High speed micro scanner for 3D in-volume laser micro processing

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ABSTRACT

Using an in-house developed micro scanner three-dimensional micro components and micro fluidic devices in fused silica are realized using the ISLE process (in-volume selective laser-induced etching). With the micro scanner system the potential of high average power femtosecond lasers (P > 100 W) is exploited by the fabrication of components with micrometer precision at scan speeds of several meters per second. A commercially available galvanometer scanner is combined with an acousto-optical and/or electro-optical beam deflector and translation stages. For focusing laser radiation high numerical aperture microscope objectives (NA > 0.3) are used generating a focal volume of a few cubic micrometers. After laser exposure the materials are chemically wet etched in aqueous solution. The laser-exposed material is etched whereas the unexposed material remains nearly unchanged. Using the described technique called ISLE the fabrication of three-dimensional micro components, micro holes, cuts and channels is possible with high average power femtosecond lasers resulting in a reduced processing time for exposure. By developing the high speed micro scanner up-scaling of the ISLE process is demonstrated. The fabricated components made out of glass can be applied in various markets like biological and medical diagnostics as well as in micro mechanics.

Keywords: high speed micro scanner, in-volume selective laser-induced etching, femtosecond laser radiation, micro components, glass materials

1. INTRODUCTION

By taking advantage of the physical process of nonlinear absorption a modification of transparent and brittle materials with focused ultrashort laser pulses can be performed [1,2]. Amorphous materials like glass can be processed and machined by ultrashort pulsed laser radiation. Due to the generated high intensity in the focal volume a modification even in the volume of these materials is possible whereas the surface is not modified. By using high numerical aperture microscope objectives with NA > 0.3 for focusing laser radiation the depth of the modification in the material is limited by the working distance of the optical element and the absorbed power in the focal volume generating a modification. The modification in the material consists of a local density change and a change of the refractive index [3]. Therefore, the optical properties of the material are locally changed. Optical in-volume waveguides are realized by translating the focal volume of focused laser radiation perpendicularly to the beam propagation direction of radiation [4,5]. By adding a subsequent wet etching process the modified material can be removed by aqueous solutions. In this way three-dimensional micro channels and micro components can be fabricated [6,7,8].

The technique for femtosecond laser exposure can consist of a scanner system in combination with translation axes. But these systems are only able to exploit the productivity of rather low average power lasers (P < 5 W). For a high throughput and for exploiting the newly developed high average power femtosecond lasers (P > 100 W) a new development of high speed scanning systems is necessary [9]. The goal is the combination of high scanning speeds (v > 10 m/s) with micrometer precision. For this reason a modular high speed scanning system has been developed. By processing digital computer-aided design (CAD) data the scanner system enables the possibility to directly expose the complete sample appropriate to the desired structure. The trajectories which will be scanned by the laser radiation using the scanner system are generated from the CAD data by computer-aided manufacturing (CAM) software. In this way the laser system and the positioning systems are controlled simultaneously. The main advantage using the so-called digital
photonic production technology is the independence of the production cost from the lot size. For no masks or mold are needed the components are directly fabricated from the digital data leading to individualized production. The complexity of component designs is only reflective of the data volume and the appropriate data storage. By using cheap data storage devices the production cost may be nearly independent on the component design complexity. The final cost for fabrication a cylindrical hole or a gear for example is almost the same.

2. EXPERIMENTAL SETUP

2.1 High speed micro scanner
For realizing high speed processing of transparent materials with micrometer precision a galvanometer scanner is combined with acousto-optical and/or electro-optical beam deflection and translation stages. The so-called high speed micro scanner can be operated with high average power femtosecond laser radiation of more than $P = 100$ W. The laser radiation is guided to the samples by the mirrors of the beam path and the mirrors of the scanner.

2.2 Preparation of the data
Digital three-dimensional CAD data of the required micro component have to be prepared prior to laser exposure. Firstly, the data has to be converted into stacked two-dimensional scanning trajectories. By slicing the data of the three-dimensional micro component two-dimensional laser exposure is performed in layers. The software directly controls the mirrors of the galvanometer scanner, the movement of the translation axes and the laser.

2.3 Laser exposure
The used laser system is a femtosecond fiber laser with an average power of about $P = 5$ W which is amplified by a slab-amplifier to about $P = 150$ W. The radiation is focused by microscope objectives with high numerical apertures ($NA > 0.3$) beneath the surface of glass materials. In this way the materials are locally modified.

If the micro component has a diameter larger than the scan field of the scanner system quadratic tiles of about 800 x 800 µm are stitched side by side leading to a completely exposed two-dimensional area. For exposure in three dimensions the vertical position of the focal volume is changed and the complete structure is exposed layer by layer from bottom to top.

2.4 Wet chemical etching
After laser exposure the whole sample is wet chemical etched with an aqueous solution for several minutes to hours. During the process only the exposed material is etched whereas the unexposed material remains nearly unchanged. In this way the modified material is selectively removed by the acid. The selectivity describes the ratio of the etching rate of the exposed and the unexposed material. Depending on the material the selectivity can be as high as 1,000. After the etching process the samples are cleaned with ethanol and characterized by optical microscopy.

3. RESULTS AND DISCUSSION

3.1 High speed micro scanner
Two modular high speed micro scanning systems have been developed for the fabrication of three-dimensional micro components in transparent materials: the upright and the inverse micro scanner. An acousto-optical modulator as well as an electro-optical modulator is modularly combined with a galvanometer scanner and translation axes. For both systems one prototype has been developed and experiments regarding the structuring of micro components in glass have been performed.

Upright micro scanner
The upright micro scanner has been developed for the fabrication of individual prototypes and small series of micro components. The scanner can be flexibly mounted to an existing three-dimensional translation stage (Figure 1).
The sample is placed on the x-y-table whereas the scanner is mounted to the z-axis enabling the vertical positioning. The upright micro scanner in which the laser radiation propagates from top to bottom enables the fabrication of a mounted and free rotating gear produced in fused silica for example (Figure 2). The fabricated gear has a diameter of 3 mm and the depth of the cavity in which the gear is freely rotating is 1 mm. The gear is produced directly on its shaft. No additional alignment or assembling is required after using the ISLE process.

Figure 2. Picture of a mounted gear which can freely rotate on its shaft. In the upper left corner a cut of the fabricated shaft is shown. The complete sample is fabricated with the ISLE process without additional assembling afterwards.
Inverse micro scanner
The laser radiation is propagating from bottom to top in the inverse micro scanner giving access to the mounted sample in the upper part of the system behind the sliding blue door (Figure 3). The translation stage is integrated in the case behind the sliding door containing a laser safety window. The inverse micro scanner system has been developed for production with high throughput and can be optimized for a special geometry provided by the customer. With this system a flexible adaption is possible enabling also a flexible focusing for various focal volumes of laser radiation.

The high speed micro scanner enables a precision up to about 1 µm with scan speeds up to several meters per second and high average laser power (P > 100 W). Both systems have been equipped with a reflected-light microscope and a CMOS camera for sample alignment and process control. By utilizing a second light source also transmission light microscopy can be used. For measuring the laser power transmitted through the sample and calculating the absorbed power in the focal volume afterwards a power meter is included.

3.2 Micro components in fused silica
In fused silica straight micro channels with a cross sectional area of 50 x 630 µm are fabricated to investigate the up-scaling of the ISLE process (Figure 4). The laser focus with a focal diameter of 1 µm is scanned on a circle with a diameter of 630 µm with a velocity of 10 m/s. The sample is laterally translated in the x-direction, simultaneously. The experiments are performed with pulse durations of 500 fs and 5 ps at a repetition rate of 27 MHz. The pulse energy is varied between 0.5 and 1.1 µJ which corresponds to powers of 13.5 to 29.7 W.

Before the etching process some micro cracks are observed in the cross sections of micro channels fabricated with the pulse duration 500 fs. After etching the cracks have been removed for pulse energies from 0.5 to 0.9 µJ (Figure 4). For pulse energies 1.0 and 1.1 µJ cracks at the corners of the cross sections occur. For 5 ps pulse duration a micro channel is formed not until 0.7 µJ pulse energy is used. The length is about 3 mm and the width is varying between 300 and 500 µm for only a part of the modified volume is removed. For 0.8 µJ the obtained micro channels structured with 500 fs and 5 ps laser radiation are comparable and have a length of 8 mm. When the pulse energy is further increased the micro channels get a larger height and cracks occur at the corners especially for 500 fs pulse duration. At pulse energies larger than 0.8 µJ the cross sectional shape of the micro channels is more rectangular for 5 ps than for 500 fs.
Using the upright high speed micro scanner also micro channels for microfluidic devices can be fabricated. For medical diagnostics a microfluidic device has been produced in the volume of fused silica (Figure 5). The used laser parameters are the same for all shown buried micro structures only the distance of adjacent structure lines is varied leading to a different color appearance due to refraction and interference in the observer’s eyes, respectively. The middle of the micro channel is formed similar to the ones shown in Figure 4. At the top end and the bottom end of the micro channel a connection for a flexible tube is produced. In this way fluidics can be filled into the micro channels and be characterized by optical microscopy for diagnostics.

Figure 4. Micrographs of micro channel cross sections after etching in fused silica. The micro channels have a length of 3 to 8 mm, a height of 50 to 80 µm and a width of up to 630 µm. The pulse durations of laser radiation are 500 fs (left) and 5 ps (right).

Figure 5. Micrographs of micro channel cross sections after etching in fused silica. The micro channels have a length of 3 to 8 mm, a height of 50 to 80 µm and a width of up to 630 µm. The pulse durations of laser radiation are 500 fs (left) and 5 ps (right).

Figure 5. Picture of a micro fluidic device with four micro channels in fused silica. Each of the micro channels can be connected to a flexible tube for microscopy of fluidics.
4. SUMMARY

A modular high speed scanning system has been developed for realizing digital photonic production of three-dimensional micro components in transparent materials. The material is exposed in the volume generating a modification which has a higher etchability than the unexposed material. Using the ISLE process the fabrication of precise micro components which can be even already assembled is possible. The developed high speed scanner system can be utilized with high average power femtosecond lasers ($P > 100$ W). Using high velocities of about 10 m/s several millimeter long micro channels are demonstrated in fused silica. With pulse durations of 500 fs and 5 ps rectangular cross sections of the micro channels are achieved with pulse energies from 0.8 to 0.9 µJ (21.6 to 24.6 W at 27 MHz repetition rate). Optimization in terms of rectangular micro channels without cracks has to be performed for further development of high quality micro fluidic channels. Especially the up-scaling to higher average laser powers has to be further investigated. The presented high speed micro scanner and the fabricated micro components will be soon commercially available from the spin-off of the LLT, RWTH Aachen University called LightFab.

REFERENCES


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