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Ultrafast Bessel beams for high aspect ratio taper free micromachining of glass

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ABSTRACT

Although ultrafast lasers have demonstrated much success in structuring and ablating dielectrics on the micrometer scale and below, high aspect ratio structuring remains a challenge. Specifically, microfluidics or lab-on-chip DNA sequencing systems require high aspect ratio sub-10 µm wide channels with no taper. Micro-dicing also requires machining with vertical walls. Backside water assisted ultrafast laser processing with Gaussian beams allows the production of high aspect ratio microchannels but requires sub-micron sample positioning and precise control of translation velocity.

In this context, we propose a new approach based on Bessel beams that exhibit a focal range exceeding the Rayleigh range by over one order of magnitude. An SLM-based setup allows us to produce a Bessel beam with central core diameter of 1.5 µm FWHM extending over a longitudinal range of 150 µm. A working window in the parameter space has been identified that allows the reliable production of high aspect ratio taper-free microchannels without sample translation. We report a systematic investigation of the damage morphology dependence on focusing geometry and energy per pulse.

Keywords: Bessel beams, ultrafast laser, material processing, filamentation

1. INTRODUCTION

The field of micro- and nanofluidics exponentially expands its field of applications, from fundamental research purposes to sophisticated micro-Total Analysis Systems (µTAS) with increasingly demanding complexity and finesse for chemical analysis, sensors, drug screening or chemical micro-reactors[1]. More recently, a strong research effort has been dedicated to trapping, detection, manipulation and measurements on single macro-molecules such as DNA, in nano-channels and nano-pores[2][3]. Most complex micro and nano-fluidics components are fabricated in poly(dimethylsiloxane) (PDMS) or poly(methylmetacrylate) (PMMA) since these polymers can be easily processed by conventional lithography or soft lithography techniques with a high throughput [4].

However, these materials suffer from two drawbacks. First, their resistance to solvents is low and many proteins adsorb on these materials. Second, they can hardly be used for engraving photonic components, as femtosecond waveguide burning: many local defects lead to a low optical damage threshold and low transparency. Glass is ideally suited for the integration of optical components and its ultra-low chemical reactivity allows for the realization of combined photonic and fluidic systems [5].

In this context, the machining of long channels in glass with a few micrometers in diameter is a key fabrication step. For this, femtosecond laser processing has attracted much interest since it allows for processing both microchannels and waveguides in the same glass sample [6]. The well defined threshold of femtosecond laser ablation renders the ablation quasi-deterministic and allows for the processing of microstuctures in 3 dimensions. Since its broad range of applications, versatility, fast prototyping ability, femtosecond laser processing is currently an active field of intense research [7].

Femtosecond laser microstructuration has been successfully used for microchannels processing in various glasses with high aspect ratio. A two-step technique has been introduced by Marcinkevicius et al [8]: it first consists in a femtosecond laser irradiation of the glass sample. Then, immersion in a fluorhydric acid solution leads to selective etching of the irradiated regions. All kinds of shapes and high aspect ratio were produced with typical channel diameters between 1 and 100 µm. This approach is very efficient, but chemical etching requires several hours [9] and waveguides can be burned in the same irradiation step as microchannels only with much precautions.

Direct channel drilling in ambient air by femtosecond laser ablation does not allow high aspect ratio ablation. Redeposition, debris evacuation limits the accessible aspect ratio to less than 5 for channels of 10 to 100 µm diameter when drilling in ambient air..

Rear-side drilling with water immersion has been introduced by Li et al [10] to answer the problems of producing high aspect ratio microchannels with adaptable diameters, low taper, reduced damaged zone and low number of cracks. Indeed, when the laser processing is performed from the rear surface and followed by translation inward the sample, the translation keeps almost identical ablation parameters along the drilling, that produce channels with low taper. The contact with water at the site of optical breakdown in the transparent sample leads to bubble formation that expels the debris out of the channel, thus avoiding the need for high intensities to extract ablation debris. Microchannels of diameter 5 µm with an aspect ratio up to 50 have been demonstrated at an effective translation speed of 0.3 µm/s including waiting times [10]. Ultrasonic wave agitation helps to increase the channel quality and processing speed at the expense of a channel diameter increase [11]. In this configuration, microchannels were processed with diameter on the order of 30 µm with an aspect ratio of ~20 at a speed up to 30µm/s. To the best of the authors' knowledge, the smallest channels diameters with longest channel lengths in glass were obtained by strong focusing, multiple pass, with effective drilling velocities lower than 1 µm/s.

Immersion-assisted microdrilling of glass by femtosecond laser has thus been shown as very promising for the prototyping of 3D micro- and submicrometer- channels. However, the effective drilling velocity is rather low and a key experimental condition is to precisely maintain the laser focal spot on the ablation front.

A simple approach to directly process high aspect ratio structures is to use high aspect ratio beams. Bessel beams [12] have been previously used for laser processing in metals [13]. However, this led to channels with taper due to the non-transparency of the material. Although Bessel beams have been used to induce index modification in glass [14], direct drilling with femtosecond Bessel beams in transparent media has never been performed. Besides, the propagation of intense femtosecond laser pulses in the filamentation regime also lead to high aspect ratio beams. Several studies of filamentation applied to micromachining and microstructuring in glass have been realized up to here [15]. UV filaments generated in air have also been demonstrated to generate high aspect ratio holes in $LiNbO_3$ [16]. However, the generation of filaments by Gaussian beams is rather complex to control and difficult to apply to laser micromachining since the plasma channel has not a constant density along the propagation direction due to temporal splitting and nonlinear losses. More, at high laser power, the beam enters in a multifilamentation regime [17][18].

In this context, we report a novel and experimentally straightforward approach using femtosecond Bessel filaments, that have recently attracted much attention [19-[21] Filaments created by femtosecond Bessel beams have exceptional properties. Indeed, they are stationary solutions to the nonlinear propagation of ultrashort pulses in the presence of nonlinear losses in Kerr media [22]. They do not lead to multifilamentation, even for powers up to 100 critical powers and can provide plasma channels with constant electronic density [20].

We show here that femtosecond Bessel filaments have the potential to answer these problems. We investigate here in which conditions Bessel beams can lead to high aspect ratio drilling in glass with water assistance and investigate the stability conditions of Bessel filaments by means of a systematic study of the damage morphology on energy and beam position in the sample.

2. EXPERIMENTAL SETUP

Our experimental setup is shown in Fig. 1a. Here we generated a Bessel beam by using a non-pixelated spatial light modulator to imprint the spatial phase of an axicon onto the beam of a regeneratively amplified 100 fs Ti:Sa laser operating at a central wavelength 800 nm. This Bessel beam was then de-magnified by a factor 1/M = 110 using a telescope consisting of a lens of focal distance f = 1 m and a ×20 microscope objective (MO). The resulting beam has a Bessel Gaussian profile with a conical angle $\theta = 10°$, central spot diameter d =1.5 µm FWHM and depth of focus D =150µm FWHM. Although the beam has a Bessel-Gauss profile, it will be designated throughout this article by Bessel beam. The beam has been characterized by imaging in 3D its intensity distribution by translating a CCD camera associated to a 40x magnification arrangement. The study was conducted with borosilicate glass (Corning 0211) samples of thickness 150µm.

3. FOCUSING GEOMETRY

The first geometry investigated was the the following: the center of the Bessel beam was placed on the sample center since the FWHM of the Bessel beam is of same size as the sample thickness. Fig 1b (top) shows the intensity distribution in the sample.. Fig. 1c (top) shows the corresponding damage in the glass slide realized after an illumination by 500 laser shots. The sample has been imaged from side under a Differential Interference Contrast (DIC) microscope. The fringes on both sides of the glass slide are due to Fresnel interferences from the microscope illumination conditions. The result is clearly unsatisfactory since the damage is not homogeneous along the propagation direction.

Therefore, two other focusing geometries were compared: frontside ablation, corresponding to Fig. 1b (center) and rear side focusing with water immersion (Fig 1b, bottom). For an easier comparison of the crater profiles, we realized micro-trenches with in-sample plane translation of the Bessel beam. The samples were then cleaved and imaged by Scanning Electron Microscopy (SEM).

Front-side laser machining with Bessel beams has already been used to ablate metals [13]. In this case, the channels produced had a moderate aspect ratio (~10) and a non-negligible taper which was due to beam truncation by the metallic interface. For glass, we also observed tapering for all front-side trenches realized. A striking example is shown on figure 1c (center). The reason of the tapering is that when the sample is processed in ambient air, the ablation debris are partially redeposited on the sample surface and lower the ablation threshold for following laser pulses. This leads to ablation by the side lobes.

On the contrary, rear side processing under water immersion can produce trenches with vertical walls. A typical example is shown on Fig 1c (bottom) that was obtained with 100 pass and in-plane translation velocity of 0.5 mm/s. The aspect ratio of the trench is 5 and the walls are parallel within an error bar of 3°. Fig 2 shows the processing of a microchannel in such rear-side focusing conditions without translation. The microchannel length is 83 µm and its diameter 2µm.

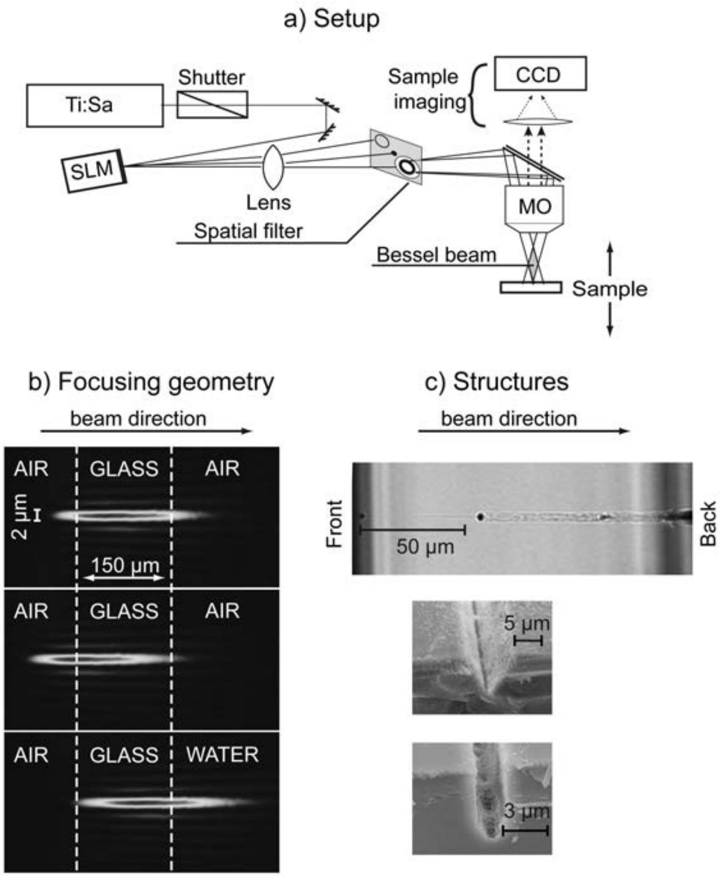

Figure 1 a)experimental setup b-c) comparison of the focusing geometry in the sample and the resulting typical structures produced

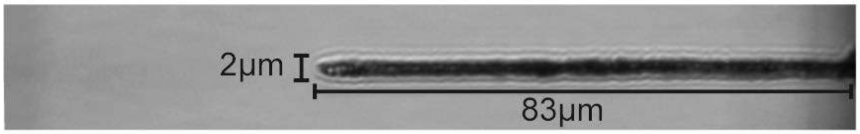

Figure 2: Microchannel processed with 1000 laser shots, without translation, in rear-side focusing conditions.

4. STABLE/UNSTABLE DRILLING REGIMES

Fig 3 shows the evolution of channel diameter and length with energy. It is immediately apparent that for energies between 6.5 and 8 µJ per pulse, the channels present no taper, as in fig. 2. Over a threshold energy 8.5 µJ, the mean channel length rapidly reduces and the channel diameter increases. Moreover, in this regime, the error bars largely increase compared to the previous regime and reach more than 80%. In this regime, the channel diameter does not remain constant over the channel length. The difference between these two regimes is attributed to two different regimes of filamentation[23]. Studies of Bessel filaments in water by Polesana et al [20] suggest that in our case, the appearance of an unstable propagation regime is triggered by a contrast of Kerr nonlinearities at the sample entrance surface.

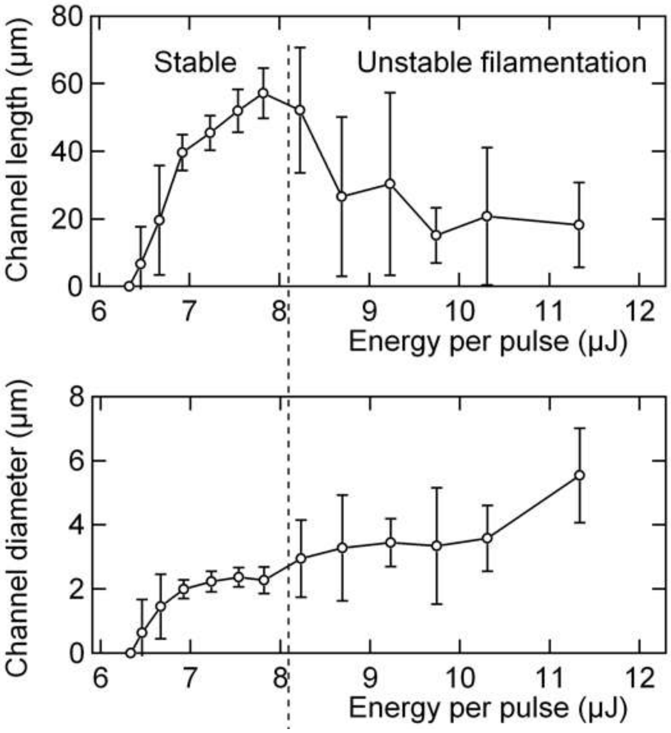

Figure 3 Dependance of channel diameter and length on energy per pulse (100Hz, 1000 shots with water immersion, rear side machining without translation)

5. DEPENDENCE ON BEAM ONSET

To get a better insight into the propagation properties, we investigated the damage produced by 1000 shots without water assistance. No deep ablation is produced. Fig 4 shows the evolution of the damage morphology produced by 130 fs laser pulses, for different energies and 4 different beam positions inside the sample.

When the beam onset is at D= 30 µm after the entrance interface, the damage track is continuous, as expected for stable filaments. The result is near identical for D=0 µm. When the beam starts before the entrance surface (D=-25 and D=-50 µm), the power at the entrance surface is non-negligible. Two different regimes show up. For D=-25µm, the damage track is not constant: dark spots appear at regularly increasing distance. This behavior is reproducible. For D=-50µm, the power at the entrance is sufficiently high to produce surface ablation. The ablated site behaves as an obscurant. The beam self-reconstructs afterwards, but regular dark spots are not visible in this regime.

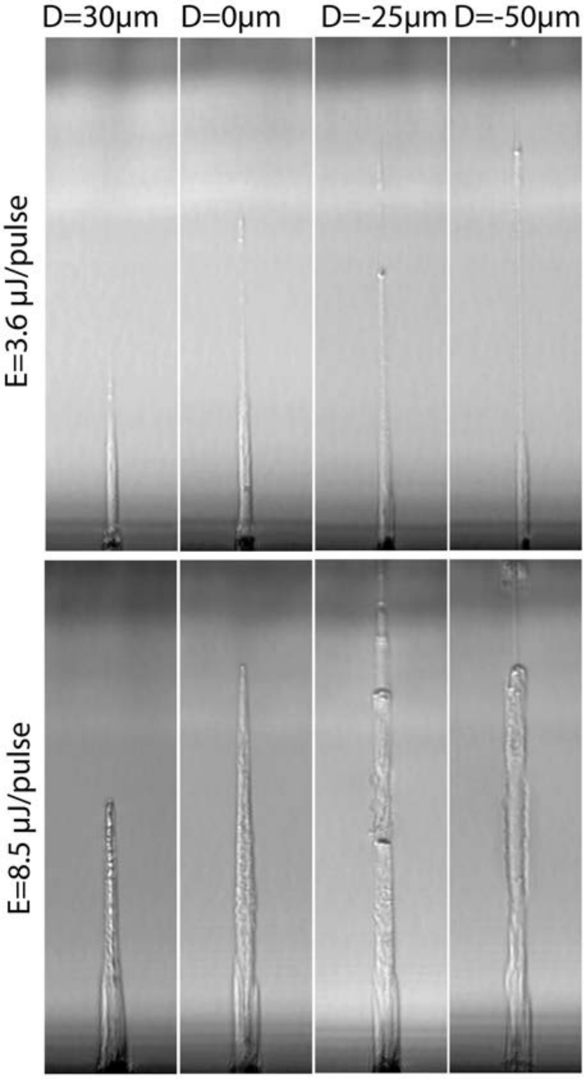

Figure 4 Image with Differential interference contrast microscopy of the damage track produced by 1000 shots, 100 Hz, 130 fs laser pulses.

Figure 5 shows the evolution of the damage with increasing pulse energy for fixed beam onset at D=-25 µm, i.e. 25µm before the sample front surface. From 3.2 to 9.1 µJ/pulse, regular dark spots indicate that plasma density strongly oscillates along the propagation. The number of oscillations increases with energy. From 10.3 µJ/pulse, the morphology of the damage changes: no dark spot is visible. Oscillations are suppressed. Two effects can explain the disappearance of unstability: the energy loss created by surface damage may reduce the nonlinear contrast at the surface, yielding softener input conditions and continuous plasma channel, and/or using higher intensities may help locking the nonlinear dynamical process of single plasma channel generation, as predicted by [20]. Further numerical work is required to better understand these experimental observations.

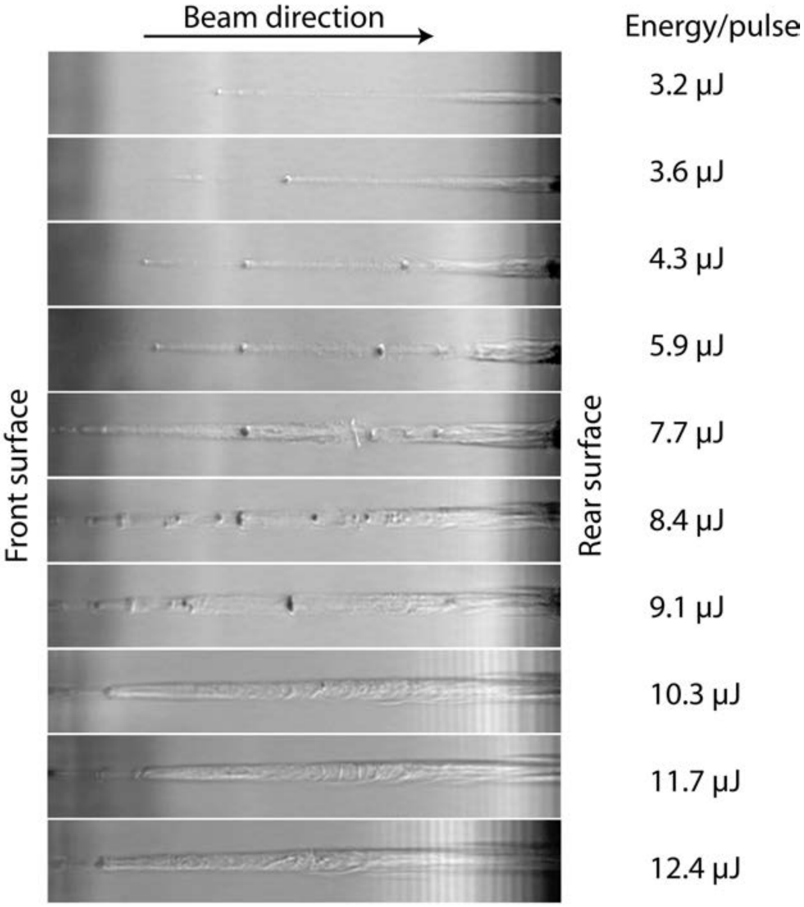

Figure 5 DIC images of the damage tracks produced by 1000 laser shots, at 100Hz, of 130 fs pulse duration for different energies, at fixed Bessel beam onset 25µm before the sample entrance surface.

6. CONCLUSION

We have experimentally investigated the nonlinear propagation of Bessel filaments for high aspect ratio laser micromachining of glass. Microchannel drilling with aspect ratio up to 40 has been exhibited. Two different regimes have been identified. We investigated the dependence of the unstable filamentation regime on energy and beam onset and showed the disappearance of unstability at high energies.

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