Femtosecond laser fabrication of integrated optical waveguides and microfluidic channels for lab-on-chip devices

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Abstract: *We use a femtosecond laser to fabricate on a glass substrate both microfluidic channels and high quality optical waveguides, intersecting each other. Waveguide-channel integration opens new prospects for in-situ sensing in lab-on-chip devices.*

Introduction

A lab-on-chip (LOC) is a device that squeezes onto a single glass substrate the functionalities of a biological laboratory, by incorporating on it a network of microfluidic channels, reservoirs, valves, pumps and micro-sensors [1,2]. It offers the capabilities of preparation, transport, reaction and analysis of very small volumes (nano- to picoliters) of biological samples. Its main advantages are high sensitivity, speed of analysis, low sample and reagent consumption and the possibility of measurement automation and standardization. This novel concept promises dramatic advances both in basic research and in clinical applications as a low-cost diagnostic tool. The next technological challenge of LOCs is direct on-chip integration of photonic functionalities, by manufacturing optical waveguides for sensing of biomolecules flowing in the microchannels. Such integrated approach has many advantages over traditional free-space optical sensing, including compactness and portability, enhanced sensitivity and possibility of parallel excitation at multiple points in the channel.

The microfluidic channels in commercial LOCs are currently fabricated using technologies borrowed from semiconductor processing, such as micro-sandblasting, wet chemical etching and deep reactive ion etching. These are intrinsically two-dimensional techniques, creating surface channels that need to be covered by a glass slab; multilayer processing is required to produce three-dimensional structures. Standard waveguide fabrication methods (ion exchange, silica-on-silicon, polymers, …) are also two-dimensional multistep processes and their integration with microchannel fabrication is very complicated, strongly limiting its application [3].

Femtosecond-laser induced refractive index modification is a powerful technique enabling single-step, three-dimensional fabrication of optical waveguides in glass [4-8], and appears to be particularly suited for their integration into LOCs. In addition, femtosecond-laser irradiation of fused silica followed by chemical etching in HF solution allows also the manufacturing of microfluidic channels, due to the enhanced (by up to two orders of magnitude) etching rate of the irradiated material with respect to the pristine one [9-12]. This opens the intriguing possibility of using a single laser system for the fabrication of both microfluidic channels and optical waveguides and also gives the capability of a real three-dimensional integration of the two structures.

In this work we demonstrate the fabrication, by femtosecond laser irradiation, of both high-quality microfluidic channels and optical waveguides on the same fused silica glass substrate. The waveguides are fabricated in order to cross perpendicularly the microfluidic channel in several points. The microchannel is filled with a fluorescent solution to verify the capability of selectively addressing its contents by coupling light into the waveguides. The results demonstrate the possibility of an *in-situ* sensing with a very good spatial selectivity and extremely high signal to noise ratio.

Experiment and Results

The experimental setup used for the fabrication process is presented in Fig.1. It starts with a regeneratively amplified Ti:sapphire laser (model CPA-1 from Clark Instrumentation), generating 150-fs, 500-μJ pulses at 1-kHz repetition rate and 790 nm wavelength.

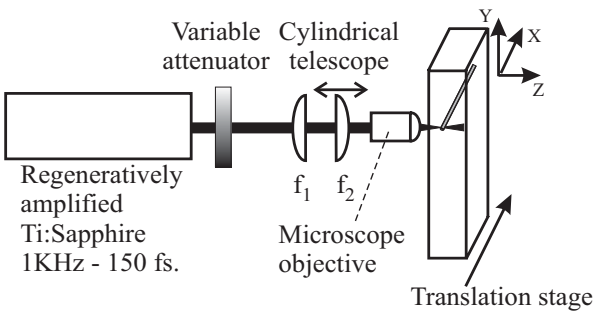

Fig.1 Schematic setup, employing astigmatig beam shaping, for writing the waveguides and the channels to be etched.

In our experiments the sample is translated perpendicular to the beam propagation direction, since it provides a superior flexibility and it allows to define structures of arbitrary length and shape. This geometry has the disadvantage of creating laser affected zones (LAZ) with highly asymmetric cross section [8,12]. In fact, the size of the LAZ cross-section perpendicularly to the translation direction is given by the beam focal diameter $2w_0$ and by the confocal parameter $b = 2\pi w_0^2/\lambda$ (see Fig.2).

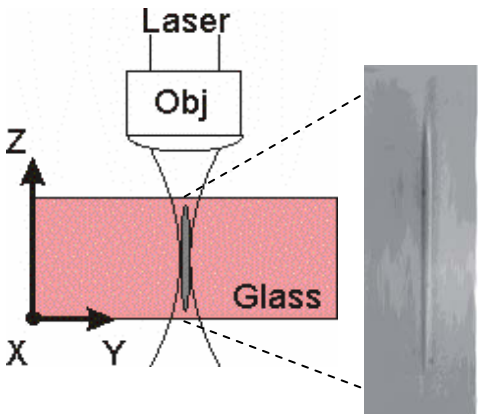

Fig. 2. Schematic of the asymmetric cross-section of the modified region in the transversal writing configuration. The blow-up is a microscope image of a waveguide cross-section fabricated with a laser beam waist w_0=3μm.

For typical focused beam sizes this results in modifications with profile dimensions markedly different along the two directions, making the waveguides and channels cross section strongly elliptical. Instead it is important to produce laser affected zones with circular cross-section, which is quite useful both for the microfluidic channels and the optical waveguides [12]. The beam, initially circular is made astigmatic by passing it through a cylindrical telescope (f_1 =50 mm, f_2=150 mm) that provides a demagnification by a factor 3 in the y direction (see Fig.1). The distance between the cylindrical lenses is finely controlled by a translation stage so as to vary the position of the focal plane in the y direction and thus to control the astigmatic difference [8, 13].

The beam is then focused by either a 20× (NA = 0.3) or a 50× (NA = 0.6) microscope objective. Typically, the focus is located from 100 μm to 300 μm below the surface of the sample, to minimize spherical aberrations of the focused beam by the glass path. The samples are translated by a precision translation stage (Physik Instrumente model M-511.DD).

The channels are manufactured by laser irradiation with pulse energy of 4 μJ through a 50× objective, and translating the sample at a speed of 20 μm/s. A subsequent etching for 3 h in an ultrasonic solution of 20% HF in water provides long and smooth channels. Etching from a single side gives channels 1.8 mm long with an entrance diameter of 85 μm (Fig.3a).

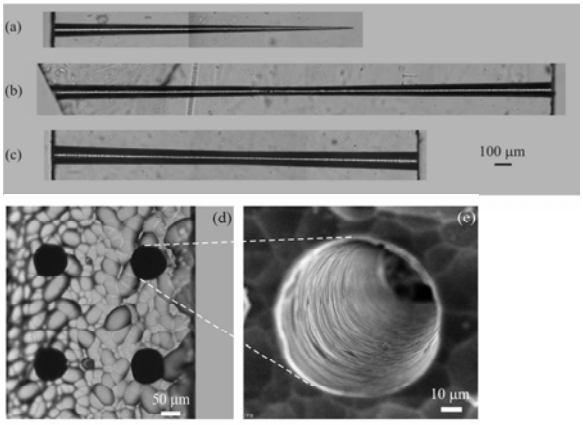

Fig. 3. Microscope images of microfluidic channels fabricated by laser irradiation plus chemical etching (see text for details). Top view (a,b,c); end view (d); SEM image (e).

By using samples of suitable lengths it is possible to etch the channels from both sides with good overlap. According to the degree of overlap different channel shapes can be obtained, such as a long one with a narrow passage in the middle (Fig.3b) or a short one with an almost uniform cross section (Fig.3c). The former has a 3 mm length with an entrance diameter of 90 μm and a waist diameter of 50 μm, while the latter has a 2.2 mm length with 110 μm diameter at the ends and 90 μm at the waist. Both shapes can find applications, for example the one with a bottleneck in the middle, besides giving the longest channel, can align in a single row the cells flowing through it, with advantages in flow cytometry and single cell fluorescence measurements.

One of the main advantages of femtosecond laser processing for microchannel manufacturing is the possibility of easily exploiting the volume of the substrate. As an example Fig.3d shows a square 2 × 2 matrix of microchannels that has been fabricated inside the substrate at depths of 100 and 350 μm, respectively, for the first and second columns. As for a single channel the matrix has been fabricated by a two step process, first each channel is inscribed by the femtosecond laser with the same irradiation parameters and changing the focus depth. After this the four channels are etched at the same time. The size and shape of the channels are well reproducible and smoothly round even for rather different focusing depths. The quality of the channels is very high, as shown in the SEM image of one of them (Fig.3e).

This result, which is rather straightforward with this technology, would require a complicated multi-step process with standard technology.

The optical waveguides are fabricated using a 20× objective, 4 μJ pulse energy and a 7.5 μm/s scanning rate. These waveguides are very smooth and uniform with almost circular cross section and excellent optical properties. The peak refractive index change is 2×10^{-3}. These waveguides support guided modes at 633 nm and 543 nm. The mode profile at 543 nm, measured with a Vidicon camera (Hamamatsu C2400) is shown in Fig. 4. Propagation losses in the green are extremely low. A first estimation by out-of-plane scattering resulted in propagation losses below the sensitivity of our set-up which is 0.5 dB/cm.

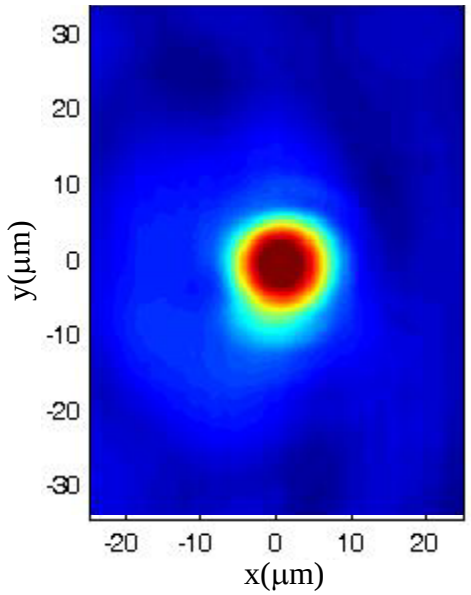

Fig. 4. Experimental near field of the fundamental guided mode at 543 nm.

In order to demonstrate the integration capabilities, three waveguides spaced by 200 μm have been fabricated crossing the central region of the 2.2 mm microchannel, according to the scheme depicted in Fig.5a.
The microfluidic channel is filled with a solution of rhodamine in ethylene glycol. When coupling green light in the waveguides by means of an optical fiber, yellow fluorescence is visible from the microfluidic channel (Fig.5b). The very good signal to noise ratio of the fluorescence is a demonstration of the high waveguide quality, in fact no stray light coming from waveguide scattering reaches the microfluidic channel, thus the excitation is very selective in space. Moreover, this fabrication technique allows an easy implementation of multiple point excitation. In Fig.5 an example of a three point excitation of the microfluidic channel is shown. This would be very useful for the realization of a device capable of measuring the velocity of a particle flow [14].

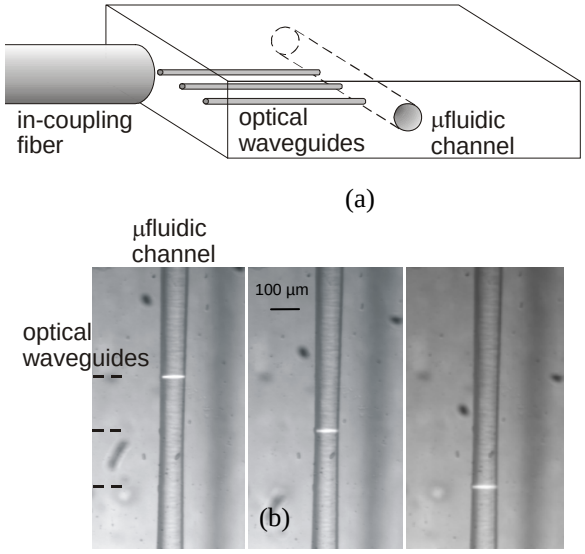

Fig. 5.(a) Schematic of the waveguides crossing the microfluidic channel; (b) microscope image of the microfluidic channel with the fluorescence excited by the optical waveguides, which are not visible due to the low refractive index change and scattering losses.

The next step will be the integration of optical detection methods, and not only excitation waveguides, in order to create lab-on-a-chip devices with integrated optical sensing functionalities.

Conclusions

In this work we presented a two-step method, laser irradiation plus chemical etching, to create microchannels with circular cross section in fused silica substrates. The reproducibility and the three-dimensional capabilities of the process have been demonstrated. The same technique has been used to produce optical waveguides in the same substrates, with excellent optical properties.
We can envisage a single production machine for the biophotonic chips, based on a high-power femtosecond laser, that can manufacture both the microfluidic channels and the optical waveguides for lab-on-chip devices.

Acknowledgements

This work was supported by the European Union within contract IST-2005-034562 (Hybrid integrated biophotonic sensors created by ultrafast laser systems - HIBISCUS).

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