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Ultrafast laser manufacturing of glass microfluidic devices

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Abstract

Microfluidic devices can be manufactured from a variety of materials, such as glass, plastics, photoresist or silicon. In many cases, glass is preferred to the other materials, in particular when a microfluidic device must sustain high pressures, be fully transparent, and remain chemically inert to injected fluids. Unfortunately, conventional manufacturing of glass microfluidic devices is a complex, time-consuming, multi-step process that involves the combination of photolithography, etching and bonding. In this paper, we present a different approach for the fabrication of glass microfluidic devices. Here, a picosecond laser is the only tool used to manufacture the entire microfluidic device. It is used for: (i) drilling the inlet/outlet ports, (ii) generating a microfluidic pattern directly on the glass surface, and (iii) enclosing a microfluidic pattern by welding the glass cover. The whole manufacturing process can be completed within 2 hours, making this method suitable for rapid prototyping of fully-functional microfluidic devices.

Keywords: Microfluidic devices; ultrafast lasers; laser ablation; laser welding; glass;

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1. Introduction

Microfluidic devices are used in many industrial and research areas, for instance, biology, medicine, pharmacology, chemistry, geochemistry and petroleum engineering research (Whitesides, 2006; Sackmann et al., 2014; Faustino et al., 2016; Leester-Schädel et al., 2016). These devices usually contain an enclosed

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network of channels whose transverse dimensions range from submicron to few millimeters. Microfluidic devices are typically made of transparent materials, such as poly-di-methyl-siloxane (PDMS), poly-methyl-methacrylate (PMMA), polylactic acid (PLA), cyclic olefin copolymer (COC) or glass. These materials provide optical access to the microfluidic pattern, enabling direct observation and investigation of various physical, biological and chemical processes during the flow of fluids.

Of these materials, glass offers a unique combination of optical, mechanical, thermal, electrical and chemical properties. Its high transparency, hardness, thermal stability, electric insulation, chemical inertness to many fluids, and high resistance to acids means that it is often preferred to the other transparent materials for the fabrication of microfluidic devices. Unfortunately, conventional manufacturing of glass microfluidic devices is a complex, multi-step process that involves different fabrication techniques and tools, as shown in Fig. 1(a), hence is time consuming and expensive in particular for the manufacture of microfluidic devices in low quantities. Microfluidic patterns on glass substrates are typically generated by chemical etching or reactive ion etching (RIE). These processes require the use of bespoke projection masks, which must be designed and fabricated prior to the etching process, dangerous chemicals (e.g. hydrofluoric acid), expensive RF plasma generators and special gases (Iliescu et al., 2012).

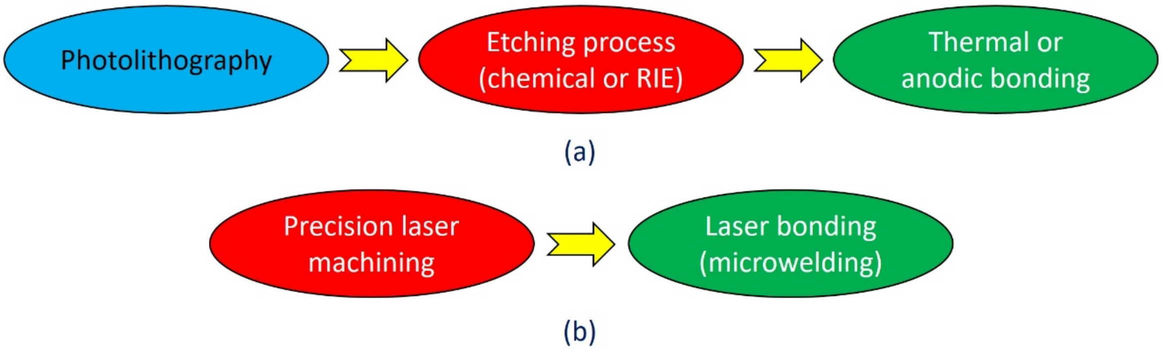

Fig. 1. (a) Conventional manufacturing of glass microfluidic devices; (b) Our laser-based technique developed for the manufacture of glass microfluidic devices.

In this paper, we demonstrate a laser-based process that enables the manufacture of glass microfluidic devices without using any additional tools. The laser is used for: (i) the generation of microfluidic patterns and inlet/outlet ports (by direct laser ablation of glass substrates) and (ii) the bonding of the glass plates (by laser microwelding), as illustrated in Fig. 1(b). The devices are manufactured using 1.1mm thick plates made of borosilicate glass called Borofloat®33 (SCHOTT AG).

2. Fabrication details

The glass microfluidic devices presented in this paper have been entirely manufactured by using a 50W picosecond laser (TRUMPF TruMicro 5x50). The laser provides approximately 6ps pulses (as measured at Full Width Half Maximum) with a pulse repetition frequency (PRF) of up to 400kHz, and wavelength of either 1030nm, 515nm or 343nm.

The microfluidic patterns are laser-machined into the surface of one glass plate, whilst through holes (for inlet/outlet ports) are laser-machined through the second glass plate, in both cases using the second harmonic wavelength (λ = 515nm). The laser beam is delivered to the glass substrate via a galvo scanner and a 163mm focal length F-theta lens, as shown in Figure 2. In this configuration, the laser spot in the focus has a diameter of approximately 22µm, as measured at $1/e^2$ of its maximum intensity.

The laser-generated microfluidic patterns are closed from the top by using the second glass plate that includes the inlet/outlet ports. To achieve successful enclosure of the microfluidic patterns, both glass plates must be cleaned from debris and dust. Following the cleaning process, they are placed one on top of the other, and then pressed against each other to obtain optical contact. To achieve permanent bonding between the two glass plates, laser welding is performed using the setup shown in Figure 2, using the 1030nm wavelength. The laser beam is focused to a tiny spot (diameter of approximately 3µm) using a 10mm focal length aspheric lens. The laser spot is focused approximately 100µm below the glass-glass interface. This enables the generation of weld seams in both glass plates across the interface, providing a permanent bond around a microfluidic pattern.

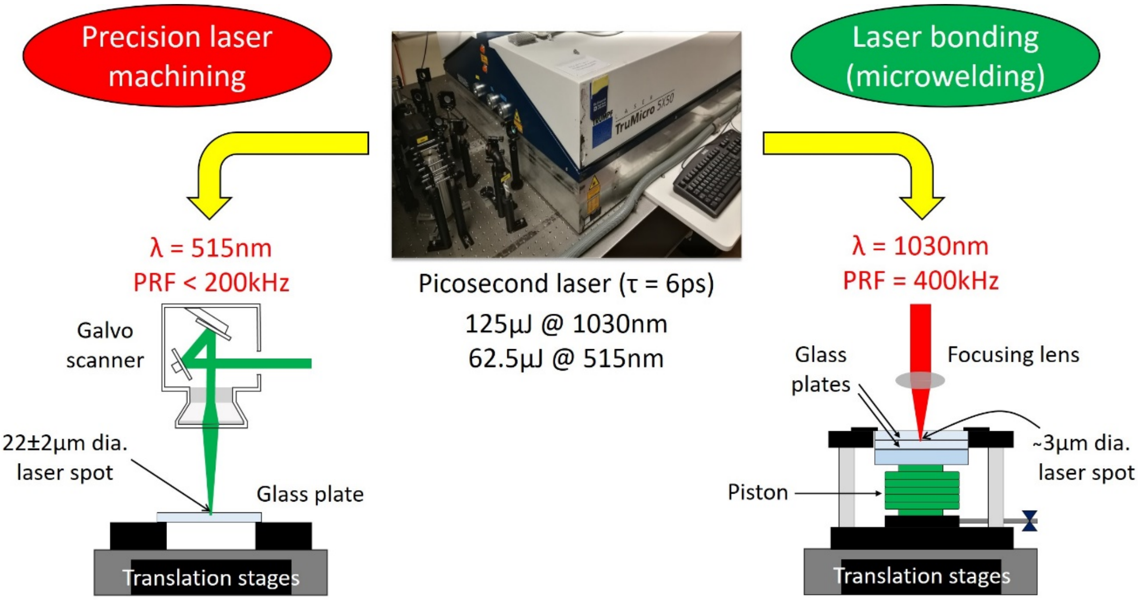

Fig. 2. Picosecond laser-based system used for the manufacturing of microfluidic devices from glass substrates.

3. Results

Our laser-based process enables the rapid manufacturing of bespoke glass microfluidic devices. Two selected examples of the devices are shown in Fig. 3. Both of these were fabricated using two 75mm long, 25mm wide and 1.1mm thick borosilicate glass plates. The microfluidic pattern shown in Fig. 3(a) comprises two inlet/outlet channels, two triangular buffers (reservoirs), and nine straight channels. The channels have the same length (20mm), the same depth (25µm), but different widths (either 0.05mm, 0.1mm or 0.2mm). The weld seams were generated around the microfluidic pattern, and can be seen in Fig. 3(a) as thin parallel lines. A distance between the lines is 0.25mm (near the pattern) and 0.5mm (further away from the pattern).

Our fabrication technique also allows us to embed 3D objects inside the microfluidic patterns. Fig. 3(b) shows a microfluidic device that comprises a 7mm diameter paper disc. The paper has a thickness of 175µm, and was used as a proxy in order to see whether the laser welding process may cause any thermal damage to the embedded objects. As can be seen in Fig. 3(b), the paper disc was unharmed by the laser beam. This means that small 3D objects (e.g. pieces of minerals, miniature sensors) can be embedded into the microfluidic devices and used as reactive agents or sensing elements to measure in-vivo the dynamic parameters, such as pressure or pH, during the flow of various fluids.

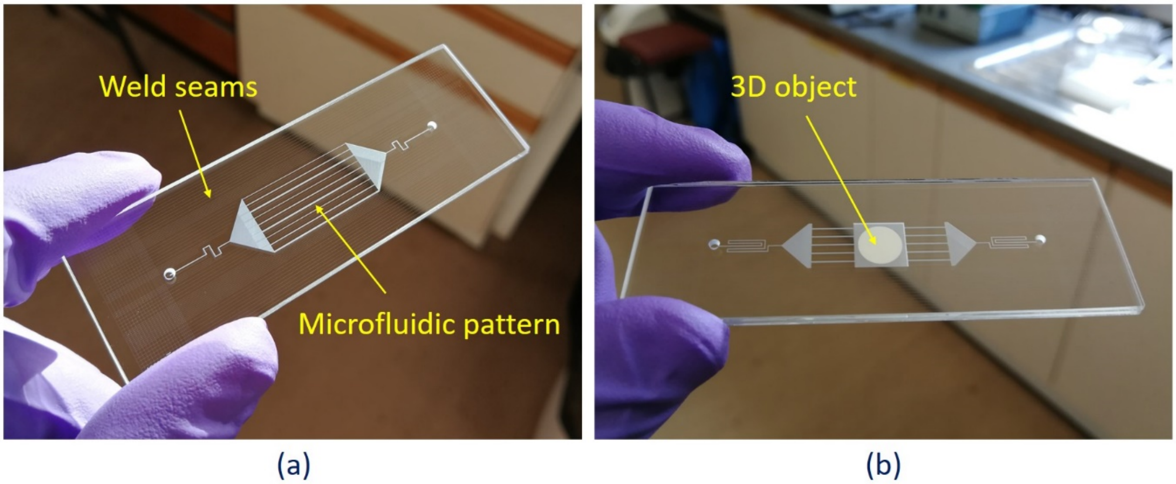

Fig. 3. Examples of the laser-manufactured microfluidic devices comprising: (a) pattern with a set of 9 straight channels of different widths (0.05mm, 0.1mm and 0.2mm); (b) 3D object (a 7mm diameter paper disc) embedded into the microfluidic pattern.

The laser-manufactured microfluidic devices are fully watertight and no leakage was observed even at injection pressures as high as 1.5 bar. As shown in Fig. 4, an injected fluid (water) flows only inside the microfluidic pattern. This image was taken during a spontaneous imbibition test.

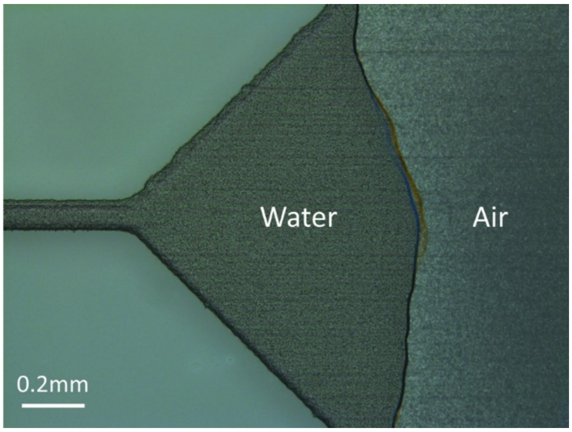

Fig. 4. Snapshot of the flow of water inside the triangular buffer during a spontaneous imbibition test.

4. Conclusions

This paper describes and demonstrates a laser-based method for the fabrication of various microfluidic devices from glass substrates, which is an attractive alternative to the time-consuming conventional manufacturing methods. Our fabrication technique uses a single tool (laser) and does not require the use of any projection masks, dangerous chemicals (e.g. HF acid), RF plasma generators, and cleanroom facilities. The method provides flexibility in the prototyping of glass microfluidic devices, and significantly reduces the time for their fabrication. Currently, we are able to manufacture fully-functional microfluidic devices in less than a couple of hours.

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