

Femtosecond non-diffracting Bessel beams and controlled nanoscale ablation

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Abstract

We review our recent results applying the stable nonlinear propagation of nondiffracting Bessel beams to femtosecond laser ablation in dielectric materials. We describe our spatial light modulator setup that allows for flexible and reconfigurable beam profile synthesis, we interpret the physics in terms of the formation of a steady plasma channel, and we present results of both multishot and single shot machining.

1. Introduction

After their initial discussion in an optical context by Eberly [1], the properties and applications of “non-diffracting” laser beams have been the subject of intense research. Aside from the fundamental interest in exploring the detailed electromagnetic propagation of these novel field profiles, important links have been established with nonlinear ultrafast optics and the formation of localized structures in optical filaments. We have recently developed novel applications exploiting the extended regime of longitudinal localization to femtosecond machining with the aim of fabricating high aspect ratio nano-channels [2-4]. In this paper, we present a review of both the experimental setup used for the creation of reconfigurable beam profile, and describe our experiments in glass reporting multishot and single shot structures. We also discuss how the physics leading to the nanochannel formation is associated with a particular regime of stable nonlinear filamentation that allows for a plasma channel of near constant density to be maintained in the material. The paper draws on work reported in Refs 2-4, but our aim here will be to provide a synthetic overview, focusing especially on the applications potential of this technique.

2. Experimental Setup

Fig. 1 shows the experimental setup that we have developed. The standard Gaussian beam profile from a 100 fs amplified Ti:Sa laser system (Spectra Physics) is spatially shaped by reflection from a non-pixelated spatial light modulator (SLM). The phase mask written to the SLM can be readily controlled by software to imprint any desired amplitude and phase transfer function. For the synthesis of Bessel beams, we use a linear phase modulation with axial symmetry, similar to that applied by an axicon. The Bessel beam is produced in the first order of diffraction and a supplementary phase tilt separates the different diffraction orders. The beam is then spatially filtered (in the focal plane of a lens with 1 m focal length) and the Bessel beam is then reconstructed after an infinitely corrected microscope objective. The lens and microscope objective act as a demagnifying telescope. Typical transverse beam FWHMs were in the range 1 to 1.5 μm , whilst the longitudinal extent of the Bessel beam in the glass sample was typically around a FWHM of 200 μm .

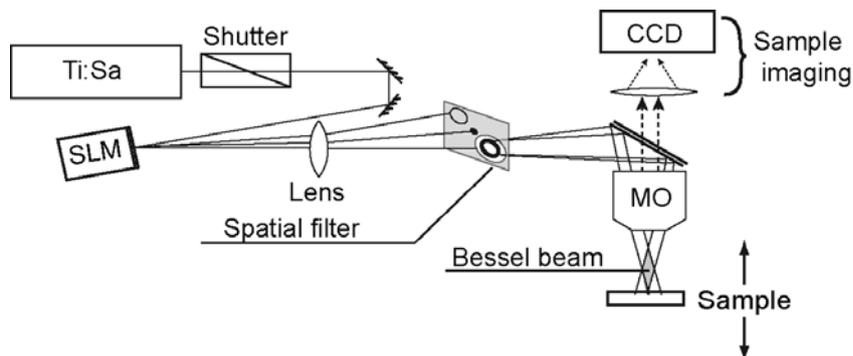


Fig. 1 Schematic of Bessel beam generation and sample positioning and imaging setups.

In the context of controlling the energy deposition in materials [5,6], this setup allows us to explore the use of Bessel beams for controlled nonlinear propagation. This possibility builds upon the important work of Porras et al who demonstrated that the nonlinear propagation equation in the presence of nonlinear ionization admits monochromatic and spatially invariant solutions in the form of a stationary class of nonlinear Bessel beams whose conical energy flow towards the central region can compensate the losses created in the core of the beam [7,8]. Although Gaussian beams typically undergo deleterious nonlinear beam distortion at ablation-level intensities, the nonlinear propagation of Bessel beams can thus resist such instabilities, allowing for uniform energy deposition over extended propagation lengths.

3. Results

Controlling the beam gating from the amplified laser system has allowed us to investigate machining in both multi-shot and single-shot regimes, and we have systematically explored the experimental parameter space for the two cases. In the multi-shot regime, optimal experimental results are obtained using a focusing geometry with the Bessel beam maximal intensity positioned near the rear surface of the sample using water-assistance on the rear side for debris evacuation. This set up and typical results are shown in Fig. 2. For a 150 μm thick Corning 0211 sample and a conical half angle of 7° , Fig. 2 (left) illustrates the basic geometry used as well as (right) the intensity distribution in the sample and the corresponding channel produced with 1000 laser shots at a 50 Hz repetition rate with energy of $7.6 \mu\text{J}/\text{pulse}$. We stress that although with our setup there is *no beam-sample displacement*, we are able to drill a microchannel of 2 μm in diameter, $>80 \mu\text{m}$ in length and near-parallel walls.

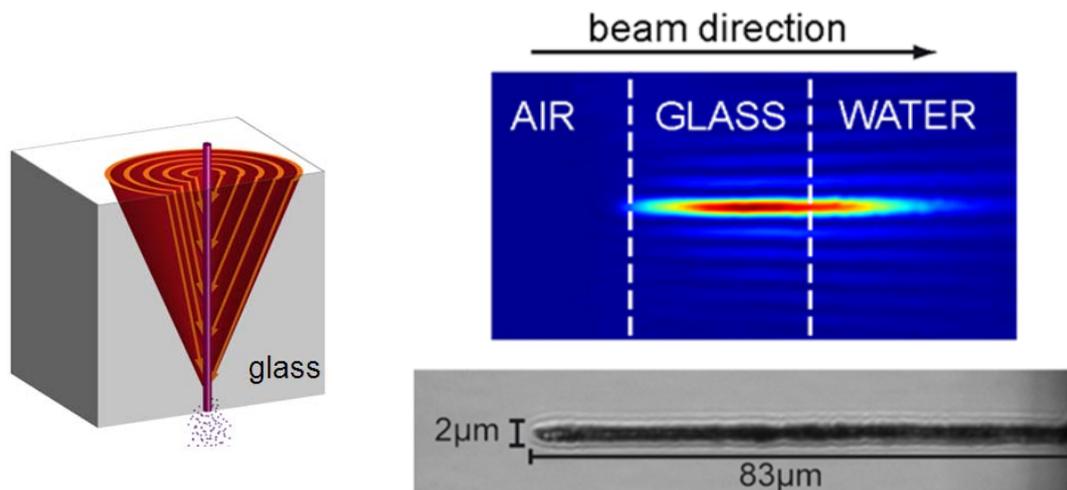


Fig. 2 Left: Illustration of Bessel beam machining process. Right Top: Bessel beam intensity profile referred to sample geometry. Right Bottom: Image of multishot channel drilled in glass (differential interference contrast microscopy)

At higher conical half-angles of around 17° in glass, we have been able to obtain even better results using rear-side illumination but using only single-shot machining, which also presents the additional advantage of not requiring water for debris evacuation from shot-to-shot. With this set up, we have obtained nanochannels with diameters in the range 200-800 nm processed with a single shot of energy 0.5-2.5 μJ . Figure 3 illustrates several results obtained in this regime. The top result shows a channel open at one end (the rear surface) after illumination by a single laser shot of 0.90 μJ ; we clearly see how extremely long nanochannels can be produced using our technique, with this result corresponding to a near constant diameter of 330 nm along a 21 μm length. In fact by optimizing parameters to exceed ablation threshold on both surfaces of a sample, through-channels have also been produced. The technique is highly reproducible, and sample translation in a regular manner beneath the laser beam can be used as a “femtosecond punch” to easily create periodic structures. The figure also shows typical results of such an experiment. We also show a detailed view of a channel opening at the rear surface to illustrate the material redeposition; work is underway to explore and model the hydrodynamics of the material ejection process, as well as to develop surface cleaning techniques to improve the structure quality further.

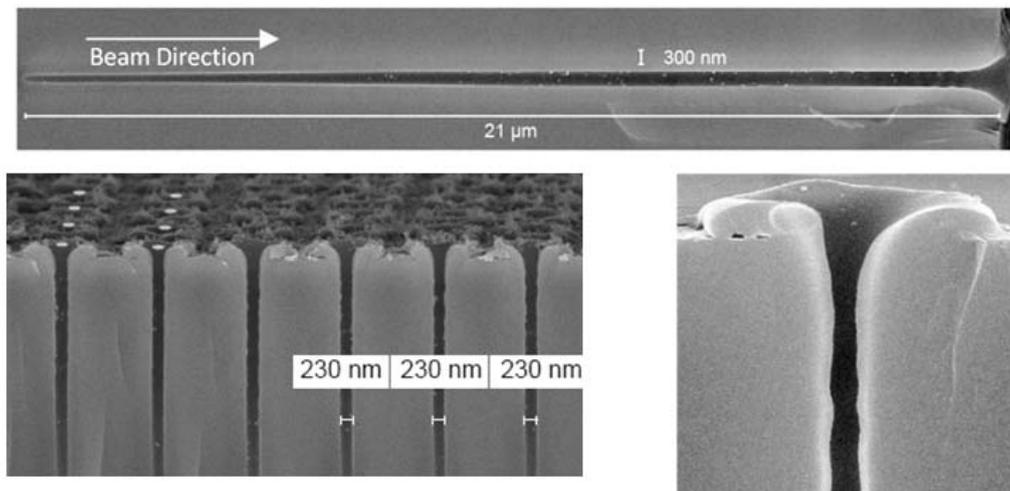


Fig. 3 Top: single channel machined with single-shot illumination. Bottom left: periodic structure machined under similar conditions. Bottom right: detail of surface profile showing clear opening as well as material redeposition.

4. Conclusions

These results have clearly shown the tremendous potential for the use of non-diffracting femtosecond laser beams to fabricate and realize high quality high-aspect ratio nanostructures in glass. This field of research is extremely interdisciplinary, requiring optimized design of laser and beam shaping parameters, careful beam characterization using the techniques of ultrafast optics, and drawing on results of nonlinear filamentation to identify the optimal light-matter interaction geometry. The channel wall parallelism and the overall quality of the fabricated structures is attributed to the intrinsic stationarity of Bessel beams which allows them to resist transverse beam breakup at ablation-level intensities. Our results represent an important application of femtosecond laser nanoprocessing, is applicable to all dielectric materials and allows for independent control of channel length and diameter. We anticipate wide application to the fabrication of a wide range of nanophotonic structures. We anticipate that future work will consider other families of non-diffracting beam for additional control of the types of structures that can be machined, and we will also consider applications in fields such as optofluidics.

5. References

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