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Multiplying optical tweezers force using a micro-lever

Chih-Lang Lin[1*], Yi-Hsiung Lee[2], Yi-Jui Liu[2,3], Jiann-Lih Hwang[2], Chin-Te Lin,[4] Tien-Tung Chung[4], and Patrice L. Baldeck [1,5]

[1] *Inst. of Biomedical Engineering and Material, Central Taiwan Univ. of Science and Technology, Taichung, Taiwan*
[2] *Department of Automatic Control Engineering, Feng Chia University, Taichung, Taiwan*
[3] *Master's Program in Biomedical Informatics and Biomedical Engineering, Feng Chia University, Taichung, Taiwan*
[4] *Dept. of Mechanical Engineering, National Taiwan University, Taipei 10617, Taiwan*
[5] *Univ. Grenoble 1 / CNRS, LIPhy UMR 5588, Grenoble, F-38041, France,*
[*] *cllin101943@ctust.edu.tw*

Abstract: This study presents a photo-driven micro-lever fabricated to multiply optical forces using the two-photon polymerization 3D-microfabrication technique. The micro-lever is a second class lever comprising an optical trapping sphere, a beam, and a pivot. A micro-spring is placed between the short and long arms to characterize the induced force. This design enables precise manipulation of the micro-lever by optical tweezers at the micron scale. Under optical dragging, the sphere placed on the lever beam moves, resulting in torque that induces related force on the spring. The optical force applied at the sphere is approximately 100 to 300 pN, with a laser power of 100 to 300 mW. In this study, the optical tweezers drives the micro-lever successfully. The relationship between the optical force and the spring constant can be determined by using the principle of leverage. The arm ratio design developed in this study multiplies the applied optical force by 9. The experimental results are in good agreement with the simulation of spring property.

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OCIS codes: (140.7010) Laser trapping; (350.4855) Optical tweezers or optical manipulation.

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1. Introduction

Micro-sized particles can be trapped in the strongly focused spot of a laser beam. This phenomenon is widely used to trap and manipulate particles, cells, and micro-objects under a microscope [1]. Such a remote photo-driven tool can uniquely elaborate mechanical and sensing functions at micro- and nanoscales. Using this technique, a number of photo-driven micro-objects have been proposed in recent years. For example, photo-driven rotations can be induced either by the net optical torque resulting from the complex shape [2,3], or by driving a movable part with an optical tweezers trap [4].

Two-photon polymerization (TPP) is an attractive technique for fabricating three-dimensional microstructures; it also facilitates the production of polymer micro-objects with arbitrary tri-dimensional shapes [5]. Polymerization only occurs at the focal point of the laser following the two-photon absorption step of photo-initiators. Structures with complex shapes are directly obtained by scanning the focus along predetermined trajectories. Recent studies have focused on the realization and demonstration of more complex devices that integrate a variety of micro-machines, such as spring, micromanipulator, and multilink systems [6-9] that can be integrated in a microfluidic environment. Use of these systems has crept into driving optical forces that are limited to a few hundred pico-Nt [10, 11].

A lever is one of the six classic simple machines; it is one of the most important devices in the structured mechanisms. A lever can either multiply the mechanical force and the distance that the opposite end of the rigid object travels, or change the applied force direction. This study demonstrates the possibility of multiplying optical dragging forces using the classic lever function of mechanics in the microscopic world. The micro-lever fabricated by using the TPP 3D-microfabrication technique is a second class lever. The optical applied force is approximately 100 to 300 pN with a laser power of 100 to 300 mW. Using the proposed arm ratio design, this study demonstrates that the optical driven force can be increased to nine times the applied optical force. Finally, the experimental results are compared with those of the simulated spring property.

2. Micro-lever fabrication

The proposed micro-lever is fabricated by using a commercial TPP 3D-microfabrication machine (Teem Photonics Inc.) using a passively Q-switched Nd:YAG microchip laser with 532 nm wavelength, 550 ps pulse-width, and 6.5 kHz repetition rate. The laser beam was expanded by a X3 telescope, coupled to an inverted microscope (Olympus IX51), and focused with a microscope objective lens (100x, NA=1.3). Commercial resin (Photomer 3015, Henkel Inc.) is used with the photo-initiator specifically designed for two-photon absorption. Polymerization occurs at the focal point in the resin under less than 0.1 mW of laser power and a 1 ms exposure time.

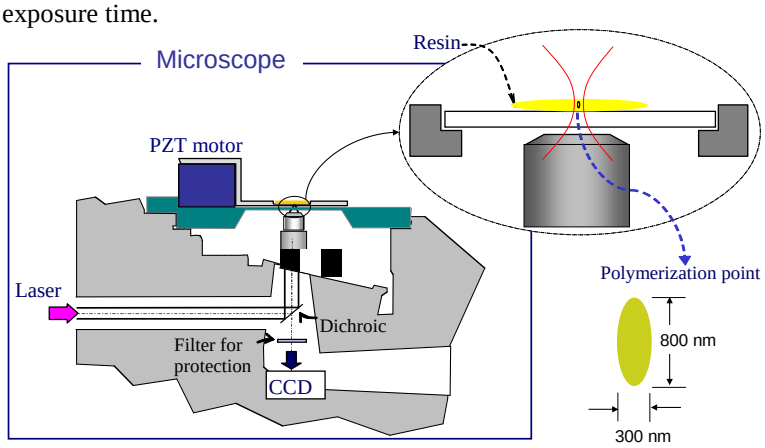


Fig. 1. Details of TPP 3D-microfabrication: the interior of the microscope frame, the enlarged sample, and the voxel-based element.

Figure 1 shows the instruments, and their details reveal that, at the focal point, local polymerization of a voxel-based element occurs in the resin, and a three-axis piezoelectric stage (Nanocube, Physik Instrumente) forms the trace to produce the required structures. In a sealed chamber (1 cm in diameter and 0.8 mm in depth) comprising a glass cover and slide spaced by double-sided tape, a few drops of acetone are added to dissolve the unexposed resin and free the polymer microstructures.

Both the micron-sized lever with different arm ratios (r_1, r_2, and r_3) and the spring drawn by AUTOCAD are shown in Fig. 2. The spheres (7 μm in diameter) are placed on the lever to form the required arm ratios, and to be trapped by optical tweezers. The total length of the lever beam is 60 μm with an "H" cross-section to lighten the weight and avoid bending. The spring's dimensions are as follows: 0.36 μm in spiral diameter, 12.5 μm in coil diameter, 10 coils, and 2.5 μm in pitch. Figure 3 shows the micro-lever products (arm ratio: 2, 2.5, 3): (a) a micro-lever photo obtained by a scanning electron microscope, and (b) a micro-lever with a spring in an acetone solution observed by transmission with optical microscope.

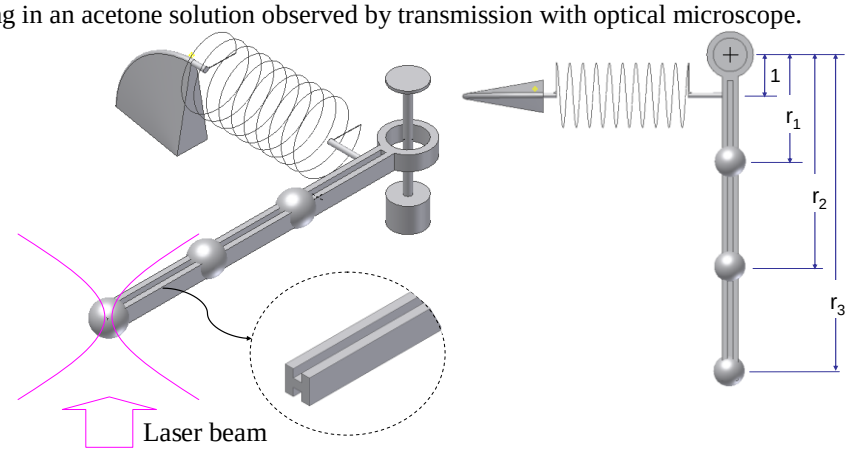
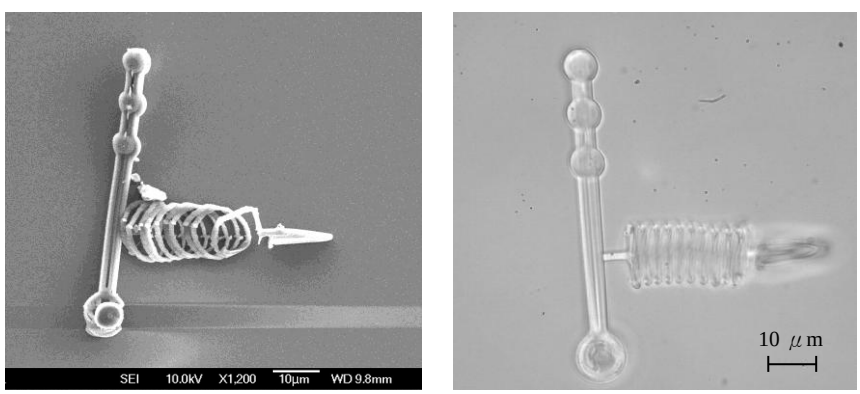


Fig. 2. AUTOCAD figures of a lever-beam with a spring. Left: the 3D-structure and enlarged portion of a lever beam with an "H" cross-section. Right: arm ratios (r_1, r_2, r_3).



(a) (b)

Fig. 3. Micro-lever product (arm ratio: 2, 2.5, 3): (a) a SEM photo of a micro-lever, (b) a micro-lever with a spring observed by transmission with an optical microscope.

3. Photo-driven micro-lever

The microscope and objective lens that were previously shown were also used for the optical tweezers. A CW Nd, namely a YAG laser at λ=1064 nm, provided the trapping beam. During the experiments, the movement of the trapped object was ascertained by direct observation through the ocular of the microscope or by using a video camera.

Before performing the photo-driven micro-lever experiment, the optical exerted forces were calibrated by dragging various sphere sizes. The optical forces applied at the spheres were measured and calculated using the Stoke's law, where η is the dynamic viscosity (Nt · s/μm^2), R is the radius of the spherical object (μm), and v is the escaped velocity (μm/s). Figure 4 shows the relationship between the optical force and laser power of different sphere sizes. The experimental result is in agreement with Wright' s (1994) theoretical and experimental result [11]. The 7 μm sphere was used in the proposed micro-lever design, and its proportional factor 1.13 was used to calculate the exerted optical forces at the micro-lever sphere.

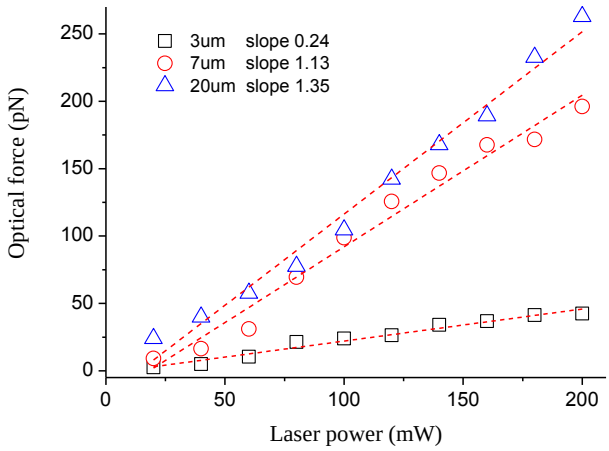


Fig. 4. The relationship between the optical exerted force and laser power of different sphere sizes.

This study assumes the following: (1) The lever beam and the fulcrum is rigid; (2) the friction force at the fulcrum is much lower than the optical dragging force; and (3) the viscosity between the lever and the solution can be ignored. The typical rotation of a beam manipulated by optical tweezers is shown in Fig. 5. The sphere trapped by optical tweezers smoothly rotates around the fulcrum under optical dragging (from Fig. 5 (a)~(h)). Rotation stops once the laser is turned off.

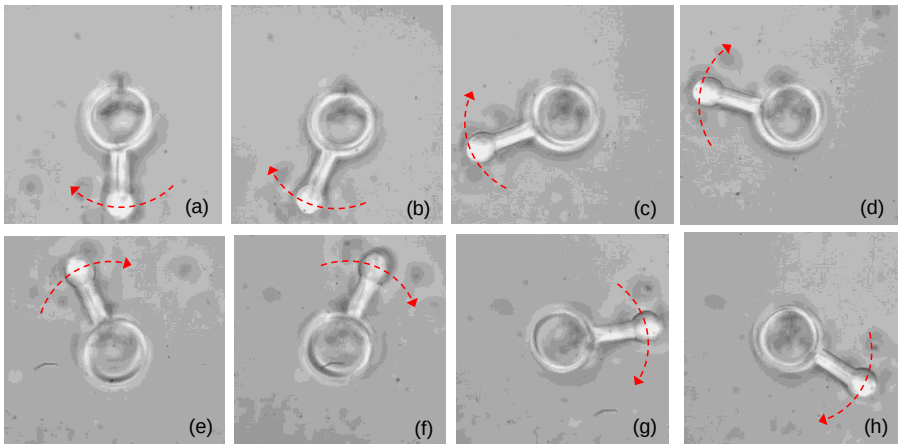


Fig. 5. Demonstration of the typical rotation of a beam when the pivot is trapped by optical tweezers.

A demonstration of photo-driven micro-lever with an arm ratio of 3 is shown in Fig. 6. Optical forces (55pN~275pN) are applied at the sphere to pull or compress the spring. The optical dragging displacement ($\triangle x_{optic}$) was recorded when the sphere was escaped from

optical trapping. The experimental result shown in Fig. 7 indicates that the two cases of pulling and compressing have similar linear proportions. This means that the spring has an appropriate elastic resilience. Measurements using different arm ratios (3, 6, and 9) were subsequently performed, as shown in Fig. 2. The experimental compression results are shown in Fig. 8.

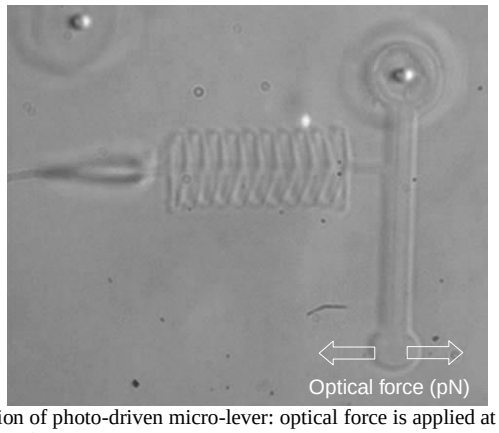


Fig. 6. Demonstration of photo-driven micro-lever: optical force is applied at the sphere to pull (right) or compress (left) the spring.

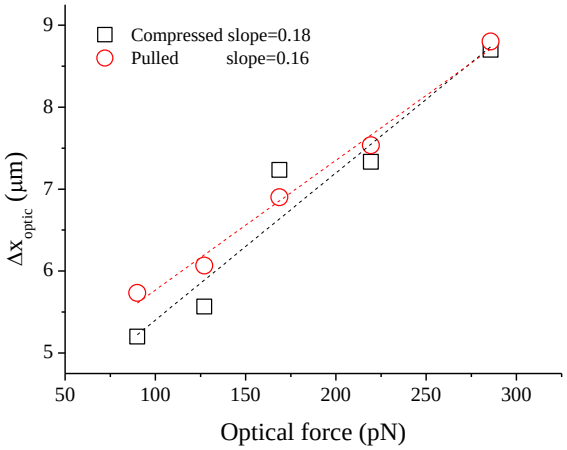


Fig. 7. The dependence of $\triangle x_{optic}$ when the optical force is increased in two directions: compression and pulling.

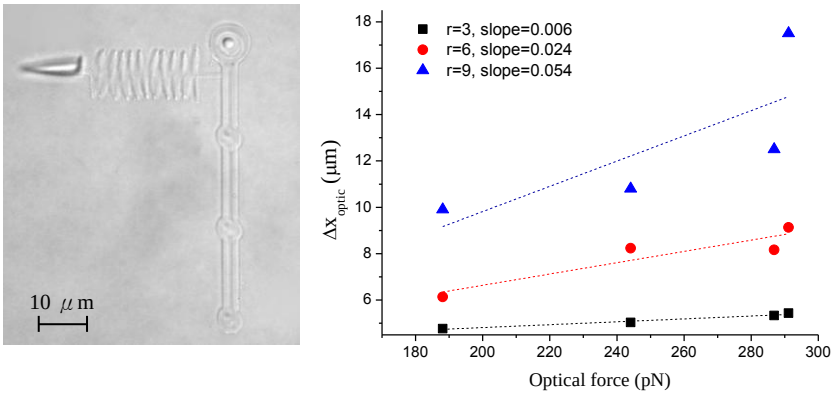


Fig. 8. (a) a micro-lever (arm ratio: 3, 6, 9) with a spring observed by transmission with an optical microscope (b) The dependence of $\triangle x_{optic}$ when the optical force for arm ratios 3, 6, and 9 are increased.

A diagram of the optical force (F_{optic}), the induced force (F_{spring}), displacements of the sphere ($\triangle x_{optic}$) and joint ($\triangle x_{spring}$), and the arm ratio is shown in Fig. 9. According to Hooke's law, the experimental spring constant can be derived by

$$k_{\exp} = \frac{F_{spring}}{\Delta x_{spring}} = \frac{rF_{optic}}{\frac{1}{r}\Delta x_{optic}} = \frac{r^2}{(\Delta x_{optic} / F_{optic})} \quad (1)$$

where $r = (l_1 + l_2)/l_1$ is the arm ratio.

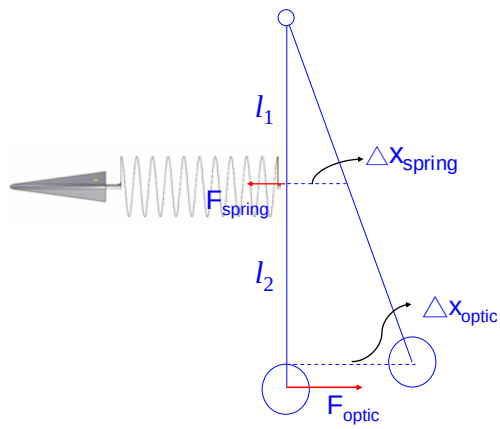


Fig. 9. The relationship diagram of the optical force (F_{optic}), induced force (F_{spring}), displacements of the sphere ($\triangle x_{optic}$) and joint ($\triangle x_{spring}$), and the arm ratio $(l_1+l_2)/l_1$

The theoretical spring constant is illustrated in the formula below:

$$k_{the} = \frac{Gd^4}{8D^3N} \quad (2)$$

where G is the shear modulus, d is the spiral diameter, D is the coil diameter, and N is the number of coils.

The experimental spring constants of the three different arm ratios 3, 6, and 9, as calculated by Eq. (1), are 1.45×10^{-4} Nt/m, 1.48×10^{-4} Nt/m, and 1.49×10^{-4} Nt/m. These values are in agreement with the theoretical spring constant of 1.52×10^{-4} Nt/m, as calculated by Eq. (2), the elastic modulus of 3.5 Gpa, and the Poisson ratio of 0.35 (Photomer 3015, Henkel Inc.). In the case of arm ratio 9, the induced force at the spring is 2490 pN under an optical force of 280 pN. This demonstrates that the photo-driven micro-lever can increase the optical force by approximately nine times.

4. Conclusion

This study successfully demonstrated the possibility of using a photo-driven micro-lever to multiply optical force. The photo-driven micro-lever can increase the applied optical force by approximately nine times. The experimental results are in good agreement with those of the simulation of spring property. We believe that this study is promising and opens a method for precisely driving micron-sized machines, such as connecting rods, valves, and other structured mechanisms.