig. 4. Series of observed pictures at 10-s intervals during simultaneous capture and translation of two particles. The target particles are indicated by circles; the ● designates the origin of the stage.

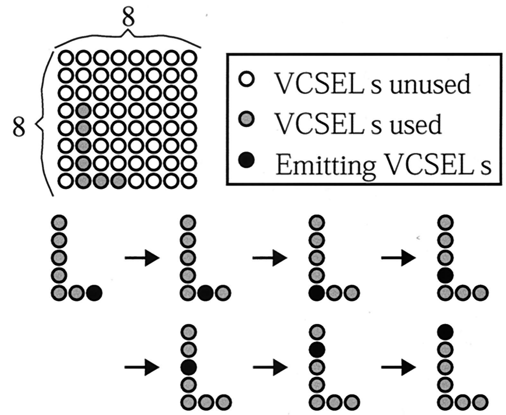

Fig. 5. VCSEL pixels that were used for nonmechanical translation (upper) and an emission sequence of the VCSELs (lower).

tion. The VCSEL pixels were turned on sequentially from the lower right to the upper left of the L shape as shown in Fig. 5. Figure 6 shows a series of six pictures at 10-s intervals. The target object was a 6-μm-diameter polystyrene particle, which is indicated by a circle; the ● designates the initial position of the target. The target particle shifts on the glass slide in response to the emission pixels of the VCSEL array. The average velocity for nonmechanical translation is 0.45 μm/s. No operation other than switching the emission pixels was carried out during the manipulation. We have verified that the method is capable of translating an object without mechanical movement.

Position control is based on the phenomenon that

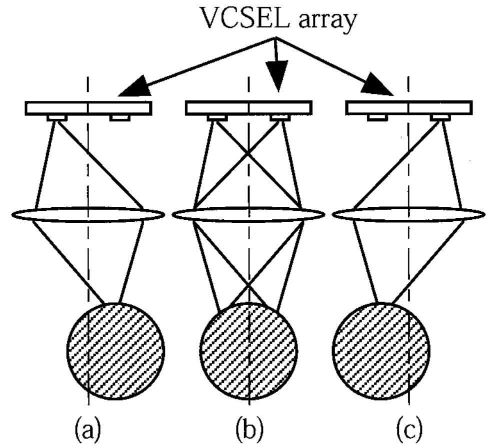

Fig. 7. Position control of particles by two VCSELs: (a) left, (b) both, (c) right. The crosshatched circles designate the target particle.

an object is captured at the position where total radiation pressure is balanced, as shown in Fig. 7. The target particle is trapped at the bright spot when a single VCSEL array is emitted [Figs. 7(a) and 7(c)]. On the other hand, when both VCSEL arrays are emitted at equivalent intensities, the particle is captured at the midpoint of the spots [Fig. 7(b)]. If the intensities of the VCSEL arrays are varied, the particle moves according to the intensity ratio. A 10-μm-diameter polystyrene particle was illuminated by two adjacent pixels on the VCSEL array during the experiment. Figure 8 shows the response time of the horizontal position of the target particle (●) when

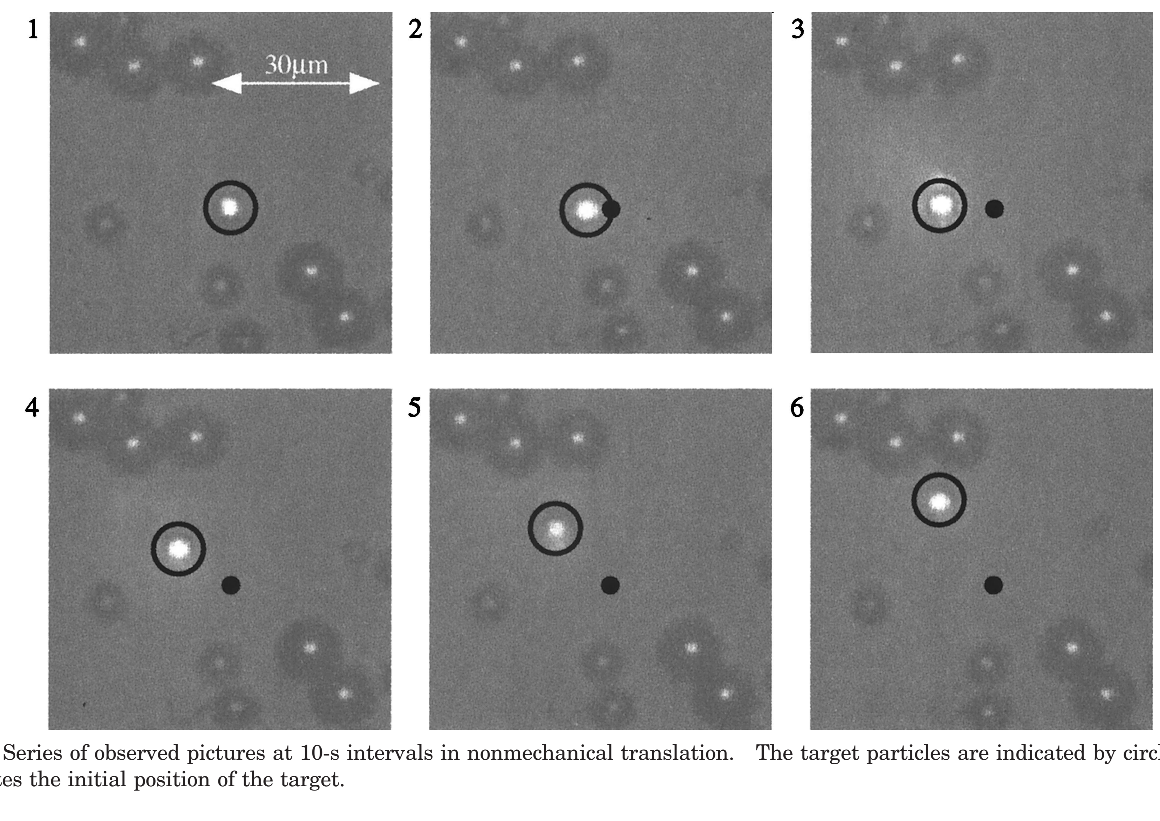

Fig. 6. Series of observed pictures at 10-s intervals in nonmechanical translation. The target particles are indicated by circles; the ● designates the initial position of the target.

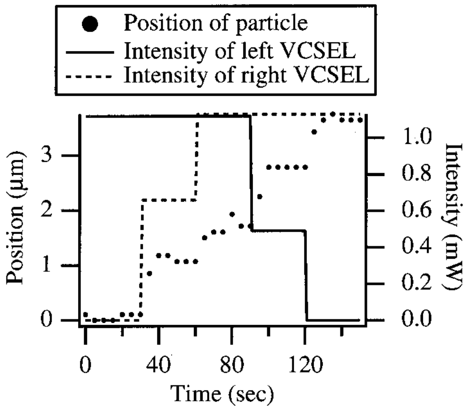

Fig. 8. Time response of the particle position for modulation of two VCSELs.

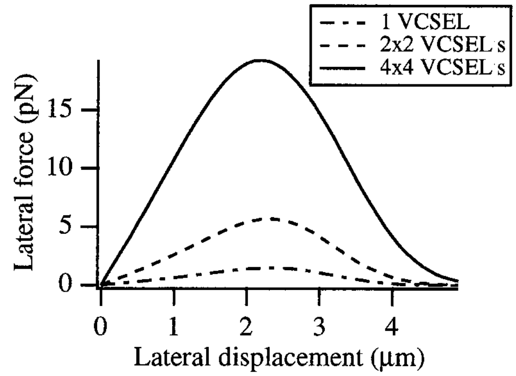

Fig. 9. Relationship between the lateral displacement of the particle and the lateral force. Coincidental illumination of the particles by solid curve, a single VCSEL; dashed curve, 2 × 2 VCSELs; dot–dash curve, 4 × 4 VCSELs.

the intensities of the pixels (solid and broken curves) were stepwise modulated. The particle responds to the emission pattern of the VCSEL array, and the position to be trapped is changed according to the intensity ratio between the two pixels. The result demonstrates that, with this method, the object position is controlled to within an accuracy that is equal to or less than 1 μm.

4. Discussion

We used a high-power laser to obtain a strong trapping force in conventional optical trapping systems. In contrast, the maximum emission intensity of a single VCSEL pixel is less than 10 mW at this stage. In spite of weak intensity, our experiments demonstrate that an object of several or tens of micrometers diameter can be captured and translated two dimensionally with a single pixel on the VCSEL array. This is a significant result for the proposed method because it suggests the potential capability for flexible manipulation with the setup of simple hardware. Also, VCSEL array trapping is useful for simultaneous manipulation. Note that the averaged trapping force given to the particle does not depend on the light intensity but on the total light energy. Trapping forces for multiple particles can be applied continuously because scanning the light beam is not required. Therefore, the light distribution for individual particles is not restricted by the scanning rate, and more flexible manipulation can be implemented than use of the time-averaged light distribution by fast beam scanning.[17]

However, the current experimental system has problems with translation speed and position accuracy, which are addressed at low light power and a coarse pitch of the optical spots at the sample plane. We expect to obtain better performance of the VCSEL array trapping by improving the configuration of the optical system.

To solve the above problems, several techniques can be considered. First, the assignment of multiple VCSEL pixels to an individual particle is a direct method to increase the translation velocity. When the particle is illuminated by N VCSELs, the total power of the trapping beams is N times as much as for a single VCSEL. We can now estimate the trapping force. We consider three cases of coincidental illumination of the particle: (1) a single VCSEL (current setup), (2) 2×2 VCSELs, and (3) 4×4 VCSELs. The trapping force for the lateral direction is estimated by the calculation method based on a ray-optic model developed by Gauthier *et al.*[18] The parameters used for the computer simulation were determined according to the experimental conditions; the target particle is 6 μm in diameter with 1.6 refractive index, the light power is 1.1 mW for a single VCSEL with a wavelength of 850 nm, and the individual beams have a Gaussian intensity profile with a beam waist of 2.6 μm (value measured with the current system). The spot pitch was assumed to be 0.5 μm at the sample plane. Figure 9 shows the calculation result of the relationship between the lateral displacement of a particle and the induced lateral force for all three cases. The maximum forces increased 3.8 times in case (2) and 13.1 times in case (3) compared with that in case (1). According to Stokes law, the required force for translating a particle in a fluid is proportional to the translation velocity. We obtained a 0.45-μm/s translation velocity for nonmechanical translation, which corresponds to case (1). We expect to achieve a translation velocity of 1.7 μm/s for case (2) and 5.9 μm/s for case (3). In addition, by shrinking the spot pitch, we reduced the amount of wasted illumination power and consistently obtained a strong force. Therefore, the average translation velocity can be significantly increased.

Based on the above results, we have determined that translation velocity can be increased to greater than several tens of micrometers per second by assigning multiple VCSELs to an individual particle. If we use the same technique, the accuracy of the position control method can be improved. For that reason, the illumination pattern can be switched based on position and motion of the target particle. An increase of the total illumination power is obviously effective for accurate control. If we combine the method for two-dimensional position control of a particle with the nonmechanical translation technique, the particle can travel over a wide area. Although improvement of the optical system is required, VCSEL array trapping can be applied to biological and other applications. VCSEL array trapping has several features that would make it useful for three-dimensional trapping: advanced rotation and oscillation control of an object, and manipulation of objects with complicated shapes.

5. Conclusion

We have presented optical manipulation of microscopic objects by means of VCSEL array sources. Simultaneous manipulation of multiple objects as well as nonmechanical translation and position control of an object have been experimentally demonstrated. Use of the VCSEL array provides an effective implementation technique for flexible manipulation with compact hardware and a simple control method. In addition, VCSEL array trapping opens the door to simultaneous manipulation for multiple objects because trapping forces for the objects can be applied continuously. Owing to versatility and simplicity, VCSEL array trapping can be used as a manipulation method for microscopic objects.

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References

1. A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and S. Chu, "Observation of a single-beam gradient force optical trap for dielectric particles," Opt. Lett. **11,** 288–290 (1986).
2. A. Ashkin and J. M. Dziedzic, "Optical trapping and manipulation of viruses and bacteria," Science **235,** 1517–1520 (1987).
3. A. Ashkin, J. M. Dziedzic, and T. Yamane, "Optical trapping and manipulation of single cells using infrared laser beams," Nature (London) **330,** 769–771 (1987).
4. S. C. Kuo and M. P. Sheetz, "Force of single kinesin molecules measured with optical tweezers," Science **260,** 232–234 (1993).
5. Y. Arai, R. Yasuda, K. Akashi, Y. Harada, H. Miyata, K. Kinosita, Jr., and H. Itoh, "Tying a molecular knot with optical tweezers," Nature (London) **399,** 446–448 (1999).
6. M. E. J. Friese, T. A. Nieminen, N. R. Heckenberg, and H. Rubinsztein-Dunlop, "Optical alignment and spinning of laser-trapped microscopic particles," Nature (London) **394,** 348–350 (1998).
7. Z. P. Luo, Y. L. Sun, and K. N. An, "An optical spin micromotor," Appl. Phys. Lett. **76,** 1779–1781 (2000).
8. A. E. Chiou, W. Wang, G. J. Sonek, J. Hong, and M. W. Berns, "Interferometric optical tweezers," Opt. Commun. **133,** 7–10 (1997).
9. M. M. Burns, J. M. Fournier, and J. A. Golovchenko, "Optical matter: crystallization and binding in intense optical fields," Science **249,** 749–754 (1990).
10. H. He, M. E. J. Friese, N. R. Heckenberg, and H. Rubinsztein-Dunlop, "Direct observation of transfer of angular momentum to absorptive particles from a laser beam with a phase singularity," Phys. Rev. Lett. **75,** 826–829 (1995).
11. K. T. Gahagan and G. A. Swartzlander, Jr., "Optical vortex trapping of particles," Opt. Lett. **21,** 827–829 (1996).
12. Y. Hayasaki, M. Itoh, T. Yatagai, and N. Nishida, "Nonmechanical optical manipulation of microparticle using spatial light modulator," Opt. Rev. **6,** 24–27 (1999).
13. F. B. McCormick, F. A. P. Tooley, T. J. Cloonan, J. M. Sasian, and H. S. Hinton, "Optical interconnections using microlens arrays," Opt. Quantum Electron. **24,** S465–S477 (1992).
14. E. M. Strzelecka, D. A. Louderback, B. J. Thibeault, G. B. Thompson, K. Bertilsson, and L. A. Coldren, "Parallel free-space optical interconnect based on arrays of vertical-cavity lasers and detectors with monolithic microlenses," Appl. Opt. **37,** 2811–2821 (1998).
15. S. M. Block, "Making light work with optical tweezers," Nature (London) **360,** 493–495 (1992).
16. N. B. Simpson, D. McGloin, K. Dholakia, L. Allen, and M. J. Padgett, "Optical tweezers with increased axial trapping efficiency," J. Mod. Opt. **45,** 1943–1949 (1998).
17. K. Sasaki, M. Koshioka, H. Misawa, N. Kitamura, and H. Masuhara, "Laser-scanning micromanipulation and spatial patterning of fine particles," Jpn. J. Appl. Phys. **30,** L907–L909 (1991).
18. R. C. Gauthier and S. Wallace, "Optical levitation of spheres: analytical development and numerical computations of the force equations," J. Opt. Soc. Am. B **12,** 1680–1686 (1995).