# Filamentation of Bessel and Bessel-like beams in solids. Applications to materials processing

**F. Courvoisier, I. Ouadghiri-Idrissi, R. Meyer, J. Del Hoyo, C. Xie,**
**M. Jacquot, L. Froehly, C. Billet, R. Giustand J.M. Dudley**
*FEMTO-ST Institute, Univ. Bourgogne Franche-Comté, CNRS,*
*15B avenue des Montboucons, 25030 Besançon, cedex, France.*
*Corresponding Author e-mail address: francois.courvoisier@femto-st.fr*

**Abstract:** Filamentation of Bessel and Bessel-like beams has enabled a number of applications in the field of transparent materials processing. Spatial phase is an important parameter to control four-wave-mixing and the cross section of plasma tracks.

## 1. Introduction

The filamentation of ultrafast laser pulses inside dielectrics has recently raised tremendous interest because of a new technological application to high-speed dicing of glass. So-called ”stealth dicing” is a two-step technique where the first consists in illuminating the glass workpiece with high intensity ultrafast laser pulses so as to create a plane with weakened material inside the bulk [1]. These allows in a second step, to cleave the material after a simple mechanical stress. This technique does not necessitate to ablate a great amount of material, which obviously is much faster than conventional laser-cutting techniques and reduces drastically the amount of unwanted debris. The typical cutting speed is around 1 m/s.

The important challenge to create the weakened plane inside glass is to control the energy deposition process along the propagation direction : this corresponds to the filamentation of the ultrafast laser pulse. In this field, Bessel beams have proven to be a very useful tool, when they can be generated in the stationary regime to homogeneously create a plasma channel. Here, we highlight several results of our recent work in this area. We demonstrate that spatial phase and amplitude shaping provides a high degree of freedom on the control of the propagation of ultrafast pulses inside dielectrics for material micro- and nano-structuring. We have investigated the regimes of generation of stationary Bessel filaments and generated other beam shapes that also create homogeneous plasma tracks with non-circular cross sections.

## 2. Control of Four wave mixing with longitudinally-shaped beams

Although femtosecond Bessel beams can sustain quasi-invariant regimes of filamentation, they can still suffer of significant modulation instability at high intensity and low cone angle. In this case, Kerr-related nonlinearities dominate the dynamics and the propagation is no longer stationary. The interference between the Bessel beam ($k_{r0}$) and the new spectral components around $k_r \sim 0$ and $\sim \sqrt{2}k_{r0}$ generates oscillations of the on-axis intensity. This is obviously deleterious to control homogeneous energy deposition inside dielectrics [2].

In this context, we have used the fact that Bessel beams can be shaped along the optical axis [3]. Figure 1 compares the growth of new spectral components for different target on axis intensity profiles with identical peak intensity. The only difference between the profiles is the onset intensity rise. It is apparent that, in the Kerr-nonlinear regime, the quadratic input profile (3) generates less FWM and therefore creates less on-axis oscillations. Detailed analysis shows that the reason of this behavior can be found in the spectral phase of the input beam. The amount of FWM can be ranked with the slope of the spectral phase, steeper slopes which correspond to a higher degree of dephasing between spectral components have lower FWM generation efficiency [4]. Interestingly, these results are still valid in the filamentation regime when plasma generation is taken into account. Our results also help and clarify the smooth vs abrupt input transition observed when a Bessel-Gauss beam is launched in a nonlinear medium [5].

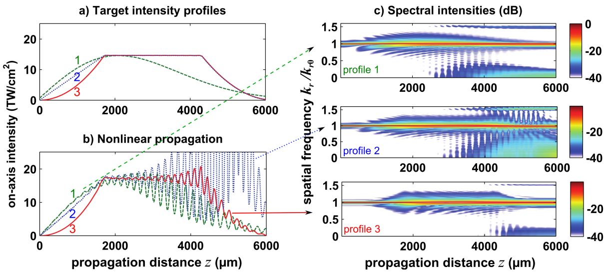

Fig 1. (a) target on-axis profiles launched, (b) simulation of pure Kerr nonlinear propagation of the 3 profiles, (c) corresponding evolution of the spectral intensity along the propagation distance.

## 3. Novel stationary elliptical channels and multiple channel formation from spatially filtered Bessel beams

For sufficiently high cone angle (typ. above 15° in dielectric medium), single shot illumination from high intensity Bessel beam yields the formation of a void inside glass, fused silica or sapphire. However, for a new applications to stealth dicing, nanochannels with non-circularly symmetric cross-sections would be desirable. In this context, we have investigated the propagation of new beam shapes based on the spatial filtering of Bessel beams [1]. An example is shown in Fig. 2 where a Bessel Gauss beam generated from an axicon is filtered in the Fourier plane of a lens. After Fourier transformation by a microscope objective, a Bessel-like beam is generated. It preserves the nondiffracting properties of the original Bessel beam while exhibiting a main lobe with an elliptical cross section. Single shot irradiation of glass with 2.8 ps pulse duration resulted in two interesting observations. First, at relatively low pulse energy, a nanochannel with elliptical cross section can be fabricated. Secondly, at higher energies, when side lobes intensity exceeds the plasma generation threshold, we observed the formation of three parallel channels separated by only $\sim 1\ \mu$m as can be seen in Fig.2(b,c). This indicates that the propagation of the filtered Bessel beam, i.e. the elliptical Bessel beam, experienced a stationary propagation even at relatively high intensity. This technique opens new perspectives for the generation and control of multifilamentation inside transparent media.

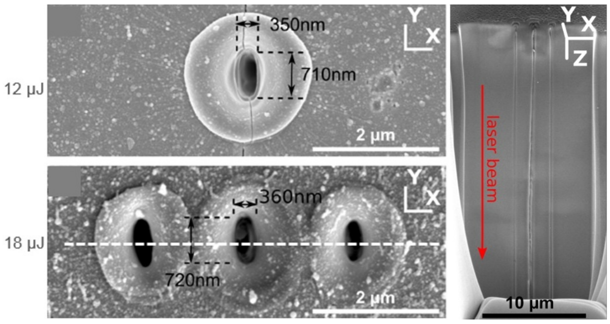

Fig 2. (left) Surface of the glass sample processed by single shot elliptical Bessel beam for two differente pulse energies, (right) image of the cross section of the 18 *mu*J case where focused ion beam milling allows a visual access along the plane marked as dashed line on the sample surface. The 3 channels processed in a single pulse are apparent, with constant diameter.

## 4. Reconstruction of pulse propagation within solids

The comparison of experimental and numerical results is a key to adjust filamentation and plasma generation models. High intensity beam sampling is already a difficult task because of the damage usually generated on the beam sampler. But this approach is obviously impossible inside solids. To answer the need for experimental characterization of the pulse propagation, we have developed a technique to reconstruct the 3D fluence distribution inside fused silica by controlling accurately the relative position between the beam and the exit surface of the sample. This approach was successfully used to characterize the propagation of Bessel vortices [6,7].

Depending on incident cone angle, several nonlinear regimes were observed : stationary, rotating and speckle - like . Experimental results could be quantitatively compared to our numerical simulations. In the stationary regime, tubular plasma could be generated in single pulse inside glass, creating cylindrical damages [7]. We anticipate that this approach can be further used for material compression.

At higher cone angle, the stationary regime is obtained over a wider input pulse energy window, and we noticed some discrepancies between experiments and simulations. These can be explained by the fact that much higher plasma densities are reached within the pulse duration, and simulation of paraxial pulse propagation fail to accurately capture the light plasma interaction.

## 5. References

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