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Using Airy beams for combined glass cutting and edge shaping

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ABSTRACT

When glass is cut to shape, ultra short laser pulses with an elongated, usually straight, focal volume (line focus) can be used to modify the workpiece throughout its entire depth with one single laser shot. At the same time, processed glass is often required to have a seamed or round edge, which usually requires an extra grinding step. Alternatively, curved line foci can be used to combine cutting and edge shaping of glass sheets in one laser process. We reconsider the Airy-Gauss beam for this purpose. Plasma ignition in the side lobes of the Airy beam and surface damage provoke unwanted effects, in particular an asymmetric laser modification of the glass sheet. We provide numerical results on origins of the asymmetry of the volume modification and show that with rather simple optical adjustments a symmetric convex edge can be created in a 920 μm thick glass sheet.

Keywords: Airy beams, Borosilicate glass, Diffractive optical elements, Laser beam shaping, Laser materials processing, Numerical analysis

1. INTRODUCTION

Ultra short laser pulses have been widely adapted as tool for industrial glass cutting throughout the past years. These cutting processes make use of the possibility of creating weakened zones within the glass volume along which the sheet can be separated in a subsequent process. The geometry of the weakened zone and the extent of damage that is created by a single laser pulse depends on the focal intensity distribution of the laser beam and on the choice of laser parameters for a given substrate. The focal intensity distribution of the optical Bessel beam is quasi invariant over propagation distances far greater than its transversal extent and exhibits a high contrast between the main lobe and the side lobes. For these reasons this beam has been widely studied and optimized and is probably the most commonly used one for glass cutting nowadays.

In recent work, a larger emphasis on the other hand has been put on focus geometries that produce a rounded or bevelled edge.¹ Indeed, briefly after we demonstrated a rounded edge using an Airy-Gauss beam in single pass and an etching step for separation,² a mechanically cleaved edge was produced with a modified Airy-Gauss beam.³ Not long afterwards a strongly curved, etched edge was demonstrated employing a multispot approach for edge shaping.⁴

A characteristic feature of the non linear propagation of the unmodified Airy-Gauss beam in glass is the preferential energy deposition in front of the linear focus.² Crucially this meant that we had to position the vertex of the parabolic Airy beam below the center of the glass sheet to be able to perforate the glass sheet completely, thus producing an asymmetric edge.

Here, we first present more numerical results that help to identify the origin of this preferential energy deposition. Subsequently we propose how a simple adjustment of the optical setup can be used to compensate for this effect of preferential absorption and demonstrate a curved, symmetric edge after etching.

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2. PREFERENTIAL ABSORPTION

The asymmetric longitudinal damage distribution along the parabolic Airy trajectory² that is observed in experiments [also see Fig. 1 (a)] can be well reproduced in non linear simulations. Kerr self-focussing seems a likely candidate to explain such a shift towards the laser source, which increases with peak power. This effect is usually included in our non linear model.⁵ Simulations without the Kerr term however indicate, that while self-focussing leads to a slightly higher lateral confinement of the focal region for long pulse durations, it is otherwise negligible. The asymmetry and shift towards the laser source in the distribution of deposited energy along the propagation are practically exclusively caused by plasma effects.

This explanation is corroborated by the observation, that the asymmetry in the simulated energy density strongly depends on the choice of the electron-electron collision time τ_c , as shown in Fig. 1 (b). Typical literature values of τ_c are in the low fs regime,⁶ with a rather large uncertainty. In fact, already assuming a constant electron-electron collision time is a rather crude approximation. Nevertheless, the sensitivity of the deposited energy density on the collision time τ_c in our model can be used to constrain this parameter. We compared the experimentally observed morphology of the Airy beam in combination with our non-linear simulations and found a rather good agreement for $\tau_c = 20$ fs.

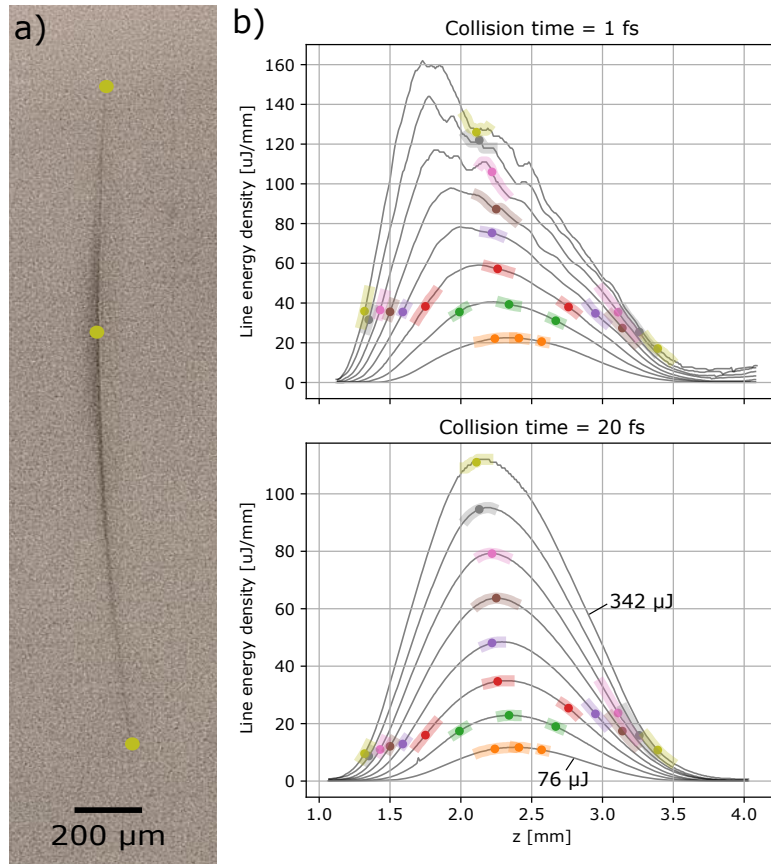


Figure 1. Longitudinal cross section of volume modification (a) for $f = 20$ mm, $t_p = 10$ ps and $E_p = 342$ J with the ends and the maximum indicated by yellow dots. These characteristic points are also marked on the graphs of the energy loss or line density of deposited energy (b) for various pulse energies and two values of the assumed collision time. The error of determining the position on the microscope image is shown as a broad bar. The longer collision time $\tau_c = 20$ fs yields good agreement, with the energy density at the ends being nearly constant across all pulse energies and the energy density maxima occurring at the positions of maximum damage.

3. SYMMETRIC EDGE WITH AN AIRY BEAM

In previous work, it has been demonstrated that lateral offsets of the Gaussian input beam and the cubic phase mask can be used to reposition the Airy focal line. When the beam remains centered on the mirror plane of the 2D cubic phase, the symmetry of the focal distribution is conserved. To compensate for the effect of preferential absorption described in the section before, we adjust the Airy parabola by controlling the offset x_0 of the Gaussian input beam on the cubic phase mask (DOE) by adding a small tilt with a mirror that is placed early in the beam path of our previous optical setup.² The modified setup is shown in Fig. 2. For our choice of parameters, the resulting tilt of the Airy parabola in the glass is in good approximation proportional to x_0/f , where f is the focal length of the microscope objective (MO).

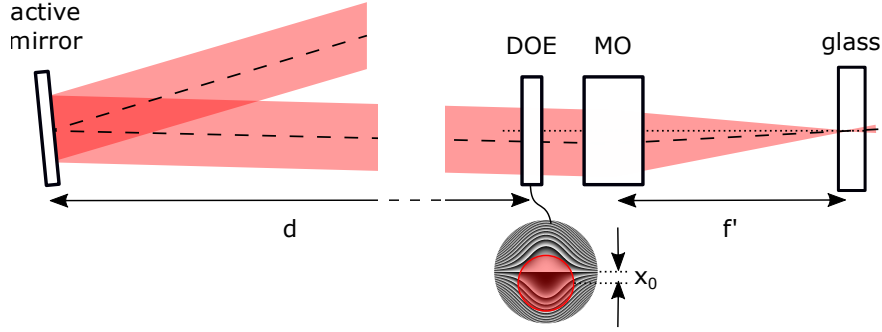


Figure 2. Optical setup as in Sohr et al.,² using a diffractive optical element (DOE) and microscope objective (MO) to create the Airy-Gauss beam. A small tilt early in the optical path ($d \approx 3$ m) effectively introduces a lateral offset x_0 of the Gaussian input beam with respect to the DOE and MO. Note that the offset beam is still centered on the mirror plane of the cubic phase mask.

By fully illuminating the DOE (9 mm clear aperture diameter) with a 10 mm diameter Gaussian input beam we increase the uniformity of the intensity distribution along the propagation compared to previous experiments.² We use an increased burst energy of 300 μ J to achieve sufficiently strong modifications while the other laser parameters remain the same. For this set of parameters we find that a lateral offset x_0 of 350 μ m compensates the asymmetric energy deposition. Such offset corresponds to a tilt of the Airy beam by 2°. We place the resulting modifications, that have a length of ca. 800 μ m, at the center of a sheet of borosilicate glass (SCHOTT Borofloat 33) that is 920 μ m thick. This way we avoid complications due to the lower damage threshold at the surface.⁷ Additionally, we choose a pitch that is sufficiently large to avoid overlap between neighbouring modifications, see Fig. 3.

In a subsequent etching step, uniform removal of the unmodified covers at both surfaces occurs before the increased etching rate of the laser modified glass⁸ leads to a separation when the etching radius exceeds the modification pitch at each depth within the sample, see Fig. 4. The resulting convex edge is symmetric to the accuracy of the relative focus position within the glass.

4. CONCLUSIONS

The permanent modifications that are produced by a focussed Airy beam in borosilicate glass exhibit an asymmetric distribution of damage. This asymmetry increases with the pulse peak intensity and can be attributed to plasma ignition in the side lobes and a resulting shielding of the parts of the beam that feed the lower part of the focal line.

This asymmetry can be compensated by tilting the Airy beam which we achieve by using an input beam with a lateral offset on the phase mask. By taking care to avoid unwanted surface or interaction effects we obtain a symmetric edge as a result of etching after Airy beam laser structuring of a 920 μ m thick SCHOTT Borofloat 33 sheet.

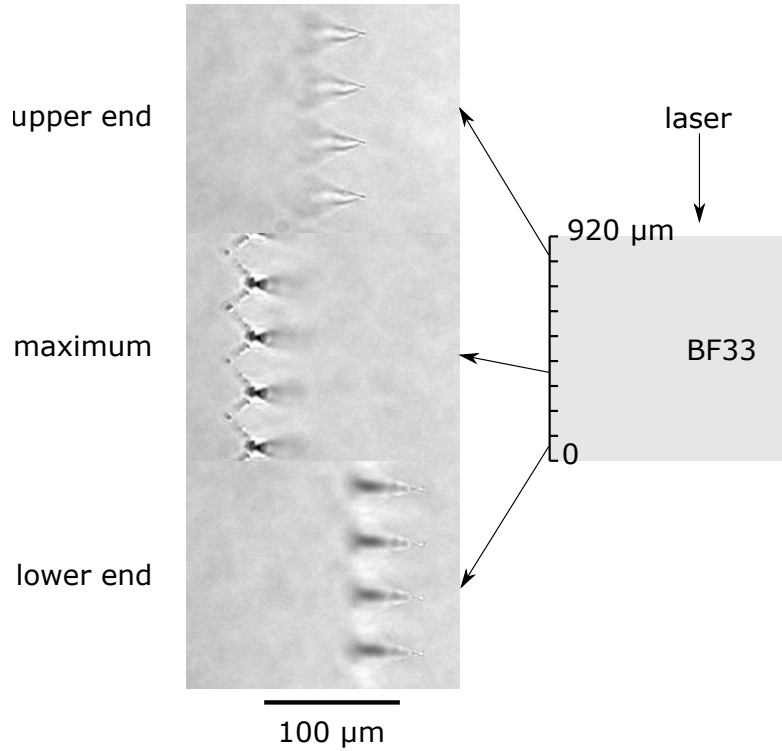


Figure 3. Lateral cross sections of the permanent modifications as used for glass cutting at three different depths within the glass. Positions of the cross sections within the glass are indicated on the left.

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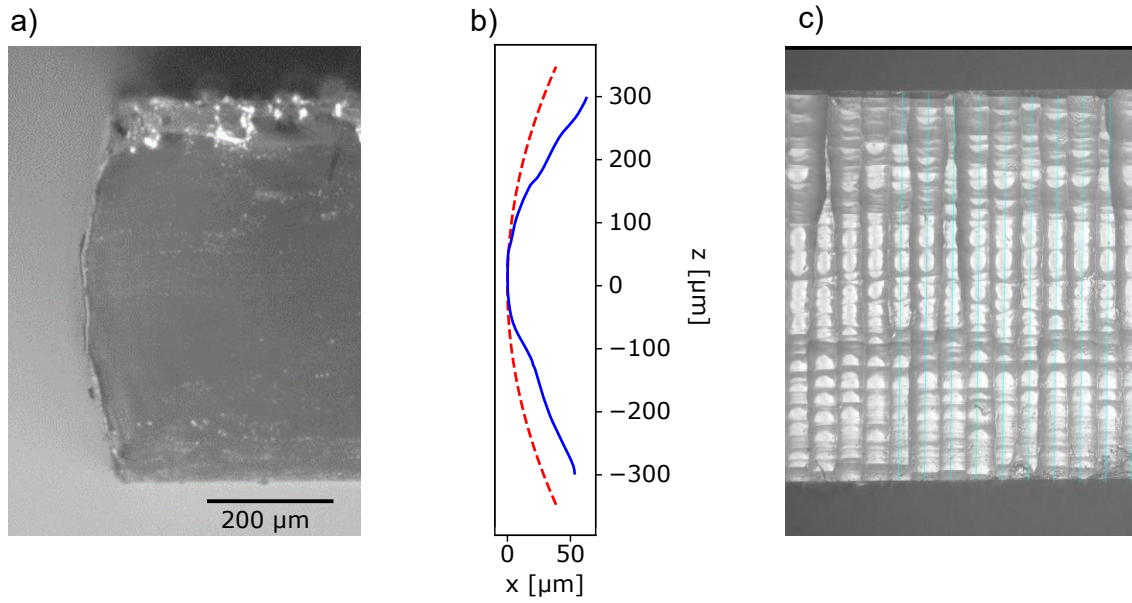


Figure 4. Convex edge (a) resulting from the etching of in volume modifications with an Airy beam using a 10 mm diameter Gaussian input beam offset by $x_0 = 350 \mu\text{m}$, $f = 10\text{mm}$, 2 pulse burst, $300 \mu\text{J}$ burst energy, 5 ps. The average height profile (b, solid blue) measured by confocal light microscopy in side view of the convex edge (c) shows a stronger curvature than the theoretical Airy profile (dashed red) due to etching, similar to previous results.²