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Optically Driven Mobile Integrated Micro-Tools for a Lab-on-a-Chip

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Abstract: This study proposes an optically driven complex micromachine with an Archimedes microscrew as the mechanical power, a sphere as a coupler, and three knives as the mechanical tools. The micromachine is fabricated by two-photon polymerization and is portably driven by optical tweezers. Because the microscrew can be optically trapped and rotates spontaneously, it provides driving power for the complex micro-tools. In other words, when a laser beam focuses on the micromachine, the microscrew is trapped toward the focus point and simultaneously rotates. A demonstration showed that the integrated micromachines are grasped by the optical tweezers and rotated by the Archimedes screw. The rotation efficiencies of the microrotors with and without knives are 1.9 rpm/mW and 13.5 rpm/mW, respectively. The micromachine can also be portably dragged along planed routes. Such Archimedes screw-based optically driven complex mechanical micro-tools enable rotation similar to moving machines or mixers, which could contribute to applications for a biological microfluidic chip or a lab-on-a-chip.

Keywords: archimedes screw; microrotor; optical tweezers; two-photon polymerization

1. Introduction

The lab-on-a-chip has attracted scientific interest from related biological fields because it is convenient, rapid, and accurate, while requiring few consumables. Many studies [1–6] have examined the technology. Specially designed micromachines with critical components increase lab-on-a-chip functions. In this case, optically driven micromachines are important because they have no mechanical contact, no electrical wires, are controlled by a remote, and enable variable manipulation. These optically driven tools perform mechanical and sensing functions on a micro and nanoscale. Using this technique, several optically driven elemental micromachines have been proposed, such as micropumps [7–10], microactuators [11,12], and microvalves [13]. They are expected to contribute to manipulating, sorting, drilling, and treating biological cells. Recent studies have focused on more complex machines that integrate the basic elements with additional mechanisms for performing multiplicate operations [14–18], and the issue of optical driving on asymmetrical objects [19]. In this case, a transmission with precise applied force control is essential for operating the complex micromachines. Moreover, to fulfill variable functional biological application requirements, microfluidic chip operation is becoming more complex and diverse. However, few studies have focused on the relationship between driving power and functional tools, and most mechanisms in these studies are immobile in the microchannels.

In this study, we fabricated Archimedes screw-based micromachines using two-photon polymerization (TPP). As in the previous works [20,21], the Archimedes screw is optically trapped and rotates spontaneously. This function provides the power source for the integrated complex micro-tools. Finally, an optically driven mobile micromachine is also tested.

2. Fabrication of Archimedes Screw-Based Micromachines

TPP is a convenient technique for fabricating 3D microstructures with arbitrary 3D shapes [22]. Structures with complex shapes can be directly obtained by scanning a laser-focusing point along predetermined trajectories. This study fabricates micromachines using a commercial TPP 3D-microfabrication machine (Teem Photonics Inc.) with a passively Q-switched Nd:YAG microchip laser with a 532 nm wavelength. The laser beam was expanded by a telescope coupled to an inverted microscope (Olympus IX51) and focused using a microscope objective lens (100×, NA = 1.3). Commercial resin (Photomer 3015, Henkel Inc., Ambler, PA, USA) was used with a photo-initiator specifically designed for two-photon absorption. Polymerization occurred at the focal point in the resin with less than 0.1 mW of laser power and a 1 ms exposure. Figure 1 shows a diagram of the experiment.

To demonstrate optical manipulation, a three-blade Archimedes screw with a 1/3 cycle was fabricated. The screw was 4 μm in diameter and 10 μm high. The sphere and complex microrotor were 3 μm and 13 μm in diameter, respectively. Figure 2 shows the dimensions of the Archimedes screw-based micromachines. A SEM photograph of the TPP microfabrication product is shown in Figure 3.

Figure 1. The two-photo polymerization 3-D microfabrication system.

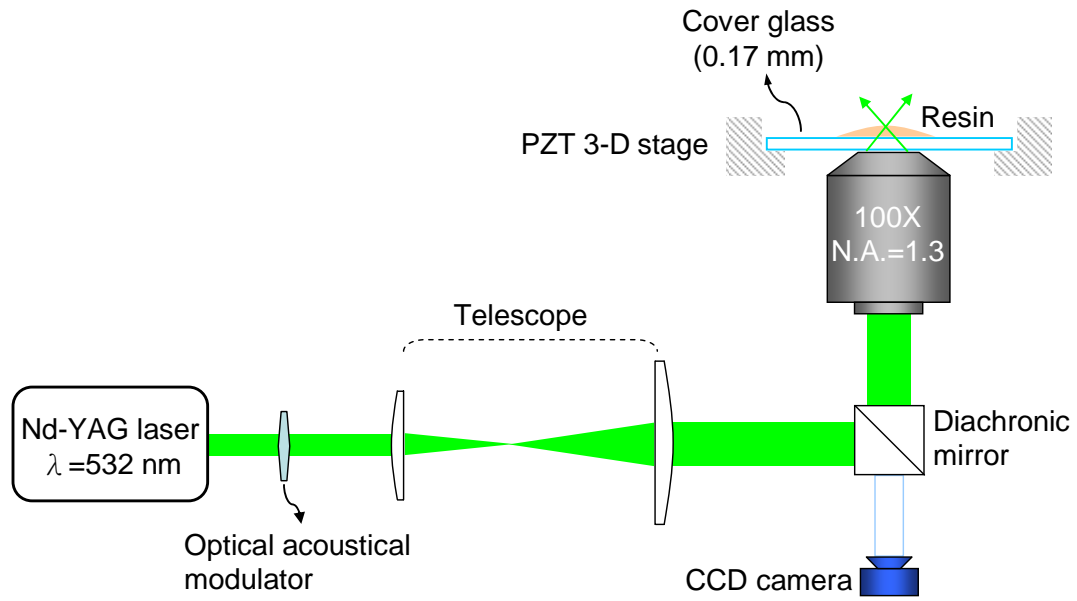


Figure 2. Dimension of the Archimedes screw-based micromachines: (a) 3-D view; (b) side view; (c) bottom view.

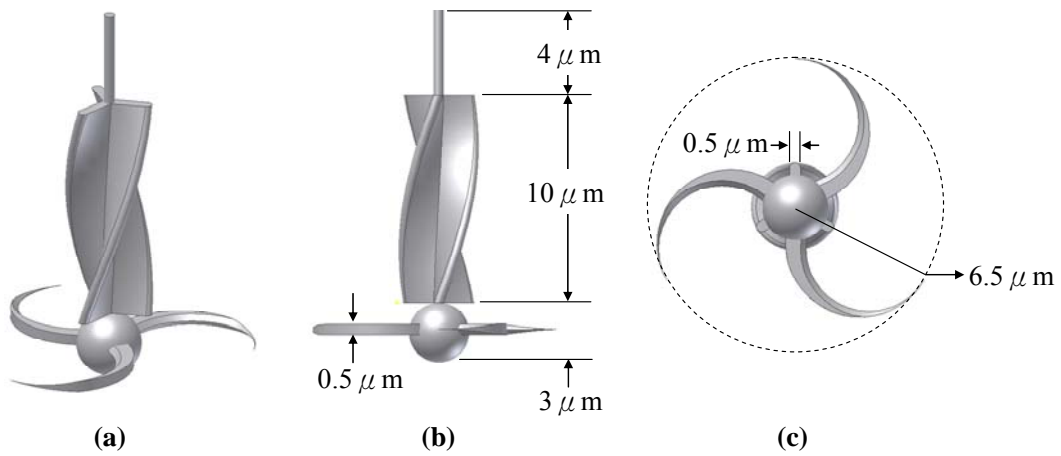
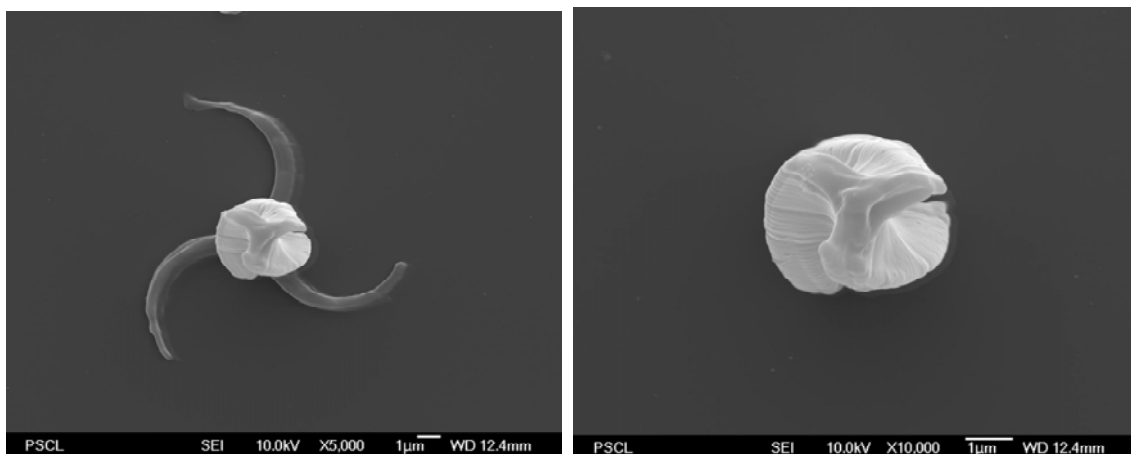


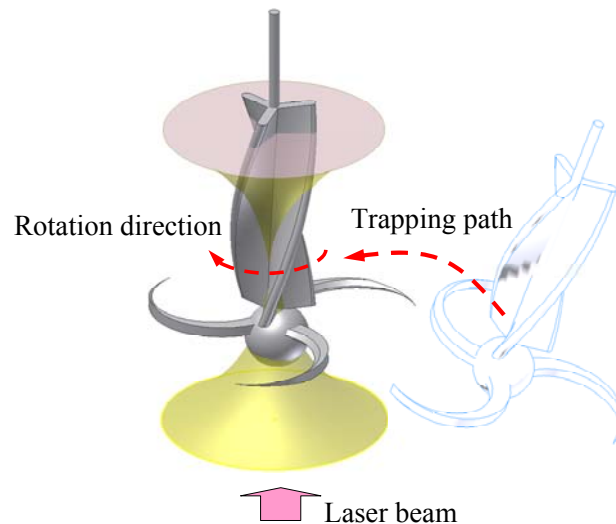
Figure 3. The SEM figures (top-view) of the Archimedes screw-based micromachines (left) and Archimedes-screws (right).



3. Optical Driving Demonstration

A commercial optical tweezers (PALM MicroTweezers, ZEISS Inc.) is used to perform the optical driving demonstration. The micro-tools are grasped and rotated by the Archimedes screw, as shown in Figure 4. Because elongated objects in optical traps align along the beam axis [23], a rod was designed at the center of the Archimedes screw. The height and diameter of the integrated micro-tool were $17\ \mu\text{m}$ and $13\ \mu\text{m}$, respectively, ensuring that the structure aligns along the laser beam axis. In the earlier tests, the knives were directly combined with the blades of the Archimedes screw. The result showed that the integrated micro-tool could not rotate symmetrically, and that it was not stable when dragged by the optical tweezers. In this study, a sphere was set as a coupler below the screw to connect the three knives. It also acted as an anchor to stabilize the micro-tool.

Figure 4. Schematic figures of the optically driven integrated micro-tool: once the optical tweezers turns on, the micro-tool is trapped toward the laser focus, and then the Archimedes screw is spontaneously rotated by the optical tweezers, and drives the micro-tool.



The rotational speeds of the micromachines were measured by detecting the light period perpendicular to the image plane of the knives. An oscilloscope was used to visualize the photodiode signal. The laser powers were measured at the objective. Figure 5 shows the demonstration results. The rotational efficiencies of the Archimedes screw and the integrated micro-tool (screw and knives) were $10.3\ \text{rpm/mW}$ and $1.8\ \text{rpm/mW}$, respectively. The optical driving mobile micro-tool was demonstrated with $80\ \text{mW}$ of laser power, as shown in Figure 6. The optical tweezers dragged the micro-tool along the planned routes in an S-shape and a corner shape. The results indicate that the micro-tool is easily carried anywhere along variable routes.

Figure 5. The rotational efficiencies (rpm/mW) of the Archimedes screw and the integrated micro-tool (screw + knives).

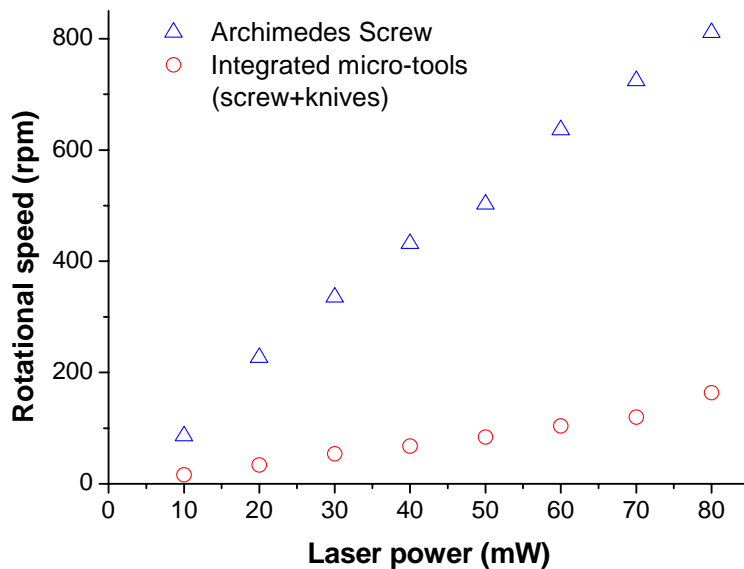


Figure 6. The demonstrations of the optical driving mobile micro-tools: (a) an S-shape; (b) a corner shape.

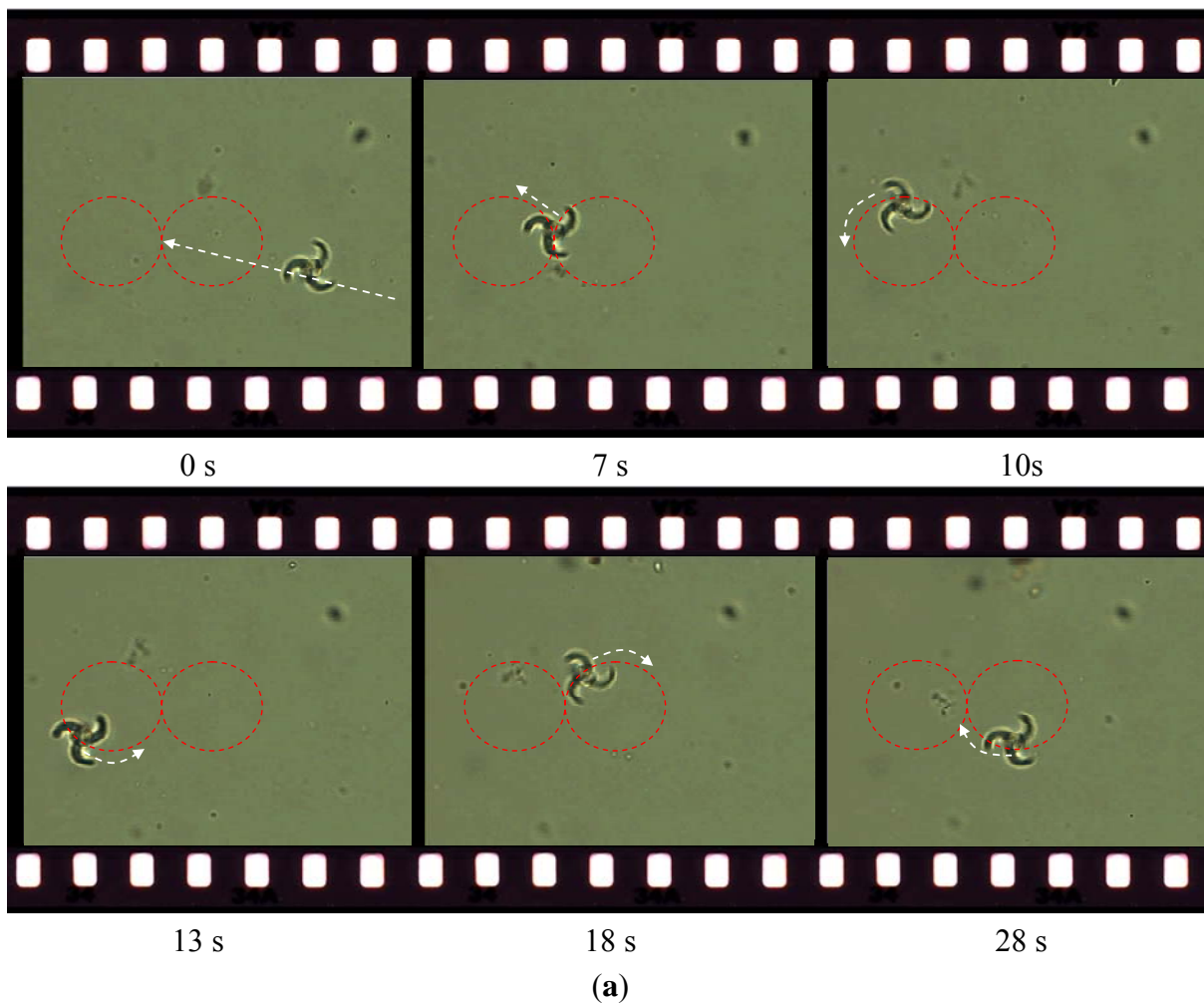
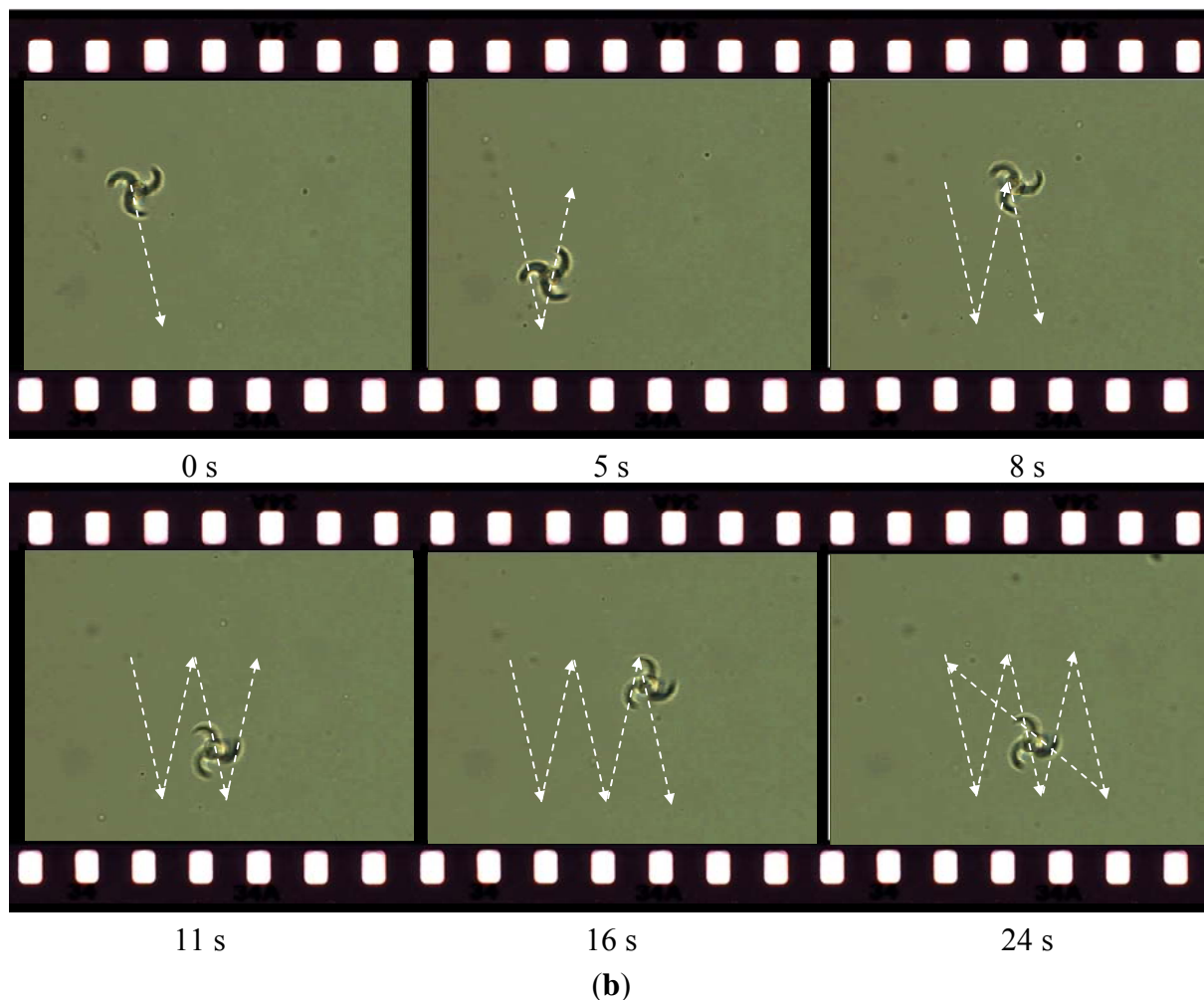


Figure 6. Cont.



4. Conclusions

This study successfully fabricated a complex optically driven micro-tool using TPP. The micro-tool was integrated with three components: an Archimedes screw as the driving power to transmit the optical force, three knives as functional tools, and a sphere as the coupler to connect the screw and knives. Such optically controlled micromachines provide a new method of directly transmitting applied optical forces to functional tools. This optically driven mechanism is expected to be a versatile, powerful tool for mobile manipulation in microfluidic channel and lab-on-a-chip applications.

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