Laser Fabrication and Manipulation of an Optical Rotator Embedded inside a Transparent Solid Material

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We report the fabrication and rotation of an optical rotator confined in a microcavity inside silica glass material, based on the techniques of femtosecond laser-assisted etching and laser manipulation. The rotator thus prepared may act as a micropump and micromixer. The material of this rotator is identical to that of the host substrate, because femtosecond laser-assisted etching is an internal removal process. As a result, the rotator as well as substrate has high chemical stability and good optical transparency. We also describe tests in which we demonstrated that this fabrication technique is versatile enough to allow one to parepare two types of rotators with different shapes.

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1. Introduction

Controlled irradiation of focused femtosecond (fs) laser pulses allows the three-dimensional (3D) microstructuring of transparent solid materials assisted by succeeding chemical etching. The superb results attainable with fs laser pulses are brought about by the multiphoton absorption in very small areas of the materials due to extremely high photon density. Because of physical and chemical modification caused by the multiphoton absorption, the irradiated areas acquire increased solubility to chemicals such as hydrofluoric acid. As a result, the fabrication of 3D microchannels has been realized for sapphire [1], quartz [2], and silica glass [3] with high optical quality as well as for photostructurable glasses such as “Foturan” produced by Schott [4,5,6]. This technique is called femtosecond laser-assisted etching. The structured transparent materials thus prepared can find useful applications in micro total analysis systems (μ-TAS) [7] and as micro-optical elements.

Two-photon polymerization of photoresist is a well-known 3D microfabrication technique. Maruo and Inoue [8] have fabricated microchannels on the surface of substrates in which an optically driven micropump is included and demonstrated control over the flow of water with an accuracy of sub-PL. This is an excellent use of this technology, but because the structure is made of organic photoresist materials, the applicable fluid is limited. Since fs laser-assisted etching can process inert inorganic materials such as sapphire and silica glass, it can be applied to a wider range of fluids. In addition, it is easy to make a movable object inside a microcavity by properly designing the laser-modified region, because fs laser-assisted etching is an internal removal process. In this case, the movable object is made of the same material as the host, so it can have good chemical and optical properties. We have proposed the concept of a rotator confined in a microcavity inside a transparent solid material, as shown Fig. 1, and very recently reported the fabrication of such a structure [9, 10].

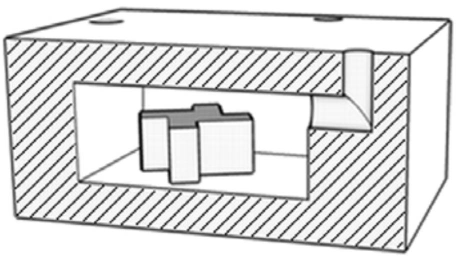

Fig. 1 Schematic cross-sectional image of the optical rotator inside a silica glass. The object is about 10 μm high by 10 μm wide, and it will rotate under laser trapping.

Given that the structure is embedded in the substrate, direct mechanical force cannot be applied to control it. Thus we adopted the laser manipulation technique [11,12], which is known as a non-contact method to control the position (momentum) of a micro-sized transparent object. The technique also allows us to control rotation (angular momentum) of the object by optical force. In the present case, a special shape with dissymmetry [13] is appropriate to achieve our intension, although other methods for rotating micro-objects using only a single laser beam have also been reported [14,15]. The spinning of a micrometer radiation pressure motor with dissymmetry was analyzed using geometrical optics [16]. The rotator with a dissymmetrical shape is called an optical rotator. In this work we have used the same process to fabricate two rotators with different dissymmetry and shapes, which are called the “Four-wing” and “Top-sloped” rotators. The rotation speeds of the rotators are compared based on the mechanism that induces torques for rotation.

2. Experiment

The preparation of the structures consisted of two steps. First the focused fs laser pulses were irradiated inside the transparent materials placed on a moving stage along the pre-designed pattern. Then the substrates were soaked in etching solutions for a given period of time, and a microcavity was formed as designed.

A fs Ti:Sapphire regeneratively amplified laser beam was used as a light source, and an objective lens was used to focus 20-Hz laser pulses with a central wavelength of 800 nm on the sample. The sample was attached to a computer-controlled piezoelectric transducer stage, and the irradiation position was controlled synchronizing to the laser pulse. Individual spots were irradiated by single pulses. The pulse-to-pulse distance along an optical axis was 2 μm, and the interval perpendicular to an optical axis varied from 1.0 μm to 0.25 μm. The wet etching was carried out by dipping the specimen in 2% hydrofluoric acid for 2 hours at room temperature.

The laser trapping experiments were carried out in two independent setups.

3. Results and discussion

3.1 Four-wing rotator

The four-wing optical rotator is shown in Fig. 1. The shape of this rotator with four blades is very similar to that reported by Higurashi and co-workers [13]. This rotator has four-fold rotational symmetry with respect to the axis of rotation. Under the laser trapping with a focused beam, the incident light passes the side surfaces of the rotator. The refracted light at these side surfaces generates radiation pressure. The four-wing rotator has a rotation torque because these forces at each side surface are directed in the same direction.

For fabrication, the sample of silica glass was irradiated by a focused fs laser at a pulse energy of 75 nJ by a 100x oil-immersion objective (NA=1.35). The pulse-to-pulse distance (perpendicular to an optical axis) was 0.25 μm.

Figure 2(a) is a phase-contrast image of an object irradiated inside the silica glass before etching, and Fig. 2(b) is a phase-contrast image after etching. Under this irradiation condition, photomodification occurred without crack formation. Four pipes surrounding the microcavity were attached to allow etching solution to penetrate into the microcavity. As shown in Fig. 2(b), the rotator was embedded in the microcavity because the nonirradiated region remains as a rotator after etching. The fabricated structure was about 12 μm wide and 10 μm high. It is clearly shown in Fig. 2(b) that the fabricated structure was separated from the microcavity. In addition, when the microcavity was filled with water, Brownian motion was observed.

We were able to confirm that the embedded optical rotator can rotate by applying the laser trapping technique to rotate the fabricated structures inside the silica glass. The light source was a continuous wave (CW) ND:YAG laser (Spectra Physics, J20US-CW) with a wavelength of 1064 nm. The structure was irradiated in an inverted optical microscope by the focused CW laser through a 100x oil-immersion objective lens (NA=1.40) and a 10x dry objective lens (NA=0.40). The microcavity was filled with water. We used a CCD camera connected to an HDD/DVD recorder to observe of the trapped rotator.

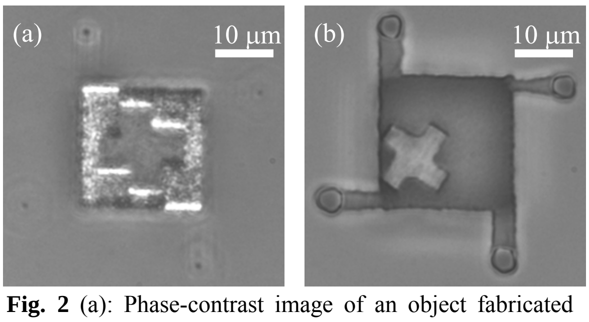

Fig. 2 (a): Phase-contrast image of an object fabricated inside a silica glass before etching. (b): Phase-contrast image of the optical rotator in silica glass after etching.

Figure 3 shows sequential optical microscope images of the rotating object under laser trapping. The rotator rotated counter-clockwise at 98 rpm when manipulated at a laser power of 4 W and at 3 rpm at 200 mW. The rotational speed was nearly proportional to the laser power from 200 mW to 4 W, as shown in Fig. 4. The rotation using laser trapping needed laser power higher than 200 mW. The rotational direction agreed with that reported previously [13], and the direction was reversed by reversing the rotator. When NA of the objective lens that focused the laser beam was smaller, the rotational speed was lower. For a 10x objective lens (NA=0.40), the rotational speed was about 5 rpm with a 4-W laser beam. This is in accordance with previous studies [13,16]. The reason for the NA-dependent rotational speed is explained by the assumption that only the light passing through the side surfaces generates torque.

3.2 Top-sloped rotator

We next attempted to fabricate an optical rotator with a different shape. Because the technique of fs laser-assisted etching consists of only fs laser irradiation and wet etching, a change in rotator shape does not make the fabrication difficult. As no additional process is needed, this method is very flexible. By changing the pattern of laser pulse irradiation, we built the rotator with a different form using the process described above. The second rotator was a square

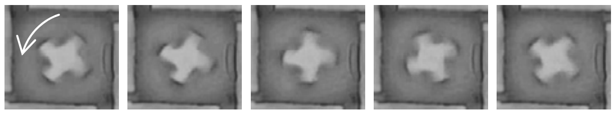

Fig. 3 Sequential optical microscope images (30 s^{-1}) of the rotating object under laser trapping. A 4-W laser beam was focused by the 100x objective lens. The white arrow indicates the rotation direction.

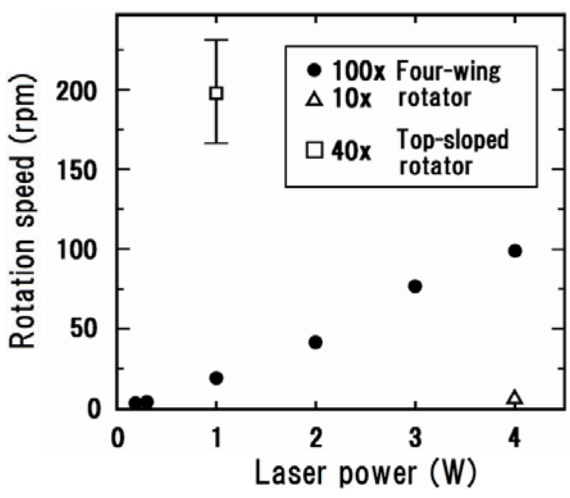

Fig. 4 Rotational speed of two types of optical rotators vs. laser power.

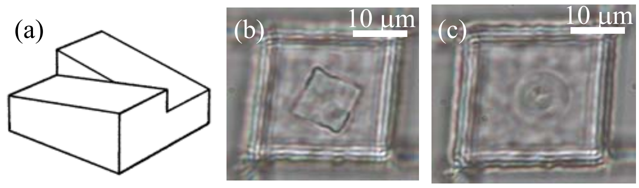

Fig. 5 (a): The design of a top-sloped rotator. (b): Optical image of the rotator in silica glass after etching. (c): Optical image of the rotator under laser trapping. A 1-W laser beam was focused by a 40x objective lens.

cuboid with segmented slopes on the top, and thus it had two-fold rotational symmetry, as shown in Fig. 5(a). Hereafter this type of rotator is referred to as a top-sloped rotator. Here, "top" indicates the surface from which the trapping laser beam comes. The principle of operation of the top-sloped rotator has been theoretically studied by Ukita and Nagatomi [17]. In this type of rotator, almost all the incident light hits the sloped surface to generate torque, and higher-speed rotation can be expected relative to the four-wing rotator. In the four-wing rotator the incident ray passing through the side surface to provide torque is very small.

In the fabrication of second type of rotator, the 40-nJ fs laser pulse was focused on a silica glass substrate by a 100x objective lens (NA=1.40 oil) and the pulse-to-pulse distance (perpendicular to the optical axis) was 0.5 μm. In the laser trapping, the light source was a CW fiber laser (LPG photonics, YLR-10-LP) with a wavelength of 1064 nm. The structure was irradiated in an inverted optical microscope by the focused CW laser through 100x (NA=0.90), 40x (NA=0.75), and 10x (NA=0.30) dry objective lenses. The microcavity around the rotator was filled with water, and a CCD camera connected to an HDD/DVD recorder was used for observation as in the case of the four-wing rotator.

The fabricated top-sloped rotator is shown in Fig. 5(b). It is about 9 × 9 μm wide and about 3~5 μm high. Under the combination of laser power at about 1 W and with a 40x objective lens, the rotator spun around a tilting rotation axis. With a laser power larger or smaller than 1 W, this rotator would not rotate. The origin of this strange power-dependence is unclear; here we have tested only one top-sloped rotator but we plan to fabricate and carry out laser trapping with other rotators. With the CCD camera at a maximum capturing rate of 30 s^{-1}, the rotation speed transcended the bounds of the time resolution of observation. Thus the rotational speed could not be measured exactly. We examined video frames from the CCD camera and assessed the rotational speed at a laser power of 1 W at 200 ± 30 rpm, as shown in Fig. 4. Even though the setup was different from the four-wing rotator technically, it is obvious that this rotational speed was much higher than that observed for the four-wing rotator.

3.3 Future perspective

In this experiment, only one structure acting as a rotator confined in a microcavity was fabricated in each microcavity. The number of fabricated structures is not limited, however, when using fs laser-assisted etching. We can increase the number of structures in a microcavity, and we can connect microcavites through microchannels that also can be fabricated using the same technique. Furthermore, embedded structures of another function can be fabricated, such as valves. In addition this fabrication can be performed at the intended position because we can optically monitor the irradiation. Thus we can add extra 3D microstructures to the already-structured transparent substrates.

4. Conclusion

We have fabricated and rotated optical rotators in a microcavity inside a silica glass substrate by using the techniques of fs laser-assisted etching and laser trapping. The rotational speed of the embedded structure was proportional to the trapping laser power. We demonstrated that by using fs laser-assisted etching, one can fabricate an optical rotator accommodating any three-dimensional shape. We also showed that an embedded optical rotator could be designed to spin rapidly. This fabrication technique offers technical merits of the movable embedded elements, including high chemical stability and good optical transparency for μ-TAS.

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