Tunable thermal diffusion and heat accumulation in transparent materials based on varying the scanning speed of a femtosecond laser

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Abstract. Based on heat accumulation effects, symmetric optical waveguides in glass can be obtained via femtosecond laser irradiation. Such modification inside glass is interesting in terms of developing integrated mini-optical devices with 3-D structures and micro channels for biosensors. This work experimentally investigated the formation of micro-channels inside porous glass irradiated with an 800 nm, 100 fs, and 250 kHz femtosecond laser with scanning speeds ranging from 250 μm/s to 1000 μm/s at a fixed power of 300 mW. Strong heat accumulation effects were thus observed at laser scanning at 250μm/s, which offered significant variations in structure morphology.

1. Introduction

In recent years' femtosecond lasers have attracted significant attention with regard to localised modification of structure in bulk transparent materials. Microstructures can be obtained in three dimensions by changing the refractive index of a substrate material [1-3], and several possible applications of this have been investigated, such as binary data storage in three dimensions [4], single nanostructuring [5–9], multimode waveguide splitters [10–12], and waveguide amplifiers [13]. The mechanisms behind these processes differ based on various laser parameters sources and materials, as such processes arise from the systematic characterisation produced by changing the refractive index of transparent materials [14-16]. Femtosecond lasers, with their high repetition rates, have opened new routes for manipulating thermal effects to control the properties of microstructures fabricated by focusing a laser pulse inside glass [3] (Fig. 1).
Laser pulse allows diffusion of energy deposition outside the focal volume before the next pulse where the repetition rate is low; (b) Energy accumulates in the focal volume when the repetition rate is high, developing temperatures a few nanojoules higher in the region of the focal point [17].

The heat accumulated around the focal length is based on the repetition rate of the application of laser radiation, as the absorption time of the shorter laser pulses is longer than the time between pulses [18-19] as shown in Fig. 2.

![Figure 2](image)

**Figure (2).** Formation of micro channels inside glass: (a) thermal diffusion with femtosecond laser with a repetition rate of 100 kHz and a scanning speed of 1mm/s; (b) heat accumulation with femtosecond laser with a repetition rate of 1 MHz and a scanning speed of 10 mm/s

2. **Experimental Details**

The substrate used for fabricating the micro-channels was high-silica glass, a mesoporous type prepared by eliminating the borate phase of phase-divided alkali-borosilicate with a solution of warm acid. The composition of porous glass is roughly 0.5Na2O -4B2O3 95.5SiO2 )wt.%(. The pores have a mean diameter
of about 10 nm and uniformly occupy roughly 40% of the volume of the glass. A three-dimensional connective arrangement of these pores forms inside the glass, allowing water to run inside them, and the porous glass substrate becomes highly transparent after the immersion process [8].

The system of micromachining via femtosecond laser utilised a laser source (Coherent, Inc) that emits a laser at 800 nm with 100 fs, operating at a 250 kHz rate of repetition. A system for imaging, based on a computer simulation of the stage in three dimensions (XYZ), and devices for controlling the beam and optics (Fig. 3) were also included. In order to centre the ray inside the glass, a microscopy objective lens with a numerical aperture of 0.8 was utilised, and the glass was immersed in a dish filled with solution that was positioned on the stage to translate and control the incident power of the laser; a suitable neutral density filter can also be used for such purposes.

![Numerical aperture](Image)

Figure (3). Experimental set up

3. **Results and Discussion**

Ultra short pulses at a 250 kHz repetition rate allowed the development of several heat effects while reducing damage and avoiding micro-crack formation during laser material processing as shown in Figure 4.
Figure (4). The influence of heat via the irradiation by fs laser at a 250kHz. repetition rate with laser power of 300 mW

The microchannel morphology indicated that the strong thermal effects at 250 kHz gave rise to a low heat increase at 300 mW during the generation of microchannels, while stronger heat accumulation effects were achieved at 400 mW (above the ablation threshold).

Figure 5 shows the formation of micro structures in porous glass, which are indicative of cumulative thermal effects alongside the laser spot’s non-uniform re-solidification. The heated area became much bigger than the central dimensions after multiple laser pulses, with the temperature increasing above the melting temperature of glass. Increasing of quantity of incident laser pulses thus increases the modified glass radius.
Figure (5). Structures produced with 300 mW laser pulses focused with an objective lens of numerical aperture 0.8.

Figure 6 shows that using the laser at 400 mW causes the dimension of these structures to top increasing later when utilising the previous lasing parameters. The arrangement changes the laser’s location in front of the focus, causing the intensity to drop below the threshold value. Thus, despite increasing the laser power, further deposition has been stopped, suggesting that the thermal mechanism can be influenced. Only the associated μm-sized focal point at the middle is irradiated directly, yet the structures beside that region expand to as much as 1,000 μm, starting from the central dot. The profile becomes spherical and the dimensions of the structures is increased based on increasing the number of laser pulses.
Figure (6). Structures produced by 400 mW, 100-fs focused laser pulses at 250-kHz, using an objective lens of 0.8 NA.

4. Conclusions

In this experiment, microchannels with low cracks and relatively high surface roughness were achieved using moderate laser power with value is higher than the threshold of ablation of the material. To avoid heat accumulation, a suitable scan speed is required, which can be determined by the initial heated volume and the rate of diffusion of heat. During fs laser machining, the volume of the heat accumulation is then investigated by the primary heated area size and the thermal distribution rate.

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