Microchannel fabrication in PMMA based on localized heating by nanojoule high repetition rate femtosecond pulses

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Abstract: Microchannels are fabricated in a poly(methyl methacrylate) substrate by high repetition rate, nanojoule femtosecond laser pulses. The mechanism for channel fabrication is based on the localized heating of the substrate due to the high repetition rate of the laser, resulting in smooth walled cylindrical channels. Microchannels with diameters of 8 – 20 μm can be fabricated at 800 μm/s using 80 fs pulses at a repetition rate of 80 MHz and energy of 0.9 nJ/pulse.

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References and Links

1. Introduction

Fabrication of micro-structures in dielectrics using femtosecond lasers has gained momentum recently due to the benefits associated with multiphoton excitation. When femtosecond pulses are focused within the volume of a substrate, nonlinear excitation can lead to physical processes such as avalanche ionization, electron plasma formation and shock-wave induced micro-explosions. Considerable research has been conducted into the effects of machining or micro-structuring transparent materials based on shock-wave induced micro-explosions [1-3]. According to 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].

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 amplified femtosecond pulsed lasers producing microjoules per pulse were used to overcome the optical breakdown threshold of the substrate, typically glass or fused silica.

Polymers as substrates have advantages over their glass counterparts as their properties are more easily tailored for specific applications and 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 nanojoule femtosecond pulses. Considerable research has also been conducted into the different applications involving fabrication by femtosecond pulses in polymers, such as three-dimensional data storage [15] and fabrication of photonic band gap structures [16, 17].

The significant benefit from amplified pulsed systems is the ability to overcome the breakdown threshold with a single femtosecond pulse, thereby reducing any possible affects due to heating. However, amplified laser systems typically have repetition rates in the kHz, which could limit the machining speed whereas the non-amplified systems have repetition rates in the MHz.

In this paper we present a study of the 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 channel properties on the different fabrication parameters. Based on the fabrication method demonstrated in this paper cylindrical microfluidic channels can be fabricated in PMMA with diameters ranging from 8 µm to 20 µm.

2. Experimental setup

The experimental setup used in the experiment is illustrated in Fig. 1. A Spectra Physics Tsunami femtosecond pulsed 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 by 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 cover-slip correction built in. The samples were polished blocks of commercial PMMA mounted in a glass dish filled with de-ionized water. The samples were immersed in water in order to reduce the aberrations resulting from the type of objective used and the sample-immersion medium interface. The sample holder was...
mounted on x-y stepper motor translation stages, with the objective mounted on the z axis stepper motor translation stage. Monitoring of the fabrication process was 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.

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

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. 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 z direction. Water as an immersion medium for femtosecond drilling 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 in this paper 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 modified material caused by the decomposition of the polymer substrate due to the high temperatures. Subsequent post fabrication processing is used to develop the microchannel.
3.1. Fabrication mechanism

In order to fabricate microchannels in PMMA under nanojoule high repetition rate femtosecond pulse conditions a two-step procedure was utilized:

1. **Laser exposure**: the PMMA samples are exposed to 0.9 nJ in the focal region at a wavelength of 750 nm, while the focal spot is translated through the sample at speeds between 100 μm/s and 1 mm/s. The absorption cutoff for the PMMA samples is 370 nm, which indicates that the dominant absorption process of the focused laser is two-photon absorption. Given the repetition rate of the laser of 80 MHz, in the time it takes the sample to move a distance equal to the size of the focus spot at a speed of 1 mm/s, 3.3×10^4 pulses will have been absorbed by the sample. 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 lead to a localized increase in temperature. The delay between successive repeated laser scans allows the temperature in the irradiated region to decrease further by diffusion. The density of the material in the irradiated region is reduced due to the heating, which is reduced even further with every repeated laser scan. As the scans are repeated the region of less dense material is extended uniformly, radially away from the focal region. As the energy is low enough to not induce optical breakdown there is no debris created during the laser exposure.

2. **Post-exposure annealing**: after the laser exposure the samples are annealed on a hotplate at a temperature above the glass transition temperature of the material. As the laser irradiated region has a different density to the bulk material it is affected slightly differently than the bulk material. This in effect results in differing amounts of expansion as the temperature is increased, thereby producing a microchannel.

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 bulk substrate as shown in Fig. 2(a). The width of the central region is 6.5 μm, which is surrounded by another region of modified material with a width of 17.5 μm. The substrate was exposed to femtosecond pulses with energy of 0.9 nJ at a wavelength of 750 nm. With an energy of 0.9 nJ per pulse there is no direct optical breakdown of the material 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 placed on a hotplate at a temperature of 200°C for 30 seconds. Annealing the sample at a temperature above the glass transition temperature of the formed a microchannel in the substrate shown in Fig. 2(b). The width of the channel in Fig. 2(b) is 9 μm. A magnified section of the channel before and after annealing is illustrated in Figs. 2(c) and (d). Variation of the channel diameters is observed near the interface between the sample and the water immersion medium as boundary effects dominate. Even at the lower energies used ablation can occur at the surface of the sample as the focal spot moves into the sample. Confirmation of a hollow channel structure can be seen in Fig. 2(e) where water has entered the channel via capillary action.

Such large channel diameters with respect to the focal spot size may be as a result of heating of the polymer through multiple passes, which allows additional energy transfer to the polymer matrix increasing the region of interaction and thereby resulting in larger diameter channels are the post-exposure annealing.
Fig. 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.

3.3. Effect of fabrication speed

Microchannels were fabricated in a PMMA substrate at speeds of 500 μm/s to 1 mm/s with energy of 0.9 nJ in the focus at a wavelength of 750 nm. Fig. 3 shows the change in channel width and depth as the speed at which the sample is translated is increased. Here the depth of the channel refers to the axial dimension of the channel, as the fabrication geometry used will create elliptically shaped channels. It can be seen from Figs. 3(a) and (b) that 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 substrate is polished to remove any ablation effects near the substrate and immersion water interface. The channel dimensions are then measured directly from the channel cross sections. Due to the large number of pulses absorbed by the sample on a millisecond timescale and with a 10 s delay between repeated scans, it is proposed that the diffusion of heat through the matrix results in a channel with a cross-section 650 times that of the focal region.

In order to characterize the shape of the channel, the function α is defined as the ratio of the width to depth, where 1 represents a circle. The value of α for the focal region of the objective used is 0.16. Fig. 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 uniformly diffusive process begins in the centre of the focal spot and expands radially.

The microchannels shown in Fig. 3(d) were fabricated at 900 μm/s using 10 repeats with a repeat delay of 10 s. An advantage of this method of channel fabrication is that it produces channels with relatively smooth channel walls.
3.4. Effect of repeated fabrication

The nature of the fabrication process in this paper is such that the energy required to reach plasma expansion and micro-explosions and thus optical breakdown is not achieved when the sample is 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 annealing, where the delay between repeats is fixed at 10 s. However, at fabrication speeds between 100 and 700 μm/s channels can be formed from a single scan after annealing. This indicates that while the temperature increase wasn’t great enough to induce optical breakdown it was enough to modify the density of the material in the interaction region.

The effect of repeated scans over the same region can be seen in Figs. 4(a), (b) and (c). For any given fabrication speed an increase in both the width and depth of the channel is associated with an increase in the number of repeats. From Figs. 4(a) and (b) there is a limit below which a channel can not be formed; this occurs at increasingly higher energy levels 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 Fig. 4(c).

The channels shown in Fig. 4(d) were fabricated at 800 μm/s with the number of repeats varying from 3 to 10, with a repeat delay of 10 s. As can be seen from the figure all of 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

The repeated energy absorption is shown to affect both the size and shape of the channels due to the localized heating and diffusion of the fabrication process. In Fig. 5 it is shown that for channels fabricated at 800 μm/s with 10 repeats there is an increase in the width of the channel as the delay 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 substrate to cause the same broadening effect as in the 10 repeat case.
4. Conclusion

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.

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