

Application of metal film protection to microfluidic chip fabrication using CO₂ laser ablation

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Abstract The CO₂ laser ablation is a common technique for patterning the microchannels and holes used in microfluidic devices. However, the ablation process frequently results in an accumulation of resolidified material around the rims of the ablated features and a clogging of the base of the microchannel. In the article, these problems are resolved by means of a proposed metal-film-protected CO₂ laser ablation technique. In the approach, the substrate is patterned with a thin metallic mask prior to the ablation process and the mask is then stripped away once the ablation process is complete. The feasibility of the proposed approach is demonstrated by fabricating two micromixers with Y-shaped and T-shaped microchannels, respectively. It shows that for a designed channel width of 100 μm, the metallic mask reduces the ablated channel width from 268 to 103 μm. Moreover, the bulge height around the rims of the channel is reduced from 8.3 to <0.2 μm. Finally, the metallic mask also prevents clogging in the intersection regions of the two devices. The experimental mixing results obtained using red and green pigment dyes confirm the practical feasibility of the proposed approach.

1 Introduction

Using a laser technique to fabricate a microfluidic channel is a faster alternative compared to conventional techniques

by combining photolithography process with polymer casting (Chung and Shih 2007; Liang et al. 2010) or hot embossing (Peng et al. 2010; Gerlach et al. 2002) or injection moulding (Reotting et al. 2002) or photo-patterning (Huikko et al. 2003) in terms of rapid prototyping. PMMA is a common choice for the fabrication of biomedical devices because of its optical transparency, ease of fabrication, biocompatibility and low cost. Chen et al. (2008) discussed various methods for the fabrication of PMMA microfluidic chips and the CO₂ laser ablation is particularly attractive due to its versatility, low-cost and fast speed (Jensen et al. 2003; Chung and Lin 2011). However, the heat generated during the ablation process results in a large temperature gradient, which leads to the formation of bulges around the rim of the ablated feature, clogging of the microchannels and a large heat affected zone (HAZ). Cheng et al. (2004) showed that the surface quality of the channels ablated in PMMA substrates can be improved by performing a thermal annealing treatment after the laser ablation process. Huang et al. (2010) reported that a smooth surface can be obtained by preheating the PMMA substrate and immersing the substrate in water during the ablation process. Wang et al. (2011) removed the bulge formed at the rim of a microchannel ablated in PMMA using a wet chemical etching technique. In this article, an effective metal-film-protection method is proposed for PMMA microchannel fabrication via CO₂ laser ablation. In the approach, we used the through-patterned metal layer put on the PMMA and then performed laser ablation. The patterned metallic layer was used as a mask during a laser ablation process in order to produce the required microchannel configuration in the substrate. The feasibility of the proposed approach is demonstrated by patterned two PMMA substrates with a Y-shaped and T-shaped microchannel, respectively. The ablated channel widths are then compared with those of

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two channels prepared without a metal mask. In addition, the bulge height around the rim of the two channels is also compared with that of two channels prepared directly in air. Finally, a series of mixing trials are demonstrated using red and green pigments as samples.

2 Experimental procedures

The ablation experiments were performed using a commercially available air-cooled CO₂ laser system (VL-200, Universal Laser system Inc., USA) with a maximum laser power of 30 W, a central wavelength of 10.6 μm, and a maximum scanning speed of 1,140 mm/s. The focal length of the lens was about 38.1 mm and the smallest beam spot size was approximately 76 μm which is defined as the double distance from the center of Gaussian intensity distribution to that with 1/e² maximum intensity. The Gaussian laser beam focusing on the plane surface is assumed to maintain a constant TEM₀₀ mode. The PMMA is commercial molding compound type (CM-207, CHIMEI Inc., Taiwan) of which material properties listed in Table 1. The metal mask film was fabricated from SUS-304 stainless steel foil of 0.03 mm thick in wet etching solution of FeCl₃ to form the through-etched mask patterns with the feature of various channel widths of 50–100 μm. Then the metal film is directly put on PMMA and simply fixed with thermal-resistant tape. A (x,y,z) positioning stages is used for scanning the laser over the sample surface. During ablation, the CO₂ laser source moves along x-direction or y-direction and a part of laser energy through the metal foil irradiates on PMMA to ablate the microchannel. Finally the foil mask is removed to get the required microstructure. In this study, the widths of the Y-channel and T-channel were both specified as 100 μm. A constant laser power selected from 1.5 to 5 W was performed at a scanning speed from 34.2 to 228 mm/s in order to create a wide-shallow channel which is suitable for microfluidic devices. In both cases, the channels were formed in a one-step scanning pass. The morphology and profile of the laser ablated PMMA microchannels (with and without the metal mask) were examined by an optical microscope (OM, OLYMPUS BX51M, Japan), and α-step profiler (Kosaka Lab, ET3000, Japan), together with a desktop scanning electron microscope (SEM,

Phenom G2 Pro, Netherlands). The performance of the resulting Y-channel and T-channel micromixers was then evaluated by means of simple mixing experiments. A series of mixing experiments were performed using red and blue pigment solutions. Two pigment solutions were injected into the inlets, and at junction of two inlets channels pigment solution began mixing. Finally, the purple solution can be obtained at the outlet.

3 Results and discussion

Figure 1a, b shows the SEM micrograph and alpha-step profile of the Y-shaped PMMA microchannel formed by CO₂ laser ablation in air with 1.5 W at a scanning speed from 34.2 mm/s. In Fig. 1a, an obstacle in the close-up of the channel's clogging area which may cause the

Table 1 Material properties of commercial PMMA sheet

Material	PMMA
Density (kg/m ³)	1,200
Specific heat (J/kg K)	1,400
Thermal conductivity (W/m K)	0.193
Absorption coefficient (cm ⁻¹)	502 (for 2,800–25,000 nm)

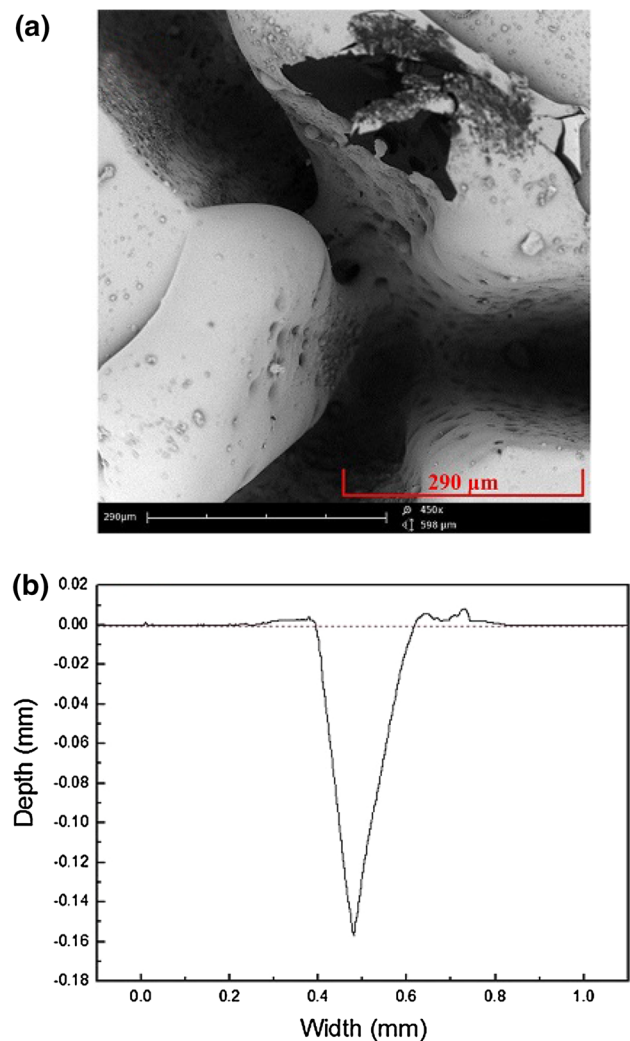


Fig. 1 a The optical micrograph and b alpha-step profile of the PMMA Y-shape microchannel by direct CO₂ laser processing in air

fluid unable to flow is formed at the base of the channel in the intersection region due to resolidification of the molten PMMA. In addition, Fig. 1b shows that a large bulge is formed on the surface of the substrate at the rim of the channel as a result of resolidification of the PMMA splashed out of the microchannel during the ablation process. (In practice, the laser source has a Gaussian distribution, and thus an accumulation of resolidified material also occurs on the walls of the channel near the channel opening, as shown in Fig. 2a). From inspection, the channel

width is about 268 μm while the bulge height is 8.6 μm . Similar observations were obtained for the T-shaped microchannel (note that the results are deliberately omitted for reasons of brevity).

In order to resolve the clogging phenomenon in the intersection region of the channel and the bulge effect around the rim of the ablated channel, the ablation process was repeated using the proposed metal-film-protected CO₂ laser ablation technique (see Fig. 2b). In practice, the SUS-304 stainless steel film serves a number of important

Fig. 2 Schematic flow charts of CO₂ laser ablation on PMMA: **a** directly in air, **b** assisted with metal film

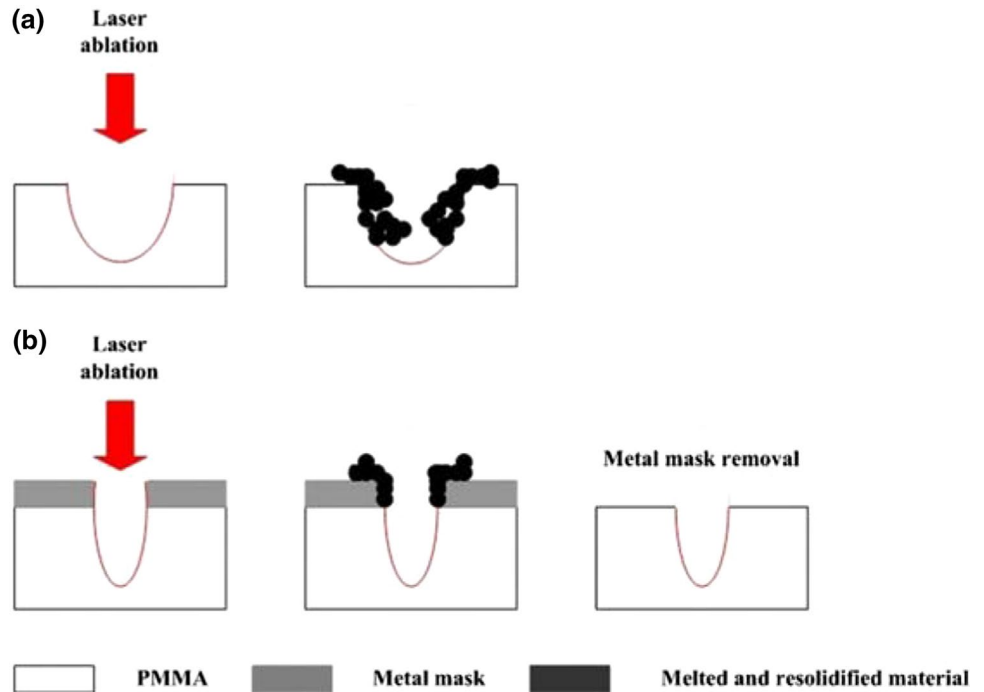
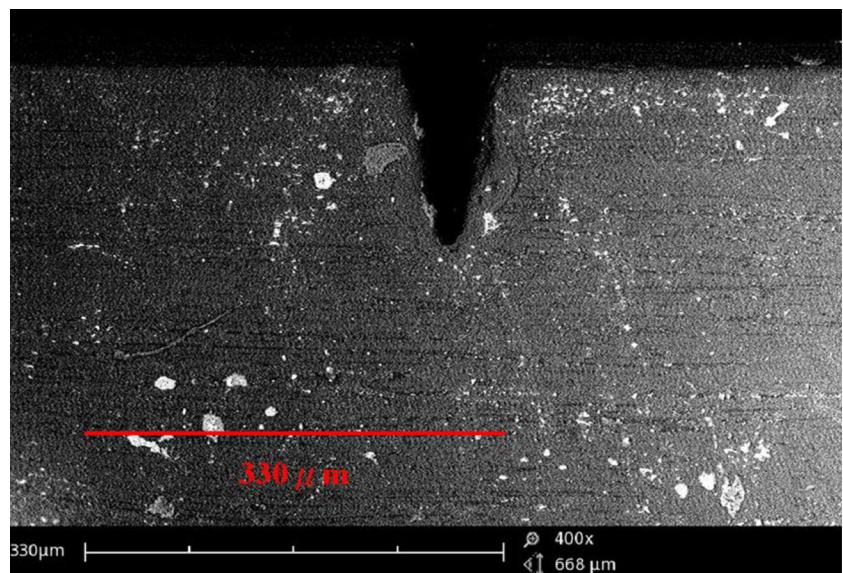


Fig. 3 SEM image of the cross-section profile of a cross-shape channel on the PMMA substrate ablated using metal-film-protection method. It evidences the merit and mechanism of metal-film-protection method



purposes, namely (1) a physical mask which may limit the channel width to a width less than the focal spot size, (2) a physical shield which prevents bulge formation around the rim of the ablated channel when it is etched away, and (3) a thermal conductor which transfers the heat away from the ablated channel and therefore prevents the formation of a large heat affected zone around the channel. Figure 3 show the SEM image of the cross-section profile of a cross-shape channel on the PMMA substrate ablated using metal-film-protection method to evidence the merit and mechanism of metal-film-protection method.

Figure 4a, b presents OM micrographs of the Y-shaped and T-shaped PMMA microchannels, respectively, formed using the proposed metal-film-protected CO₂ laser process. The intersection regions of the two channels are both free of resolidification structures (obstacles) due to the more rapid removal of the laser-induced heat by the metallic film. Furthermore, both channels have a width of approximately 103 μm . In addition, as shown in Fig. 4c, the bulge-like feature at the rim of the ablated channel has a height of just about 0.2 μm . In other words, the effectiveness of the proposed method in resolving the clogging and bulge problems associated with the traditional ablation process performed directly in air is confirmed. The formation of some metallic droplets may occur at the channel edges. It could be attributed to the laser heat effect on foil edge for few molten metal resolidification. This phenomenon sometimes happens at the channel edge but less at the channel bottom. Also, it could be eliminated by thick foil film or lower laser beam energy. It is found that the laser generated microfluidic channels in Fig. 4b could have different channel widths. The deviation of having different channel widths may be attributed to the loose contact of simply fixing the metal foil on PMMA at the T-junction and the uneven distribution of laser energy during ablation. It could be improved by smoothening foil and pressuring for close contact at the T-junction together with stabilizing laser output energy.

The practical feasibility of the proposed method was confirmed by injecting a solution of low-viscosity deionized water mixed with 0.1 wt% Rhodamine B into the Y-shaped and T-shaped micromixers. The fluorescence microscope images shown in Fig. 5 (acquired once the two channels were completely filled with solution) showed that both channels were completely filled and free of leaks. It indicates the absence of obstacles in the intersection regions and confirms the removal of the vertical bulge-like features on the top of the patterned substrates. The metal film can employ the central laser energy to ablate the PMMA substrate at a short time and reflect or block the surplus laser energy on the masked area. In addition, it can conduct the residual heat via high-conductivity metal film and eliminate the defects during ablation. So in proof of this theory, using

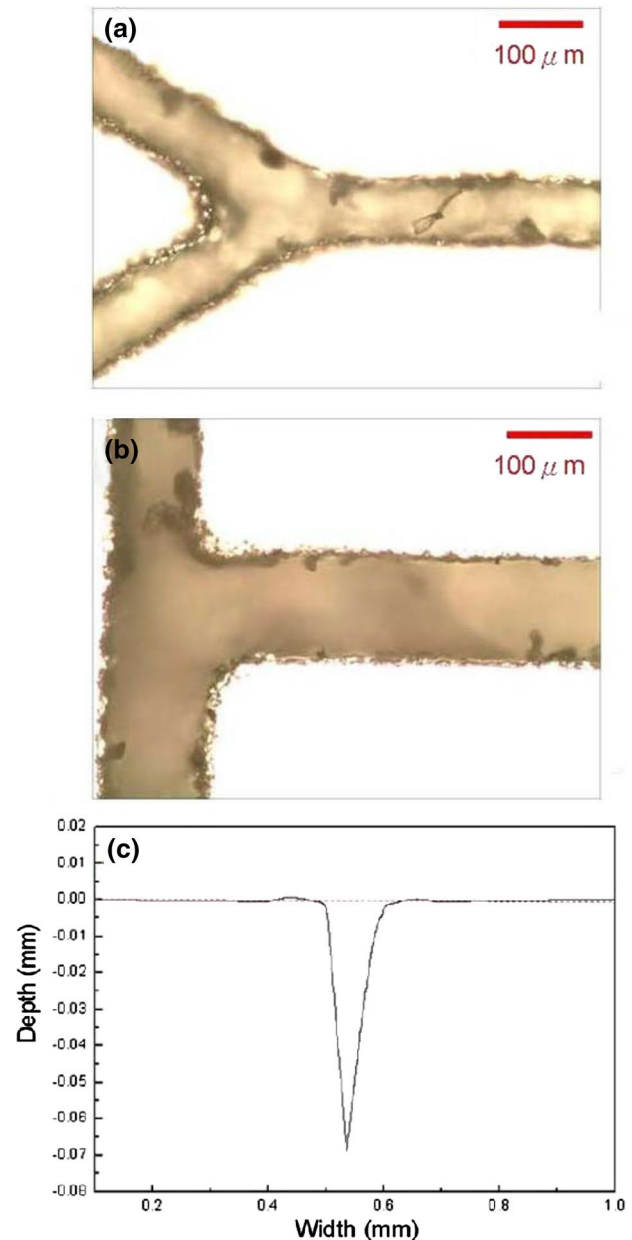


Fig. 4 The optical micrograph of **a** Y-channel and **b** T-channel width of 100 μm and **c** alpha-step profile of PMMA microchannels using CO₂ laser ablation with metal-film-protection method

metal mask can be effective to prevent melted resolidified material, from series of dye trials.

Finally, a series of mixing experiments was performed using red and blue pigment solutions. Two pigments of red and blue solution were injected via inlets into the channels, and at junction of two channels pigment solution follow to mix. The mixing result of purple solution via color change can be obtained from the outlet. Figure 6a, b shows the experimental images of the mixing results in the mixing channels ablated directly in air and using the proposed

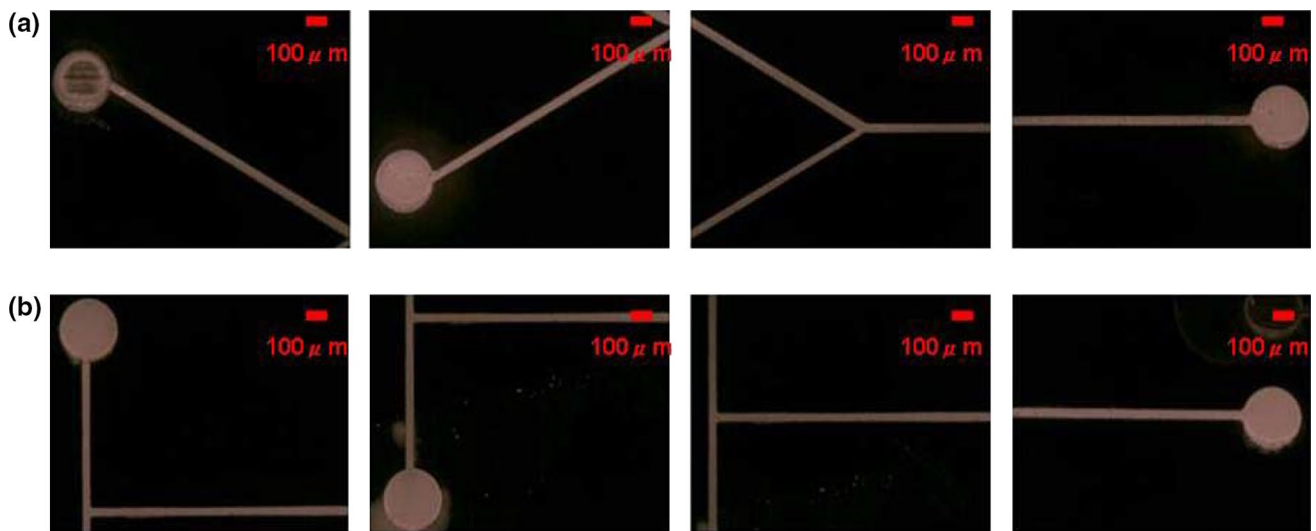
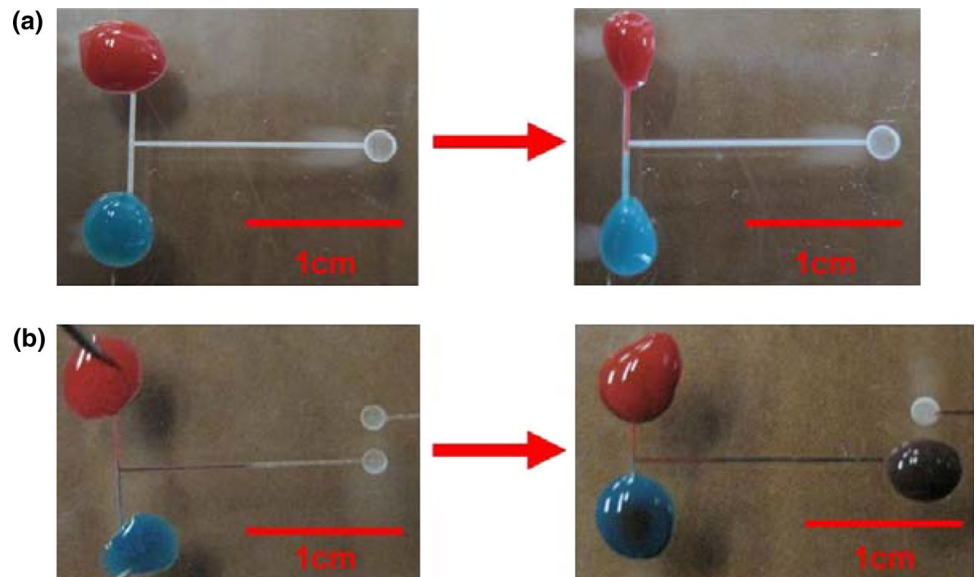


Fig. 5 An example of PMMA microfluidic device using Rhodamine B to dye flow test: **a** Y-channel, **b** T-channel with an inlet

Fig. 6 T-channel of PMMA microfluidic device using pigment to dye mixing test: **a** directly in air, **b** assisted with metal film



metal-film-protected method, respectively. In Fig. 6a, an incomplete mixing of the two species occurs as a result of the obstacles in the intersection region which is from the resolidified material clogging during ablation on PMMA in air at the junction. By contrast, in Fig. 6b, an efficient mixing of the red and green pigments occurs. In other words, the results confirm the effectiveness of the proposed mask in limiting the resolidification of molten PMMA in the base of the microchannel. The mixing channel using CO₂ laser ablation with metal mask can effectively solve traditionally resolidified block because metal mask cut off laser heat affected zone. Compared to the photolithography, CO₂ laser can be quick and inexpensive fabrication on mixing channel.

4 Conclusion

A simple effective approach called metal-film-protection CO₂ laser processing has been demonstrated for the fabrication of PMMA by reducing the feature size and minimizing bulges, resolidification, and clogging phenomena. It has been shown that for Y-shaped and T-shaped microchannels with a design width of 100 μm, the ablated channel width is reduced from 268 μm when using no mask to around 103 μm when using a mask. In addition, the bulge height is reduced from around 8.6 μm to just about 0.2 μm. Finally, it has been shown the two ablated microchannels are used to perform a series of dye mixing trials using two pigments (red and blue) solution as samples. We successes in two

pigments solutions mixing, and can obtain purple solution after mixing. Overall, the results shows that the proposed metal-film-protection CO₂ laser process provides a rapid, low-cost and extremely effective means of fabricating micromixers and potential for other microfluidic devices.

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