Submicron manipulation tools driven by light in a liquid

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Optically driven micromanipulators with submicron probe tips are proposed and developed by using two-photon microstereolithography. The micromanipulators are worked by maneuvering their movable component with a focused laser beam, and an actual pair of microtweezers was opened and shut precisely. We also propose an effective method of controlling movable micromachines with great freedom of movement. In this method, a dot is attached to a movable component for trapping and driving it by a single laser beam. A microneedle was induced to perform several types of motion such as rotation and translation. The optically driven micromanipulators are useful for bionanotechnology applications that require work to be done in aqueous solutions. © 2003 American Institute of Physics. [DOI: 10.1063/1.1533853]

Manipulation techniques at the nanometer scale are indispensable for progress in nanoscale science and technology. Recently, some types of nanomanipulators such as carbon nanotube nanotweezers and micromachined nanotweezers have been developed for grabbing or probing nanoscale objects. These tweezers are useful for handling mesoscopic clusters and particles, and for electrical measurements of heterogeneous materials and nanoscale devices. However, since these tweezers are based on electrostatic force, they are not ideal for aqueous solution work such as manipulation of cells, microbes, and single molecules.

In this letter, we report promising micromanipulators with submicron probe tips suitable for aqueous solution work. The micromanipulators are driven by optical trapping based on radiation pressure from a tightly focused laser beam. Since optical trapping enables remote manipulation of micro-objects in biological fluid environments, the micromanipulators are well suited for applications in bionanotechnology to which electrostatic types of manipulators cannot be applied. In addition, we propose an effective method of controlling movable micromachines with a great degree of freedom of movement.

As examples of the optically driven micromanipulators, we have created microtweezers and a microneedle for grabbing and probing micro/nanoscale objects in a liquid. These optically driven micromanipulators were fabricated by an assembly free, single-step process based on a method of two-photon microstereolithography developed by our group. In recent years, two-photon microstereolithography and two-photon three-dimensional (3D) microfabrication have been utilized for making various types of 3D microstructures such as microsprings, microtubes, and photonic crystals. However, almost all the microstructures were fixed on a base. Although microrotators have been developed very recently, they were merely wire-frame components. On the other hand, we succeeded in fabricating, not wire-frame components, but more sophisticated movable micromachines with submicron probe tips: a pair of microtweezers and a microneedle.

To fabricate movable micromachines with submicron probe tips, we optimize the scanning pattern of the laser beam to reduce the deformation of a solidified object due to the shrinkage of the photocurable resin during polymerization. Optimal laser scanning for each microstructure enables us to fabricate even freestanding micromachines such as microtweezers and microneedles. Our technique to fabricate the microtweezer arm in the current experiments is a good example. Initially, an attached shaft and stopper were fabricated by scanning a laser beam circularly while the focal plane was lowered. Next, the circular parts of the arm were formed by circular scanning, and then the arm was added by scanning the laser beam in arcs with different radii from the outside of the previously formed circular part. Finally, a submicron probe tip was formed at the end of the arm through point-by-point exposure.

The movable component floats freely in the photocurable resin, unattached to the shaft, but the viscosity of the photocurable resin keeps it from moving throughout the entire process. After the 3D fabrication process, the unsolidified resin is washed out with a rinse made from a glycol ether ester, leaving only the movable microstructure.

We used a two-photon microstereolithography system that we previously developed with a Ti:sapphire laser (wavelength: 763 nm, pulse width: 130 fs, repetition: 82 MHz) for the fabrication of micromanipulators. Figure 1 shows a scanning electron microscope (SEM) image of the microtweezers. The microtweezers had probe tips measuring only 1.8 μm in length and 250 nm in diameter. The probe tips were fabricated by point-by-point exposure with 30 mW laser power. Each exposure lasted 100 ms, and the entire fabrication process was completed in only 6 min.

To drive the microtweezers, the optical system used for the two-photon microstereolithography was also applied with a Ti:sapphire laser operated in cw mode. In a preliminary experiment, the left-hand arm was fixed to the shaft while the right-hand arm of the microtweezers was trapped and swung by the scanning of the focused laser beam, as shown in Fig.

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In this case, the tweezers are driven as follows: The laser beam is initially focused on the arm so that the gradient force of the radiation pressure traps the arm in its equilibrium position. Next, the laser beam is shifted from the equilibrium position, thereby subjecting the trapped arm to an attractive force. As the laser beam scans in an arc, the attractive force induces the tweezer arm to follow the locus of the scanning laser beam at the same speed.

Figure 2(b) shows optical microscope images of microtweezers opened and shut in the rinse. The probe tips were precisely closed without any gap between them. The position of the tweezers can be controlled very precisely and easily, as the position of the probe tip is directly fixed by the focal position. With electrostatic-type tweezers this is impossible: as the separation of the two probe tips of the electrostatic-type tweezers is not proportional to applied voltage, the tips close suddenly and adhere to each other when a critical actuating voltage is reached, which makes it much more difficult to precisely control the position of the electrostatic tweezers compared with the optically driven type. While the position control of the tweezers is limited by the positioning accuracy of the laser beam deflected by galvano scanners, the galvano scanners are sufficiently accurate to close the probe tips of the microtweezers. The positioning accuracy of our current system with closed-loop galvano scanners (GSI Lumonics, M2 scanners) is about 15 nm. In addition, the force of the tweezers can be controlled in the order of femtonewton by adjusting the trapped position along the arm. We have already verified the validity of this force control in experiments on the force control of micromanipulators.

We also propose an effective method of controlling movable micromachines with great freedom of movement. In our method, we design and fabricate a movable component to which a dot is attached to focus a laser beam. By scanning this laser beam focused on the dot, we can control the movement of the components in any motion. This method provides a simple way to drive a micromachine with great freedom of movement by a single laser beam.

The proposed method allows us to drive a microneedle with two degrees of freedom. Figures 3(a) and 3(b) show a SEM image and a schematic design of a microneedle. Since the probe tip of the needle is attached to the slotted arm, this microneedle can provide translational motion as well as rotational motion. A dot is attached to the end of the slotted arm. By trapping the dot with a focused laser beam, the microneedle can be manipulated with the desired motion. Figures 4(a) and 4(b) show the experimental results of translational and rotational motions with a microneedle that has a point of diameter 250 nm. The photographs shown in Fig. 4(a) are sequential images observed at intervals of 1 s. The distance of translational motion was 6.8 μm. In the experiment...
ment shown in Fig. 4(b), the rotation speed was 34 rpm with laser power of 200 mW. The rotational and translational motions of a microneedle are limited by the viscous drag force, which affects the microneedle. The viscous drag force, is proportional to the speed of the motions of the microneedle. Since the maximum speeds of these motions depend on the radiation pressure generated by a focused laser beam, the maximum frequencies are determined by the laser power. We have experimentally confirmed that the maximum frequencies of rotational and translational motions are proportional to the laser power.

We demonstrated that the microneedle was useful for manipulating a micro-object in the liquid. Figures 5(a) and 5(b) illustrate the mechanical stimulation of a micro-object by the microneedle. A tiny particle of dust floating in the liquid was pushed with the arm of the microneedle or pricked with its probe tip. The probe tip was sufficiently strong to prick the micro-object without any deformation of the tip. The Young’s modulus and flexural strength of the photocurable resin were 3.3 and 3.1 GPa, respectively.

In summary, we have developed submicron manipulators driven by light through the use of an assembly free, rapid fabrication method in two-photon microstereolithography. The main advantages of these optically driven submicron manipulators are as follows: remote drive in an aqueous solution, force control on the order of femto-Newton, and elimination of the need to use ultra-high-precision 3D stages to move the probe tips. In addition, since the size and shape of our manipulators can be quickly modified using 3D computer-aided design, they can be easily optimized for particular biological samples. The flexible, rapid fabrication can provide custom-built nanotools to fulfill the needs of specific samples.

In the near future, such optically driven micro/nanoscale manipulation tools will be integrated into 3D polymeric microfluidic circuits by combining the two-photon microstereolithography technique with the other microstereolithography techniques developed by our group.14,17 The optically controlled microfluidic devices including various types of manipulation tools are useful for biotechnology applications such as nanosurgery systems for living cells and nanoanalysis systems for single molecules.

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