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Advanced spatial and temporal shaping for glass cutting application

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Abstract

The use of ultrashort lasers combined with Bessel-like beams is becoming an attractive method for glass cutting as process speed and quality constantly improve. Laser technology potentially offers cutting of the arbitrary complex shapes even for thick glasses. By combining non-diffractive beam shapes and femtosecond bursts it is possible to generate crack along the laser trajectory which enables glass cleaving with minimal mechanical force. We show that flexible optimization of the burst parameters allows to maximize the crack length, which improves the throughput and minimizes damage while cutting glasses up to 3mm thickness in a single pass.

Keywords: Laser marials processing; Glass processing;In-volume modification; Beam shaping

1. Glass cutting using shaped ultrashort beams

Combining Bessel-like beam shaping and use of ultrashort laser pulses is essential for glass processing to ensure a high aspect ratio interaction area with homogeneous energy distribution. Several industrial systems adopt this approach, when a single intense pulse is used to induce required modification prior to separation. Using pulse bursts, however, can give additional benefits to the laser glass cutting method. Indeed, bursts of ultrashort pulses have been successfully used for metal processing, for example, to optimize surface ablation of metals and semiconductors (Neuenschwander *et al.* 2019) or to enhance plasmon colors (Guay *et al.* 2017). For the glass cutting application the burst function is equally important, bursts trigger either

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filamentation process (Esser *et al.* 2011) or favorize cracks generation (Hendricks *et al.* 2016, Mishchik *et al.* 2017) inside the glass. The possibility to produce the cracks directed along the cutting trajectory is essential for the optimization of the glass cutting process (Dudutis *et al*. 2016, Mishchik *et al.* 2017). Top-down through crack facilitates the separation process with no chipping, when only a minimal mechanical force is required for the pieces' separation. In the case of thin (<200µm) and ultrathin glasses a self-cleaving effect may be achieved. The possibility to generate long cracks (length is measured in the cutting plane) also leads to a more efficient use of the laser power. Cracks extend much further than the region of initial local energy deposition (~2µm), therefore, cutting may be performed at much higher speed.

1.1. Optimization of glass cutting using FemtoBurst™ function

The glass cutting experiments have been performed using Tangor femtosecond laser (Amplitude Systemes, 1030nm, 100W, pulse duration <500fs) which has been equipped with a FemtoBurst™ function. This function of burst customization allows to choose the number of pulses and to set individually the amplitude of each pulse in the burst. In this presentation we have studied the effect of the burst shape, and number of pulses on the efficiency of cutting as well as time separation between the pulses of 25 and 50ns.

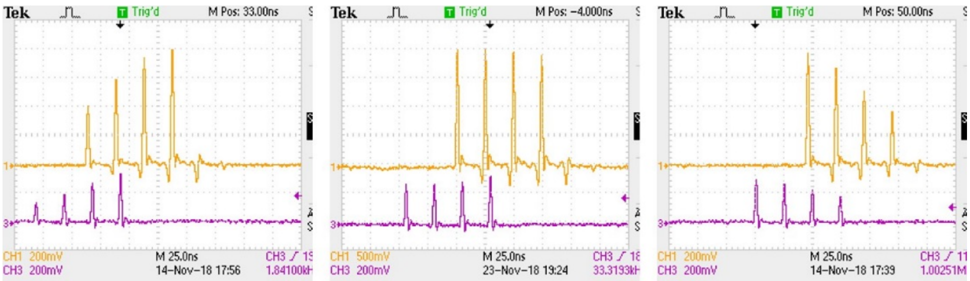

Fig. 1. Example of "rising", "flat" and, "falling" bursts, 25 ns time separation between pulses. Purple line – driving signal, Yellow line – photodetector signal at the laser output

The setup of glass cutting is similar to the one described in Mishchik *et al.* 2017, when a Bessel beam is formed by a refractive axicon. After imaging the primary Bessel-beam with a telescope with a demagnifaction ratio M=10-20, a secondary beam is produced. The beam length l_b and conical angle θ_b can be controlled by changing injected beam diameter d_b and the demagnification ratio *M*. Typically, the value $10° < \theta_b < 20°$ is used. The values of conical angle and beam diameter have been optimized to create l_b in order of 1mm inside the glass.

These Bessel-beam parameters were used to test different burst shapes. Figure 1 demonstrates examples of the output burst forms (yellow line), produced by preshaping seed pulses (purple line) before injecting them into the amplifier. Such method is used to compensate burst form deviation due to laser gain saturation.

The table 1 summarizes the burst shapes used in the experiment: burst with a rising or falling slope have been compared with flat pulse distributions for 4, 5, 6 or 8 pulses and 25 ns delay between pulses. For the flat burst consisting of 4pulses, the 25 ns time interval was compared to 50 ns interval between pulses. In each experiment, bursts of identical energy of 160µJ have been used to induce crack by a single burst exposure. The averaged crack length l_c (measured each time inside the glass volume after averaging several shots, cf. Fig. 2a,b) reflects the process efficiency.

Table 1. Crack length for selected burst shapes. Burst energy Ep=160μJ is equal for each experimental condition and it is distributed along the length of Bessel beam of 1.1mm (at the level of $1/e^2$)

Conditions	Crack length		
	"Rising" burst	"Flat" burst	"Falling" burst
4 pulses at 25 ns delay	25 μm	>30 μm	18 μm
5 pulses at 25 ns delay	26 μm	>30 μm	25 μm
6 pulses at 25 ns delay		22 μm	
8 pulses at 25 ns delay		19 μm	
4 pulses at 50 ns delay		26μm	

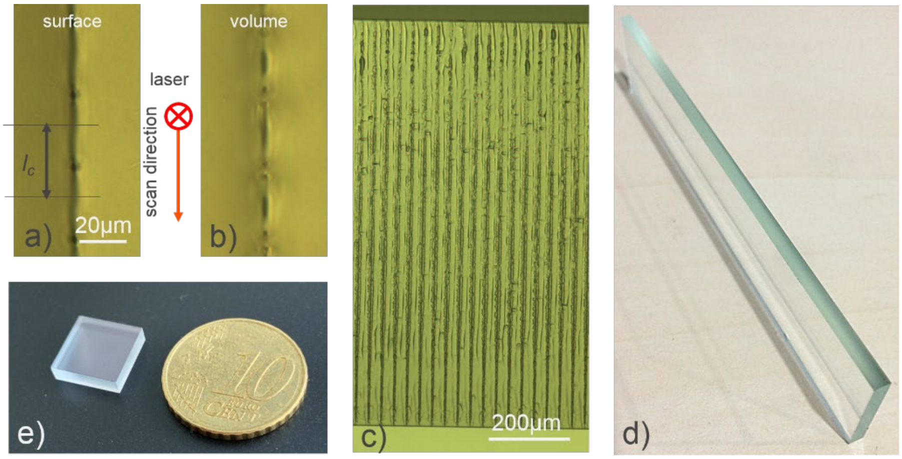

Fig. 2. Cutting of soda-lime glass in optimal conditions. a-c) Cutting of 1mm soda-lime glass using Bessel beam length of 1.1mm. Burst of 4 pulses with energy of Ep=160μJ have been used for cleaving. c) After separation edge shows individual laser impacts separated by 30μm with homogeneous energy distribution. d-e) Cutting of 2.8mm thick soda-lime glass in single pass using 680μJ at conical angle θ_b=10°.

The best results are achieved for a flat distribution of pulses inside the burst. Indeed, according our previously published results (Mishchik *et al*, 2017), there is an optimal pulse energy. If the energy is higher, the pulse will be absorbed in a bigger volume instead of contributing to a higher density of energy. If the energy is lower, absorption is not efficient enough. In our experiment, the latter effect appears for bursts of more than 6 pulses, when cracks become smaller. A time delay of 25 ns between pulses, seems better than 50 ns. Since heat does not dissipate before the next pulse arrival, pulses in the burst contribute more efficiently to heat and stress accumulation.

1.2. Cutting of thick glasses.

Burst shaping helps to optimize thick glass cutting, especially with a thickness >1mm. Indeed, the use of Bessel beams allows to scale linearly the thickness of glass to be cut with the burst energy. However, for energetic bursts, laser gain saturation leads systematically to distortion of its shape. By preshaping the seeded pulses, we were able to compensate this effect to achieve bursts of 5 pulses with total energy up to 1mJ and flat distribution of intensity among the pulses.

To cut thick glasses, the setup has been modified. The conical angle has been reduced to θ_b=10° that allows to generate longer Bessel beam for a given beam diameter. By using d_b=9.5mm, this configuration enables us to reach the length of Bessel beam of 3.8mm inside the soda-lime glass. These adapted laser beam parameters have been used to induce homogeneous modifications and to process 2.8mm thickness glass in a single pass. For 680µJ burst energy of 5 pulses at a target, the crack length of the order of ~20-25µm enables us to cut at 225mm/s at 10 kHz repetition rate, thus, less than 10W of laser output power is used. The example of straight cut and dicing are shown in Fig. 2(d,e).

1.3. Influence of pulse duration

Another parameter which influences the energy absorption is the pulse duration. We have tested efficiency of the cleaving process of 1mm soda lime glass in our stanfard Bessel beam configuration (see the section 1.1) for burst of 4 pulses of total energy of 160µJ. Use of sub-ps pulses with pulse duration <1.5ps will systematically produce intense modification with long cracks, as illustrated in the Fig 3.

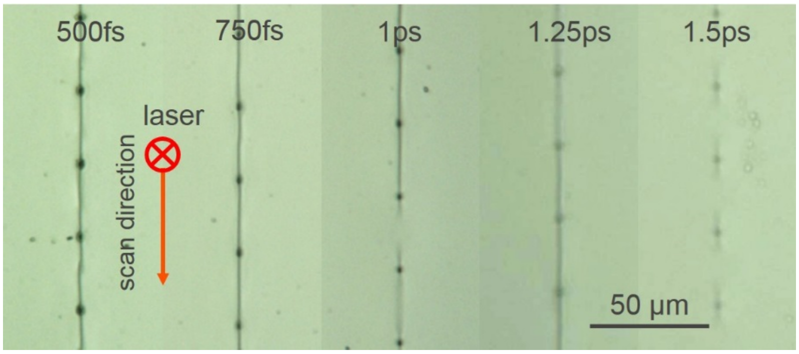

Fig. 3. Cutting efficiency of soda-lime glass with different pulse durations. Bessel beam length is 1.1mm, burst of 4 pulses with energy of Ep=160µJ with equal pulse distribution have been used in each condition.

In summary, burst shaping is a strategy to deposit a minimum of energy inside the glass volume and to achieve a strongest modification enabling glass laser cleaving. It allows high speed and precise cutting of glasses from several tens of µm up to few mm in single pass.

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