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Scanning optical cavity for internal roughness measurement of embedded micro-structures

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ABSTRACT

Non-invasive characterization and quantitative analysis of embedded microstructures are essential aspects when dealing with microfluidic platforms. This relevance is even more evident in micro-channels embedded in fused silica quartz, fabricated by laser-assisted-etching in HF solution. For these structures, an optimal optical imaging requires extremely flat and smooth surfaces as to avoid cylindrical lens effect and light scattering. The typical internal walls roughness left by laser micromachining is a critical aspect to be taken into account when dealing with on-chip imaging. In this work we investigate the internal walls roughness through a micro-cavity scanning tomography system, able to acquire quantitative optical measurements directly in close embedded micro-channels, and so in a non-invasive way. This system combines the advantages of a low-coherence system with a lens-free configuration and high sensitivity of the optical cavity, suitable for metrology of lab-on-a-chip internal structures.

1. Introduction

Femtosecond laser micromachining is a well-established tool for 3D precise micro-fabrication especially in transparent materials where the high non-linear absorption enables a directly embedded and extremely localized material modification. In particular, thanks to the unique potential to fabricate waveguides and empty micro-channels in fused silica quartz, it is extremely appealing for lab-on-a-chip applications where an accurate alignment of micro-optics and fluidic-components is required in one single substrate [1,2]. In contrast to standard lithographic processes, where the planarly processed layers have to be stacked and bonded together, the mask-less laser irradiation easily allows three-dimensional designs and a rapid prototyping of "buried" optofluidic chip. Microfluidic platforms in glass, fabricated by laser-assisted-etching in solution (HF o KOH), result particularly beneficial for biological analysis as well as cell treatment thanks to high substrate transparency (UV-nearIR), hydrophilicity and being chemically inert. On the other hand, an optimal optical imaging requires extremely flat and smooth surfaces as to avoid cylindrical lens effect and light scattering. Micro-channel cross-section shapes can be easily tailored (from rounded to square or even star-like) by means of the multi-scan writing technique, therefore any special geometry can be realized case by case. On the opposite, the typical internal walls roughness left by laser micromachining is a critical aspect to be taken into account when dealing with on-chip imaging. In recent years, different techniques, such as Atomic Force Microscopy (AFM), Optical Coherence Tomography (OCT), Ellipsometry and Confocal Microscopy, have been applied in order to monitor and characterize the geometry and roughness of 3D microstructures [3]. When using these techniques, some issues have to be considered during measurements. For example, it is necessary to realize not only an optical imaging of exposed preassembled devices, but also to analyze the final assembled devices in which the channels are embedded. In addition, the resolution can be affected by optical scattering, more emphasized at UV and visible wavelengths, and by complex interference from multiple layers and surfaces. The system proposed in this work is based on optical scanning cavity fed by a low-coherence source able to acquire quantitative optical measurements directly in close embedded micro-channels. Optical cavities have always played a relevant role in many applications and studies [4–7], in particular, scanning optical cavities have recently focused the interest in microscopy thanks to their high sensitivity in particle detection [8], in contrast-phase imaging and also in optical tomography [9]. This compact and lens-free technique exploits both the low-coherence property of the source, in order to realize optical tomography, and the confinement of light inside the cavity to reach high sensitiveness without the use of lens. The effect of light focusing is also preserved in the inner layers of the sample, allowing in this way to overcome the trade-off, usually encountered in OCT, between depth of focus and lateral resolution [10]. The system is able to extract contrast-phase and topographic information from the

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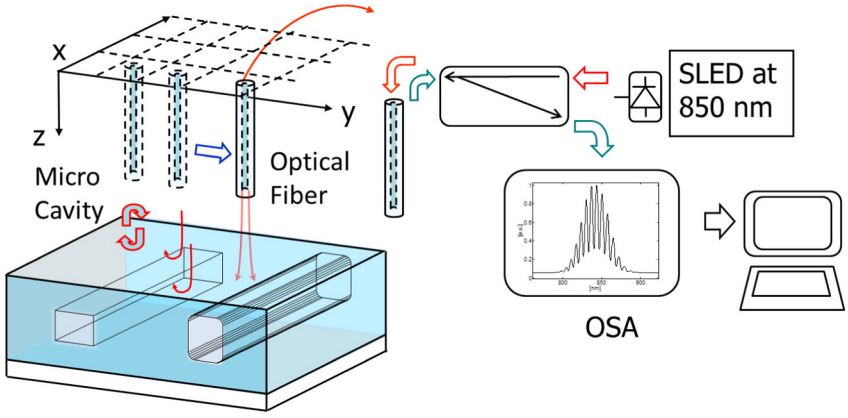

Fig. 1. Scheme of the optical scanning system used to acquire the image point-by-point.

back-reflected interference signal coming from the cavity. All these features play a key role for non-invasive analysis techniques (tomography and quality check) of lab on chip. In this work, the geometry and internal walls roughness of microfluidic channels in glass have been investigated. In particular, quantitative parameters, such as root mean square and correlation lengths are extracted in order to have a detailed analysis of the top and bottom surfaces that enclose the embedded channels. With the aim to highlight the critical aspects of the sample and the performance of the system, a set of exposed sample surfaces have been also analyzed and compared with AFM measurements.

2. Experimental details

2.1. Optical scanning system

In scanning microscopy a probe is moved over a sample in order to build up an image. The information obtained can describe different properties of the sample due to the localized interaction between the probe and sample. Here, the probe is a cleaved optical fiber and the interaction between the probe and the sample occurs through a micro cavity. The latter is realized by approaching the facet of fiber to the surface under investigation, within a working range of tens of micrometers. In Fig. 1, it is reported the optical set-up together with the optical scanning probe used to acquire for each point the back-reflected spectrum coming from the micro-cavity. The optical fiber has a numerical aperture ranging from 0.10 to 0.14 and Mode Field Diameter equal to 5.6 μm. It is fed by a broadband diode laser at 850 nm (bandwidth FWHM = 40 nm, operating current = 150 mA, output power = 0.6 mW), whose wavelengths allows to reduce the optical scattering. A directional coupler brings the back-reflected signal from the optical probe toward a high speed optical spectrum analyzer (Ocean Optics-HR4000). The spectrum analyzer is a high-resolution USB spectrometer with a bandwidth ranging from 650 to 1080 nm. Combining the spectral range of the optical grating with the number of detectors and the pixel resolution, the USB spectrometer provides an optical resolution of about 0.6–0.7 nm. The scan above the sample is made at constant height (around 50 μm) without any control feed-back in the normal direction. In this configuration, the main limiting factor for the scanning velocity, is related to the acquisition time achievable by the Optical Spectrum Analyzer in each scanning point (4 ms/point). However, due to the limit imposed by the piezoelectric control software, in our home-made system a typical value of scanning frequency is around 2 Hz/line. In the transverse direction the sample is moved with nanometric accuracy, thanks to the presence of a piezo-scanner controlled by means of a dedicated software. The optical probe is scanned over a surface of 100 μm × 100 μm with a grid of 256 × 256 pixels. The resolution of

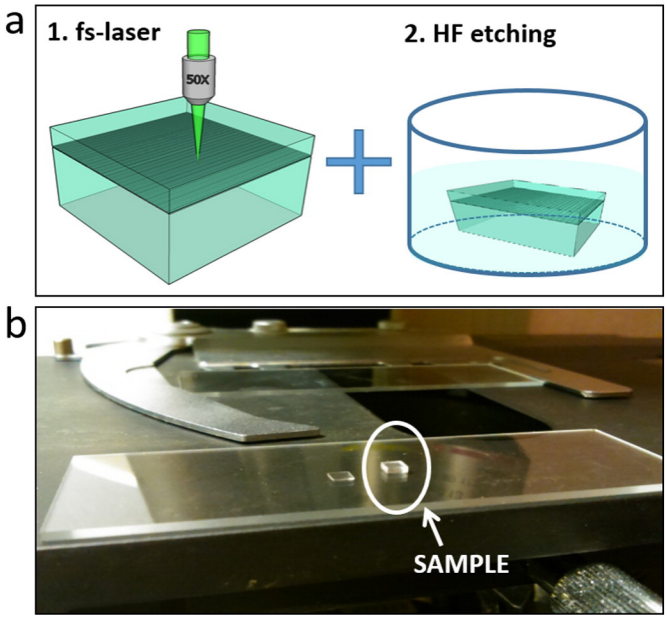

Fig. 2. a) 3D sketch of the samples fabrication: fs-laser irradiation of a flat wall and subsequent HF etching; b) the open out sample after the etching step. Surface A and Surface B are fabricated horizontally at 200 μm depth; Surface C is irradiated vertically to mimic the side-wall of a close channel.

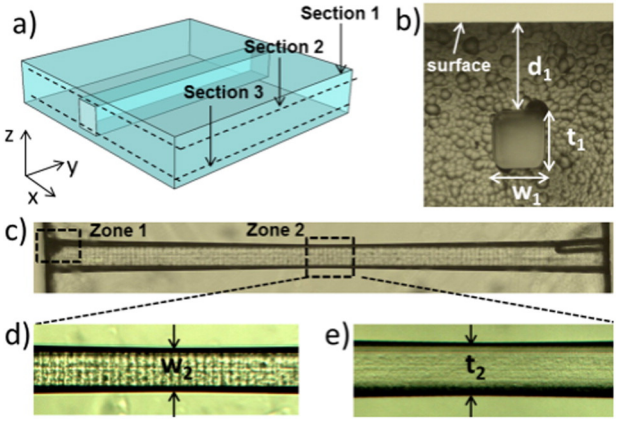

Fig. 3. (a) 3D image of the microfluidic square channel realized inside a glass sample. Optical microscope images of the (b) cross section at the sample border; (c) top view of the channel: dashed lines highlight the zones exposed to investigation; (d) top vision and (e) lateral vision of the central region. Dimensions acquired by optical microscope (±3 μm) are: d1 = 247 μm, t1 = 161 μm, w1 = 149 μm, d2 = 265 μm, t2 = 125 μm, w2 = 100 μm, as in [9].

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