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NOTE

Templateless prototyping of polydimethylsiloxane microfluidic structures using a pulsed CO_2 laser

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Abstract
We present a novel process (through cutting and pattern transfer processes) for rapidly prototyping polydimethylsiloxane (PDMS) microfluidic structures without a replication template using a CO_2 laser. The process typically takes less than 30 min to make a PDMS microfluidic chip from idea to device. In addition to time saving, the process also drastically cuts down equipment and operating costs by eliminating the use of masks, templates, wafer fabrication equipment and consumables needed in the template-making process. We further demonstrate the capability of the process in the rapid prototyping of a variety of microstructures from a 2 μm thin layer up to a 3.6 mm high structure on a single PDMS layer with accurate thickness control as well as smooth top and bottom surfaces. Various process characteristics and challenges for the PDMS laser prototyping process are addressed in this note.

1. Introduction

PDMS material is widely used to prototype microstructures for microfluidic and biological applications because of its low material and fabrication costs, compatibility with many biological and chemical reactions, and optical transparency and low autofluorescence [1–3]. However, most of the existing PDMS prototyping processes require a template to carry out soft lithography [4–7]. The template fabrication processes, such as photoresist lithography or silicon deep reactive ion etching (DRIE), are typically associated with long process time and high cost. Therefore, rapid and direct machining of PDMS microstructures is of importance in the areas of microfluidics and bio-MEMS.

Laser ablation of polymers has been used as a quick method to fabricate microfluidic chips, many of which use polymethyl methacrylate (PMMA) as the chip material since PMMA can form smooth and neat grooves by a CO_2 laser and PMMA sheets can be bonded together easily at an elevated temperature [8–10]. In addition, other laser sources, such as an Nd:YAG laser, UV-excimer laser and femtosecond-pulsed laser, and other materials, such as metal, Si, polycarbonate, wax and even adhesive types, have been used for fabricating chips or template/stamps for soft lithography [11–14]. For the PDMS material, Wolfe *et al* used a specialized Ti:sapphire laser to write patterns on a PDMS surface [14]. However, this technique can make only a shallow recess of within a few micrometres with a rough bottom over the surface of a PDMS layer. This limits its use in making a large number of microfluidic devices which are typically characterized by channels and chambers of dimensions from tens of micrometres to a few millimetres and with a smooth bottom.

We report a novel laser through-cutting and pattern transfer (TC&T) process to prototype PDMS microfluidic structures without a replication template using a CO_2 laser. The process significantly reduces the prototyping time and cost by eliminating masks, templates and the corresponding microfabrication processes, facilities and

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consumables required. The processing time is further reduced by using preformed PDMS sheets, which avoid hours of PDMS curing needed in replication processes. Using a commercial CO_2 laser system also helps to reduce the cost of fabrication facilities. With the TC&T process, we are able to form PDMS features with a depth of 2 μm up to 3.6 mm and with an aspect ratio above 10 when cutting a PDMS layer thicker than 1 mm. Furthermore, the process also allows us to achieve an accurate thickness control as well as smooth top and bottom surfaces on a microstructure. The smallest lateral feature size we prototyped is about 30 μm which is limited by the scanning resolution and spot size of the commercial laser system used by us. Such a lateral resolution is not as high as photolithography using expensive hard chromium masks. However, this limit is comparable to prototyping processes using printed transparency masks and adequate for many applications especially for microfluidics devices. Special problems associated with PDMS laser through-cutting such as debris and ashes are addressed and solved by parameter optimization. As an application, a bioreactor chip fabricated with this technique and its microfluidic performance are demonstrated.

2. Experimental details

It can be easily demonstrated that a CO_2 laser is able to cut into PDMS material to form a microchannel of a limited depth as a simple way to directly prototype a PDMS microstructure. However, we found few major drawbacks of making such a PDMS channel based on the above laser engraving method. First, when a multiple scan (raster scan) is used to fabricate channels wider than those achievable by a single scan, the bottom surface of the channel is rough. Second, it is difficult to keep the channel depth uniform, especially when we make shallow channels (e.g. less than 10 μm) and when there is a cross or T-junction in the channel system, no matter whether the laser is pulsed or continuous, raster scanned or single scanned [10]. To resolve these problems, we developed the TC&T process which incorporates a flat acrylic substrate underneath the PDMS layer. With the TC&T process, the channel bottom is smooth and the channel depth can be as shallow and accurate as a PDMS layer thickness can reach, e.g. a few micrometres.

The TC&T process starts from the preparation of a PDMS layer according to the desired thickness of the microstructure, e.g. the depth of a microchannel. Figure 1(*a*) shows that a PDMS layer with a thickness ranging from below 2 μm to a few millimetres is formed on a 2 mm thick acrylic sheet (with a size of 50 mm × 75 mm which was laser cut to form a commercial cast acrylic sheet) by spin coating or volume-controlled casting of a PDMS prepolymer (10:1 parts A and B of Dow Corning Sylgard 184, fully mixed and then degassed in vacuum), followed by curing on a levelled surface in an oven at 80 °C for 2 h. The PDMS layer is then cut using a commercial CO_2 laser marker (VersaLaser VLS 2.30 from Universal Laser System Inc. with a 30 W CO_2 laser source and a high power density focusing optic (HPDFO) lens assembly) using vector patterns designed with CorelDraw software. A

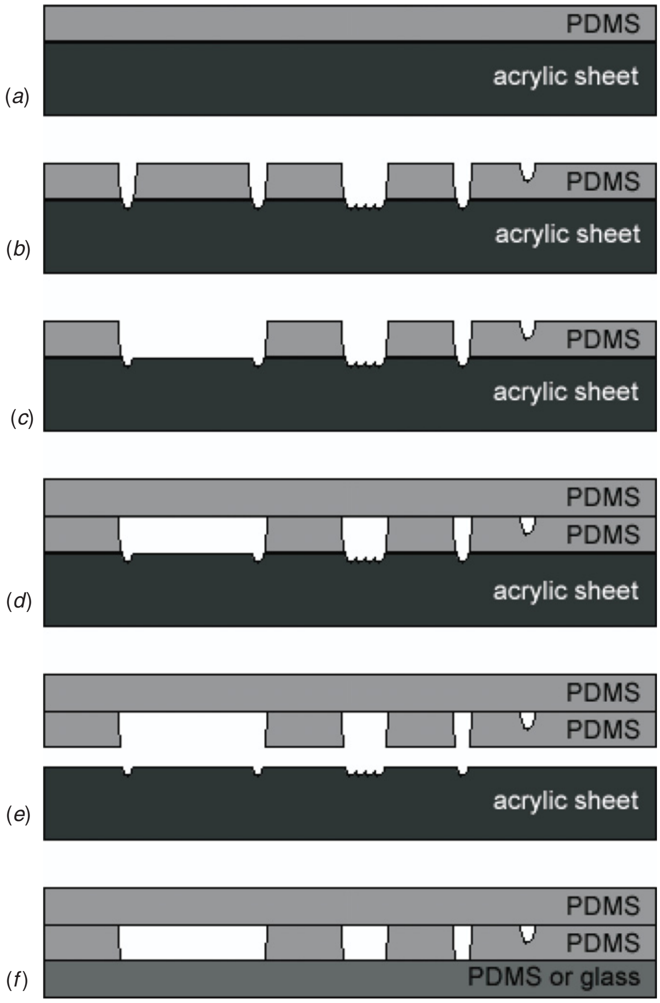

Figure 1. TC&T process for templateless fabrication of PDMS microchannels. (*a*) PDMS sheet preparation with a controlled thickness by spin coating (for layer thickness below 130 μm) or volume-controlled casting (for layer thickness above 130 μm) on an acrylic substrate. (*b*) Through-cutting of the PDMS layer by a CO_2 laser. (*c*) Peeling off the unwanted region of the PDMS layer. (*d*) Bonding to a flat PDMS sheet. (*e*) Releasing the PDMS structure from the acrylic substrate. (*f*) Transferring and bonding the PDMS structure to the PDMS or glass layer to form a closed channel.

releasable PDMS pattern is formed when the laser power is set to a suitable level for the laser to cut through the PDMS layer and form a shallow groove on the acrylic surface, as shown in figure 1(*b*).

Few different cutting strategies can be applied to remove unwanted PDMS regions. For example, only the contour of a channel is cut by the laser and the unwanted part of the PDMS layer is peeled off from the acrylic substrate using a tweezer, as shown in the left of figure 1(*c*). Alternatively, the unwanted region can be ablated away by the laser using a raster mode (see the channel in the middle of figure 1(*b*)). The narrowest channel is formed by a single laser scan, which can result in a channel width as narrow as 30 μm depending on the cutting depth. To transfer the patterned PDMS layer, another layer of the PDMS is bonded on top of it (figure 1(*d*)) to separate it from the acrylic substrate and bonded onto another layer of the

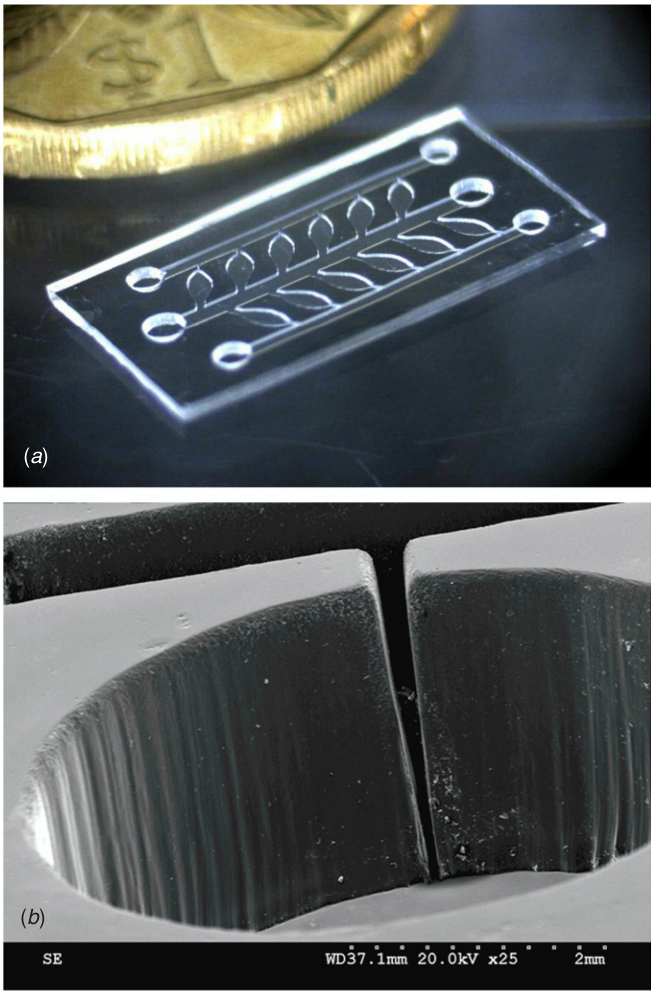

Figure 2. (*a*) A photo of a capillarity-driven microfluidic microreactor array fabricated using the TC&T process. A one Singapore dollar coin is placed beside the chips for size comparison. (*b*) An SEM image of a high aspect ratio channel and a PDMS chamber with a height of 2.5 mm for cell study.

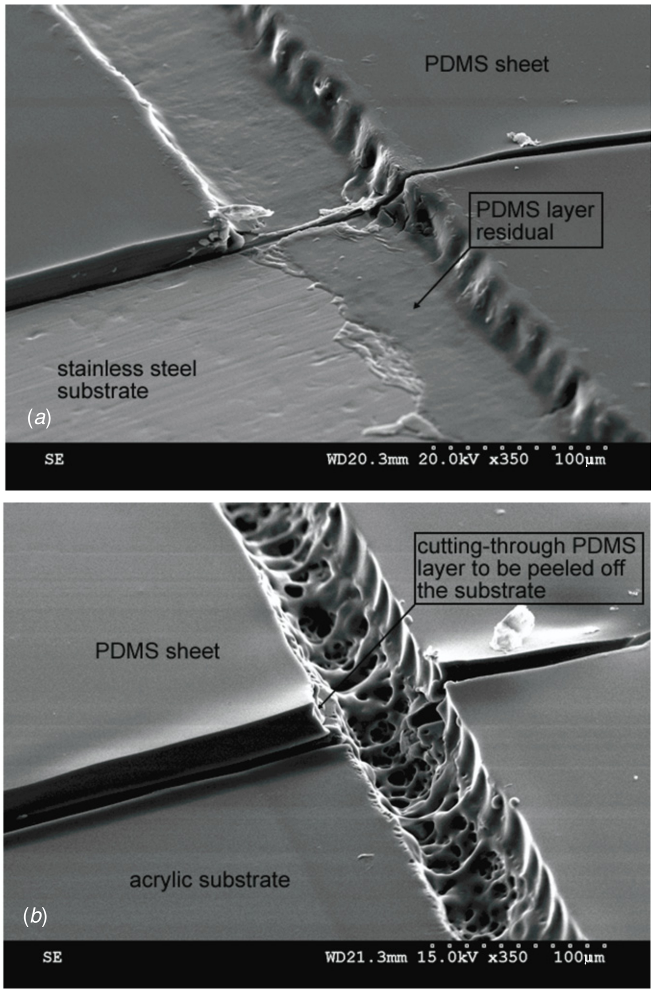

Figure 3. Cutting a 22 μm PDMS sheet on substrates made of different materials. The PDMS layer on the bottom left was knife cut and removed. (*a*) On a stainless steel substrate, the PDMS layer cannot be cut through totally even with large laser power, leaving a thin layer of the PDMS residual on the substrate. (*b*) On an acrylic substrate, the laser can cut through the PDMS layer, leaving a groove over the acrylic surface.

PDMS or glass to form a closed microchannel (figures 1(*e*), (*f*)).

Figure 2(*a*) shows a capillarity-driven microfluidic reactor array fabricated by using this technique. The middle PDMS layer with a thickness of 100 μm was laser patterned to form an array of leaf-shaped microchambers, a stem channel (800 μm wide and 100 μm high) to supply a liquid sample into the leaf chambers and two air venting channels (500 μm wide and 100 μm high) on both sides of the chip. At the tip of each leaf chamber, there is a microchannel (60 μm wide and 100 μm high) acting as a capillary passive valve connected to the air venting channels. The top and bottom layers are made of a 300 μm thick PDMS sheet, and few liquid access holes are also cut on the top PDMS layer. The microfluidic performance of the chip is discussed in section 3.7. The capability of making ultra-high PDMS microstructures with a high aspect ratio using this technique is shown in figure 2(*b*), in which a chip structure containing cell culture chambers and microfluidic channels were fabricated by laser cutting a 2.5 mm thick PDMS sheet.

3. Results and discussion

3.1. Choice of the substrate material

A critical requirement of the substrate material is that the PDMS layer can be easily peeled off from the substrate after cutting. Glass slides or silicon wafers are not suitable since they form strong bonding with the cured PDMS layer. We tested metal sheets made of aluminium and stainless steel since a PDMS layer can be released easily from the metals. However, we found that the PDMS layer cannot be totally cut through on the metal substrates. A thin PDMS residual layer with a thickness of 2–4 μm remained on the metal surface even when the laser power was increased (figure 3(*a*)).

Acrylic sheets are used as a substrate for the PDMS cutting in this work. First, the cured PDMS can be easily peeled off from the acrylic surface. Second, the laser is able to cut into the underneath acrylic sheet surface to form a groove to break the

PDMS layer (figure 3(*b*)). The groove formed on the acrylic surface does not influence the patterned PDMS layer since the PDMS will be peeled off from the acrylic substrate. Moreover, acrylic sheets are cheap and disposable.

3.2. Preparation of PDMS sheets with different thicknesses

PDMS sheets with different thicknesses can be prepared by spin coating or volume-controlled casting of the PDMS prepolymer on acrylic sheets, and then curing at 80 °C for 2 h. The thicknesses of a PDMS layer ranging from 1.5 μm to 130 μm can be achieved by varying the spin coating speed or time [4]. For example, spinning at 650 rpm for 1 min results in a PDMS prepolymer layer with a thickness of about 100 μm, while spinning at 10 000 rpm for 5 min results in a thickness of 2 μm. An even thinner PDMS layer can be reached by spin coating using a diluted PDMS prepolymer with toluene (e.g. 0.5 μm by ten times the dilution and spin at 1500 rpm for 1 min), as reported by Wu *et al* [15]. PDMS sheets with thickness larger than 130 μm are simply formed by volume-controlled casting of the PDMS prepolymer on a levelled acrylic surface. For example, 1 ml of the PDMS prepolymer spreading on a 10 cm^2 levelled substrate surface with an enclosure results in a 1 mm thick PDMS sheet.

3.3. Cutting ability of a CO_2 laser on PDMS material

The CO_2 laser system we used is equipped with a 30 W laser source and a HPDFO lens. The HPDFO lens is able to generate a laser spot of 0.001″ or 25 μm in diameter, which allows us to make a 30 μm wide groove on a PDMS sheet at a low laser energy level. The laser head is RF excited with an internal tickle, and a built-in interlock and can be operated from CW to their maximum optical modulation frequency (pulse rate) of 5 kHz. The RF power supply operates at a frequency of about 40 MHz. An external TTL signal is used for optical modulation. There are three parameters controlling the laser cutting in the machine: the laser power, the scan speed of the lens head mounted on an *XY* stage and the laser pulse resolution named as pulses per inch (PPI). The PPI or proportional pulse control (PPC) of the laser machine allows an operator to define spacing between the laser pulses for optimized cut penetration or smoothness of cut regardless of the scan speed. The highest resolution provided in the laser machine is 1000 PPI (∼40 pulses per mm). The other two parameters, the speed and the power, work in coordination to determine the cutting depth.

Different combinations of the power, the speed and the PPI have been tested on PDMS material. By varying the speed and the power, we are able to engrave the PDMS at a depth from 17 μm to 3.6 mm in a single scan, as shown in figure 4(*a*). We noted that there is a maximum cutting depth of 3.6 mm on the PDMS, which is much larger than those made by other microfabrication methods such as an SU-8 thick photoresist and DRIE. Figure 4(*b*) shows the effect of the scan speed on the cutting profile, in which the scan speeds of 1.0–5.0% of the full speed (about 0.25 m s^{-1}) were used for stable lens head movement and acceptable cutting speed. Figure 4(*c*) shows

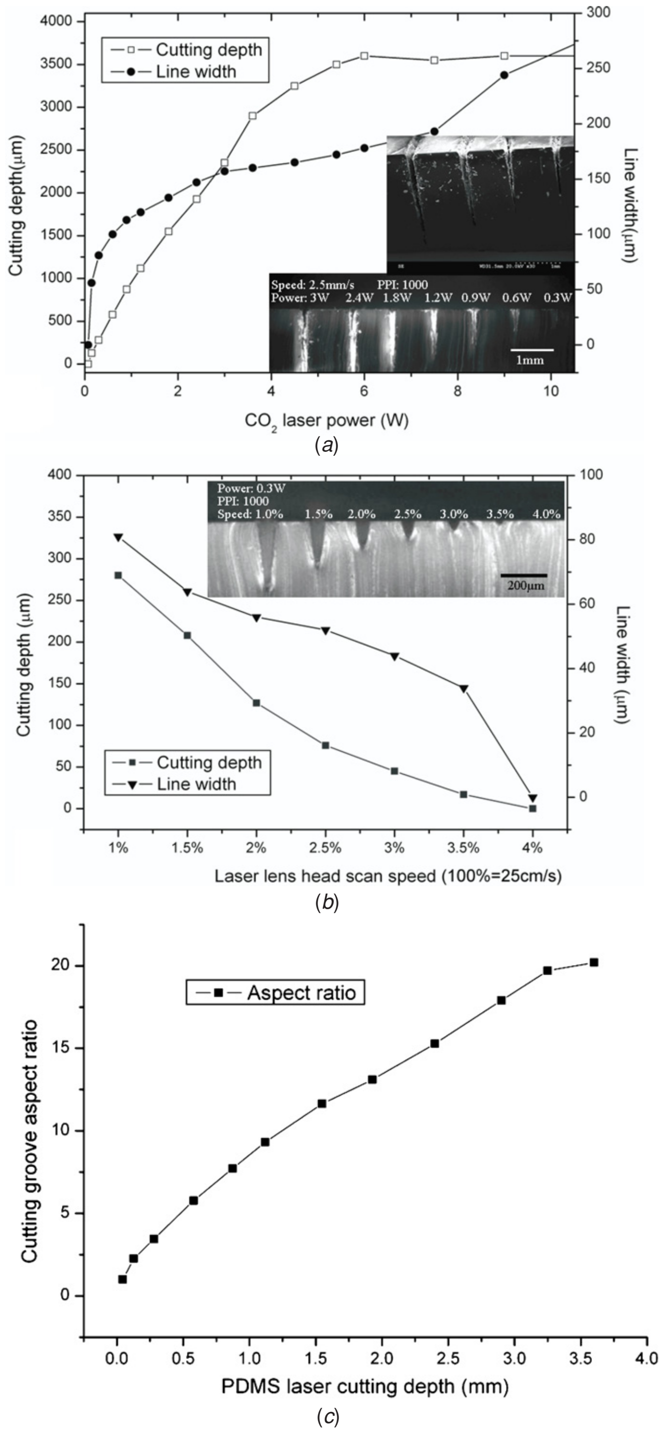

Figure 4. Geometric profiles of the grooves on PDMS material engraved by a pulsed CO_2 laser using different cutting parameters. (*a*) Cutting depth and width versus laser power, with the lens head speed fixed at 1% (2.5 mm s^{-1}) and the resolution at 1000 PPI (∼40 pulses per mm). The white colour over the grooves in the inset photo shows the white ashes generated during laser cutting when the cutting depth exceeds 700 μm. (*b*) Cutting depth and width versus lens head scan speed, with the laser power fixed at 1% (0.3 W) and resolution at 1000 PPI. (*c*) Aspect ratios of the grooves achieved at different cutting depths.

that a groove aspect ratio as high as 20 can be achieved on the PDMS sheet.

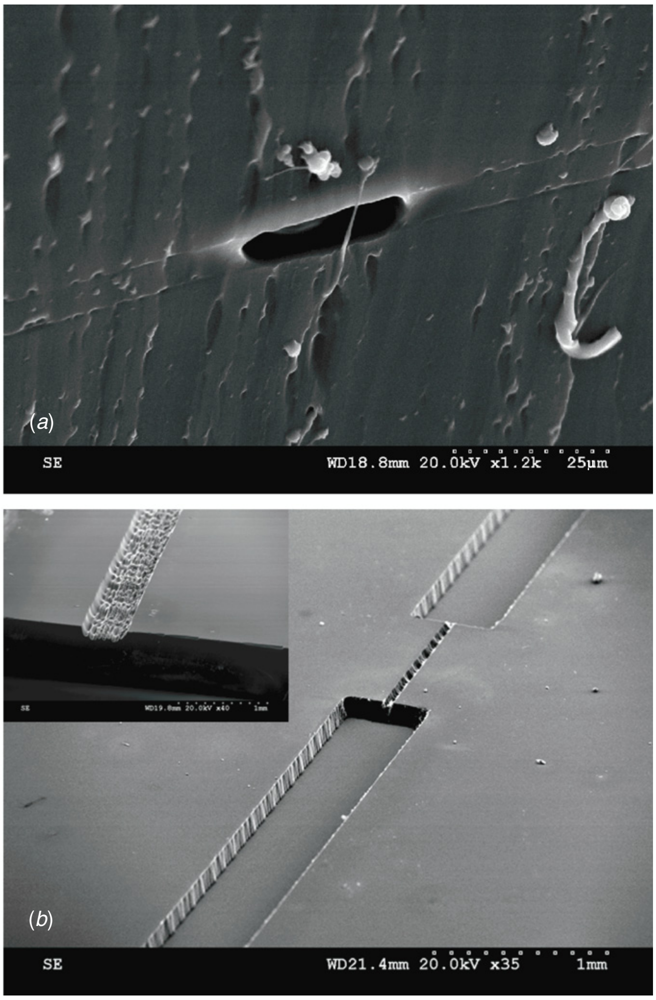

Figure 5. (*a*) Cross-sectional view of a PDMS microchannel with a height of 7 μm which is controllable by forming a PDMS layer of the same thickness for laser through-cutting. (*b*) Channels with different widths and depths formed by a combined use of the through-cutting and the blind-engraving techniques. The wide channel has a smoother bottom when compared with the channel bottom formed by the raster scan (the inset).

3.4. Channel forming by the TC&T process

The TC&T process shown in figure 1 is capable of achieving small feature height (figure 5(*a*)) and smooth top and bottom channel surfaces when compared with the simple process of raster scan blind engraving, as shown in the upper left corner of figure 5(*b*). The depth of a channel formed by the TC&T method is determined by the thickness of the preformed PDMS sheet, which can be precisely controlled and can be made very small. Figure 5(*a*) shows a cross-sectional view of a channel formed by cutting a 7 μm thick PDMS sheet and bonding with upper and lower PDMS layers using an adhesive. The corners of the channel are rounded due to slight reflow of the adhesive [4]. Furthermore, combined use of the through cutting and blind engraving can form a more complex microfluidic channel system with different channel depths on a single PDMS sheet (figure 5(*b*)).

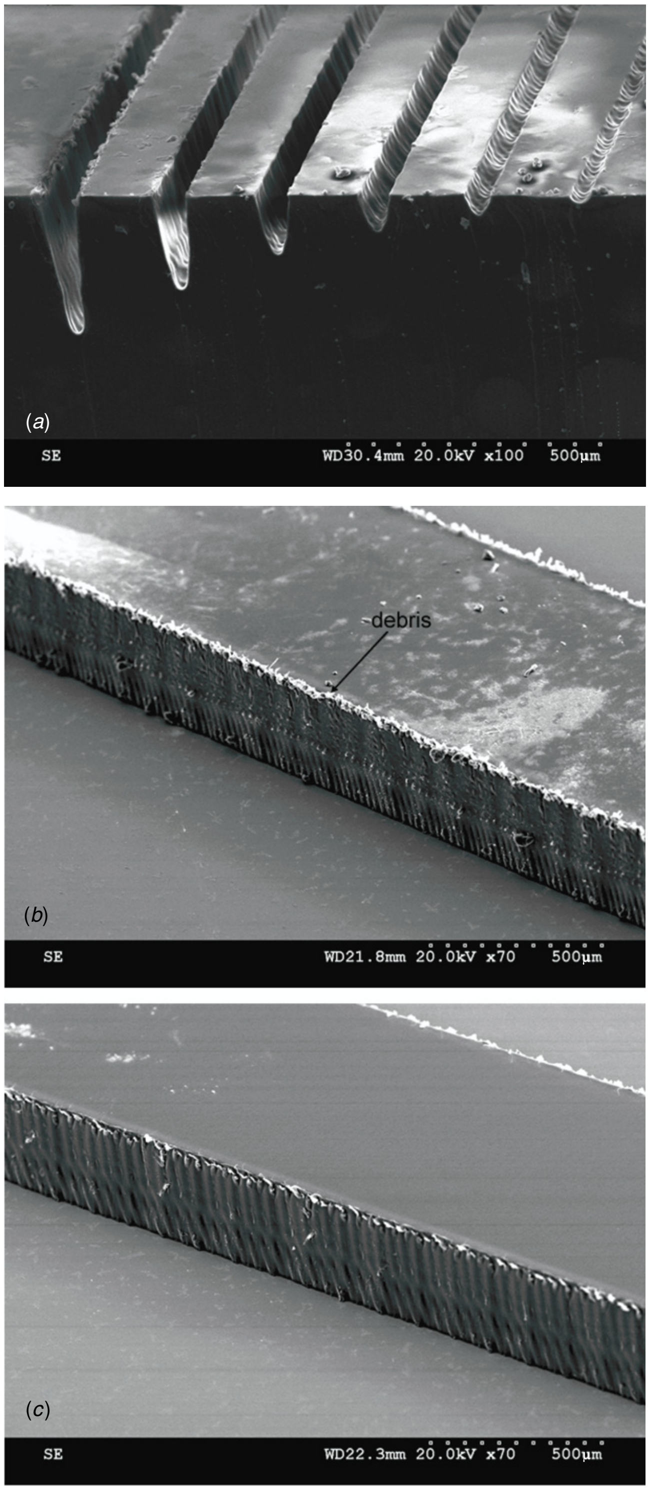

Figure 6. (*a*) At 1000 PPI, the sidewall is neat and clean when cutting the PDMS with a depth smaller than 200 μm and a line width of above 60 μm. (*b*) Debris appeared on the upper corner when cutting through a 300 μm thick PDMS sheet at 1000 PPI. (*c*) When reducing the resolution to 600 PPI (~24 pulses per mm), the 300 μm thick PDMS was cut through with little debris.

3.5. Rapid PDMS bonding for releasing a patterned PDMS layer

We need to adopt a rapid PDMS bonding method to make the entire TC&T process rapid. There exist several techniques to

Table 1. CO_2 laser cutting parameters for PDMS sheets.

PDMS sheet thickness	Laser power	Speed setting	Measured scanning speed	Resolution setting (pulses per inch)	Pulse frequency (pulses per second, or Hz)	Line width (μm)	Remarks
20 μm and below	0.3 W	3%	7.5 mm s^{-1}	1000	300	45	Higher PPI to reduce sidewall roughness
50 μm	0.3 W	2.4%	6.0 mm s^{-1}	1000	240	53	
100 μm	0.3 W	1.8%	4.5 mm s^{-1}	1000	180	60	
150 μm	0.3 W	1.4%	3.5 mm s^{-1}	1000	140	68	
300 μm	0.6 W	1.2%	3.0 mm s^{-1}	600	72	90	Lower PPI to reduce debris
700 μm	0.9 W	1%	2.5 mm s^{-1}	300	30	113	Lower PPI to suppress debris and ashes
1.5 mm	2.1 W	1%	2.5 mm s^{-1}	300	30	127	

bond the PDMS with the PDMS or glass to carry out steps (*d*)–(*f*) shown in figure 1. A widely adopted method is the O_2 plasma treatment of the PDMS surface for permanent bonding [16]. A lower cost alternative is the corona discharge treatment [17]. A side effect of the above methods is the change of hydrophobicity of the PDMS surface which may influence the fluidic properties of a chip, even though this side effect might be utilized in some cases. The PDMS can also be bonded with the PDMS or glass using a thin layer of the PDMS prepolymer as an adhesive followed by curing at an elevated temperature [4, 15], which can be accomplished in 5 min at 120 °C. Such a bonding method has the advantage of smoothing the bonding corner due to reflow of the PDMS adhesive. The thickness of the adhesive layer (PDMS prepolymer) is controlled to 1–4 μm by spin-coating speed because the reflow of the adhesive may also block narrow channels if the adhesive layer is relatively thick. Another bonding method utilizing the property that two PDMS layers made using different mixing ratios of the polymer base and curing agent can bond together naturally can also be used [1]. All the above methods have been tested to be able to form bonding that is strong enough to release the patterned PDMS layer from the acrylic substrate.

3.6. Surface quality of the PDMS channel sidewall and optimization of the through-cutting parameters

We noted that the sidewalls of the PDMS microstructure formed by the pulsed CO_2 laser are not as smooth as the channel bottom as shown in figure 5(*b*). Generally, they generate only negligible disturbance to the laminar flow field in a microchannel. When higher smoothness of a channel is wanted, the reflow of a extra amount of the adhesive (PDMS prepolymer) can be used to round the bonding corner and to smooth the sidewall by cladding a thin PDMS layer on it [4].

Despite the above observation, a smooth and neat sidewall after laser cutting is still an advantage. We found that the surface roughness of the sidewall is dependent on the scanning resolution (the PPI setting) and the dot size (or the line width as shown in figure 4) formed on the PDMS which is determined by a combination of the laser power and the scanning speed. We found that the resolution at the highest 1000 PPI is suitable for cutting a PDMS sheet thinner than 200 μm with a line width of above 60 μm. Within such an optimal cutting zone, the sidewall is neat and clean, with an average roughness of about 0.8 μm (figure 6(*a*)). However, at 1000 PPI when the PDMS sheet is thicker than 200 μm, debris appears at the upper corner of the groove due to higher laser energy being required (see figure 6(*b*)). When further increasing the laser energy to cut a thicker PDMS sheet (e.g. 700 μm thick or above), white ashes may form over the sidewall (see figure 4(*a*)). The ashes and debris can be wiped away by a tissue wetted with isopropanol. However, such a cleaning process is generally inconvenient. By reducing the PPI, which results in a marginal increase in the surface roughness, the debris and ashes can be largely reduced (figure 6(*c*)). The other case outside the optimal zone is that when the line width required is below 60 μm, as shown on the 30 μm wide channel on the right of figure 6(*a*), the sidewall roughness increases a bit due to the 25 μm laser spot movement pitch at 1000 PPI which is the resolution limit of the machine. The minimum line width and the sidewall roughness can be further reduced by a few means including modifying the laser machine to a higher PPI, improving the focusing lens and using other types of lasers with a shorter wavelength.

Based on the above discussion, we optimized the operation parameters for the pulsed CO_2 laser for cutting PDMS sheets with different thicknesses, as listed in table 1. Table 1 can be used as a guideline when operating other pulsed CO_2 laser systems.

3.7. Microfluidic test

The chip shown in figure 2(*a*) was tested for its ability to load the sample and isolate reactors all by capillary action. A water solution was used to demonstrate the distribution of a sample liquid into the leaf-shaped microreactors. The sample liquid contains 0.1% of xylene cyanole to render the liquid blue for better visualization and 0.1% of Triton X-100 to adjust its contact angle to 46° on the PDMS surface. When a drop of the sample liquid (about 4 μl) was added to the inlet access hole (figure 7(*a*)), the liquid flowed into the leaf reactors through the stem channel under capillary forces. The liquid flow stopped at the passive valves (60 μm wide) at the tips of the leaf reactors

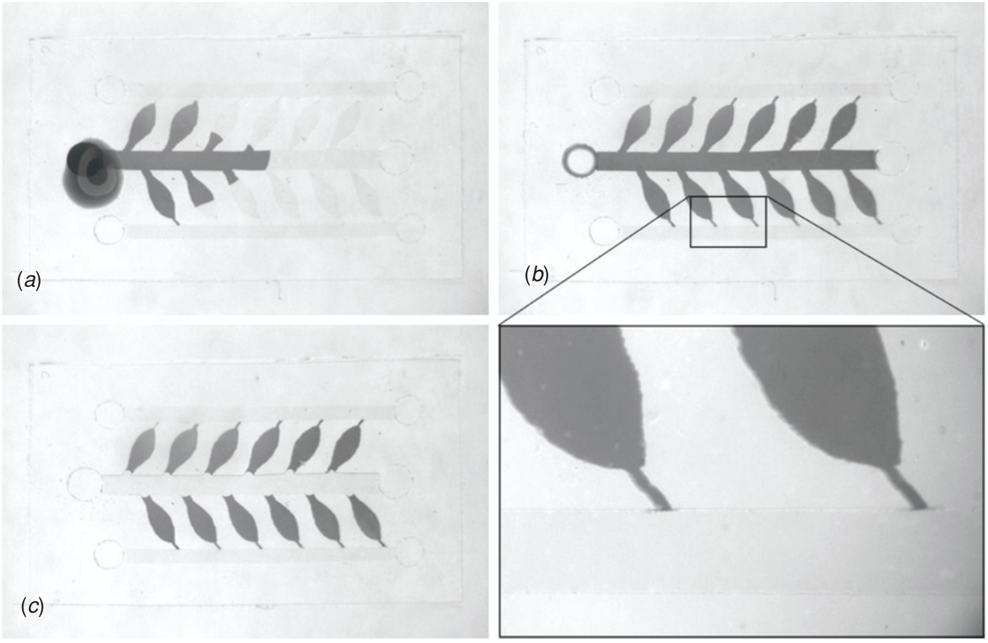

Figure 7. Microfluidic test using the PDMS chip fabricated by a pulsed CO_2 laser. (*a*) Liquid loading process. (*b*) Liquid retained in the leaf reactors without leaking to the air venting channels due to confinement of the narrow openings of the passive valves. (*c*) Liquid remained inside the leaf reactors after removing the liquid in the stem channel by an absorbent.

after filling of the reactors (figure 7(*b*)). Liquid in the stem channel is then removed by an absorbent without dragging out the liquid inside the reactors to create an array of isolated reactors (figure 7(*c*)).

4. Conclusions

We have developed a method for the templateless formation of a PDMS microfluidic structure by using a CO_2 laser, which has the merits of short prototyping time below 30 min from concept to final device. The cost of application is low since it eliminates the need of steps such as the fabrication of masks and PDMS replication templates, as well as corresponding microfabrication equipments and processes as in the conventional PDMS replication method. We have also shown the flexibility of this method to make a microfluidic structure of variable cavity depths. Furthermore, if applying the TC&T process to multiple layers of the PDMS, even a 3D microfluidic system can be made rapidly. With this method, we are able to form microchannels with a depth of only 2 μm up to 3.6 mm, characterized with accurate topography thickness control, with smooth top and bottom surfaces. As a conclusion, this quick and low cost method can be widely used for the fabrication of the PDMS microstructure in many applications where the lateral feature size is not so critical.

Acknowledgment

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