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Water-assisted drilling of microfluidic chambers inside silica glass with femtosecond laser pulses

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ABSTRACT Microfluidic chambers embedded in silica glass are drilled by water-assisted ablation with a femtosecond laser. The continuous scanning ablation increases the processing speed up to 50 μm/s. Not only may microchambers or microtrenches be obtained at high speed and in one step, but also combined structures consisting of cascaded microchambers and microtrenches may be fabricated. The inner-wall morphology of the microchambers is analyzed by a scanning electron microscope.

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1 Introduction

Microfluidic chambers are fundamental components in a variety of devices such as labs-on-chips, microsensors and micrototal analysis systems. Conventionally, microchambers are achieved by a semiconductor planar technique based on photolithography. This technique is widely adopted in biological and chemical laboratories, but multilayer and multistep processes are needed to form three-dimensional (3D) microstructures. With the rapid development of chirped pulse amplification, femtosecond lasers are commercially available. When intense femtosecond laser pulses are focused into the bulk of a transparent medium, optical breakdown will only occur in the confined neighborhood of the focus because of nonlinear multiphoton absorption. This facilitates the direct 3D material processing with high spatial precision. Therefore, many researchers have paid much attention to the fabrication of microfluidic components such as microchambers, microchannels and micromixers with femtosecond laser pulses [1–13]. An approach including femtosecond laser irradiation, heat treatment and chemical etching has been carried out to fabricate microfluidic elements inside photosensitive glass [1–4]. Leaving out the baking process, Marcinkevičius et al. made hollow microchannels inside silica glass [5]. More recently, water-assisted ablation was utilized to machine microchannels without postfabrication such as heat treatment and wet etching [8–13]. During drilling, the inflow of water dispersed ablated material and debris. The redeposition and clogging were greatly reduced, and so microholes with high aspect ratio could be obtained.

In this paper, we machined microchambers inside silica glass by water-assisted ablation with femtosecond laser pulses. In order to obtain 3D microstructures quickly, the sample was continuously moved under irradiation of a 1-kHz pulse train. The drilling began with the rear surface in contact with water. Debris was efficiently removed by water that wicked into the microstructure. The sample was translated according to the programmed pattern, so that trenches and chambers were fabricated inside the glass.

2 Experiments and results

In this paper, we used a regeneratively amplified Ti:sapphire laser system (Spitfire, Spectra Physics), which delivered pulses with a duration of 120 fs (FWHM), a center wavelength of 800 nm and a repetition rate of 1 kHz. The laser beam propagated along the $+z$ direction. A long working distance objective with a numerical aperture of 0.50 (LMPLFL50X, Olympus) was applied to focus the laser pulses. The energy of an incident pulse could be continuously attenuated by a combination of a half-wave plate and a Glan prism. A shutter was used to switch the laser beam. The silica glass sample was mounted on a computer-controlled XYZ translation microstage with 0.1-μm resolution. The thickness of the sample was 1 mm. In order to *in situ* monitor the machining process, the sample was optically polished on four sides. A top view and a side view were obtained at the same time by two sets of transilluminated optical microscope systems. A schematic configuration of the setup is shown in Fig. 1a, which is similar to that in Ref. [11]. The experiment was conducted at atmospheric pressure. In the machining process, the ablation front would always be in contact with deionized water. In order to avoid the refractive-index-modulated filament in front of the ablated zone, we stretched the pulse duration to ~ 300 fs by adjusting the compressor gratings of the laser system [14].

In our previous papers, we completed microchannels by repetition of drilling and waiting for the inflow of water [8–11]. At each position, the pulse train was fired approximately three times in an interval of several seconds. An additional waiting time was also needed for the water wicking up and the debris dispersing into the water. The deeper the microchannel, the longer the waiting time required. However, we

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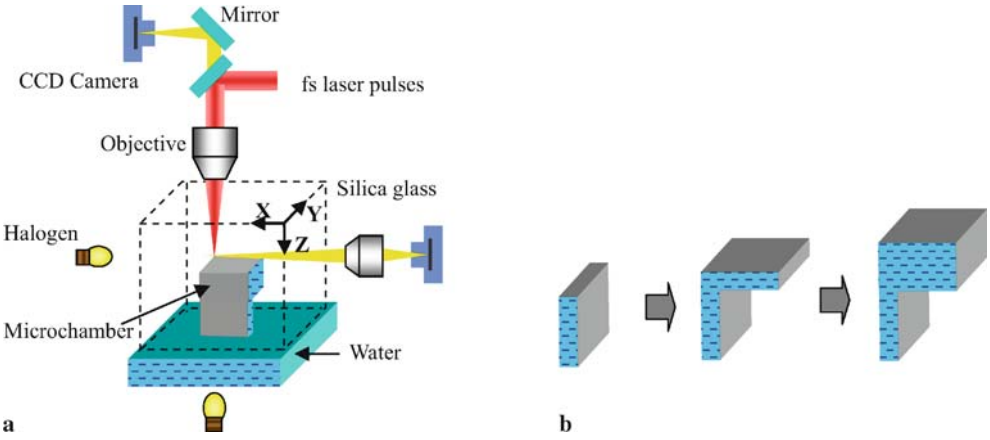

FIGURE 1 (**a**) Schematic setup and (**b**) the procedure for machining a microchamber inside silica glass

found that the sample could be continuously moved without waiting when the exit of a structure like a trench or a chamber was large enough. As shown in Fig. 1b, a microtrench was first fabricated from the rear surface. After that, the sample was moved in the xy plane to form a shallow chamber. Then, it was moved 1 μm in the z direction to make the chamber deeper. The procedure was repeated until the designed microchamber was completed. During drilling, the sample was moved at 50 μm/s and exposed to the 1-kHz femtosecond laser pulse train. Each spot was exposed by ∼ 30 pulses. No waiting time was needed and the structure could be completed at high speed.

The energy was selected as 1.4 μJ/pulse, which corresponded to a fluence per pulse of 80 J/cm^2 with a spot diameter of ∼ 1.5 μm. Stronger pulses would result in worse roughness of the bottom wall of the chamber. In addition, when intense femtosecond laser pulses propagated through a transparent medium, multiple foci and a long filament would occur [15, 16]. The spherical aberration of an air–glass interface might also elongate the focus along the propagation direction and result in multiple foci [17, 18]. These factors would make the bottom wall more rough. Therefore, we drilled the microstructures with lower pulse energy. Figure 2 shows a microstructure including a microtrench and a microchamber. The trench has a length of 75 μm, a width of 5 μm and a depth of 60 μm. The chamber had the same length as the trench and its width and thickness were about 75 μm and 50 μm, respectively. The whole structure was completed in about one hour. In fact, we fabricated the trench and the initial part of the chamber at a pulse energy of 1.4 μJ, which would ensure the smoothness of the bottom wall of the chamber. After the depth of the chamber was 4 μm, we increased the energy to 1.7 μJ/pulse. Due to the elongation of the focus, the step distance along the z direction was increased to 2 μm. Thus, the fabrication speed was further accelerated.

Similar to the microchannel drilling, the ablation debris ejection and efficient dispersion into water were critical. Therefore, an appropriate scanning speed of the sample was required to be chosen [12]. When the speed was below 10 μm/s, the buildup of residual bubbles prevented water from touching the ablation front and from dispersing the debris efficiently. When the speed exceeded 100 μm/s, the exposure time to the material was too short and the ablation was inadequate. In our experiments, the scanning speed of the microstage was selected to be 50 μm/s.

Using this technique, more complicated microstructures could be obtained. For example, Fig. 3 demonstrates a structure of two chambers cascaded with trenches. This whole structure was completed in one step. In the fabrication process, we could see that some bubbles were released and detached through the monitors. This fact revealed that the ablation always occurred at the interface between glass and water, and proved that the trenches and the chambers were empty.

For a further characterization of the inner-wall morphology, the yz facet of the sample was polished until the ma-

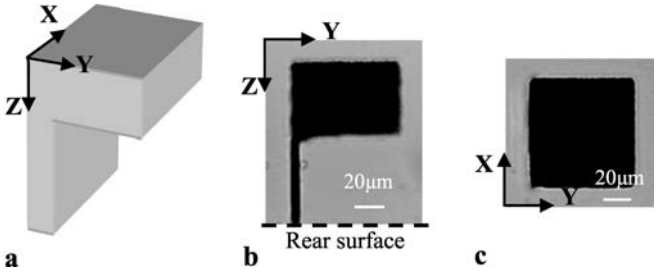

FIGURE 2 (**a**) Schematic configuration of a microchamber; optical micrographs of (**b**) a side view of the yz plane and (**c**) a top view of the xy plane of the microchamber, respectively. The incident energy: 1.4 μJ/pulse. The scanning speed: 50 μm/s

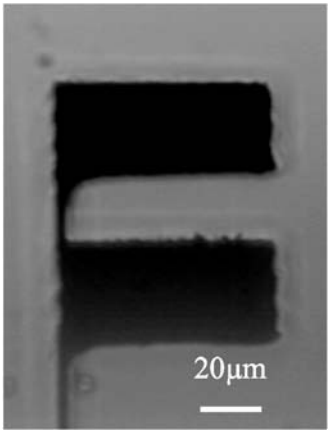

FIGURE 3 Side view of a double chamber serially drilled in silica glass. The incident energy: 1.4 μJ/pulse. The scanning speed: 50 μm/s

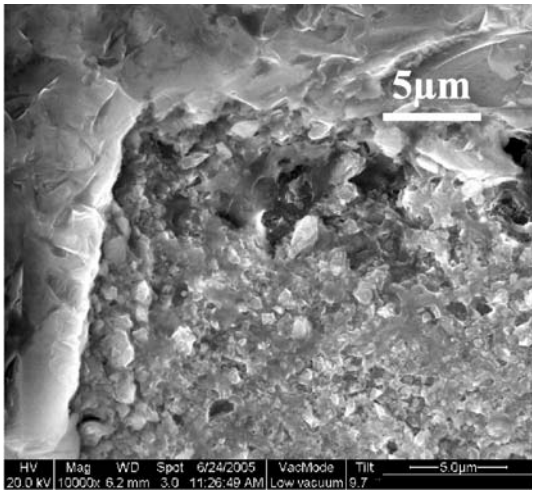

FIGURE 4 SEM image of one corner of a chamber

chined microchamber emerged. Figure 4 shows a scanning electron microscope (SEM) image of one corner of a fabricated chamber. One can see that the inner wall has a microscale roughness. In Ref. [19], the surface morphology of a microchannel was rough with bulges and ridges. When multiple laser pulses were overlapped, the succeeding pulse exposed previously formed craters. Then, an interaction of light diffraction and a flow of molten material would cause the surface roughness [19]. The morphology of the chambers in our experiment was relatively smooth. The reason may be that the ablation occurred in water. Water generated a 'clean ablation' effect, which evidently reduced the debris redeposition and melt recast [20]. The access of water weakened the oxidation induced by ablation due to less oxygen contact. Furthermore, a high-pressure state produced smaller condensation particles that were easier to remove. And, the collapse of the bubbles was also helpful to further carry away the ablation debris. In our experiment, although the microstage was translated at a speed of 50 μm/s and several tens of pulses launched on one spot, the water assistance effectively improved the smoothness of the ablation interface.

3 Conclusion

In conclusion, we obtained combined structures consisting of microchambers and microtrenches inside silica glass by water-assisted ablation with femtosecond laser pulses. In this technique the sample was continuously moved under irradiation of a 1-kHz pulse train, which accelerated the drilling speed. The inner-wall morphology of the chamber was analyzed by a SEM. The improvement of wall roughness was attributed to the in-water ablation. This expedient and high-speed method facilitates the fabrication of microfluidic devices in biotechnology and micro-optics.

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