Microchannel fabrication in PMMA based on localized heating using high-repetition rate femtosecond pulses

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ABSTRACT

Femtosecond laser pulses with energy of 0.9 nJ per pulse and a 80 MHz repetition rate at a wavelength of 750 nm were used to fabricate straight microchannels in a PMMA substrate. The size and shape of the microchannels can be controlled by changing the fabrication parameters of speed, the number of fabrication repeats and delay in-between fabrication repeats. It has been proposed that the absorption of energy in the focal region modifies the density of the polymer matrix, which after annealing the sample above the glass transition temperature results in the formation of the microchannels. Diffusion of heat through the substrate is a uniform process which has the effect of creating symmetrically shaped channels. This fabrication method is expected to have applications in the fabrication of microstructures or microfluidic devices in polymer substrates.

Keywords: Microfabrication, femtosecond, microchannels

1. INTRODUCTION

Micro-structures fabricated in dielectrics using femtosecond lasers have gained momentum recently due to the benefits associated with multiphoton excitation. When femtosecond laser pulses are focused within the volume of a substrate, nonlinear excitation can lead to physical processes such as avalanche ionization, plasma formation and micro-explosions. Considerable research has been conducted into the effects of micro-machining or micro-structuring of transparent materials based on micro-explosions[1-3]. Based on these nonlinear processes a range of applications have been investigated, including three-dimensional optical data storage[5], fabrication of optical waveguides[6], micro-structuring of optical components[7-9] and fabrication of microchannels[10, 11]. The fabrication of microchannels in dielectrics for the development of complex three-dimensional microfluidic devices has also been thoroughly investigated[7, 10, 12-14]. In all those applications regeneratively amplified femtosecond pulsed lasers producing μJ to mJ per pulse were used to overcome the optical breakdown threshold of the substrate, typically glass or fused silica.

Using polymers as substrates have advantages over their glass counterparts as their properties are more easily tailored for specific applications and they are cheaper and easier to manufacture. One of the advantages of polymers is their lower threshold for optical breakdown, which can be reached using non-amplified nJ femtosecond pulses. There has also been substantial research conducted on the different applications involving fabrication by femtosecond pulses in polymers, such as three-dimensional optical data storage[15] and fabrication of photonic band gap structures[16, 17]. The significant benefit from using regeneratively amplified pulsed laser systems is the ability to overcome the breakdown threshold with a single femtosecond pulse, thereby reducing any possible side effects due to heating. However, amplified lasers systems typically have repetition rates in the kHz, which could limit the machining speed whereas the non-amplified systems have repetition rates up to MHz.

Here we present a study of the physical characteristics of microchannels fabricated in a water-immersed poly(methyl methacrylate) (PMMA) substrate under high repetition rate, nanojoule, femtosecond laser pulses. Using transmission optical microscopy we investigated the dependence of the channel properties on different fabrication parameters. Based on the fabrication method demonstrated in this paper cylindrical microchannels can be fabricated in PMMA with diameters ranging from 8 μm to 20 μm.

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2. EXPERIMENTAL SETUP

The experimental setup used in the channel fabrication experiments is illustrated in Figure 1. A SpectraPhysics Tsunami femtosecond pulse laser producing 80 fs pulses at a repetition rate of 80 MHz was used as the fabrication laser. The per pulse energy in the experiments was maintained at 0.9 nJ, which is below the energy threshold required to ablate PMMA. The laser beam was focused into the sample with a long working distance, water immersion objective with numerical aperture 0.9 (Olympus, LUMPlanFL/IR). The objective is designed to be immersed in water and as such has no built-in cover-slip correction. The PMMA samples were commercial blocks of PMMA which have been cut and polished, then mounted in a glass dish filled with de-ionized water. As the fabrication takes place within the volume of the sample the spherical aberrations introduced from the mismatch in refractive indices between the immersion medium and the sample need to be compensated. In order to reduce the spherical aberrations the samples were immersed in water which has the effect of reducing the mismatch in the refractive indices and using an objective designed to be immersed in water without cover-slip corrections. The sample was mounted on x-y stepper motor translation stages, with the objective mounted on the z axis stepper motor translation stage. The fabrication process was monitored via a CCD camera positioned behind the objective lens, allowing for the viewing of the x-y plane. In the experiment, fabrication of the microchannels was in the x-y plane at a depth of approximately 75 μm below the sample surface.

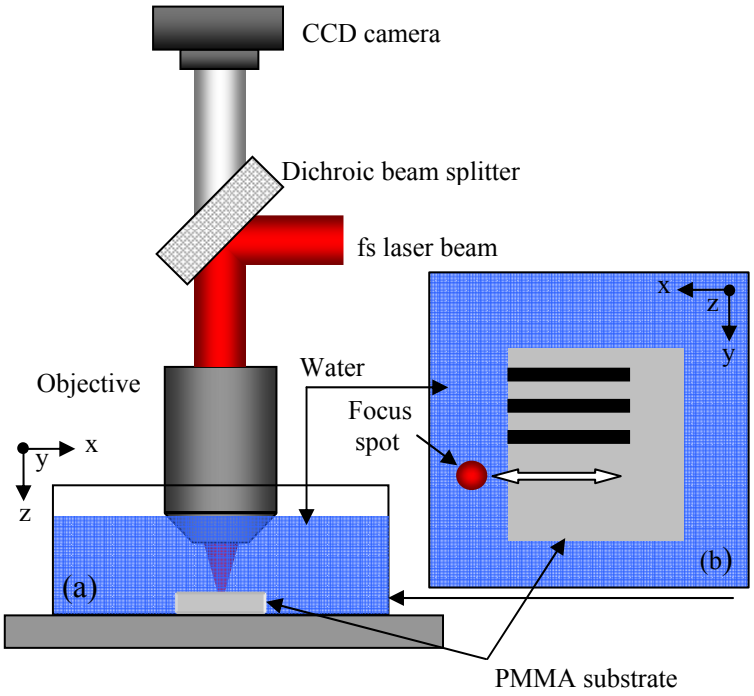

Figure 1: Schematic diagram of (a) the experimental setup for fabrication of microchannels and (b) the fabrication geometry in the sample.

During fabrication the focus spot is initially focused in the water beside the sample and then translated laterally through the water-sample interface and into the sample. The direction of fabrication is an important factor when the incident intensity reaches a level high enough that ablation from the water-sample interface begins. As the sample is translated perpendicular to the direction of propagation of the laser beam it is expected that the microchannels will reflect the elongated shape of the focal region along the optical axis (z direction). Water as an immersion medium for femtosecond drilling under ionization or ablation has been demonstrated to improve the fabrication process by assisting in the removal of debris from inside and near the edge of the channel[12, 14], which can otherwise impede the process. However,

in these experiments water immersion was used to reduce aberrations and improve the performance and consistency of the fabrication method.

3. RESULTS AND DISCUSSION

The fabrication process in PMMA under high repetition rate nanojoule femtosecond laser pulses described here does not have the required energy per pulse to achieve optical breakdown through direct ionization of the substrate. Instead, it is proposed that the absorption of multiple pulses results in a significant increase in the temperature for a localized region surrounding the focal spot, which becomes the dominant fabrication process[18]. Located within the region affected by the fabrication process is a volume of modified polymer material which is caused by the decomposition of the polymer sample due to the high temperatures reached in the focal region. Subsequent post fabrication processing is required to develop the modified region into a microchannel.

3.1 Fabrication mechanism

As the energy from the nJ femtosecond pulses is not enough to overcome the optical breakdown threshold before the onset of temperature based micro-explosion a two-step fabrication procedure is used to produce microchannels:

The PMMA samples are exposed to 0.9 nJ pulses at a repetition rate of 80 MHz and a wavelength of 750 nm, while the focal spot is translated through the sample at speeds between 100 μm/s and 1mm/s. The absorption cutoff for the PMMA samples is 370 nm, which indicates that the dominant absorption process for the focused laser beam is two-photon absorption. Based on the repetition rate of the laser, 80 MHz, in the time it takes the sample to move a distance equal to the size of the focal spot at a speed of 1mm/s, 3.3×10^4 pulses will have been absorbed in approximately the same region. As the excited electrons relax back to the ground state over a period of picoseconds [19] and in doing so transfer energy to the polymer matrix, the successive pulses will therefore result in a localized increase in temperature. The delay between repeated laser scans of the same region allows the temperature in the irradiated region to decrease further due to diffusion. As the scans are repeated the region of modified material is extended uniformly, radially away from the focal region, producing a symmetrical region around the focal spot of modified material

After the sample has been exposed to the laser irradiation a post-bake on a hotplate is carried out at a temperature above the glass transition temperature of the sample. As the laser irradiated region has a different density to the bulk material it is affected differently than the bulk material. This difference in densities results in a hollow microchannel being produced during the post-bake annealing.

3.2 Effect of annealing

During and after the fabrication process it can be seen that there is a region of material with modified optical properties compared with the surrounding bulk sample as shown in Figure 2 (a). The sample was exposed to femtosecond pulses with energy of 0.9 nJ at a wavelength of 750 nm and a translation speed of 800 μm/s, with the sample region being repeatedly irradiated 10 times in succession. From Figure 2(a) it can be seen that there is a central region of width 6.5 μm, which is surrounded by another region of modified material with a width of 17.5μm. With an energy of 0.9 nJ per pulse there is no direct optical breakdown of the sample as evident by the lack of visible radiation typically emitted during plasma generation. The sample was translated at 800 μm/s with the same region being repeatedly irradiated 10 times in succession. After the irradiation the sample was heated on a hotplate at a temperature of 200°C for 30 seconds. Annealing the sample at a temperature above the glass transition temperature formed a microchannel as shown in Figure 2(b). The width of the channel in Figure 2(b) is 9 μm. A magnified section of the channel pre- and post- annealing is illustrated in Figures 2(c) and (d), respectively. Variation of the channel diameters is observed near the interface between the sample and water immersion medium. Even at the lower energies used in these experiments, ablation can occur at the surface of the sample as the focal spot moves through the interface. Confirmation of a hollow microchannel can be seen in Figure 2(e) where water has entered the channel via capillary action.

The large channel diameter, with respect to the focal spot, may be as a result of the continued heating of the sample under repeated irradiation. The additional energy transferred to the polymer matrix increases the region of interaction and thereby results in a larger diameter channel after the post-exposure annealing.

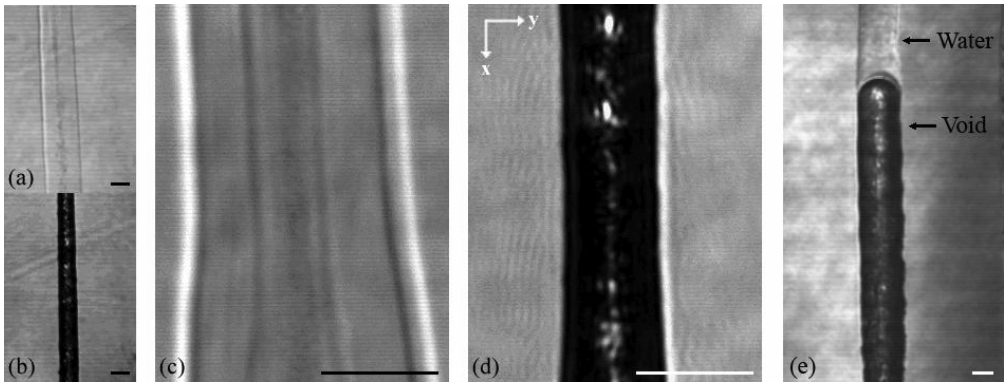

Figure 2: Transmission images of a microchannel. (a) before and (b) after annealing at 200°C for 30 seconds. (c) and (d) are magnified sections of the channel before and after annealing. (e) illustrates that hollow channels are formed as water enters the channel via capillary action. The scale bars are 10 μm.

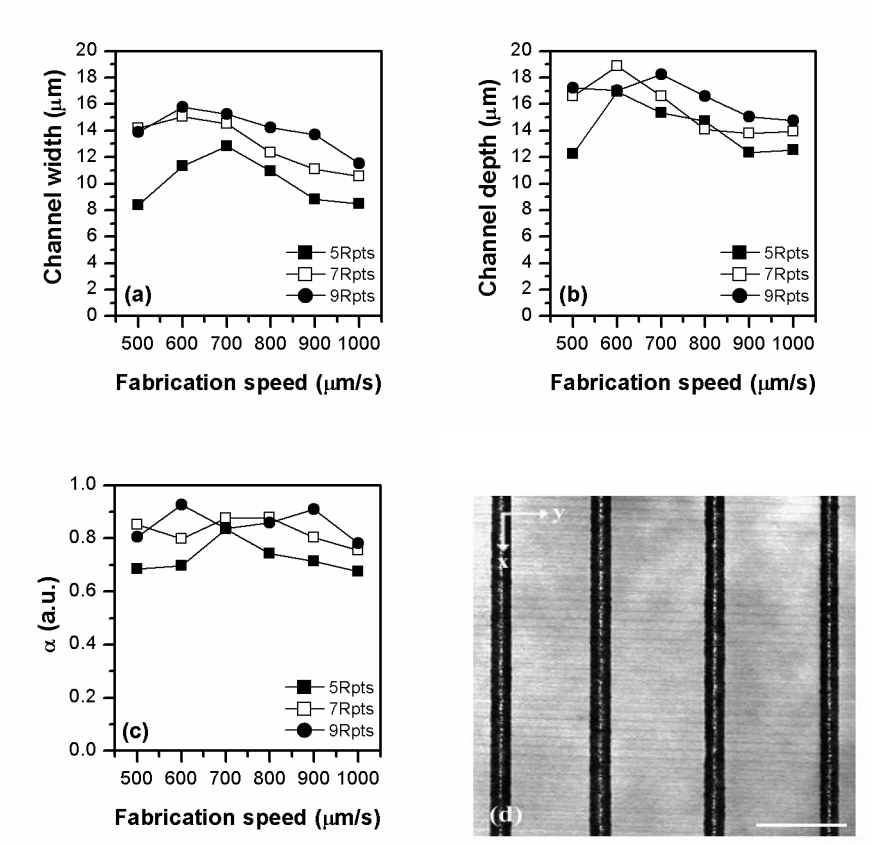

Figure 3: Measured microchannel characteristics as a function of the fabrication speed. (a) width, (b) depth and (c) ratio of width to depth. (d) transmission image of microchannels. The scale bar is 50 μm.

3.3 Effect of fabrication speed

Microchannels were fabricated in a PMMA sample at speeds ranging between 500 μm/s and 1 mm/s with a pulse energy of 0.9 nJ in the focus at a wavelength of 750 nm. Figure 3 shows the change in channel width and depth as a function of the fabrication speed. The depth of the channel refers to the axial dimension of the channel, as the fabrication geometry used will produce an elliptical focal spot. From Figures 3(a) and (b) both the width and depth of the channels decrease as the speed of fabrication is increased. In order to measure the width and depth of the channels the edge of the sample is polished to remove any ablation effects near the sample and water immersion interface. The channel dimensions are then directly measured from the channel cross sections. It is proposed that diffusion of heat through the matrix as a result of the repeated scans results in a channel with a cross-section 650 times that of the focal region.

In order to characterize the shape of the channel, a function α is defined as the ratio of the channel width to depth, where $\alpha = 1$ corresponds to a circle. The value of α for the focal spot of the 0.9 NA objective used in these experiments is 0.16. Figure 3(c) shows that the cross-section of the channel is considerably more circular than the elliptical profile of the focal spot. Based on the shape and size of the channel with respect to the focal spot it would indicate that some uniform diffusive process begins in the focal spot and expands radially.

The microchannels shown in Figure 3(d) were fabricated at 900 μm/s using 10 repeats with a delay between repeats of 10 s. An advantage of this method of channel fabrication is that it produces channels with relatively smooth channel walls, which can be created in within the volume of a bulk polymer material.

3.4 Effect of repeated fabrication

The nature of the fabrication process used in these experiments is such that the energy required to reach plasma generation and micro-explosions are not achieved when the samples are translated at speeds greater than 100 μm/s. As a result repeated scans over the same region are employed in order to create the conditions required to produce a channel after the sample is annealed, where the delay between repeats is fixed at 10 s. At fabrication speeds between 100 and 700 μm/s channels can be formed from a single scan after annealing. This indicates that the temperature increase wasn't enough to induce optical breakdown, however it was enough to modify the density of the material in the interaction region.

Figures 4(a) – (c) show the effect on the channel characteristics as the number of repeated scans is changed. For any given fabrication speed an increase in channel width and depth is associated with an increase in the number of repeats. From Figures 4(a) and (b) it can be seen that there is a limit below which a channel can not be formed; this limit occurs at increasingly higher numbers of repeats for faster fabrication speeds. As the number of repeated fabrications is increased, the subsequent reheating of the irradiated region produces a more uniform heating of the surrounding medium resulting in an almost circular channel cross-section, as seen in Figure 4(c).

The channels shown in Figure 4(d) were fabricated at 800 μm/s with the number of repeated scans varying from 3 to 10, with a repeat delay of 10 s. The channels were fabricated at a depth of approximately 75 μm below the surface of the polymer.

3.5 Effect of delay between repeated fabrication

It has been shown that repeated energy absorption of nJ pulses will affect both the size and shape of the channels due to the localized heating and diffusion of the fabrication process. In Figure 5 it is demonstrated that for channels fabricated at 800 μm/s with 10 repeats there is an increase in the width of the channel as the delay between repeats is increased. At 800 μm/s, the energy deposited from 5 repeats is just above the threshold required to modify the density in the interaction region and therefore there is not enough subsequent heating of the surrounding substrate to cause the same broadening effect as in the 10 repeat case.

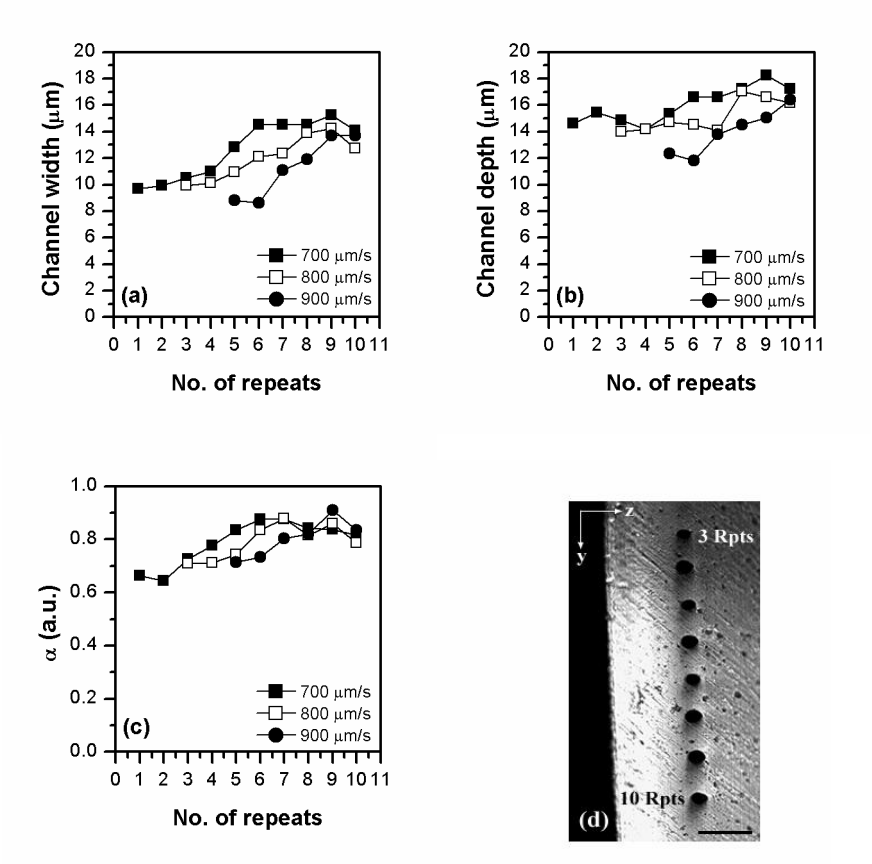

Figure 4: Measured microchannel characteristics as a function of the number of fabrication repeats, (a) width, (b) depth, (c) ratio of width to depth. (d) transmission image of microchannel cross-sections. The scale bar is 50 μm.

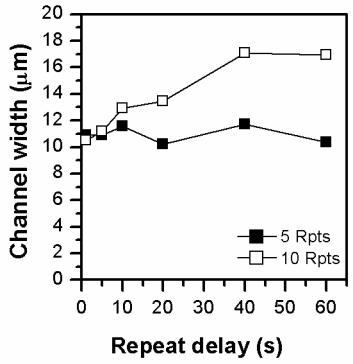

Figure 5: Measured microchannel characteristics as a function of the delay between repeats.

4. CONCLUSION

Microchannels have been fabricated in a poly(methyl methacrylate) substrate by high repetition rate, nanojoule femtosecond laser pulses. It has been demonstrated that low pulse energy multiphoton absorption leads to localized heating in an interaction region surrounding the focal spot. The interaction region consists of a volume of polymer with a modified density with respect to the bulk material that upon post-fabrication annealing at a temperature above the glass transition temperature results in the formation of microchannels. Femtosecond laser pulses with energy of 0.9 nJ per pulse and 80 MHz repetition rate at a wavelength of 750 nm were used to fabricate straight microchannels in a PMMA substrate with diameters ranging from 8 – 20 μm.

5. ACKNOWLEDGEMENTS

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