Microcutting and Hollow 3D Microstructures in Glasses by In-volume Selective Laser-induced Etching (ISLE)

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3D microfluidic devices and assembled micro mechanics inside fused silica glass are produced directly from digital CAD data e.g. for markets like medical diagnostics. To exploit the potential productivity of new high average power fs-lasers (150 W – 1 kW) a modular high speed scanning system has been developed. Acousto-optical beam deflection, galvo-scanners and translation stages are controlled by CAM software. Using a lens with 10 mm focal length a focus radius of 1 µm is scanned with a velocity of 12 m/s on 400 µm track radius enabling the up-scaling of the ISLE-process using large repetition rate and large average power.

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1. Introduction

Microfluidic devices for applications e.g. in medical diagnostics benefit from chemically inert transparent materials like glass or sapphire. 3D micro structuring enables new designs of complex integrated microfluidics or assembled micromechanics. In-volume selective laser-induced etching (ISLE) of microchannels in fused silica glass and sapphire is a fabrication process under investigation for more than eight years now [1-6]. Since special micro-scanners with CAM software [7] have been developed and versatile table-top machining centers are in development [8], 3D digital production of complex micro structured parts is possible using ISLE [9]. However since traditional focus scanning using translation stages and galvo-scanners are only able to exploit the productivity of low average power fs-fiber lasers (<5 W) the recent development of high average power fs-slab amplifiers (150 W – 1 kW) makes the development of fast laser scanning necessary. Therefore, the development of a high speed micro-scanner is the challenge to enable fast digital photonic production of microstructured transparent devices.

2. Experimental

In-volume selective laser-induced etching (ISLE) is a two-step process: In the first step material transparent to the laser radiation is modified locally inside the volume. For this purpose ultrashort laser radiation (λ=1030 nm, repetition rate 0.5-27 MHz) from an fs-fiber laser (P=5 W) amplified by a slab-amplifier (P=150 W, repetition rate 5-27 MHz) is focused inside the glass material with a numerical aperture of 0.3. In the focus volume the intensity of the laser radiation is large enough to enable the absorption by multi-photon processes because the material is transparent at lower intensities. A connected volume inside the material is modified by scanning of repetitive pulses, which must have at least one contact to the surface of the work piece. For digital production of 3D microstructures from the CAD data a set of stacked 2D scanning trajectories are computed (slicing; Fig. 1 left), which are fed subsequently from bottom to top to the CAM software controlling the translation stages, the modules of the scanning system and the laser power synchronously. If the structure to be produced is larger than the scanning field of the lens, the 2D trajectories are divided in adjacent tiles by the CAM software and are scanned and stepped subsequently (Fig. 1 center).

In the second step the work piece is exposed to aqueous solution of potassium hydroxide (KOH) [10] for 48h in an ultrasonic bath. Because the material, modified by the laser radiation, is etched much faster than the unmodified material, the modified volume is selectively removed resulting in hollow structures inside the work piece. The selectivity, that is the ratio of the etching rate of the modified material to the etching rate of the unmodified material, can be as high as 1,000. After etching, the microstructures are cleaned with water and ethanol and characterized using optical microscopy (Fig. 1 right, Fig. 7).

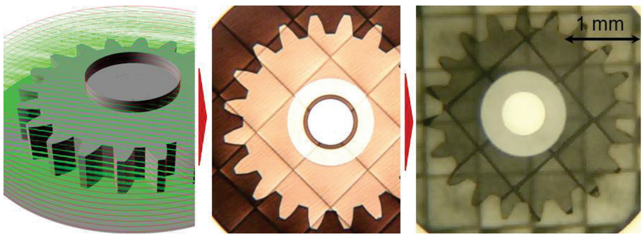

Fig. 1 Laser trajectories generated from 3D CAD file (schematic, left), micrograph of modified structure (center) and resulting microstructure after etching (right)

3. Results

3.1 High Speed Microscanner

For rapid digital production of 3D microstructures parts with 1 µm precision utilizing high average power fs-lasers (P=150 W) a modular scanning system has been developed. Modular combinations of acousto-optical beam deflection, galvo scanner and translation stages have been set-up as a prototype called LightFab (Fig. 2), which can be equipped with various focusing optics. For example using a telecentric lens with 10 mm focal length a focus radius of ω_0= 1 µm is scanned with a velocity of v=12 m/s on a 400 µm track radius. Therefore, spatial separation of laser pulses (without spatial overlap of the pulses) is possible at laser repetition rates as high as f=5 MHz.

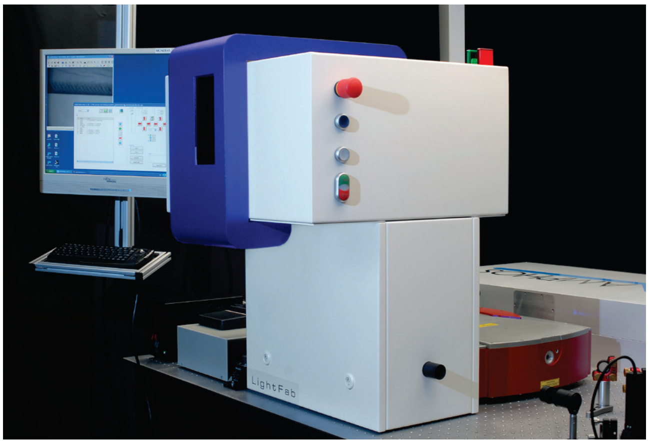

Fig. 2 Modular high speed micro scanner system LightFab

3.2 Absorptivity

Since the absorptivity of glasses depends on processing variables such as repetition rate, velocity and the applied pulse energy it is measured during modification to determine the absorbed power [11]. Using the borosilicate glass D263 the absorptivity increases with increasing repetition rate and pulse energy from 0% to >60% (Fig. 3). Increasing the velocity from 1 mm/s to 200 mm/s is resulting in a decrease of the absorptivity of ~10% in average. Using a laser power > 0.5 – 2 W more than 50% of the laser power are absorbed in the material and the absorption is dominated by linear absorption processes like absorption by thermally excited electrons in the volume heated by heat accumulation of multiple pulses [12]. Therefore, a further increase of repetition rate, laser power and scanning velocity is considered to result in an almost linear increase of productivity of the laser modification process.

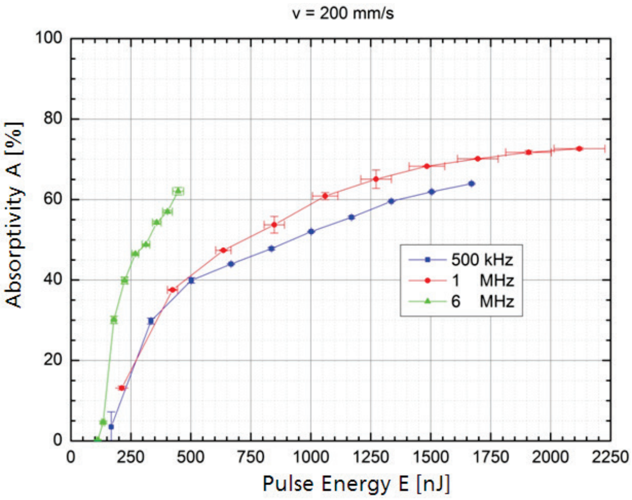

Fig. 3 Absorptivity measured in D263 during modification with 0.5-6 MHz repetition rate and scanning velocity of 200 mm/s

3.3 3D Microfluidic Device

A 3D micro fluidic device for medical diagnostics has been produced by ISLE in 2 mm thick fused silica. The microstructure consists of a tapered buried flat microchannel for microscopic diagnosis and two cylindrical inlet pipes each equipped with connectors for flexible tubes (Fig. 4).

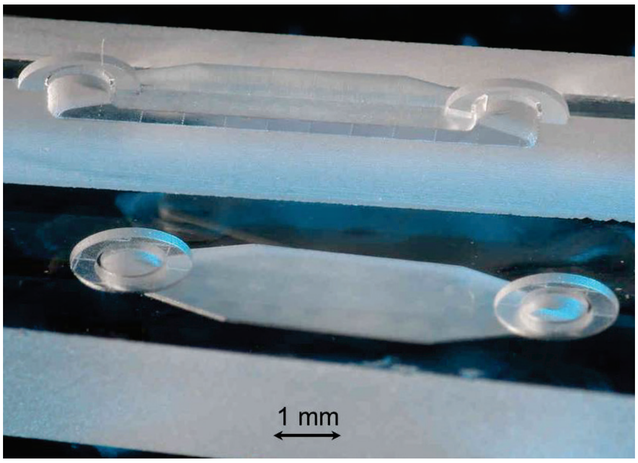

Fig. 4 3D micro fluidic device in 2 mm thick fused silica made by ISLE directly from CAD file (top-view and cross-section) in fused silica

To investigate the up-scaling of the ISLE process a straight micro channel with a cross-sectional area of 50x630 µm has been produced in fused silica by scanning the laser focus ω_0= 1 µm on a circle of 630 µm diameter with a velocity of v=10 m/s and simultaneously translating the sample with (Fig. 5). Using pulse duration of 500 fs, a repetition rate of 27 MHz and a laser power of 16.2 W the ISLE process is possible without visible cracks after etching (Fig. 5, top). Increasing the power to >24W results in microchannels with visible cracks (Fig. 5, center). Using pulse duration of 5 ps by stretching the laser radiation, a laser power of > 24 W is necessary to initiate the ISLE process resulting in microchannels with already visible cracks (Fig. 5, bottom).

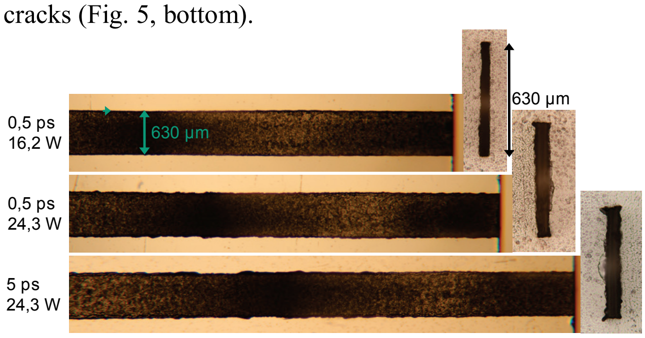

Fig. 5 Micro channel 8 mm long and 630 µm wide (top view, left) and cross-section 50-80 µm x 630 µm (right) in fused silica

3.4 Assembled micro mechanics and microcutting of holes in fused silica

Further demonstrations of applications of ISLE with the use of high speed scanning include the production of a 50x50 field of holes with a diameter of 73 µm (Fig. 7). A tolerance of the holes' diameter of ±1 µm has been obtained by microcutting the 1 mm thick fused silica: The surface area of a cylinder has been modified by helical scanning of the laser focus and after etching the cut-out glass cylinders are removed. Using an average laser power < 4 W the processing time is < 1 s per hole. Further up-scaling of the productivity is planned using high power laser radiation.

To demonstrate the fabrication of assembled micromechanics by digital photonic production from 3D-CAD data using ISLE in fused silica a gear has been produced already mounted on its axis (Fig 1). The gear has a diameter of 3 mm and a thickness of 500 µm and after the etching step it is able to rotate freely on its axis 600 µm in diameter (Fig. 8). Due to limited selectivity of the etching process the minimal gap width is ~10 µm and the minimal gap height is ~20 µm and a surface roughness R_Z~1 µm are obtained while a precision of 2 µm is possible after taking the tapering due to etching into account.

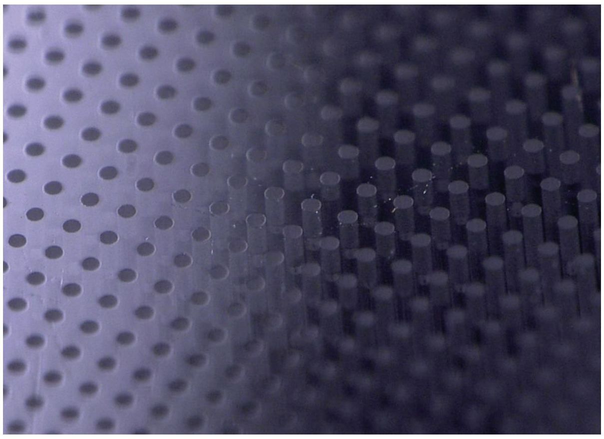

Fig. 7 Holes with 73 µm diameter made by cutting 1 mm thick fused silica glass using ISLE

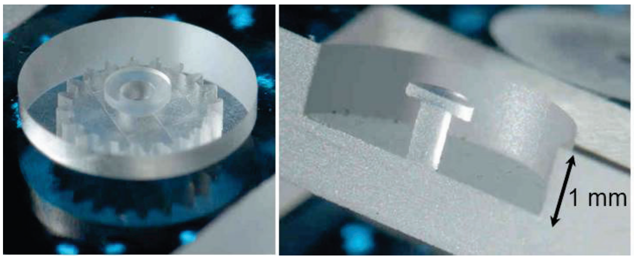

Fig. 8 Free rotating gear (left) produced directly from CAD data already assembled on its shaft (cross-section, right) by ISLE

4. Summary and Outlook

Using In-volume selective laserinduced etching (ISLE) digital photonic production of microfluidic devices and already assembled micromechanical parts has been demonstrated directly from the 3D CAD data.

To utilize high average power fs-lasers (P=150 W) a modular high speed scanning system has been developed. By combination of acousto-optical beam deflection, galvo scanner and translation stages using a lens with 10 mm focal length a focus radius of ω_0= 1 µm has been scanned with a velocity of v=12 m/s on a 400 µm track radius.

The scaling of the ISLE process to high power (30 W) and high velocity (10 m/s) has been demonstrated by fabrication of 8 mm long microchannels in fused silica free of visible cracks using fs-laser radiation. Using ps-laser radiation up to now the fabricated microchannels are not free of cracks. Further process optimization is needed to clarify, whether a processing window exist for the fabrication of crack-free microchannels using ps-laser radiation for ISLE.

Both the microstructured parts made by ISLE and the high speed microscanner will soon be made commercially available via a spin-off by the authors.

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