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Ultrafast laser cutting of transparent materials: the trend towards tailored edges and curved surfaces

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ABSTRACT

We report on ultrashort pulsed laser fabrication strategies for glass articles with customized edges and curved surfaces. To achieve single-pass, full-thickness modifications along the entire substrate, processing optics are presented that allow for beam shaping of non-diffracting beams and, additionally, for aberration compensation of phase distortions occurring at the tilted or curved interfaces. The efficacy of our concepts is presented by evaluating the surface and edge qualities of separated glass tubes with complex inner and outer contours as well as glass chamfer structures.

Keywords: Beam shaping, ultrafast optics, laser materials processing, structured light, cutting of transparent materials

1. INTRODUCTION

Concepts for laser cutting of transparent materials by introducing volume modifications and subsequent separation by mechanical, thermal or chemical stress were successfully transferred to industry within recent years.[1–3] This was enabled by the availability of reliable ultrafast laser platforms such as a TruMicro 2000 series laser,[4] and adapted processing optics, such as the TOP Cleave cutting optics.[3] The latter ensures a controlled energy deposition into the working volume using advanced spatio-temporal beam shaping.[2,5] With these concepts single-pass, full-thickness modifications with m/s-feed rates were demonstrated for plane substrates with complex inner and outer contours. The processing optics can be adapted to the thickness of a wide variety of substrates ranging from ultrathin (< 0.03 mm) to architectural glasses (> 8 mm).

Based on the developed processing strategies for perpendicular processing, recently, there is an increased demand for customized glass edges, such as, e.g., chamfer or bevel structures. Apart from visual benefits, this is due to the increased edge stability and a reduction of potential edge fractures. Additionally, substrate geometries are becoming more complex and there is interest in cutting glass with curved surfaces, such as tubes, syringes and ampoules as required in large quantities in medical technology.

We will review strategies for cutting of plane substrates and introduce adapted techniques for the fabrication of glass bevels or the cutting of curved substrates. In both cases, the applied focus distributions require sensitive aberration corrections to compensate phase disturbances caused by the beam transition through tilted or curved interfaces. The efficacy of our concepts is presented by evaluating surface and edge qualities of separated glass tubes as well as glass chamfer structures.

2. CUTTING OF TRANSPARENT MATERIALS—THE STATE OF THE ART

There are different processing strategies known for ultrafast laser cutting of transparent materials.[1,6,7] Generally, these concepts are based on the spatially controlled energy deposition onto the surface or into the volume of the workpiece. Particularly relevant for an industrial implementation are such concepts, in which the entire substrate thickness can be modified within a single pass. There are two known approaches for this, both of which are based on generating uniformly and confined high intensities along the substrate through the appropriate

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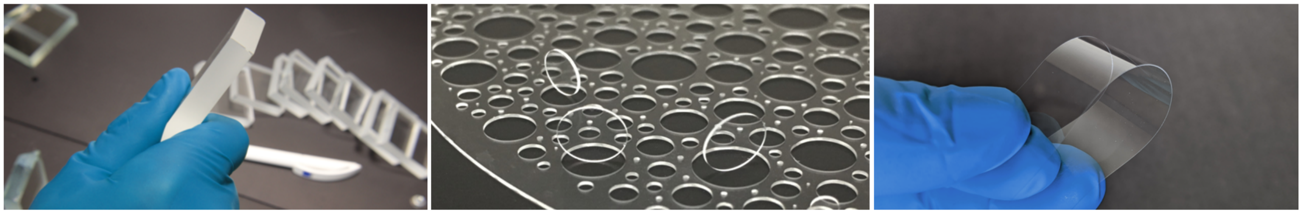

Figure 1. Selected glass cutting examples highlighting the performance of the TOP Cleave cutting optics. Cutting of 10 mm-thick soda-lime glass using a special version of a TruMicro Series 5000 laser emitting 1.5 mJ pulses (left). Separating complex inner contours from TOP Cleave modifications and subsequent ultrasonic bath-assisted chemical etching[17,18] (middle). Controlled cutting of ultrathin glasses (thickness $< 30\,\mu$m) using a TOP Cleave PRO optics with preferential focus orientation and crack control[16,19] (right).

choice of the focus shape. One concept foresees to generate a length-adapted non-diffracting beam inside the volume of the substrate. Through the self-healing properties of this beam class, energy is deposited where the corresponding focus distribution exhibits high intensities—linear propagation considerations for the focus design are sufficient.[2,8–10] A second concept makes use of the non-linear propagation characteristic of diffracting ultrashort pulses in matter which can differ significantly to the situation in vacuum. Making use of a controlled equilibrium of Kerr-lens based self-focusing and plasma defocusing elongated focus zones called filaments[11] can be generated exhibiting non-diffracting beam properties, too. In both cases, adapted laser parameter enable to mainly induce micro explosions which cause weakened areas characterized by voids, cavities and increased stress—so called type III modifications.[12,13] The actual separation is achieved by means of a second process step where external stress is applied to these areas acting as breaking layer.[1,6]

Considering the above mentioned approach using non-diffracting beams, usually shaped with axicon-like elements,[14–16] different processing optics and corresponding ultrashort pulsed laser platforms are commercially available.[3] The state-of-the-art for laser cutting of sheet-like transparent materials is summarized in Fig. 1. Substrate thicknesses from < 0.03 mm (ultrathin glasses) to $\gtrsim 8$ mm (architectural glasses) can be modified with single passes and $\sim$ m/s feed rates.[17] Edges of removed inner and outer contours typically exhibit a mean surface roughness of $S_a \lesssim 1\,\mu$m. Induced laser modifications enable different separation strategies, such as, e.g., thermal, mechanical or chemical. Exemplary processing results (Fig. 1) were achieved using TruMicro Series lasers[4] in combination with the TOP Cleave cutting optics.[3] With regard to the processing head, there has been recent progress which is discussed in the following.

The modular concept of the TOP Cleave cutting optics is characterized by being particularly compact, light and robust and, thus, can be subjected to high accelerations ($> 50\,\mathrm{m/s^2}$). Modules for different beam guidance strategies are equally available as different beam expanders, see Fig. 2 and corresponding beam deflector configurations. There will be TOP Cleave versions optimized for the use with TruMicro Series lasers operating in the infrared ($\lambda = 1030$ nm) and green ($\lambda = 515$ nm) wavelength to cut colored glasses, such as infrared filter glasses. The optical concept is based on a diffractive optical element for the generation of non-diffracting beams and adapted focusing units for the mid-NA region of up to 0.5. Additionally, in designing these objectives, particular emphasis was placed on achieving large working volumes and large working distances. The central beam shaping module is designed to shape radial symmetric non-diffracting beams for uni-directional processing. Likewise, the optics can be equipped with beam shaping elements exhibiting preferential focus orientations (PRO module) for facilitated glass separation.[5,16,19] For aligning the focus orientation to the local contour, a rotational actuator is available. Further beam shaping modules comprise elements for single-pass cutting of curved surfaces, such as glass tubes (TUBE module), including concepts for sensitive aberration correction,[20] cf. Fig. 2. In order to adapt the optics for the respective application, a flexible exchange and adjustment of the central beam shaping element is ensured by the DOE cassette.

With additional configurations, as depicted in Fig. 3, further options for beam delivery are offered. For example, a swivel axis enables to incline the processing head with respect to the workpiece to fabricate tailored edges, such as chamfer or bevel structures.[21] A manual adjustment of focus position is provided by a linear z-axis. To exploit the power and energy performance of a potential high-power ultrashort pulsed laser system, such as, e.g., a TruMicro 6000 Series laser, beam splitting mirrors and displacement units can be applied for

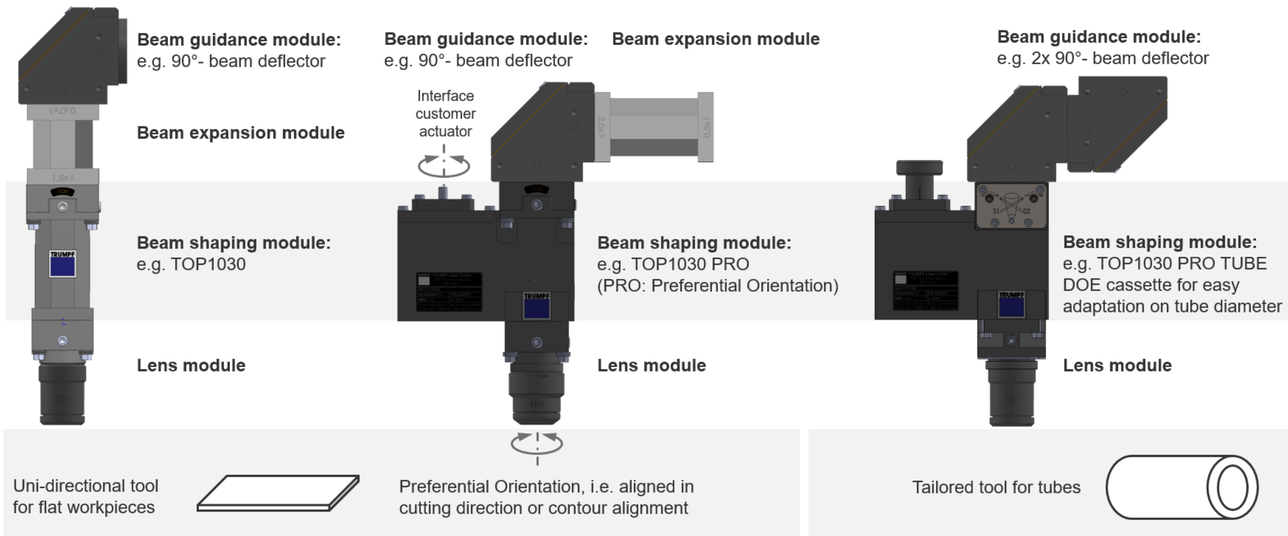

Figure 2. Module overview for TOP Cleave cutting optics with different options for flexible beam guidance, beam expansion and focusing. Central elements for providing structured focal fields are implemented into the respective beam shaping module enabling, for example, facilitated glass separation (PRO module)[19] or cutting of curved surfaces (TUBE module).[20] A DOE cassette ensures to flexibly exchange and align the central beam shaping element to adapt the optics for the respective application.

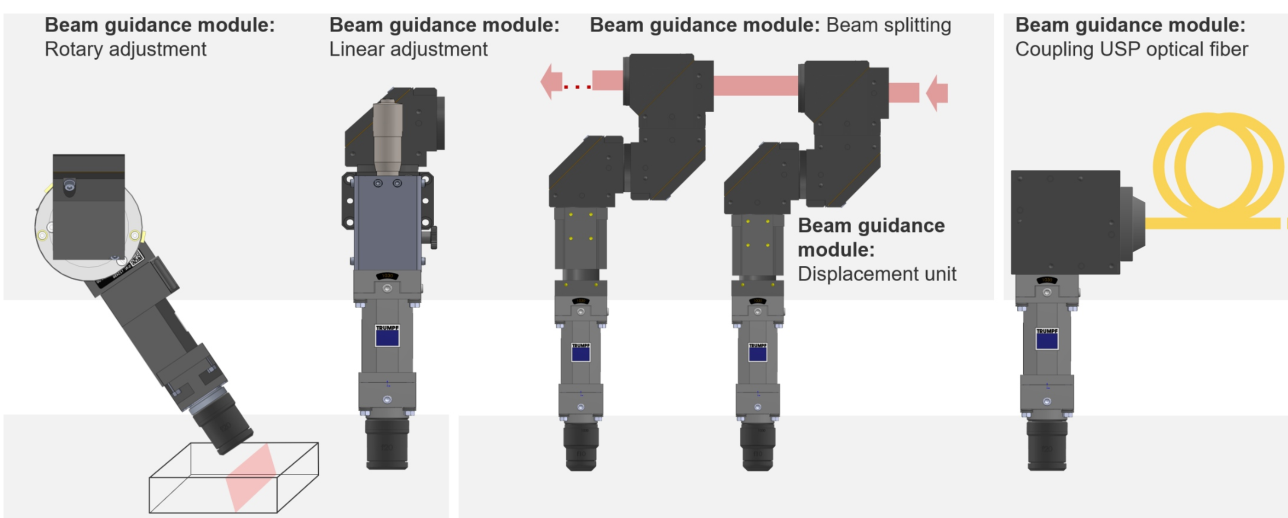

Figure 3. Further TOP Cleave cutting optics modules for adjustment, beam splitting and (hollow core) fiber coupling. The rotary adjustment (left hand side) is particularly useful for tailored edge cleaving and requires an adapted beam shaping module (similar to the tube-cutting module depicted in Fig. 2).

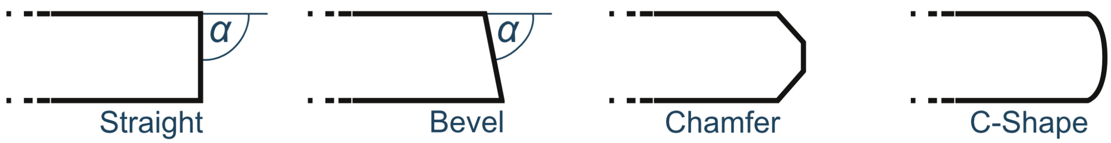

Figure 4. Comparison of different edge geometries for reducing the edge angle α from the typical perpendicular situation ($\alpha = 90°$, see straight case on the left) and to increase edge stability especially when local cracks are weakening the substrate.

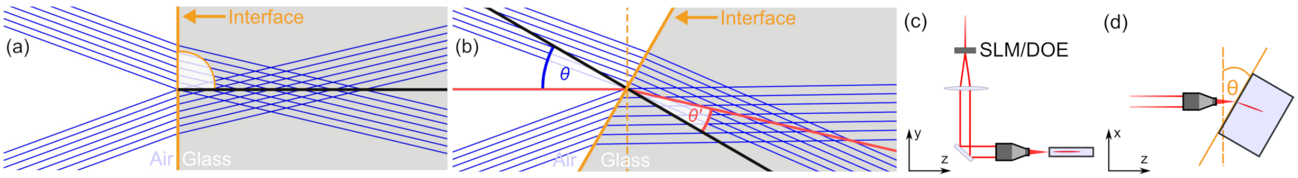

Figure 5. Ray optical representation of the non-diffracting beam's focus situation for incident illumination $\theta = 0$ (a) and for inclined illumination $\theta > 0$ (b).[21] Corresponding schematic of the optical setup with an SLM or DOE as axicon-like element implemented into a $4f$-setup (c) with definition of the inclination angle θ (d).[21] In this concept the refraction angle θ' (b) can be identified with the edge angle definition of Fig. 4, thus $\alpha = 90° - \theta'$.

parallel processing and throughput scaling, respectively. Available on request is a further module for delivering fiber guided ultrashort pulses using a hollow-core fiber.[22]

3. TAILORED-EDGE CLEAVING

Glass cleaving concepts of sheet-like substrates as presented in Fig. 1 are based on laser modifications which extend perpendicularly from entrance to exit surface. The separated substrate usually exhibits a perpendicular edge, too, without any taper angles, thus, $\alpha = 90°$, see straight edge in Fig. 4. To protect the edge and for increasing its stability, especially when local cracks and chippings are at hand that may have been caused by impacts, the edge angle needs to be reduced, ideally to $\alpha_{\min} = 45°$ in case of bevels or chamfers.[23] To this, several concepts are established which are mainly based on mechanical grinding and polishing.[24] However, in order to avoid post-treatment and additional cleaning steps as well as to increase the process speed, a laser-based process is also being sought here. In the following, different concepts are discussed to achieve beveled substrates as simplest form of a tailored edge. Until further notice, we always refer to optical concepts that create a non-diffracting focus distributions inside the volume of the material.

In general, it is preferred to machine the workpiece with a vertical processing head and to incline the focus distribution. Following this concept, tilt "aberrations" needs to be applied to the non-diffracting beam. Depending on where these aberrations are introduced to the corresponding optical field (near-, far-field or in between), wedges (near-field) or simple transverse misalignments to a focusing unit (far-field) can generate inclined non-diffracting beams with tilt angles up to $\sim 10°$ in vacuum ($\sim 7°$ in glass). Admittedly, these inclination angles are comparatively small, however, the optical realization is simple and there is no necessity for complex rotational axes systems.[25] Besides the advantage of already protecting the edge, it is known that inclined focus distributions can be used to facilitate inner contour separation.[25,26] As there is no material expelled during the modification step, a damage-free removal of inner contours is a challenge. However, using the tilted non-diffracting beam in a first step and a subsequent perpendicular modification step, enables to generate a cutting gap by releasing the inner contour with tilted edges. Now, the separation from components with perpendicular edges becomes possible including challenging contours such as, e.g., glass rings of a few 100 µm wall thickness.[25,26]

A further increase of the focus inclination angle and, thus, a decrease of α, cf. Fig. 4, is achieved by tilting the processing head, see Fig. 5. Considering the refractive index mismatch (typically air vs. glass) and Snell's law, corresponding Fresnel coefficients, as well as the required cone angles forming the non-diffracting beams, highest achievable values for θ' are in the range of 35°, cf. Fig. 5 (b) (with $\theta \approx 50°$, $\alpha \approx 55°$ in this particular case). As can already be seen in the geometric optical representation depicted in Fig. 5 (b), the tilted surface will yield aberrated focus distributions that can be compensated with phase-only elements and telescopic setups shown in Fig. 5 (c) and (d). The axicon-like element that is shaping the non-diffracting beam and compensating for potential phase

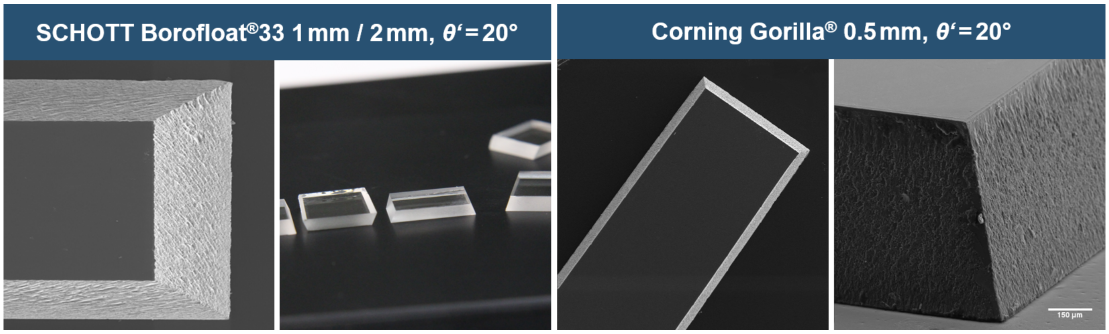

Figure 6. Processing results of different glass substrates with bevel edges, $\theta' = 20°$. After inducing laser modifications with aberration-corrected non-diffracting beams[21] the samples were separated mechanically. Corresponding mean surface roughness was determined to $S_a \sim 1\,\mu m$.

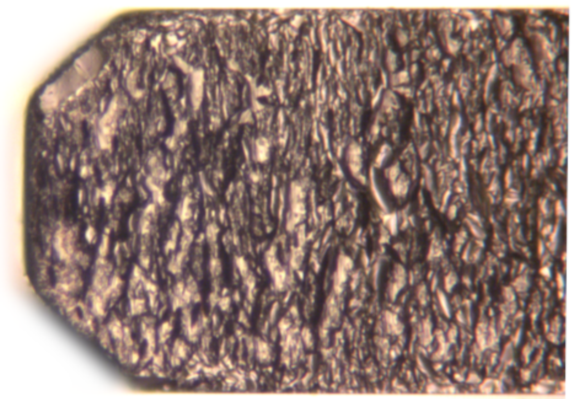
Figure 7. Chamfered edge ($\sim \pm 45°$) in 550 µm-thick Corning Gorilla glass achieved from single-side processing in combination with an ultrasonic bath-assisted selective laser etching strategy.

distortion is realized diffractive optically using flexible liquid-crystal-on-silicon-based spatial light modulators or stationary diffractive optical elements.[21] In Ref. 21 we demonstrated the efficacy of this aberration-correction using pump-probe microscopy[10,27] and directly measured temporally and spatially resolved the successful energy deposition as known from focusing non-diffracting beams behind plane surfaces in incident illumination.

Processing results highlighting a successful machining of bevel structures in different glasses and thicknesses are depicted in Fig. 6. Achieved samples were mechanically separated using running pliers and exhibit a mean surface roughness of about $\sim 1\,\mu m$. Although demonstrated here for $\theta' = 20°$ only, a modified TOP Cleave cutting optics, cf. Fig. 3, in combination with TruMicro Series lasers can achieve beveled edges with $\theta' = 30°$-angles.

At this section's end, as an outlook, we would like to present a $\sim \pm 45°$-chamfer structure in 550 µm-thick Corning Gorilla glass achieved with an optical concept that is not commercially available, yet. We show the sample in Fig. 7 which was laser modified with an optical head requiring single-side access only and achieved an effective cutting speed in the order of hundreds of mm/s. The final chamfer geometry was achieved from applying an ultrasonic bath-assisted selective etching concept.[18]

4. CLEAVING OF CURVED-SURFACE SUBSTRATES

As demonstrated in the previous section, sensitive aberration compensation is required to achieve non-diffracting focus distributions behind tilted interfaces for successful cleaving application, cf. Figs. 5 and 6. The situation for curved interfaces depends on the actual interface shape and especially on local radii, however, will require a similar phase correction as required for tilted interfaces, see Fig. 8. In the simplest case, the curved surface corresponds to that of a cylinder. This local geometry is of particular interest since vials, ampoules or syringes, as required

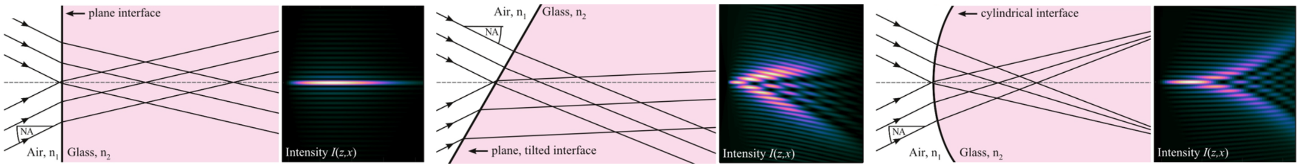

Figure 8. Focusing non-diffracting beams behind plane (left), tilted (middle) and cylindrical interfaces (right). Sensitive pre-compensation of occurring aberrations is required for the last two cases to restore the salient features of this focus class and to achieve a confined energy deposition along the entire substrate thickness.[5, 21]

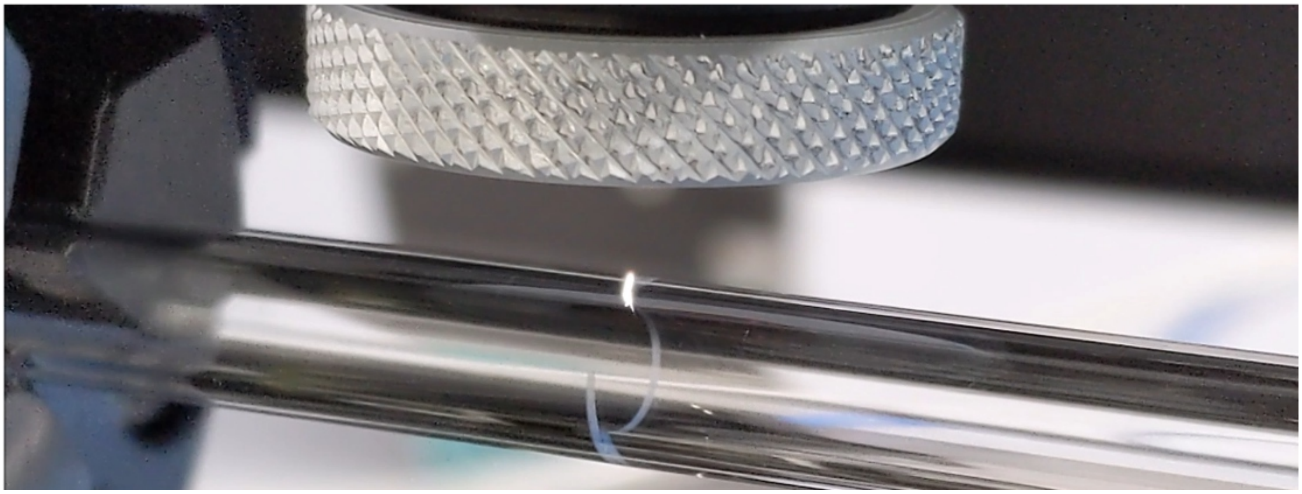

Figure 9. Plasma response of the glass tube, camera-recorded during inducing laser modifications from aberration corrected non-diffracting beams. The borosilicate tube is rotated along its cylindrical axis with respect to the optical axis of the processing optics illuminating the tangential surface perpendicularly from the top, see housing of the focusing unit. Besides the elongated plasma glow, full-thickness modifications along the entire wall thickness are visible to the naked eye. The entirety of modifications acts as breaking layer at which the actual separation is achieved, by applying mechanical, chemical or thermal stress, cf. Fig.10.

in large quantities by the medical industry, at least locally exhibit cylindrical surfaces. Completely determined by radius of curvature R_T, wall thickness w_T and refractive index n_2, a characteristic interference pattern is achieved when focusing non-diffracting beams behind these surface, see right-hand-side of Fig. 8. One can clearly see, that a confined energy deposition is only partially possible, since the on-axis intensity is characterized by strong interferences of maximum contrast. Intuitively, the optical impact of the tube's cylindrical surface can be compensated using a cylindrical lens of a well-defined radius, for details see Ref. 20. One realization foresees to implement a cylindrical lens directly in front of the axicon-like element. Shaping the non-diffracting beam and applying the aberration correction is thus possible with two standard components. We prefer, however, the diffractive realization as single holographic element with multiplexed functionalities of mentioned axicon and cylindrical lens,[5, 20] as adjustment effort is significantly reduced and implementation into an industrial processing optics is facilitated, cf. Fig. 2.

In the following, the developed optical concept is applied to modify glass tubes of different geometries $[R_\mathrm{T} = (1\ldots20)\ \mathrm{mm}, w_\mathrm{T} = (0.1\ldots2)\ \mathrm{mm}]$. Ultrashort laser pulses at $\lambda = 1030\,\mathrm{nm}$ emerged from a TruMicro 2030 laser are illuminating the axicon-like element shaping the aberration-corrected non-diffracting beam.[20] The optical axis of the processing optics is aligned perpendicular to the glass tube's tangential surface. During the laser modification step, tubes are rotated around their symmetry axis enabling feed rates of $\gtrsim 100\,\mathrm{mm/s}$ by employing 20 W of average power. Pulse energy, burst parameters and spatial pulse distance are adequately chosen to (mainly) generate elongated type III modifications[13] inside the wall volume of borosilicate tubes with a single pass. The entirety of modifications acts as breaking layer at which the actual separation is achieved. Full-thickness modifications are, e.g., confirmed by the material's plasma response to the pulse which is homogeneously elongated along the entire wall thickness, see Fig. 9.

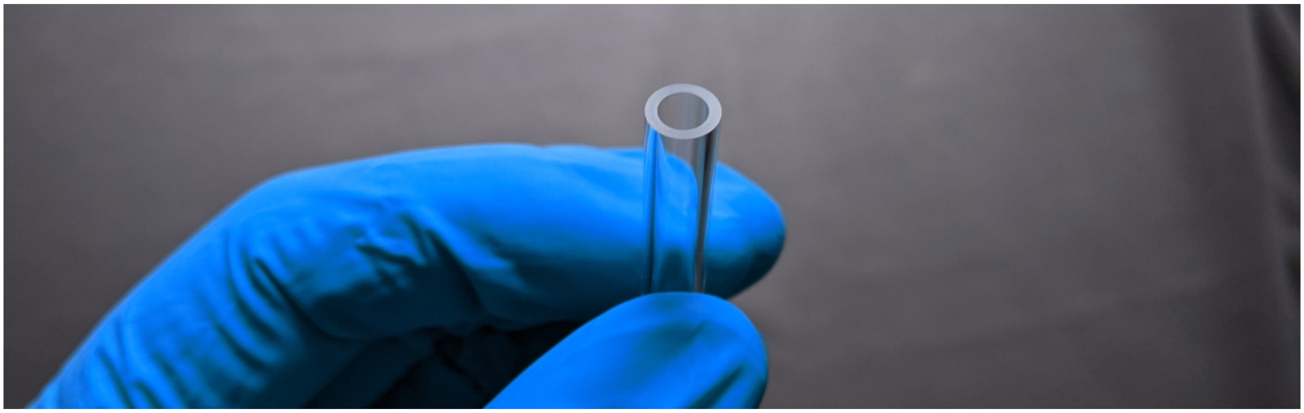

Figure 10. Mechanically separated glass tube made of borosilicate glass (Radius $R_\mathrm{T} = 3.9\,\mathrm{mm}$, wall thickness $w_\mathrm{T} = 1.05\,\mathrm{mm}$). Volume modifications were achieved using an adapted TOP Cleave cutting optics and a TruMicro Series 2000 laser in a single pass. Mean surface roughness of the tube edge was determined to $S_a \lesssim 1\,\mu\mathrm{m}$ (area evaluation). By exploiting 20 W of average power, feed rates of $\gtrsim 500\,\mathrm{mm/s}$ were achieved. Although not demonstrated here, further scaling to m/s-feed rates is feasible using industry-grade multi millijoule- and multi hundred-watt-class[28] ultrashort pulsed laser systems, such as a TruMicro Series 6000 laser.

Due to remarkable thermal properties, tubes made of borosilicate glass are of particular interest for the medical industry. We therefore focus on this material and would like to emphasize that the parameters presented in the following are strongly dependent on the respective glass type and associated tube geometry.

Borosilicate tubes of radius $R_\mathrm{T} = 3.9\,\mathrm{mm}$ and wall-thickness $w_\mathrm{T} = 1.05\,\mathrm{mm}$ were modified using aberration-corrected asymmetric non-diffracting beams. The asymmetric focus distribution enables a facilitated separation due to a control of cracks.[16,19] By exploiting 20 W average power from a TruMicro Series 2000 laser maximum feed rates of $\gtrsim 500\,\mathrm{mm/s}$ ($\sim 30\,\mathrm{Hz}$) were achieved. The actual separation was realized mechanically and quantified using a four-point flexural load test. Figure 10 depicts the edge of a separated glass tube whose mean surface roughness was evaluated on the area to $S_a \lesssim 1\,\mu\mathrm{m}$. The required flexural load for mechanical separation based on a four-point bending test was $\sim (50 \pm 20)$ N (strong R_T-dependent). This comparatively low value, which was achieved in particular through the use of an aligned asymmetric non-diffracting beam and crack control[16,19] enables a thermally induced mechanical stress-based separation for borosilicate tubes.

5. CONCLUSION

We have reviewed the state of the art for single-pass laser cutting of transparent materials based on the TOP Cleave cutting optics in combination with TruMicro Series lasers. The modular optical concept was introduced and its flexibility was discussed by means of novel machining concepts for cutting of tailored edges and curved surfaces. Several remarkable glass articles, such as substrates with beveled edges or glass tubes prove the efficacy of the developed optical concepts where adapted phase-corrected non-diffracting beams enable industry-ready materials processing strategies.

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