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Using femtosecond laser to fabricate highly precise interior three-dimensional microstructures in polymeric flow chip

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This paper reports using femtosecond laser marker to fabricate the three-dimensional interior microstructures in one closed flow channel of plastic substrate. Strip-like slots in the dimensions of 800 μm × 400 μm × 65 μm were ablated with pulse Ti:sapphire laser at 800 nm (pulse duration of ~120 fs with 1 kHz repetition rate) on acrylic slide. After ablation, defocused beams were used to finish the surface of microstructures. Having finally polished with sonication, the laser fabricated structures are highly precise with the arithmetic roughness of 1.5 and 4.5 nm. Fabricating such highly precise microstructures cannot be accomplished with nanosecond laser marking or other mechanical drilling methods. In addition, since laser ablation can directly engrave interior microstructures in one closed chip, glue smearing problems to damage molded microstructures possibly to occur during the chip sealing procedures can be avoided too. © *2010 American Institute of Physics.* [doi:10.1063/1.3504970]

I. INTRODUCTION

Polymeric materials offer versatile and low-cost advantages to fabricate and to prototype microstructures. In particular, poly(methyl methacrylate) (PMMA), an inexpensive polymer popularly used to make rugged components, is suitable to produce disposable sensing devices in clinical, biological, and chemical applications. Conventional microfabrication technologies such as laser ablation, mechanical machining, and molding have been successfully used in making polymeric microchannels. However, crafting interior structures with high precision is still problematic due to thermal effects inherent in machining processes and difficulties of direct three-dimensional fabrication.

Despite the fact that a large variety of polymeric materials can be machined with laser markers successfully, even using nanosecond UV laser, the involvement of the thermal process can lead to unwanted deviations from the optimum quality of the structure, i.e., the heat-affected zone will be several microns. Besides, heating effects in machining processes such as mechanical drilling and blasting have been found to alter the chemical and mechanical properties of substrates permanently. The generated heat during machining propagates for microns even when the fabricated area is limited to tens of microns or less. Having been flushed with fluids under pressure, the substrate materials in heated zones are gradually stripped to damage the device durability, especially for bioanalytical applications. Therefore, there remains a need to develop heating-suppressed micromachining technology to fabricate microfluidic chips.

Femtosecond laser ablation has effectively advanced a number of manufacturing techniques

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such as drilling, cutting, fabrication of complex patterns, and surface property modification.[1–3] Compared with nanosecond laser sources, femtosecond laser has lower ablation threshold and can much more spatially focus energy into the working substrate. Therefore, undesired thermal effects are diminished to obtain better-shaped structure.[3,4] Tightly spatial focusing of laser beam due to multiphoton absorption provides another advantage to fabricate structures inside the devices. Unlike injection molding technique only able to pattern features on the substrate slide,[5] chip sealing can be accomplished prior to fabrication processes to avoid the damages of patterned features due to thermal heating or glue smearing.

There have been many reports using femtosecond laser to fabricate waveguide devices on the surface or inside PMMA substrates with submicron features.[6–9] But less studies in this field have concentrated on machining of microstructures with high precision. In this paper, ultrashort pulse provided by near IR femtosecond laser is demonstrated as a powerful tool to directly fabricate precisely defined three-dimensional structures on the surfaces of a buried flow channel inside a chip device. Since PMMA has high transmissivity at the infrared wavelength, i.e., the energy of each photon at near IR range (~ 1.55 eV) is far below the PMMA band gap energy (~ 4.92 eV), the nonlinear multiphoton absorption only occurs at the focal point with high peak power intensity and can precisely confine the absorption regions, resulting in more precise fabrication of microstructures. More detailed explanations of the mechanisms of femtosecond laser micromachining of PMMA can be found in the papers.[10] Briefly, photochemical pyrolic reactions occurred upon UV illumination directly cleave the polymer backbone and the bond breakings propagate along the polymer chain to produce monomers.

During ablation process, a certain amount of pulse energy is required to remove the materials, and usually this energy leads to form raised ridges at the bottom of ablation area. These undesired defects will distort the dimensions of microstructures out of the expected range when ablation process is not well controlled. In this paper, we investigate how to use femtosecond laser ablation to directly fabricate microstructures with high precision on the work piece inside one closed microfluidic chip. These microstructures can be used as mixing components when external electric field is applied.[5] Besides, the size derivation of each microstructure out of the expected range is inspected using the images of scanning electron microscopy (SEM) of high resolutions.

II. METHODS

Femtosecond laser ablation with near IR wavelength (800 nm) source is employed to fabricate microstructures on PMMA substrates. These microstructures can be embedded into microfluidic chips as mixing elements to perform biochemical assays without contaminations stripped from damaged surfaces crafted with conventional machining techniques. The dimensional reproducibility of microstructure was examined with SEM.

A. Microfluidic chips preparation

The design of microfluidic chip components is shown in Fig. 1. This chip was composed of three pieces of industrial thermoplastic PMMA slides (thickness of 2 mm). We first used CO_2 laser engraver (Universal, V460) to mark the flow channels of Y-shape on the middle piece of PMMA slide and to drill three holes on the top slide. These channels and holes were engraved directly under high power without repetitive laser beam writing. Therefore, thermal damage on the surface was only limited. Finally these three slides were stationed with a clamping apparatus as a simulated sealed device to directly fabricate interior microstructures using femtosecond laser ablation marker.

B. Laser fabrication

The laser engraving on PMMA substrates was accomplished with a regenerative amplified mode-locked Ti:sapphire laser (Spectra Physics, Spitfire Pro) with a central wavelength of 800 nm, pulse duration of ~ 120 fs after the compressor, repetition rate of 1 kHz, and a maximum pulse energy of ~ 3.5 mJ. A schematic diagram of the femtosecond laser micromachining system is

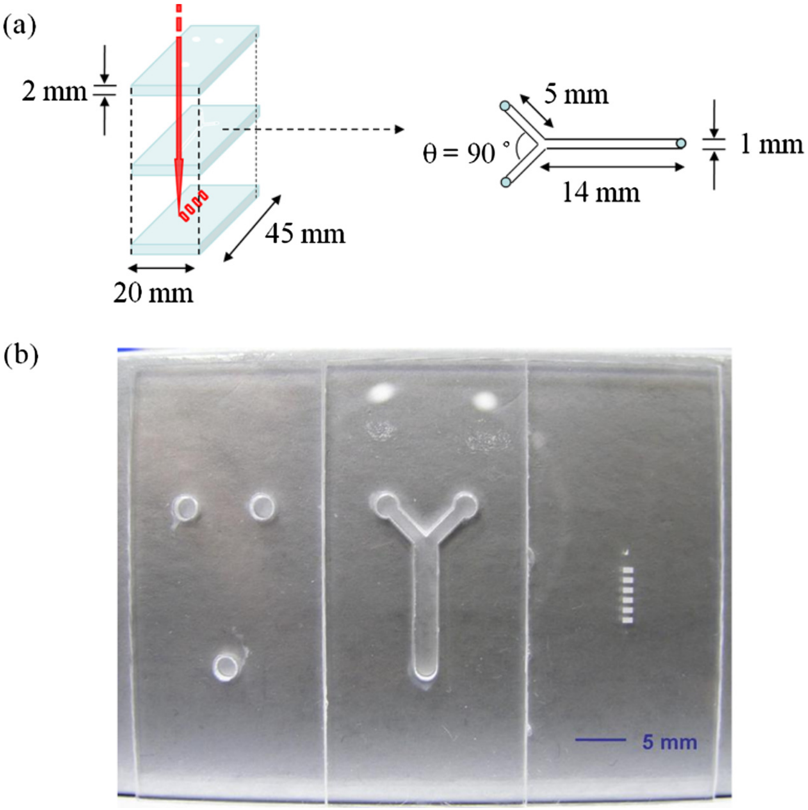

FIG. 1. (a) Schematic diagram of microfluidic chip containing microstructures. The red arrow represents the ablation beam femtosecond laser. As guided by a dashed arrow, the details of the Y-shape flow channel are shown in the side graph. (b) The images of top, middle, and bottom slides after ablation.

shown in Fig. 2. In order to adjust the pulse energy of a laser beam, a linearly polarized Gaussian laser beam was first attenuated by a rotatable half-wave plate and a polarization beam splitter. One portion of the laser beam was split off with a beam splitter and the deflected beam was directed into a power detector to measure the pulse energy of the laser beam. The transmission laser beam

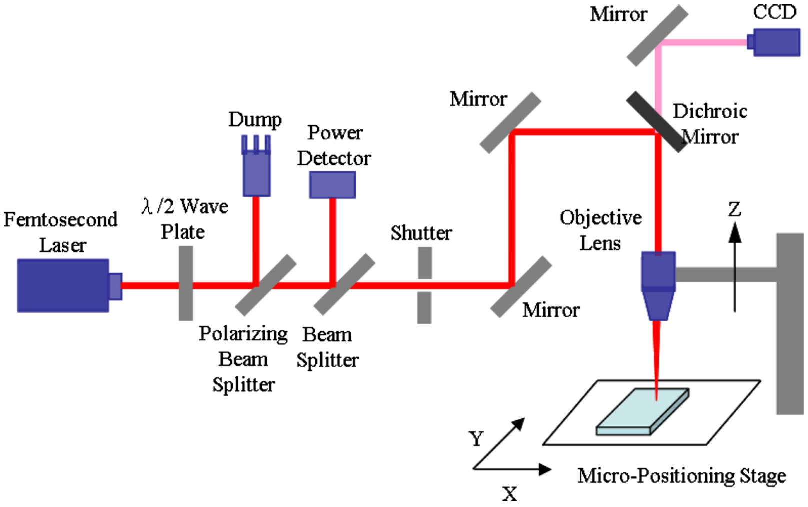

FIG. 2. Schematic diagram of a femtosecond laser micromachining system for fabrication of microstructures.

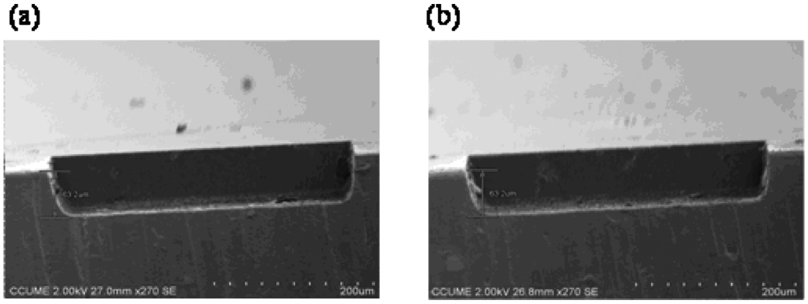

FIG. 3. SEM images of microstructure micromachined by femtosecond laser. (a) and (b) are two separate microstructures fabricated on the same PMMA slide.

was passed through a mechanical shutter and a series of reflective mirrors system. Finally, the transmission beam entered a 10X microscope objective lens (NA 0.26; Mitutoyo, M Plan Apo NIR) (NA denotes numerical aperture) mounted on a Z stage and was focused along the normal direction on the surface of the PMMA substrate of a microfluidic chip mounted on an X-Y stage. The focus spot size on the surface of the substrates is approximately 5 μm in diameter. Microstructures were fabricated by translating a PC-controlled X-Y stage with accuracy smaller than 1 μm and translating the laser focused position using a Z stage. One charge-coupled device camera was used to monitor the fabrication process.

To minimize the dust produced by laser ablation, a low laser fluence finishing method to fabricate microstructures ($800\ \mu\text{m} \times 400\ \mu\text{m} \times 65\ \mu\text{m}$) was therefore employed. Each microstructure was first created with 2 μJ pulse energy, repetition rate of 1 kHz, and pass overlap of 50% while stage moving rate was maintained at 0.5 mm/s. The crafted microstructure was covered with small debris dust particles stripped from the substrate when the ablation was finished. Next, the stage z-axis was raised for 10 μm to defocus the laser beam on the work piece under lower laser fluence and the stage moving rate was increased to 2 mm/s to resume the ablation on the microstructures for sweeping the dust which was left during the previous laser ablation step.

C. SEM image acquisition and surface roughness measurement

When the laser graving was accomplished, the microfluidic chip was immersed in an ultrasonic oscillation device for 1 h to remove the remnant dust particles. The bottom piece of PMMA slide was cut in two pieces to visualize the depth of microstructures. The microstructures were observed with SEM (Hitachi, S3400N) from side view (Fig. 3). Two separate microstructures look virtually identical, which has demonstrated the high precision capability of this ablation technique.

The arithmetic roughness (Ra) of PMMA slide was measured prior to fabrication processes. The center line of one slide along the long axis was divided in five segments. The Ra value of each segment ranges between 1.5 and 4.5 nm. The roughness measurements along the other two lines in the middle between the edges and the center line show similar results. The roughness of PMMA surface is negligible. The roughness of finished surface on the microfabricated structures was also measured. Along the long axis of each microstructure, the Ra value ranges between 120 and 250 nm, within the depth resolution of focused laser beam. There is no significant difference in Ra values between the long and short axes. The Ra value of finished surface is 0.3% or less of the microstructure height. High precision microfabrication in a closed flow channel directly crafted with femtosecond laser marker was accomplished.

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