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Glass cutting with femtosecond pulses: industrial approach with beam engineering

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Abstract

We develop a dedicated method for glass cutting by laser cleaving. The presented method allow to control the crack orientation and thus optimize the cutting velocity with high quality (pending patent) via a beam engineering module added to the laser. We cut a 500µm thick sample of glass with a single pass. At repetition rate of 100kHz and 80µJ per pulse, cutting is possible at a speed of 600mm/s. Our original method allow also curve cutting. Resulting average roughness of sidewall is less than 1µm. Cutting of other material like sapphire, quartz, fused silica, tempered glass was equally demonstrated.

Keywords: femtosecond laser processing, glass cutting, beam shaping

1. Introduction

Ablation can obviously be used for glass cutting. It is flexible and easy to use but it remains a time-consuming method, preventing the access to numerous industrial applications. Using a simple engineering model applied for Sapphire, cutting by ablation a 50 µm tick sample can reach 250 mm/s with a 100 W average power laser at 1 MHz and a polygonal scanner (20 µm spot diameter and 25 m/s scanning speed). But cutting more than 100 µm in depth is difficult. For glass and other transparent dielectrics, focused

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ultrashort laser pulses may induce highly localized structural modifications. If energy concentration is particularly high, laser-induced stresses and irreversible modifications allow material cutting with high speed. Thus, ultrashort lasers become a versatile tool for machining and direct-write fabrication of numerous devices in optics, photonics, and electronics. Figure 1 give some example of glass cutting for Gorilla glass with the laser cleaving method that we present in this work.

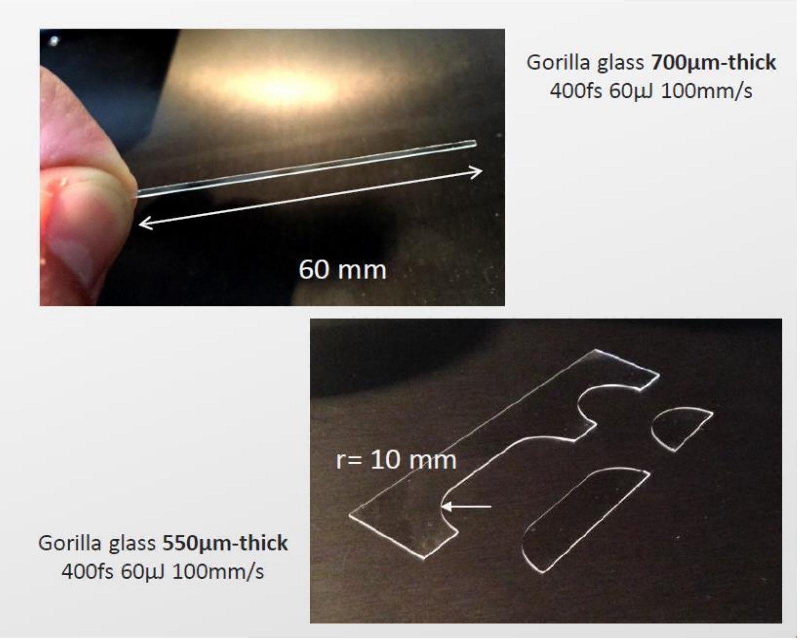


Fig. 1. Example of glass cutting with laser cleaving

2. Laser cleaving with burst of pulses and Bessel beams

In glass cutting applications, extended depth focusing has to be created with uniform energy deposition along the whole material thickness. This can be achieved using a Bessel beam. This non-propagative beam is produced by interferences of the incident Gaussian beam at a conical angle θ_β (cf. Figure 2) and appears as a long and narrow filament surrounded by circles of higher interference orders. The diameter of the central intensity peak is only few microns but has a length in depth of several hundred microns. However, the use of Bessel beams meet some difficulties for femtosecond (fs) pulses. During fs pulses propagation at a grazing angle of $10^\circ<\theta_\beta<20^\circ$, the beam is deviated by the induced plasma, that leads to relatively low free electrons concentration and weaker damage [1,2,3]. For thick glasses cutting, when conical angles $\theta_\beta<10^\circ$ are employed, these nonlinear effects completely prevent the formation of permanent modification [4]. To overcome this difficulty, the chirping of laser pulses was proposed, and ps-pulses can be used [2]. However, in this case, laser absorption efficiency is reduced. As shown in this work, an efficient alternative solution for spatio-temporal control of energy deposition is to use bursts of fs-pulses.

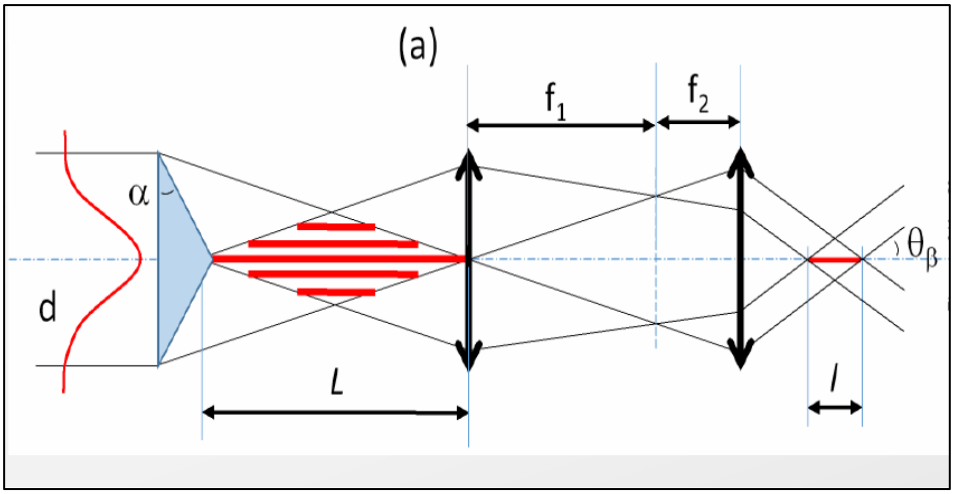


Fig. 2. Use of Bessel beam for glass cutting. Primary beam is produced with a axicon and projected with a demagnifying telescope setup to the focal region.

To illustrate the effect of using burst of pulses, calculated results of energy deposition is presented in figure 3. Modeling during Gaussian focusing is done with NA=0.4 objective and temperature maps calculated 2µs after the pulse incidence. Thermal maps illustrate the differences in energy deposition between 1µJ single pulse and burst of 5 pulses (1µJ in burst or 0,2 µJ per pulse) with 25 ns delay between sub-pulses. Numerical simulation of energy deposition was performed solving wave equation accounting for photoionization and nonlinear propagation. Numerical model is explained elsewhere [5]. Results of modeling depicted in the figure 3 shows that redistribution of energy between sub-pulses has advantages. Indeed, since each pulse in burst has lower intensity, it induces less nonlinear effects, therefore, a pulse energy is absorbed in smaller volume. Furthermore, since the delay between two pulses is less than heat diffusion time, following pulses contribute to the temperature increase in the focal zone. Thus, higher temperature and higher thermal stresses may be achieved.

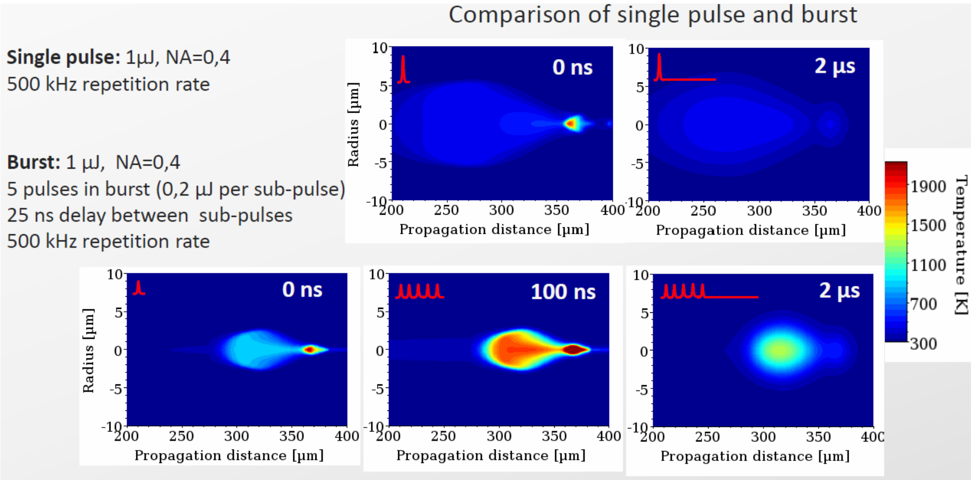


Fig. 3. Calculation of thermal deposition of energy, illustrating the effect of laser burst mode.

3. Experimental results

A hybrid Yb fiber/slab femtosecond laser system operating at 1030 nm (YUJA, Amplitude Systèmes, 10W at 100kHz, 400fs) is used as a source of laser pulses. By selecting few pulses from the oscillator and amplifying them in the slab crystal, high energy bursts are produced. 40.5 MHz oscillator frequency defines a delay of 25ns between the sub-pulses in the burst. Setup for the Bessel beam generation is depicted on figure 2. Primary Bessel beam is produced with an axicon and then projected with a telescope with a demagnification ratio of $M=f_2/f_1$ to the focal region. Length of the Bessel beam in the focal zone can be adjusted according the formula $\boldsymbol{l} = (\boldsymbol{ndM}\verb|^|\mathbf{2})/\mathbf{2}(\boldsymbol{n}-\mathbf{1})\boldsymbol{\alpha}$, where d is the beam diameter, α is the base angle of axicon, and n is the refractive index of the glass. In this work, we have studied propagation of Bessel beam constructed at different cone angle $\boldsymbol{\theta_b} = (\boldsymbol{n}-\mathbf{1})\boldsymbol{\alpha}/\boldsymbol{Mn}$. We have preserved the length of the Bessel beam keeping the magnification ratio M at the same value and increasing twice the beam diameter and the base angle. Interferences are constructed at two different cone angles θ_β of 13.3° and 6.7°. In the same time, the core diameter becomes twice smaller for higher cone angle. For incident pulse energy of 10µJ, the peak fluence is much higher than the modification threshold, estimated to be 2 J/cm^2. For higher pulse energies, non-zero interference orders may contribute to the modifications, increasing the diameter of the plasma channel. It is thus interesting to split the energy of single pulse in a burst, in which sub-pulses energy does not exceed value of 10-15µJ.

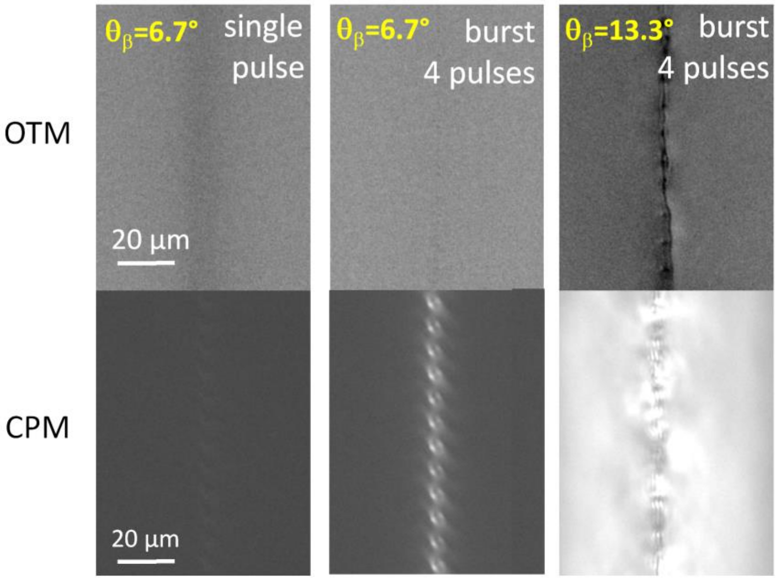
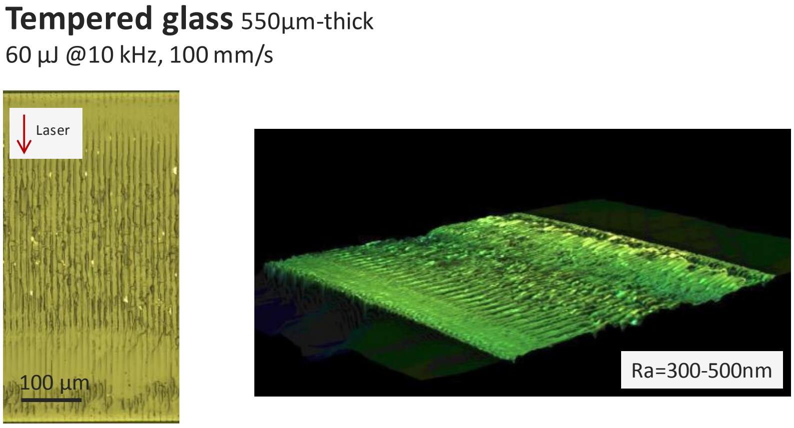


Fig. 4. Localized modification produced with 60 µJ Bessel beam in fs burst mode taken with optical transmission microscopy (on the top), and cross-polarization microscopy (on the bottom).

In-volume modification of soda-lime glass obtained with a 60µJ single pulse was compared to the one obtained with a 60µJ burst where the pulse energy is split into 4 sub-pulses and presented in figure 4. This experiment was done with two different cone angles (6.7° and 13.3°). The distance between subsequent bulk modification is 10µm. Top view of the bulk modification is taken using optical transmission (OTM) and cross-polarization microscopies (CPM). For $\theta_\beta=6.7°$ in single pulse regime, OTM reveals only weak modification (photodarkening). Corresponding CPM images show almost no stress associated with permanent modification. On the other hand, we observe strong and highly localized bulk modification in burst-mode regime using the same optical setup which leads to intense surrounding residual stress. Furthermore, depending on the conical angle, energy localization will be different, generating even stronger modifications and mechanical stresses at higher angle $\theta_{\beta,}$ before crack generation.

We develop a dedicated method to control the crack orientation and thus optimize the cutting velocity with high quality (pending patent). We cut a 500µm thick sample of glass with a single pass. At repetition rate of 100kHz and 80µJ per pulse, cutting is possible at a speed of 600mm/s. Our original method allow also curve cutting. Resulting average roughness of sidewall is less than 0,5 µm, cf. figure 5. Cutting of other material like sapphire, quartz, fused silica, tempered glass was equally demonstrated.



Optical microscopy

Optical confocal profilometry

Fig. 5. Example of cutting quality with spatio-temporal laser cleaving of tempered glass

In summary, glass laser cleaving with spatio-temporal shaping is a strategy to deposit a minimum of energy and thus to induce less defects. It allows high speed cutting and to control at the same time the stress along the cutting depth and to minimize lateral cracks.

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