Method of crack-free laser writing of microchannels on glass substrates

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Method of crack-free laser writing of microchannels on glass substrates

Sergey Baev, Victor Bessmeltsev, Nikolay Goloshevsky and Denis Katasonov

Institute of Automation and Electrometry, Siberian Branch, Russian Academy of Sciences, 630090, Novosibirsk, 1 Acad. Koptyuga Pr., Russian Federation

E-mail: nickolayg@iae.nsk.su

Abstract. Approaches to the problem of the formation of microchannels of arbitrary shape on optical glass substrates and other fragile materials without microdefects (cracks and chips) both on the surface of the substrate and inside the substrates are considered. Different approaches to the formation of laser beam trajectories within microchannels are considered. It was found that the raster scanning method improves the performance of the laser micromachining process and provides the ability to write structures of any length without longitudinal cracks with the energy characteristics of the laser spot in the focus much higher than those in the vector scanning method.

1. Introduction

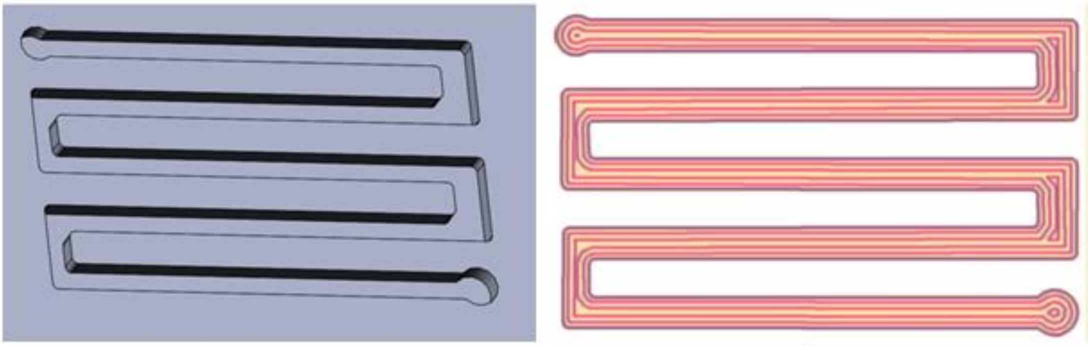
The necessity of precise formation of complex-topology microchannels in glass and other dielectric substrates arises quite often in connection with the development of microfluidics for microchip applications. Also, the requirements of the optical industry to the accuracy of the formation of optical grids and special scratches for the production of scales and limbs have increased significantly. A typical width of microchannels is in the range of 5-100 microns, the depth is 3-50 microns, the size accuracy can be smaller than a micron, and the roughness can be smaller than 0.5 micron.

The advent of the femtosecond laser writing technology has significantly improved the quality of processing, especially for glass and other brittle materials, due to a drastic decrease in thermal loading that occurs during laser processing. However, it turned out that there are limitations on the performance of micromachining of such materials even if femtosecond pulses are used. These constraints are caused by the emergence of microcracks and microchips with an increase in the pulse energy above a certain threshold [1]. For crack-free micromachining of glass, not only the range of energy parameters of the laser beam in the focusing plane, but also the methods and trajectories of micromachining have to be accurately determined [2].

This paper presents a new method of femtosecond laser micromachining of glass substrates, which ensures the maximum write performance of microchannels with complex geometry, high precision, and given roughness without defects such as microcracks and microchips.

2. Methods of laser scanning for writing microchannels on glass substrates

Figure 1a shows a typical 3D model of a micromachined object – a "biochip" consisting of a set of microchannels with a width and depth of 25 microns.



a b

Figure 1. Model of micromachined object.

Such structures can be formed by vector scanning of a focused laser beam within the boundaries of the microchannel being written, while the correspondence of the shape of the original model and micromachining results is ensured by traversing the beam along equidistant trajectories formed along its boundaries (figure 1b). The required depth of the relief can be achieved by increasing the number of passes along a given path, because, as previously indicated, for a given size of the scanning spot and the pulse duration, an increase in the pulse energy leads to microcracks and chips.

This scanning method was used to form microchannels on glass substrates in [3], where a scanning system based on galvanometric scanners and a telecentric focusing lens was used to scan the laser beam. On the basis of the developed experimental mathematical model, the range of combinations of the laser pulse overlap, average power of radiation, and speed of laser beam movement providing defect-free micromachining was determined. It was demonstrated that for extended structures for which the length of the continuous path of the laser beam is 1 mm or more, it is possible to achieve the desired quality of the microchannel and the micromachining performance of 0.03 mm^3/min at a pulse energy of 0.91-2.27 μJ, overlapping of the neighboring pulses of 53-62%, and the number of repeated passes of more than 3. However, this method of scanning has a number of disadvantages and limitations for the manufacture of objects with a large number of microchannels with linear dimensions of 0.1 mm and smaller, such as scales and limbs for optical devices.

It is known [4] that dynamic distortions introduced by scanners during vector scanning can lead to significant processing errors (figure 2). PID controllers of typical scanner drivers cannot fully compensate for such inaccuracies of the system due to inertia and damping.

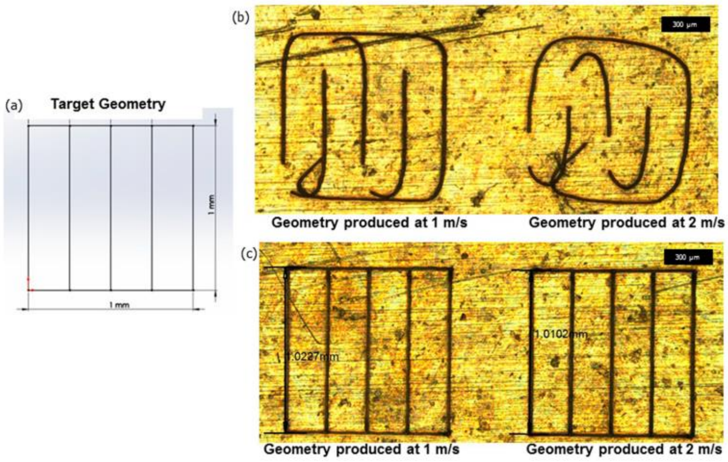


Figure 2. Effect of dynamic distortions of galvanometric scanners on laser processing accuracy: (a) target geometry, (b) writing results without distortion correction,(c) with correction [4].

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When the scanning system reproduces a given trajectory (figure 2a), there occur errors (figure 2b) if the scanning speed exceeds the dynamic capabilities of the beam deflection system. The processing elements do not reach the specified position, and the so-called "tails" are formed along the path of the laser beam both at the beginning and at the end of each individual segment; the value of such errors increases with the speed of the beam. The processing accuracy can be increased (figure 2c) by introducing additional time delays of the control signals of the galvanometric scanners and laser [5] on the trajectory elements with large rotation angles.

When the vector scanning method is used for recording microchannels with linear dimensions of about 0.1 mm, the total delay time ensuring sufficient accuracy of processing becomes significantly longer than the processing time, which leads to appreciable deterioration of the performance. Thus, for a microchannel with a size of 100×20 μm^2treated in the micromachining mode described in [3] with a linear beam scanning rate of 87.5 mm/s, the performance drops to 0.005 mm^3/min. To increase the performance (increase the depth of processing in 1 pass), it is necessary to increase the power of laser radiation by several times, which leads to various types of defects (figure 3a) in the form of cracks (figure 3b) and chips (figure 3c) at the edges of the microchannel, as well as cracks on its bottom (figure 3d).

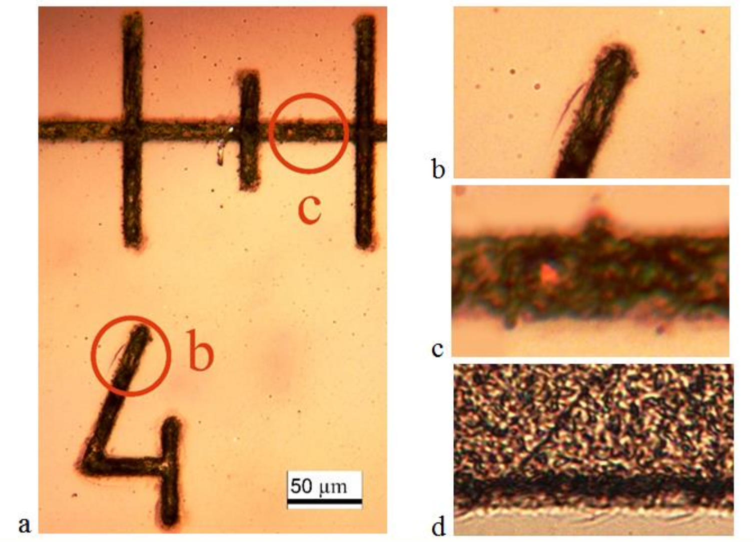

Figure 3. Microdefects that occur in the course of vector scanning of the laser beam.

Another constraint of the vector scanning method is the formation of cracks along the direction of laser beam movement in writing long lines (figure 4). The maximum length of the line without microcracks depends on the type and quality of the processed material and on the dynamic and energy characteristics of the laser spot in the focus; its typical value is 100-150 µm for K8 glass for a beam speed of 28 mm/s, spot size of 5 µm, pulse repetition rate of 50 kHz, and pulse energy of 3 µJ.

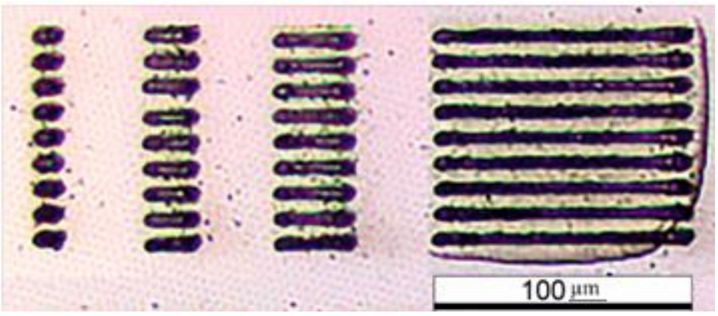

Figure 4. Cracks that occur along the direction of laser beam movement in the course of vector scanning.

The figure shows lines 10, 20, 30, and 100 μm long recorded on the surface of the glass substrate using vector scanning with identical parameters. It can be seen that a crack develops on a 100-μm line, which is associated with the development of thermal stresses in the treated substrate along the laser beam movement.

To increase the micromachining performance while maintaining the quality requirements, it was proposed to use the raster method of scanning the laser beam [6], in which scanners can operate at the maximum speeds and additional delays are not required to ensure the beam movement accuracy. A schematic representation of the structure of the raster filling in the course of writing the microchannel is shown in figure 5a, and a photo of the written element of the microchannel layer with such filling without overlap is shown in figure 5b.

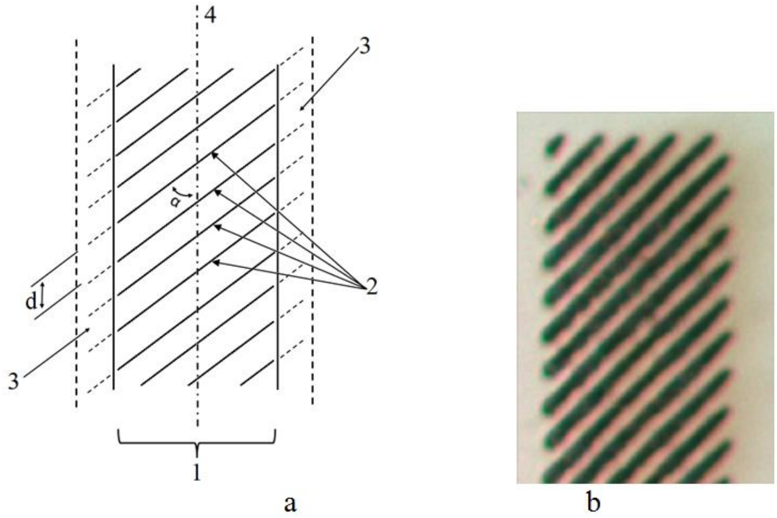

Figure 5. Raster scan method of the laser beam in the course of writing the microchannel: a – schematic representation of the method (1 –microchannel boundaries, 2 – raster lines which are scanned, 3 – "idling" zone, 4 - microchannel generatrix, α – raster angle, d – raster step); b – element of the microchannel with raster filling (the line width is 4 μm, and the raster step is 2 times larger than the laser spot diameter).

The proposed method implies filling the contour of the written microchannel (figure 5a, pos. 1) by a set of raster lines (figure 5a, pos. 2) aligned at an angle α relative to the microchannel generatrix (figure 5a, pos. 4) and distributed over its long side with a step d. Each raster line at the beginning and end is complemented with "idling" zones (figure 5a, pos. 3).

The angle α for each of the microchannels is set so that the length of the raster lines does not exceed the limit at which the cracking process begins. Periodic structures can be formed at the microchannel bottom if lines with a constant raster angle are scanned. Changing the angle of the raster randomly within specified limits in the next processing passes makes it possible to smooth out the periodic structures formed during the first scan and, thus, reduce the microchannel surface roughness. To ensure the optimal quality of micromachining, the step d must ensure overlapping in the range of 65-75% of the laser spot diameter.

Idling zones, which are 5-25% of the raster line length, are required to maintain a constant speed throughout the raster line. This allows one to provide a uniform distribution of laser pulses in all sections of the micromachining area and to avoid the formation of defects at the beginning and the end.

3. Specialized software for microchannel writing

The proposed micromachining method is implemented in a software module [7] for the "Laser technological workstation based on a laser with tunable pulse duration" FPL-1 developed at the Institute of Automation and Electrometry of the Siberian Branch of the Russian Academy of Sciences [8].

Special software for FPL-1 is designed to visualize the model of the microchannels and to set the processing parameters — laser frequency, laser beam speed, scanning strategy (figure 6), and other parameters.

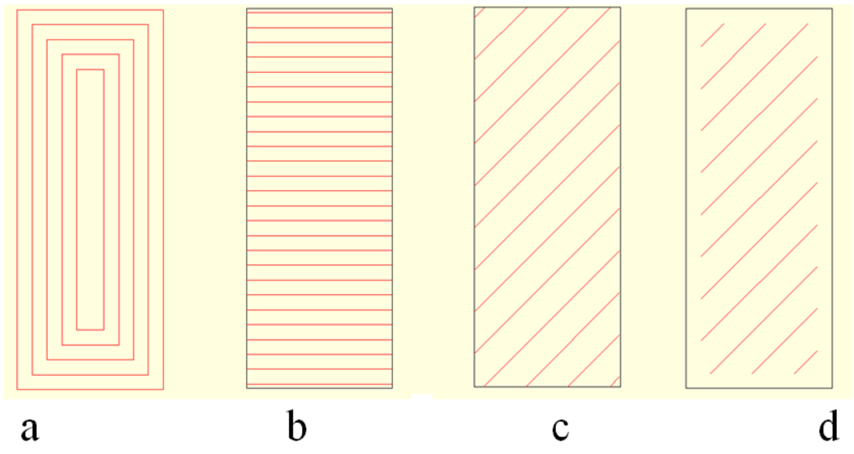

Figure 6. Scanning strategies for a rectangular microchannel: a – filling with nested contours, b – raster filling with a raster angle of 90°, c – raster filling at an angle of 45°, d – raster filling at an angle of 45° and a set indent from the microchannel boundaries.

The model of the formed microchannels is prepared in a graphical editor or using CAD software and can be represented as a 3D model in the STL format or in the form of microchannel contours in the DXF format.

The STL representation of objects allows the formation of a 3D structure of the microchannel; in this case, during the import, the model is divided into layers with a given vertical step, and then each layer is considered as an individual contour object.

During the import process of the model, a scanning strategy is defined – raster filling with raster lines with a given step and angle or nested contours (figure 6a). In addition to the raster angle and step (figure 6b and 6c), the software allows setting such a parameter as the raster indent from the microchannel boundary (figure 6d). It is also possible to carry out additional traversing of the microchannel boundary by the laser beam.

To accurately match the model of the object being formed and the substrate to be processed, the software offers a tool for registering the substrate elements using the built-in machine vision module with the use of special markers (figure 7).

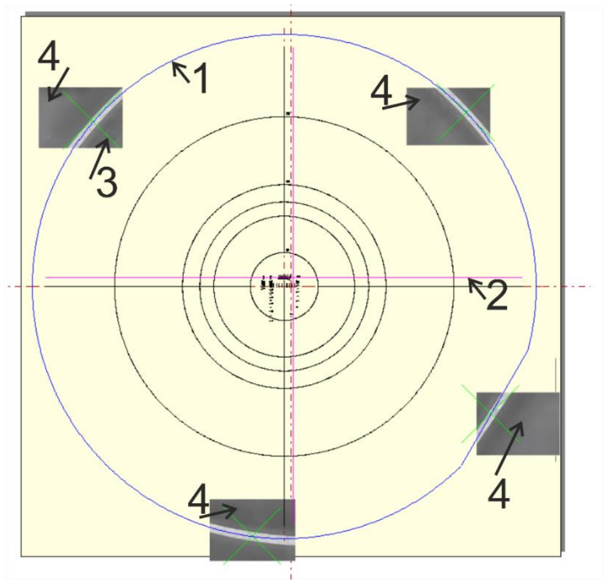

Figure 7. Result of matching the model and the substrate being processed. 1 - substrate contour, 2 - focus lines, 3 - markers, 4 - photo images of the substrate.

To perform the matching process, the model contains the image of the contour of the substrate being processed (figure 7, pos. 1), The images of the substrate fragments (figure 7, pos. 4) obtained in coordinates of the markers (figure 7, pos. 3) using the vision module are superimposed onto the imported model, after which the model is transferred and rotated.

The location of the focus lines (figure 7, pos. 2) is set within the substrate contour at the object model design stage to perform automatic focusing of the laser beam on the substrate surface and is determined by its features, for example, the position of technological holes, shape, etc. To perform automatic focusing within these lines, the distance to the substrate is measured by the built-in distance sensor. Based on these measurements, the normal vector to the substrate surface is calculated, which is used for calculating the correction of the vertical position of the laser beam focus point.

4. Conclusions

The experiments carried out using the developed hardware and software demonstrated the high quality of microchannels formed by the proposed method of raster scanning with the laser beam (figure 8).

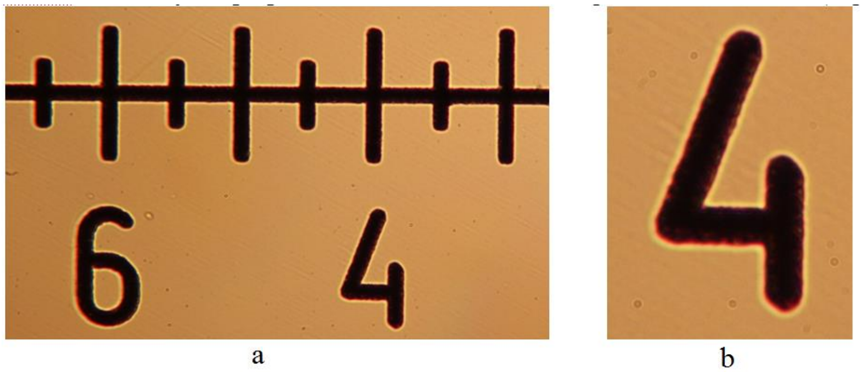

Figure 8. Image of a part of the optical scale (a) and its fragment (b) obtained by raster scanning method, the microchannel thickness is 12.5 μm, and its depth is 10 μm.

As compared to the above-mentioned vector method of scanning, the performance of micromachining of a microchannel with dimensions of 100×20 μm^2 increased by a factor of 5 up to 0.025 mm^3/min under the following laser parameters: pulse frequency of 476 kHz and pulse energy of 0.9 μJ.

Another advantage of the proposed scanning method is the ability to write structures of any length without longitudinal cracks with the energy characteristics of the laser spot in the focus much higher than those in the vector scanning method.

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