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Single-pass laser separation of 8 mm thick glass with a millijoule picosecond pulsed Gaussian–Bessel beam

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Abstract
Efficient micromachining of glass with thicknesses of up to several millimeters can be enabled by using picosecond laser pulses with energies in the order of millijoules. In the experiments presented in this article, we investigated in-volume modifications in different thicknesses of borosilicate and soda lime glass using an axicon-generated Gaussian–Bessel beam. The main objective of the study was to demonstrate the separation of 8 mm thick soda lime glass within a single pass of the laser beam.

1 Introduction

Due to the ever-expanding industrial demand for fast fabrication and increasing quality in laser material processing the development of high-power ultrafast laser systems shifted into the focus of interest [1]. Especially for laser processing of otherwise transparent materials, such as glass, high intensities are needed to exceed the thresholds for nonlinear absorption of the laser radiation [2]. Moreover, transparent materials offer the possibility to deposit and distribute the laser energy directly inside the volume. With increasing laser power this opens the way to rise the processing speeds due to the augmented lateral extension of the interaction volume [3]. This is why high-power ultrafast lasers are particularly interesting in the field of bulk modification of transparent materials. For this kind of applications beam shaping plays an increasingly important role in order to create elongated interaction volumes. Promising results have already been achieved in this field especially with zeroth-order Gaussian–Bessel beams [3–10]. The lateral intensity profile of a zeroth-order Bessel beam exhibits a localized, intense central peak with a width in the order of the wavelength surrounded by slowly decaying concentric intensity rings [11, 12]. The high intensity peak of the beam is maintained over a propagation distance that exceeds by orders of magnitude the Rayleigh length reached by conventional laser beams with the same focal diameter [13, 14]. Additionally, the so-called self-healing or reconstruction effect is another interesting feature of Bessel beams. Due to the interference of plane waves, whose wave vectors lie on a conical surface [12], the intensity profile is seen to reform after passing an obstruction that is placed in the center of the beam [15, 16].

Hence, Bessel beams bear a great potential for the microprocessing of transparent materials. The reason that Bessel beams are by far not so commonly used as Gaussian beams to date is that the power is evenly spread over its intensity rings, i.e. each ring carries an equal amount of power [16]. The power carried in the central peak therefore constitutes only a comparatively small fraction of the total power of the beam. For the majority of transparent solids the ionization threshold for permanent structural modifications lies at comparatively high intensities, namely between 10^{13} and 10^{14} W/cm^2 for pulse durations < 200 fs at $\lambda \sim 1$ µm [2]. At the lower end of the picosecond range this threshold still lies at ~ 10^{12} W/cm^2. Furthermore, the axial length over which the central intensity peak of the Bessel beam exceeds this threshold increases with the pulse energy of the beam and thus determines the length of the laser-induced modifications. In the case of cleaving applications of transparent solids, where elongated in-volume modifications serve as predetermined breaking points, therefore the use of Bessel beams so far only work properly for material thicknesses up to two millimeter [17].

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Only in the past few years, high-power ultrafast laser systems have been developed with significantly increased pulse energies and with repetition rates of several hundred kilohertz. In the picosecond range of the pulse duration Negel et al.[18] managed to exceed 2 kW of average power with a pulse energy of 6.7 mJ at a repetition rate 300 kHz. The objective of the present work was to significantly increase the material thickness that can be cleaved after a single pass of the laser beam by using picosecond laser pulses with energies in the order of millijoules. Based on an analytical description of the axicon-generated Gaussian beams, the length of the laser-induced modifications, which varies with the energy of the pulses, can be estimated. The influence of the pulse energy on the modification length was studied experimentally in borosilicate glass (N-BK7 (Schott Inc.)). Experiment and calculation show that energies in the order of millijoules allow to scale the length of the laser-induced modifications to beyond 12 mm. Based on these results we processed and cleaved 8 mm thick soda lime glass, which is the most prevalent glass type in industry.

2 Calculation of the modification length

The transverse amplitude of an axicon-shaped Gaussian beam can be described by a zeroth-order Bessel function of the first kind J_0 [14]. Several articles have been published that discuss the theoretical aspects of Bessel beams [11, 14, 19, 20]. The Gaussian–Bessel beam is determined by two independent parameters: The conical angle or half opening angle β determines the size of the lobes and the radius w of the initial Gaussian beam determines the axial length of the focal line [21]. In the case of axicon-generated collimated Gaussian beams the opening angle β is determined by the wedge angle α according to Snell's law $\beta = \sin^{-1}\left(n_a \cdot \sin\alpha\right) - \alpha \approx (n_a - 1)\alpha$ [20]. The on-axis intensity of an ideal Gaussian–Bessel beam along the direction of beam propagation z can be described by [14]

$$I(z) = \frac{4\pi^2}{\lambda} I_0\, z \left(\left(n_a - 1\right) \tan\alpha\right)^2 e^{-2\left(\frac{(n_a-1)\tan\alpha}{w} z\right)^2}. \qquad (1)$$

It can be seen, that the intensity $I(z)$ in the center of the beam depends on the parameters of the axicon, i.e. the wedge angle α and the refraction index n_a as well as on the parameters of the incident Gaussian beam, i.e. the wavelength λ, the beam radius w, the intensity $I_0 = 2E_P/(\pi w^2 \tau)$ in the center of the Gaussian beam, where E_P is the pulse energy, and τ the pulse duration. The analytical expression (1) applies for axicon-generated Gaussian–Bessel beams propagating in free space. When the axicon-generated Gaussian beam enters into the glass sample, the interference pattern is altered according to Snell's law. In order to take this into account, the wedge angle α has to be replaced with $\alpha\prime \approx \alpha/n_{glass}$ for small angles. The evolution of the peak intensity $I(z)$ along the beam propagation direction z of a Gaussian–Bessel beam is shown in Fig. 1 for the pulse energies 2.0 and 2.6 mJ. In accordance with the experimental situation the calculation was performed for a Gaussian–Bessel beam generated by transmitting a Gaussian beam with a wavelength of 1030 nm, a pulse duration of 7.3 ps and a diameter of 5 mm (1/e^2 intensity) through an axicon made of BK7 glass with a wedge angle of 20°.

In the case of laser material processing of glass, permanent structural modifications occur when the intensity reaches or exceeds a certain threshold I_M. Because laser-induced modifications are based on plasma formation inside the glass volume, the length of the modification l_M is determined by the ionization threshold, which depends on material and process parameters. Furthermore, l_M varies with the pulse energy E_P and can be calculated by setting $I = I_M$ in Eq. (1) and numerically solving for z by using the Lambert W function. The thus calculated dependence of the modification length l_M as a function of the pulse energy E_P is discussed in Sect. 4. With this relation, the threshold intensity I_M can conversely be determined experimentally by measuring l_M with given E_P.

3 Experimental setup

A home-build ultrafast thin-disk multipass laser amplifier [18] operating at a wavelength of 1030 nm was used. The laser provided picosecond pulses with energies up to 2.6 mJ at a repetition rate of 300 kHz, which corresponds to an average power of 780 W. The pulse duration of the amplified laser pulses was measured to be 7.3 ps and the beam quality factor was measured to be M^2 < 1.3. The circularly polarized beam was collimated to a diameter of 5 mm (1/e^2 intensity), transmitted through an uncoated axicon made of BK7 with

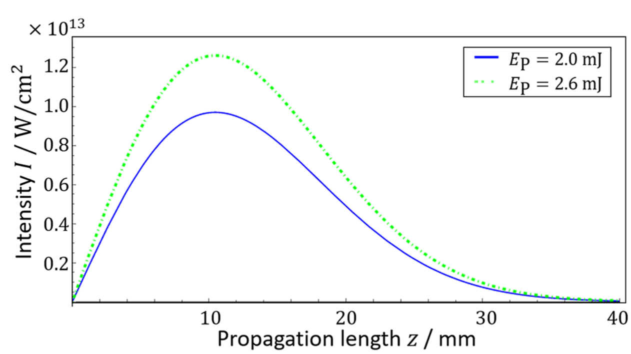

Fig. 1 Peak intensity $I(z)$ of an axicon-generated zeroth-order Gaussian–Bessel beam along the propagation direction z as given by Eq. (1) for the pulse energies 2.0 mJ (blue) and 2.6 mJ (green)

a wedge angle of 20°, and was then directed onto the glass sample. The glass sample was mounted on a translation stage with a maximum travel speed of 5 m/min.

In order to deduce the threshold intensity I_M and to determine the maximum modification length that can be achieved with the maximum available pulse energy of the laser used, the pulse energy was varied from 1.8 to 2.6 mJ. Since it could be expected that the modification length would exceed 10 mm, a raw ingot with a thickness of 26.5 mm was used for the experiment, which in this case was only available in borosilicate glass N-BK7 (Schott Inc.) in this thickness range. To reduce heat accumulation effects as much as possible the translation speed was set to the maximum value of 5 m/min (equals 83 mm/s). Thus, the pitch between two consecutive pulses in the sample was 0.3 µm. The diameter of the central lobe of the Gaussian–Bessel beam (position of the first zero of the intensity) is given by $d_B = 2.408\lambda/(\pi \sin \beta)$ and yielded to 6.8 µm in our experiment. Considering only the central lobe of the Gaussian–Bessel beam, the spatial overlap of consecutive pulses was 96%.

For the cleaving process of 8 mm soda lime glass, discussed later below, elongated in-volume modifications in the order of the glass thickness were generated using a pulse energy of 2.3 mJ at a pulse repetition rate of 300 kHz to create a preferential plane of cleaving. Additionally, the translation speed was varied in the range from 5 m/min down to 1 m/min. The cleaving was then realized by applying slight bending.

4 Results and discussion

4.1 Influence of pulse energy on the modification length

Figure 2 shows the longitudinal cross section of the 26.5 mm thick raw ingot with inscription lines processed at different pulse energies E_p (a) and the microscope image of one modification trace generated using a pulse energy of 1.8 mJ (b) and 2.5 mJ (c) before cleaving. Because laser-induced modifications are based on plasma formation inside the glass volume, scaling up the pulse energy directly affects the type of modification [22]. Depending on the input power of the laser beam and the resulting energy contained in the induced plasma inside the glass volume, laser-induced modifications range from changes of the refractive index by heating and melting of the material (see Fig. 2b), to the formation of voids, which can be generated by microexplosions that leave a less dense or hollow core (see Fig. 2c) [23]. Previous work on modifications generated by Gaussian–Bessel beams at lower repetition rates (10 kHz) with comparable translation speeds also show disrupted traces consisting of a series of voids

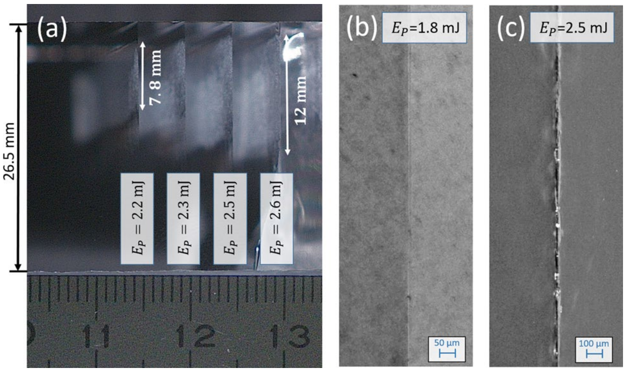

Fig. 2 Picture of the longitudinal cross section of the 26.5 mm thick laser processed raw ingot with inscription lines processed at different pulse energies at a repetition rate of 300 kHz and a feed rate of 5 m/min (**a**). Microscope image of the longitudinal cross section of one inscription line generated using a pulse energy of 1.8 mJ (**b**) and 2.5 mJ (**c**) before cleaving

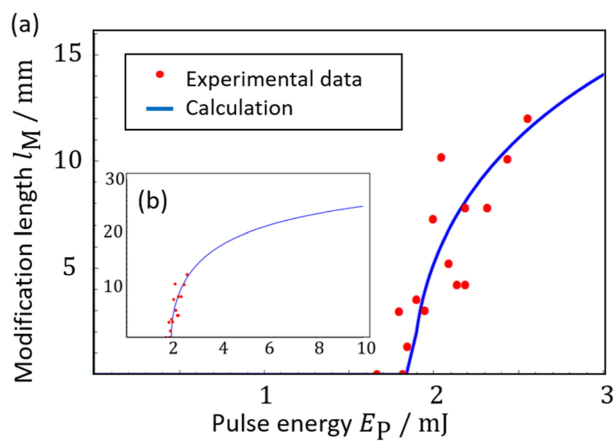

Fig. 3 **a** Length of modification for different pulse energies (red dots) and calculated modification length l_M (blue line). The threshold intensity I_M, at which modifications occur, was used as fit parameter and amounts to $(8.75 \pm 0.14) \times 10^{12}$ W/cm^2. **b** The extended parameter setup shows the theoretical limit for the modification length based on Eq. (1)

along one trace [3, 10]. The comparably high overlap and repetition rate in our experiment results in a more continuous trace permeated with molten regions owing to heat accumulation.

The modification diameter for the inscription line processed at 1.8 mJ was measured to be (7.0 ± 1.5) µm and is in good agreement with the theoretically estimated value for the diameter of the central lobe of the Gaussian–Bessel beam.

The measured length of the modification lines plotted against the set pulse energies are shown in Fig. 3 (red dots). At a maximum pulse energy of 2.6 mJ a modification length of 12 mm was observed.

The fluctuation in the measurements can be attributed to the high overlap of consecutive pulses, which was 96% at the maximum translation speed of 5 m/min. The interference pattern of the axicon-generated Gaussian beam could be disturbed by the previous modification, so that the next modification may not form as expected. In addition, the waviness of the untreated raw ingot surface could lead to further deviations in the length formation.

The blue line in Fig. 3 shows the modification length l_M as calculated with the procedure described above. 4% of power loss were assumed due to the Fresnel reflection on the borosilicate glass at the angle of incidence β. The threshold intensity I_M at which modifications occur was used as fit parameter and was found to amount to $(8.75 \pm 0.14) \times 10^{12}$ W/cm^2. The corresponding threshold pulse energy then is (1.80 ± 0.03) mJ and the corresponding threshold power of the central lobe of the Gaussian–Bessel beam is (0.80 ± 0.1) MW with a corresponding threshold energy of (5.9 ± 0.1) µJ. Because of the strong nonlinear dependency on the intensity [24], the modification thresholds for dielectrics are usually determined as fluences. In our experiments, the threshold fluence in the central lobe (limited by the first zero of the intensity) was found to be (16.2 ± 0.2) J/cm^2. The uncertainties are based on the standard error of the model fit.

The theoretical consideration shows, that with the used beam diameter of the Gaussian beam of 5 mm the length of the elongated in-volume modification can be scaled up to 25 mm (see Fig. 3b). With a pulse energy of 6.7 mJ shown by Negel et al. [18], the modification length would be 22 mm. However, if the modification length is scaled only by the pulse energy, this can lead to serve quality losses due to excessive plasma formation in the region, where the intensity considerably exceeds the threshold intensity I_M. With a pulse energy of 6.7 mJ, an intensity range would be achieved in which enlarged modification diameters and bulges could be observed [9]. Furthermore, the filamentation process by self-focusing, which starts at higher intensities, must be taken into account [25].

4.2 Separation of 8 mm thick soda lime glass

The calculation in Sect. 4.1 shows that a pulse energy of 2.2 mJ is required to separate a glass sample with a thickness of 8 mm. In order to have a certain amount of leeway in the positioning of the glass sample, a pulse energy of 2.3 mJ was chosen for the separation process. Figure 4 shows the front (a) and back (b) side of the 8 mm thick soda lime glass for one inscription line before cleaving. At the maximum translation speed of 5 m/min microcracks up to 1 mm occur on the front side along the inscription line. On the backside microcracks occur sporadically. With decreasing translation speeds, heat accumulation effects let microcracks

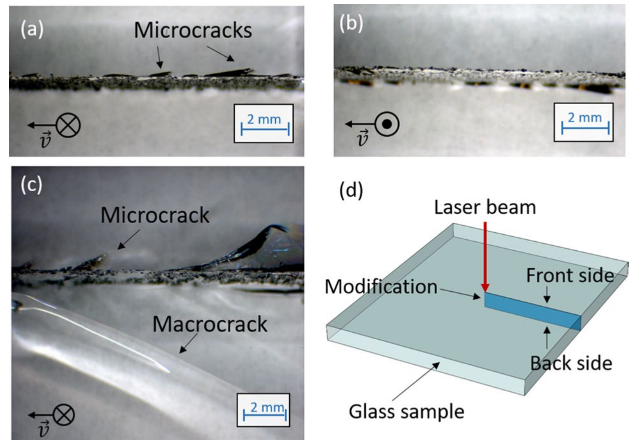

Fig. 4 Microscope image of the front side (**a**) and back side (**b**) of the 8 mm thick soda lime glass after laser inscription with an axicon-generated Gaussian–Besselbeam at a translation speed of 5 m/min. Further parameters were 2.3 mJ of pulse energy, a pulse repetition rate of 300 kHz, a pulse duration of 7.3 ps, and a wavelength of 1030 nm. The symbols ⊗ and ⊙ indicate the propagation direction of the laser beam and ← the feed direction. **c** Macrocracks (crossing the whole sample) occur with reduced translation speed of below 2 m/min. **d** Schematic representation of a glass sample with one inscription line

grow and below 2 m/min macrocracks cross the whole volume (Fig. 4c). At a translation speed of 1 m/min the glass volume cracked completely. The cracks can be attributed to heat accumulation effects caused by the low pitch of 0.3 µm at the maximum translation speed of 5 m/min. Depending on process parameters and material, the pitch should not be less than 2 µm [8], which is an order of magnitude greater than the pitch used. It can therefore be expected that the cracks will significantly reduce in size with a correspondingly lower repetition rate or higher translation speed.

After laser inscription, the glass fragmented intrinsically or could be separated by applying slight bending. Therefore, it can be expected that the breaking strength of the processed glass samples was around 10 MPa or less.

Figure 5 shows the cleaved surface of the 8 mm thick sample of soda lime glass. It can be seen that the entire cleaved surface is structured. Only in the region of microcracks chipping up to 400 µm occurs at the edge of the front side.

On closer inspection, the cleaved surface is found to exhibit cavities and molten regions with a size of up to 100 µm, which are a result of increased melt formation due to heat accumulation. Based on optical topography measurements the roughness of the cleaved surface was measured to be 7 µm (Sa), which is much higher than the roughness that can be achieved by the laser scribe cutting of glass with thicknesses < 1 mm. There, the value of the surface roughness is below 1 µm (Sa). However, the decisive advantage of the parameter set used in our investigation is that there is

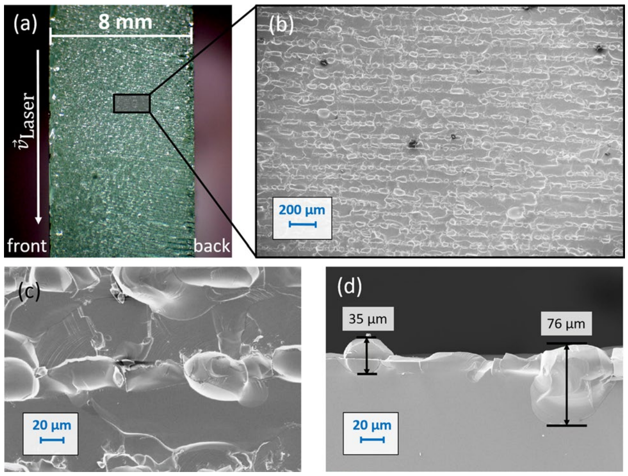

Fig. 5 **a** Cleaved surface of an 8 mm thick soda lime glass. The sample was cleaved after laser inscription with an axicon-generated Gaussian–Bessel beam. The process parameters were 2.3 mJ of pulse energy, a pulse repetition rate of 300 kHz, a feed rate of 5 m/min, a pulse duration of 7.3 ps, and a wavelength of 1030 nm. **b**, **c** Close up of the cleaved surface (top view) and **d** cross section of the cleaved surface

little or no mechanical stress necessary to cleave the glass. A rise in quality, however, can be attained by the use of a lower repetition rate [8, 9, 17] or a higher translation speed, but is also correlated to an increased tensile stress within the cleaving process.

5 Conclusion

In conclusion, we could show that by using pulse energies up to 2.6 mJ it is possible to significantly increase the length of elongated in-volume modifications in borosilicate glass up to 12 mm and we successfully separated 8 mm thick soda lime glass after laser inscription in a single pass. Hence, the material thickness that can be cleaved after laser inscription in a single pass could be increased by one order of magnitude as compared to the state of the art. Soda lime glass is the most prevalent glass type in industry and it is used in a thickness of 8 mm as an industrial standard in various household appliances. This makes the processing of 8 mm thick soda lime glass by laser very relevant for industrial applications.

For the experiments presented in this paper, a home-build ultrafast thin-disk laser was used, which provided picosecond pulses with energies up to 2.6 mJ at a repetition rate of 300 kHz, which corresponds to an average power of 780 W. To generate the in-volume modification in glass, the laser beam was transformed into a Gaussian–Bessel beam by an axicon with a wedge angle of 20°.

The roughness of the cleaved surface is with 7 µm (Sa) comparatively high. This can be attributed to the low pitch of 0.3 µm and the high overlap of 96%. To generate homogeneous modification traces and, therefore, to reduce the roughness of the cleaved surface, the glass has to be processed with a lower repetition rate or, in terms of productivity, even better at a higher processing speed.

The theoretical consideration shows that, depending on the process parameters used, elongated in-volume modifications up to a length of 25 mm could be possible. However, if the modification length is scaled by the pulse energy, this can lead to serve quality losses due to excessive plasma formation in the region, where the intensity considerably exceeds the threshold intensity I_{M}. Furthermore, the filamentation process by self-focusing, which starts at higher intensities, must be taken into account and represents an additional limiting factor.

However, laser-induced elongated modifications using Gaussian–Bessel beams offer a great potential for processing transparent materials and due to the continuous increase of the pulse energy available from ultrafast high-power laser systems it is possible to significantly increase the length of modification. Whereas the scribe and break process with conventional Gaussian beams reaches its limits in terms of cutting thickness and complexness of the outer contour [3], laser-induced elongated modifications provide a promising alternative.

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