



# Ultrafast thin-disk multi-pass amplifier system providing 1.9 kW of average output power and pulse energies in the 10 mJ range at 1 ps of pulse duration for glass-cleaving applications

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**Abstract:** An ultrafast Yb-doped thin-disk multi-pass laser amplifier system with flexible parameters for material processing is reported. We can generate bursts consisting of four pulses at a distance of 20 ns and a total energy of 46.7 mJ at a repetition rate of 25 kHz. In single-pulse operation, 1.5 kW of average output is achieved at 400 kHz when optimizing for a beam quality of  $M^2 = 1.5$ . Alignment for maximum output power provides 1.9 kW at the same repetition rate. All results are obtained without chirped-pulse amplification in the multi-pass set-up. The application potential of the system is demonstrated exploring its performance in materials processing of dielectrics. Cleaving of 3.8-mm-thick SCHOTT borofloat glass with a velocity of 1200 mm/s is demonstrated with 300 W of input power. Single-pass modification of 30 mm borosilicate glass is enabled with a Bessel beam at 1 kW of average power delivered by four-pulse bursts of an energy of 30 mJ.

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## 1. Introduction

During the last years, materials processing with of ultrafast pulsed laser sources became a rapidly growing field of industry. The average output power of commercially available ultrafast lasers is typically in the range of 100 W [1–5]. However, several applications like e.g. surface structuring [6,7] or cleaving of glass [8–11] demand even higher average powers and pulse energies. To achieve this goal, several concepts were demonstrated during recent years. Well known technologies are fiber, slab and thin-disk lasers. A slab MOPA system provided an average output power of 1.1 kW with 55  $\mu$ J of pulse energy in 2010 [12]. Based on chirped-pulse amplification (CPA) in master-oscillator power-amplifier (MOPA) fiber systems, 830 W of average output power with 11  $\mu$ J of pulse energy was reported in 2010 [13]. Deploying coherent beam combining (CBC) of four Yb-doped fiber amplifiers, an average output power of 530 W with 1.3 mJ of pulse energy was demonstrated in 2013 [14]. In 2018, a fiber-based average output power of 3.5 kW with 44  $\mu$ J of pulse energy was achieved also by means of CBC [15]. Also with a MOPA system, 2 kW of output power with 100  $\mu$ J of pulse energy were implemented in 2014 [16]. Due to the large beam diameter in the active medium, resulting in low intensities and therefore avoiding nonlinear effects, thin-disk amplifiers are capable of kW-class output powers with pulse energies in the mJ range. By means of regenerative amplifiers, pulse energies up to 220 mJ were achieved at a repetition rate of 1 kHz [17,18]. Also with regenerative amplifiers, 2 kW of output power at 20 kHz of repetition rate were recently presented with a spectrum supporting 600 fs of pulse duration [19]. While slab amplifiers, thin-disk lasers, and even fiber amplifiers are capable of multi-kW operation, techniques like CPA and, at least for fiber lasers,

CBC become indispensable in order to achieve pulse energies in the mJ range at ultrafast pulse durations. In contrast, in thin-disk multi-pass amplifiers the passes through the gain medium are scaled by geometrically multiplexing the beam by means of a mirror array. Consequently, there is no need for an intra-cavity optical switch, which tends to limit the pulse energy for CPA-free regenerative amplifiers [20]. This fact allows increasing the pulse energy to the mJ level without CPA or CBC while these techniques might still be exploited to reach even higher energies. In 2015, a few-ps CPA-free multi-pass amplifier providing 1.4 kW of average output power with 4.7 mJ of pulse energy was realized [21]. One year later, even 2 kW of average output power with 6 mJ of pulse energy were demonstrated [22]. The multi-pass concept is also suitable for longer pulse durations in the ns range [23] as well as for pulse bursts [24,25].

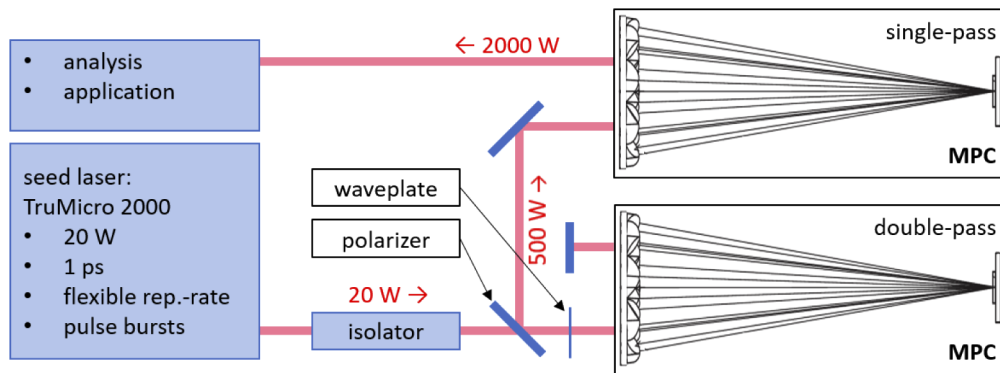
In this work, we demonstrate CPA-free amplification of a kW-class thin-disk multipass amplifier capable of exceeding 10 mJ of pulse energy. A commercial TruMicro 2000 ultrafast laser [1] serves as a seed system offering flexibility in terms of pulse duration, repetition rate and burst structure. Several operation regimes of the amplifier system are presented. For example, a pulse duration of 1 ps at an average output power of 1.9 kW with 4.8 mJ of pulse energy is achieved with  $M^2 = 2.3$ . By aligning the amplifier with respect to maximum beam quality, an average output power of 1.6 kW is achieved with 3.9 mJ of pulse energy and  $M^2 = 1.5$ . If the seed laser is operated in burst mode, with four consecutive laser pulses with full pulse energy in a temporal distance of 20 ns, an average output power of 1.2 kW is reached with a burst energy of 46.7 mJ, corresponding to 11.7 mJ of single-pulse energy. Finally, glass-cleaving applications exploiting this output performance are presented.

## 2. Experimental set-up and results

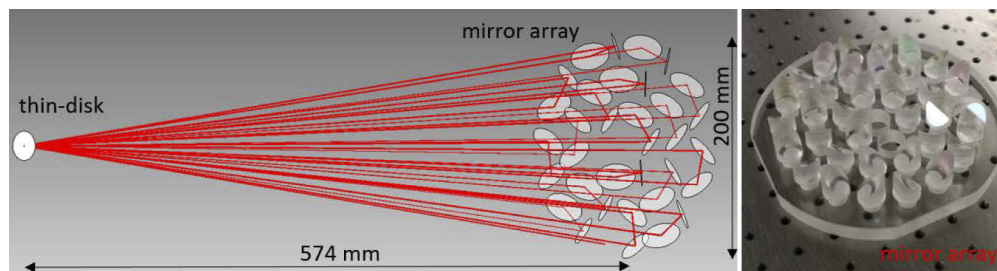
### 2.1. High-power laser source

The seed laser system consists of a commercial TRUMPF TruMicro 2000 based completely on fiber technology providing a pulse duration of 1 ps at a repetition rate of 400 kHz and 20 W of average output power at a wavelength of 1030 nm, corresponding to a single-pulse energy of 50  $\mu$ J. This solution was selected because of its flexibility in terms of pulse parameters such as repetition rate and pulse duration and the option to provide pulse bursts. It is followed by two amplifier stages, each consisting of one multi-pass cell (MPC), deploying a commercial Yb-doped thin-disk as gain medium. The first one is operated in a double-pass configuration. After a first pass, the beam is reflected back and performs a second pass through the MPC to increase the power extraction. A polarizer serves for separation of the reflected beam from the input, resulting in a total of 36 reflections at the thin-disk. At this stage, an average power of the order of 500 W is achieved. This value is sufficient to seed the second stage driven in single-pass operation with 36 thin-disk passes (18 thin-disk reflections) (see Fig. 1), resulting in approximately 2000 W of average output power. The ytterbium-doped thin-disk is pumped in its center in a spot of roughly 5 mm in diameter, which is called *pump spot* in the following. The pump radiation is continuous wave (CW) and may be varied between 2 and 4 kW. In contrast to previous results [21,22], a monolithic mirror array with superior thermal and mechanical stability is deployed, aiming at industrial applications (see Fig. 2). It contains a total 34 mirrors. These are sequentially pre-aligned in a separate alignment set-up and mounted to the base plate. The beam is geometrically multiplexed 18 times on the thin-disk for a single pass through the system (see Fig. 2), resulting in 18 thin-disk reflections. The mirrors are operating under 45 degrees, rendering transfer mirrors obsolete. The thin-disk is located at a distance of 574 mm in front of the mirror array.

The radius of curvature of the unpumped thin-disks, both in the first and second stage, is 50 m. This slightly focussing curvature compensates for the divergence of the beam with every thin-disk pass. In this way, a constant beam radius on the thin-disk without any intermediate confocal planes of small cross section is achieved, aiming at the lowest possible level of nonlinearities



**Fig. 1.** Schematic set-up of the amplifier system. The seed laser is a commercial TruMicro 2000, followed by two amplifier stages. Red lines indicate the laser beam. MPC: Multi-pass cell.

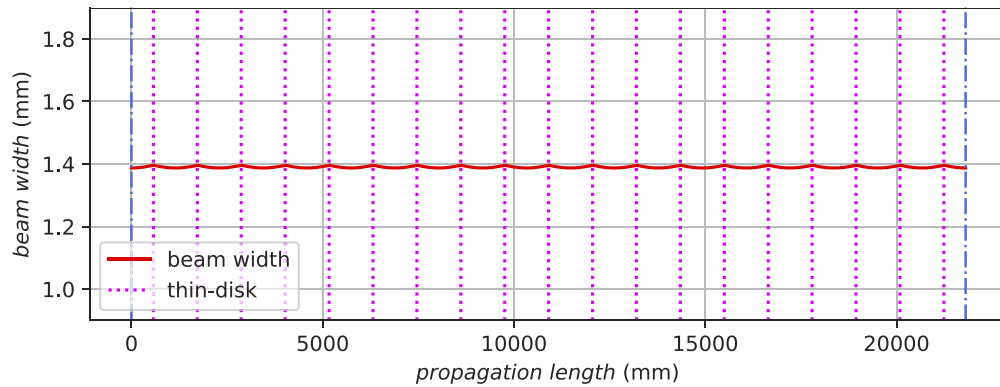


**Fig. 2.** Scheme of the multi-pass cell (MPC). The seed beam is geometrically multiplexed 18 times on the thin-disk by means of a pre-adjusted monolithic mirror array bearing a total of 34 mirrors operating under 45 degrees.

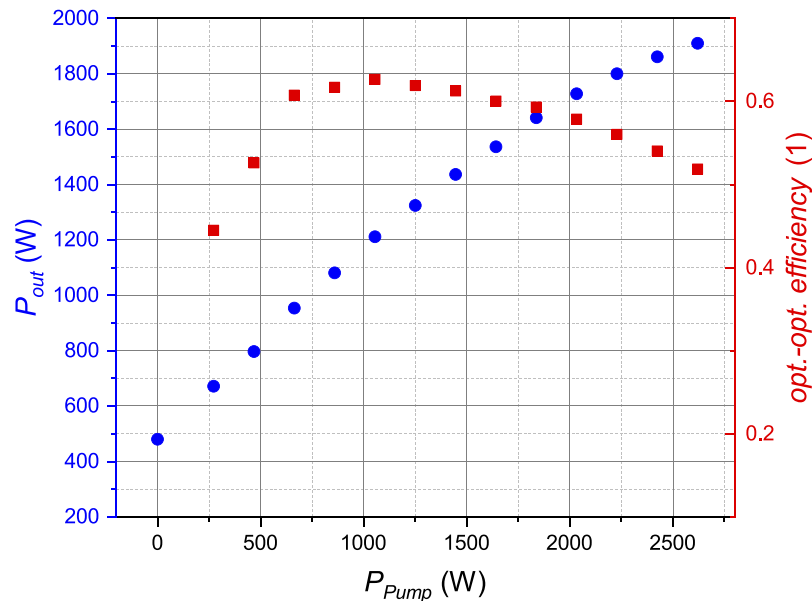
(see Fig. 3). Both thin-disks are pumped by a fiber-coupled diode laser. The thin-disk of the first amplifier stage is pumped at the zero-phonon line at a wavelength of 969 nm. This configuration combines a minimum quantum defect with strong absorption [2,26–28] in order to provide maximum efficiency and to reduce thermally-induced deformation of the thin-disk. The maximum pump power of the first amplifier stage is 1200 W. An average output power of 510 W at a beam quality of  $M^2 = 1.4$  is generated by the first MPC which is subsequently coupled into the second MPC. In order to overcome pump power limitations, the second thin-disk is pumped with both 969 nm and 941 nm coincidentally, at a power ratio of 46:54 of the two wavelengths. The maximum pump power for the second amplifier stage amounts 2800 W. With a pump spot diameter of 5 mm a maximum pump intensity of 61 W/mm<sup>2</sup> results in the first and 122 W/mm<sup>2</sup> in the second stage.

A maximum average output power of 1.9 kW with corresponding pulse energy of 4.8 mJ is achieved (see Fig. 4). The beam quality at this operating point is  $M^2 = 2.3$ . The measured autocorrelation function based on a *sech*<sup>2</sup> fit reveals a pulse duration of 1.3 ps (see Fig. 5(b)), which indicates an increase in pulse duration of 33% compared to the seed beam. This effect is due to the fiber-based TruMicro 2000 seed laser being spectrally broader than the gain bandwidth of the thin-disk, resulting in gain narrowing and a longer pulse duration.

As seen in Fig. 5(a), the output spectrum exhibits a structure with several maxima around the center wavelength of 1030 nm. These features arise from self-phase modulation (SPM) due to the third-order nonlinearity of the air and thin-disk. A comprehensive discussion can be found in [29]. This effect outweighs other effects like gain narrowing. The full width at half



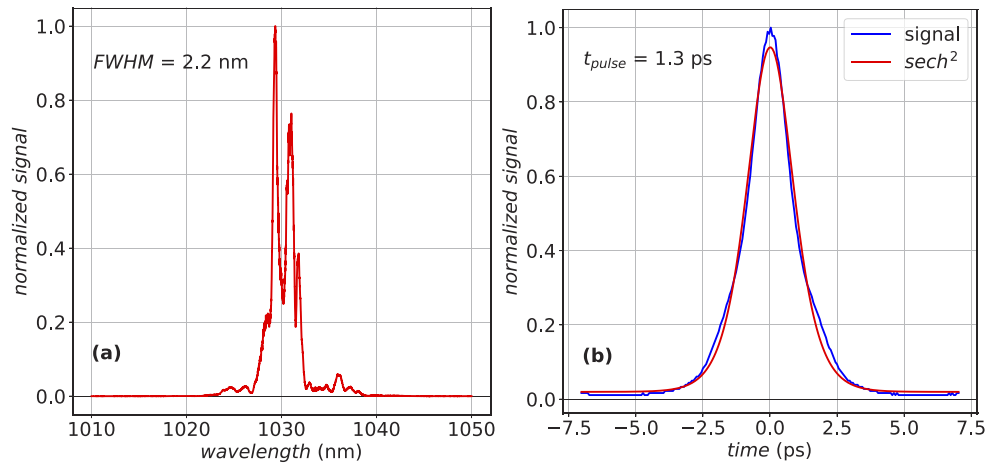
**Fig. 3.** Schematic plot of the beam width evolution during the propagation within the MPC. The divergence of the single mode beam ( $M^2 = 1$ ) is compensated by the concave curvature of the thin-disk: the beam radius on the thin-disk is constant for every pass while small focal points are avoided.



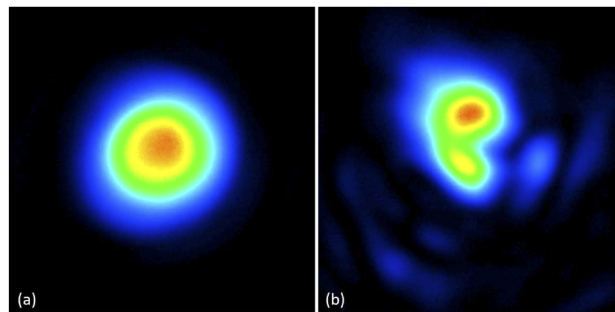
**Fig. 4.** Average output power (blue dots, left ordinate) and the ratio between optical pump and extracted power (red squares, left ordinate) versus pump power of the second amplifier stage. The roll-over in efficiency is caused by the seed power being too low to efficiently extract the stored energy at high pump powers.

maximum (FWHM) of the output amounts to 2.2 nm. A pulse duration of 1.3 ps is deduced from a second-order autocorrelation measurement (see Fig. 5(b)). The calculated Fourier limit of the spectrum depicted in Fig. 5(a) is 250 fs, opening up the possibility for further compression [30] which is a topic for future work. Adapting the pump spot to the overlapping beam passes on the thin-disk can aid to suppress perturbations of the Gaussian beam. By doing so, a beam quality of  $M^2 = 1.5$  could be achieved at 1.6 kW of average output power and 4 mJ of pulse energy. The diameter of the pump spot, both in the first and in the second amplifier stage, amounts roughly 5 mm. The accomplished intensity profile is close to a fundamental Gaussian mode (see Fig. 6(a)).

Having the MPC aligned for high output power, a more perturbed beam profile results (see Fig. 6(b)). The seed laser comprises a 50 MHz modelocked fiber oscillator, a pulse picker, and a fiber amplifier chain. Bursts consisting of four consecutive single pulses with full pulse energy in a temporal distance of 20 ns are available from this system. In this way, the repetition rate may be reduced by a factor of four while maintaining the full average seed power of 20 W. Owing to the longer temporal distance between pulse bursts, the energy stored in the thin-disk is increased, supporting a larger pulse energy of the amplified beam. With a repetition rate of 25 kHz, an average output power of 1.2 kW is achieved. These values correspond to a burst energy of 46.7 mJ and a single-pulse energy as high as 11.7 mJ.



**Fig. 5.** (a): Spectrum of the laser pulse. The full width at half maximum is 2.2 nm. (b): Second-order autocorrelation function with fitted  $\text{sech}^2$ . The deduced full-width-half-maximum pulse duration amounts to 1.3 ps. Both were measured at 1.9 kW of average output power and 400 kHz of repetition rate.



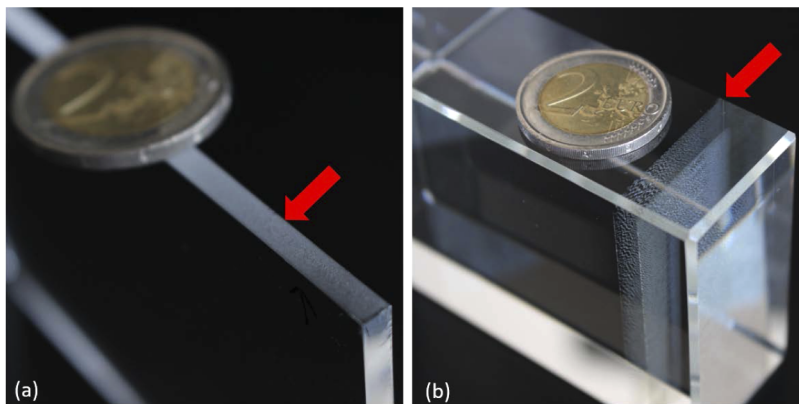
**Fig. 6.** Transverse intensity profiles of the amplified beam in the far field, colorcoded as a function of position. (a): Overlapping beam passes on the thin-disk are aligned for high beam quality. (b): Overlapping beam passes on the thin-disk are aligned for high output power.

## 2.2. Glass processing experiments

The use of ultrashort laser pulses for materials processing is widely discussed in the literature, especially with regard to industrial applications [31–34]. Nonlinear absorption mechanisms allow



for processing of almost any material, including wide band-gap dielectrics such as silica-based glass. Sensitive tuning of the process parameters in terms of pulse energy, repetition rate and pulse duration open different processing opportunities to either weld, ablate or cleave the samples. Cleaving is performed by placing consecutive structural modifications along a contour which are induced by the high optical peak intensity. Subsequently, the material parts are separated by applying a mechanical force. Here, we use the laser amplifier system described above to show its potential for glass cleaving applications. Typically, Bessel-like beams are used for cleaving applications since they offer a unique set of features ideal for separation processes, e.g., high aspect ratio ranging from the millimeter regime in longitudinal direction to few micrometers in transversal direction and high tolerance to surface impurities due to their self-healing nature [35]. In a first experiment, the TRUMPF TOP Cleave optics [35], is deployed to modify a glass sample (SCHOTT Borofloat) of a thickness of 3.8 mm in a single pass exploiting the flexible parameters of the system. We used bursts consisting of 4 individual pulses at a 20 ns temporal distance, each having 250  $\mu\text{J}$  of pulse energy, at 300 kHz of repetition rate and 300 W of average output power. Using a high-accelerating linear axis (Aerotech LMA 200 mm), a feeding velocity of 1200 mm/s is achieved. The cleaved face after successful separation is depicted in Fig. 7(a). The mean surface roughness  $R_a$  is measured by means of a confocal laser scanning microscope to  $R_a = 2,30 \mu\text{m}$ , along a lines across the face. Comparison to published cleaving results shows a slightly increased surface roughness by a factor of 2. However, the feeding velocity accomplished in this work is increased by an order of magnitude [9,36,37]. Note that even higher speed would be allowed by the available parameters of the laser source. In this work, we were limited solely by the linear translation stage. Furthermore, a slightly modified optics is implemented to enhance the length of the Bessel-like beam profile. We report, to the best of our knowledge, on the first single-pass modification of 30-mm-thick samples of borosilicate glass (see Fig. 7(b)). For this experiment, we employed a feedrate of 100 mm/s with an average output power of 1 kW with 30 mJ of burst energy, corresponding to a single-pulse energy of 7.5 mJ.



**Fig. 7.** Glass processing experiments are carried out by means of a Bessel beam which is imaged into the material. **(a):** A 3.8 mm thick sample of SCHOTT Borofloat-glass could be successfully cleaved with a feedrate of  $1200 \frac{\text{mm}}{\text{s}}$ . The cleaved edge is indicated by the red arrow. The surface roughness is  $R_a = 2,30 \mu\text{m}$ . Pulse bursts with four single pulses are used. The average output power is 300 W with 1 mJ of burst energy relating to 250  $\mu\text{J}$  of pulse energy. **(b):** A block of 30 mm thick borosilicate-glass is modified with one single pass. The feedrate is  $100 \frac{\text{mm}}{\text{s}}$  with 1 kW of average output power and a burst energy of 30 mJ which corresponds to a pulse energy of 7.5 mJ. Within the material there are two faces of modification visible next to each other (see the red arrow).

### 3. Conclusion and outlook

An 36-pass thin-disk (18 thin-disk reflections) laser amplifier was set up deploying a monolithic pre-adjusted mirror array, offering superior thermal and mechanical stability aiming at industrial purposes. Several beam parameters were implemented depending on different amplifier configurations. The highest average output power achieved was 1.9 kW with an energy of 4.8 mJ per pulse and 1.3 ps of pulse duration. The beam quality was  $M^2 = 2.3$ . Adapting the pump spot to the overlapping beam passes on the thin-disk aids suppressing perturbations of the Gaussian beam profile. By doing so, a beam quality of  $M^2 = 1.5$  was achieved at an average output power of 1.6 kW and a pulse energy of 4 mJ. Operating the seed laser in burst mode with one burst consisting of four consecutive laser pulses with full pulse energy in a temporal distance of 20 ns resulted in 1.2 kW at 25 kHz. These values correspond to a burst energy of 46.7 mJ and 11.7 J of single-pulse energy. Finally, materials processing experiments for modifying and cleaving of mineral glass are carried out. This field of technology is usually limited by the available output powers and pulse energies of ultrafast lasers. The beam source presented in this work provides kilowatt output powers at millijoule pulse energies. Therefore, it is predestinated for glass processing applications. Exploiting a laboratory version of the TRUMPF TOP Cleave-2 optics, a Bessel beam is generated and imaged into the material. A sample of SCHOTT Borofloat glass of a thickness of 3.8 mm was successfully cleaved with 300 W of average power at a feed rate of 1200 mm/s. The surface quality of the cleaved edge amounts to  $R_a = 2, 30 \mu\text{m}$ . Furthermore we report, to the best of our knowledge, on the first single-pass modification of 30-mm-thick samples of borosilicate glass, deploying 1 kW of average output power in burst operation with 30 mJ of burst energy, corresponding to 7.5 mJ of pulse energy. Future work will focus on further increasing the pulse energy and beam quality. Subsequent experiments will aim at industrial processes like laser-based cleaving of thick glass specimens used in safety and architectural applications. After acceptance, Jenne et al. [38] discussed an optimized orientation of stress distribution inside the material by usage of asymmetric beam profiles, which should be a promising approach to facilitate cleaving of very thick glass by elongated modifications induced by multi-kW high energy ultrafast lasers as presented in this work.

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### Disclosures

The authors declare no conflicts of interest.

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