FUNCTIONAL MICRO DEVICES AND SYSTEMS PRODUCED BY TWO-PHOTON PHOTOPOLYMERIZATION

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We report in this paper the femtosecond laser fabrication of micro-devices and micro-systems using two-photon-assisted photopolymerization. As an example, a micro-oscillator system consisting of a spring of 300-nm cord diameter and of a spring-end-equipped bead was produced. By laser trapping the bead, the spring was arbitrarily prolonged, compressed, and bent. The spring constant was deduced from a damping oscillation of the micro-system.

Up to date photopolymerization through two-photon absorption (TPA)[1] has been established as a powerful tool for laser precision micro-fabrication, by which various three-dimensional (3D) photonic devices[2,3] and micro/nano machine systems[4,5] are readily produced. In particular, we demonstrated[6,7] recently that the diffraction limit can be exceeded in a material system, which has a pronounced threshold response to light excitation. Sub-diffraction-limit (SDL) spatial resolutions, for example, less than 1/6 of the fabrication wavelength of 800 nm, were therefore attained. This would reduce the structure features far less than those achieved by conventional rapid prototyping. However, in contrast to the rapid progress on polymeric photonic crystals2[,3, 8] researches on micromachine are still kept at a level of demonstration. It is highly desired to make micro machines that function.

In this paper, we report the TPA laser production of a micro-oscillator system, which has a cord diameter of approximately 300 nm. The oscillator was optically driven by applying a laser trapping force. To the best our knowledge, this is the first demonstration of actual operation of a mechanical system of this small size.

The laser microfabrication system consisted functionally of 4 parts: 1) a laser irradiation source, that is, a 800-nm wavelength Ti: Sapphire laser that operated at mode-lock and delivered 150 fs pulses at a repetition rate of 76 MHz; 2) beam steering system, by which a laser beam was first expanded, then spatially filtered and focused by a high numerical-aperture (NA~1.4) objective lens into samples. A Galvano mirror set was used for moving the focal spot in two horizontal dimensions; 3) a sample holder and a controlling piezo stage for up-down movement of the sample. The 3D scanning of the focal spot was synchronized by a computer, by which pinpoint exposure in SDL accuracy was enabled; 4) monitoring and imaging system, of which the major component was a CCD (charged couple device) camera.

SCR 500 resin was used for photopolymeriz-ation. The absorption band of the resin as shown in Fig.1 starts from 540 nm downwards, clearly indicating absence of the single-photon absorption both from the resin and from the initiator at the fabrication wavelength of 800 nm. Laser irradiation renders the exposed regions insoluble, while unexposed regions are dissolved in the ethanol and removed during the post-processing stages.

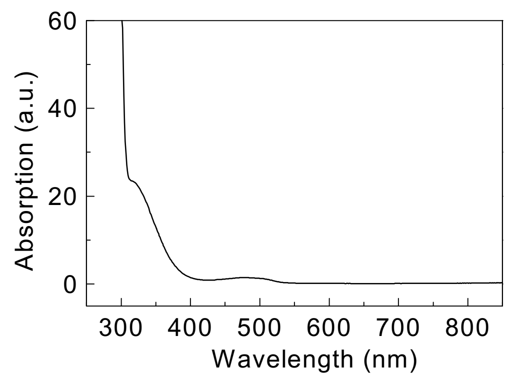

FIG.1. Absorption spectrum of SCR 500 resin, which was used in all fabrications of this study.

By raster scanning6, micro springs were fabricated, as shown in Fig. 2. They have a cord diameter of

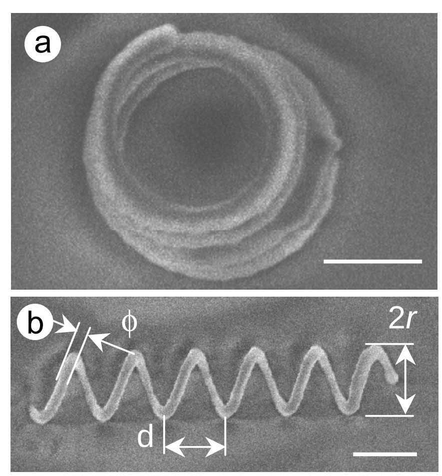

FIG. 2. Scanning electron microscopic (SEM) images of (a) an erect and (b) a siding micro-springs. Scale bars are 1 µm (a) and 2 µm (b), respectively.

ϕ=300 nm, a coil diameter of 2r=2 μm, and a pitch of d= 2 μm.

It is noteworthy that the cord diameter of the spring is far less than the fabrication wavelength. However, mechanically motivating a spring of such a small size is technically challenging. Radiation pressure may serve this purpose, which is induced by photon momentum transfer from refracted and reflected laser light to scattering particles[9,10]. This force is already well known to be strong enough to levitate and move micro-particles against gravity and a viscous drag. This optical force has been widely applied to noncontact and nondestructive manipulation of polymer latexes, liquid droplet, metal powders, biological cells, and so forth[11,12]. For optically driving the micro-spring, we fixed one end of the spring to a polymerized anchor that was attached to the glass substrate, and polymerized a bead at the other end. If the bead were trapped by a focused laser, it would follow the movement of the focal spot. By this way, the spring can be prolonged, compressed, and bent. Figure 3 is a schematic drawing of this idea.

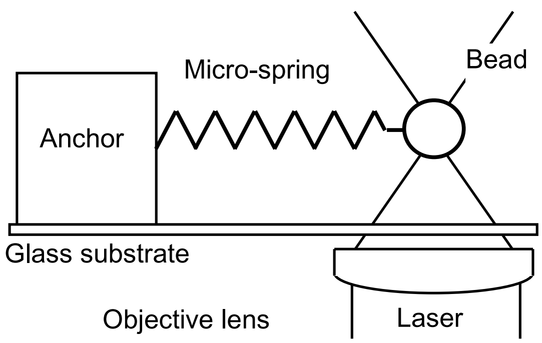

FIG. 3. A schematic system for driving the micro-spring. Since the bead can be easily trapped by a focused laser beam, the entire system consisting of the spring and the bead can be thus activated.

The anchor has a side length of 14 μm [Fig. 4(a)] and 8μm [Figs. 4(b), (c) and (d)], and the bead, located 10 μm above the glass substrate, has a diameter of 3 μm. Figure 4 (a) is an *in-situ* photo microscopic image of the fabricated oscillator system (before removing unsolidified liquid resin). The spring and the bead should not adhere to the substrate for a free movement. This was evidenced by Figs. 4 (b), (c) and (d), which was recorded when slightly shaking sample cell and therefore the bead flowed with liquid. The oscillator system was kept in the developer of ethanol so that the buoyancy would partly balance the gravity to reduce the bead-substrate friction. The same laser system as that utilized for TPA photopolymerization, but a wavelength tuned to 820 nm, was used for the laser trapping. The laser has an average power of 19 mW, which may induce a lateral trapping force of not less than 3 pN, corresponding to 20 times of the bead gravity.

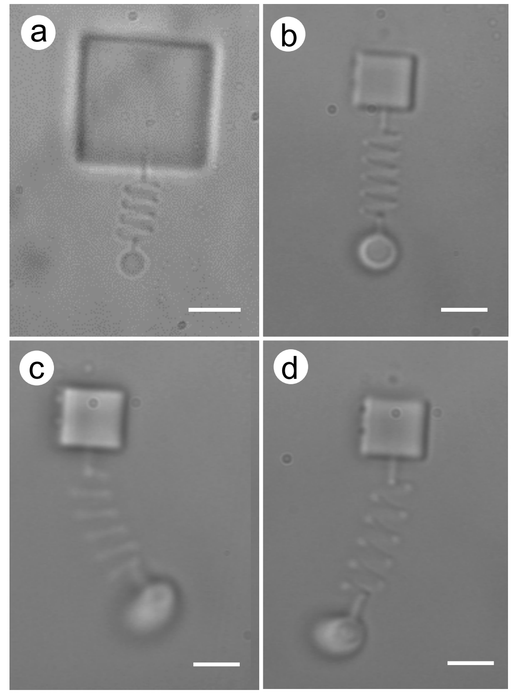

FIG. 4. Photo microscopic images of fabricated micro-oscillator system. (a) Just after the fabrication, and the liquid resin not yet removed. During developing, the bead flows with liquid to different sites (b), (c) and (d), particularly when a vibration was intentionally induced. The scale bars are 5 μm.

Experimentally it was clearly observed that the bead was three-dimensionally trapped in the focus of laser, and could be arbitrarily manipulated. When released from a prolonged state by stopping the irradiation, an oscillation was initiated. However, due to the extremely small size of the device, the viscosity plays a critical role in determining oscillation modes. In the current study, the oscillation was observed to be a highly damped one. If we assume the viscosity is proportional to the velocity of the bead (Stokes Law), i.e.

$$f_{\mathrm{vis}}=6\pi\eta r\upsilon \qquad (1)$$

where η=1.084×10-3 Pa·s (25°C) is the liquid viscosity, and υ the sphere velocity. Then the sphere damping oscillation can be expressed as:

$$m\frac{d^2x}{dt^2}=-kx-6\pi\eta r(\frac{dx}{dt}) \qquad (2)$$

where $m=1.6\times10^{-14}$ kg is the mass of the bead, k is the spring constant to be determined, and r the radium of a spherical bead. Figure 5 shows the bead displacement versus time when the spring restored from a prolonged state to the natural state.

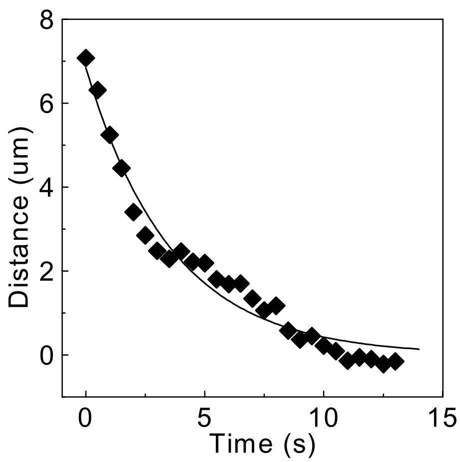

FIG. 5. Restoring curves of the micro-oscillator movement. The symbols are experimental data, and the solid curve is from a simulation.

By fitting the experimental curves with eq (2) using the least square methods, the spring constant of the oscillator was deduced to approximately 8.0 nN/m.

In conclusion, we have fabricated a sub-micron oscillator system using SDL laser micro/nano fabrication technology, which is an example of functionalized micromachines. The oscillator was activated by a laser trapping force, which offers an extremely powerful and promising driving mechanism for microsystems.

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[1] S. Maruo, O. Nakamura and S. Kawata, Opt. Lett. **22**, 132 (1997).

[2] H. –B. Sun, S. Matsuo and H. Misawa, Appl. Phys. Lett. **74**, 786 (1999).

[3] H. –B. Sun, V. Mizeikis, Y. Xu, S. Juodkazis, J. –Y. Ye, S. Matsuo and H. Misawa, Appl. Phys. Lett. (June 25, 2001).

[4] S. Maruo and S. Kawata, IEEE J. MEMS **7**, 411 (1998).

[5] H. –B. Sun, T. Kawakami, Y. Xu, J. –Y. Ye, S. Matuso, H. Misawa, M. Miwa and R. Kaneko, Opt. Lett. **25**, 1110 (2000).

[6] S. Kawata, H. –B. Sun, T. Tanaka and K. Takada, submitted.

[7] T. Tanaka, H.- B. Sun and S. Kawata, submitted

[8] B. H. Cumpston, S. P. Anaanthavel, S. Barlow, D. L. Dyer, J. E. Ehrlich, L. L. Erskine, A. A. Heikal, S. M. Kuebler, I.-Y. S. Lee, D. McCord-Maughon, J. Qin, H. Röckel, M. Rumi, X.-L. Wu, S. R. Marder and J. W. Perry, Nature, **398**, 51 (1999).

[9] A. Ashikin, Biophys. J. **61**, 569 (1992).

[10] H. Misawa, K. Sasaki, M. Koshioka, N. Kitamura and H. Masuhara, Appl. Phys. Lett. **60**, 310 (1992)

[11] Y. Inouye, S. Shoji, H. Furukawa, O. Nakamura and S. Kawata, Jpn. J. Appl. Phys. **37**, L684 (1998).

[12] T. Sugiura, T. Okada, Y. Inouye, O. Nakamura and S. Kawata, *Opt. Lett*. **22**, 1663 (1997).