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Kerr-lens mode-locked thin-disk oscillator with 50% output coupling rate

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Several approaches to power scaling of mode-locked thin-disk oscillators exist. One of these approaches is based on the increased gain provided by multiple passes through the thin-disk laser medium. For the first time, to the best of our knowledge, we applied this approach to a Kerr-lens mode-locked thin-disk oscillator. The so obtained additional gain allowed mode-locked operation with up to 50% output coupling rate. This first demonstration is of particular importance for gain media with inherently low-emission cross sections and paves the way to even more powerful Kerr-lens mode-locked thin-disk oscillators. Moreover, the experimental results indicate an increased self-amplitude modulation related to an overall increase in the soft-aperture Kerr-lens effect.

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Due to great improvements in average- and peak-power output over the last decades, ultrafast lasers find growing adoption in industrial processes and have become indispensable tools for many fields in scientific research. Average-power scalability is met by slab, fiber, and thin-disk lasers. However, thin-disk lasers are best suited to approach the problems encountered in high-power femtosecond lasers. An ultrashort laser pulse experiences in a thin disk a much lower nonlinear phase shift due to self-phase modulation (SPM) than in any other gain-medium geometry, because of the very low thickness of the disk and the large mode size in it. This property makes thin-disk geometry best suited for the design of mode-locked oscillators with high intracavity peak power and correspondingly high external peak power, because large nonlinear phase shifts are prohibitive for the generation of ultrashort pulses [1,2].

In order to exploit the potential of thin-disk geometry, a self-amplitude-modulation (SAM) mechanism is needed, which favors the formation of a soliton from hundred watts up to hundreds of megawatts internal peak power. To date, this is achieved by two commonly applied mode-locking techniques, namely, semiconductor saturable absorber mirror (SESAM)- and Kerr-lens mode locking (KLM). Both of them have been shown to be power scalable towards hundreds of megawatts internal peak power [3,4]. Under such conditions, the nonlinear contributions from air [5] or even from multilayer coatings [6] become non-negligible and limiting. Therefore, it is necessary to operate such high-peak-power oscillators under helium atmosphere [5], reduced air pressure [4], or vacuum [3] or to introduce cascaded quadratic nonlinearities for dispersion compensation [7,8], making the oscillators more bulky and expensive in the first case and more difficult to handle in both cases.

A potential remedy is proposed with the chirped-pulse mode-locking regime, which is routinely applied in fiber and to some extent also in bulk Ti:sapphire oscillators [9,10]. So far, however, demonstrations in ytterbium-based thin-disk oscillators resulted at best in a marginal, relative power improvement [11,12]. Thus, the chirped-pulse approach still requires significant research, in contrast to the anomalous dispersion soliton regime, which yields excellent temporal pulse quality, high stability, and, importantly, a reliable starting routine for thin-disk oscillators.

Regardless of the mode-locking technique or the soliton regime, the extracted power from an oscillator can be increased by raising both the output coupling rate and the round-trip gain. The increase in output coupling offers the chance to reach higher external peak powers without the need to increase the intracavity peak power and hence relaxes the requirements on SPM management and avoids the use of difficult to realize soliton regimes. The additional gain required for this purpose needs to be accumulated by multiple passes of the pulse through the thin disk per round trip, because of thickness and doping constraints in the thin disk. This concept has successfully been applied to SESAM-mode-locked thin-disk oscillators and allowed output coupling rates of up to 72% to effect 41 μJ pulse energy and 32 MW external peak power [13]. The intrinsically higher tolerance of the KLM technique to nonlinear phase shift allows the operation in air with more than 100 MW intracavity peak power, even without any special SPM-reduction techniques [14]. Therefore, the integration

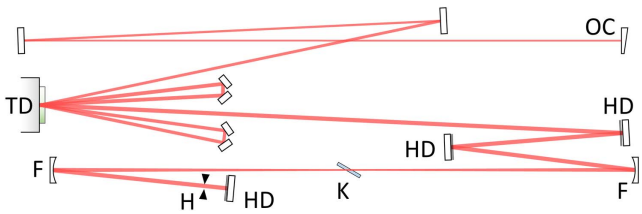

Fig. 1. Schematic of the KLM triple-pass oscillator with flat folding mirrors. OC, output coupler; HD, high-dispersion mirror (−15000 fs^2 per round trip); TD, thin disk; F, concave mirror (ROC 1.0 m); H, hard aperture (3.8 mm diameter); K, Kerr medium (3 mm thick sapphire plate). Non-labeled components are highly reflective mirrors.

of this concept into the already demonstrated high-peak-power KLM oscillators is highly promising. However, it was unclear whether the stronger thermal lensing due to multiple thin-disk passes would hinder stable operation of KLM oscillators, which are, by design, susceptible to intracavity lenses [15].

In this work, we explore the feasibility of large output coupling rates in KLM thin-disk oscillators with both a flat and an imaging beam-folding arrangement. The latter approach finally allows us to couple out up to 50% of the circulating power at an intracavity peak power of 80 MW and pulse duration (τ) of 290 fs.

In the first part of our experimental work, an already known oscillator [16] was replicated. Its cavity contained two reflections on a Yb:YAG thin disk via a pair of flat folding mirrors. The disk (TRUMPF Laser GmbH) had ≈18 m radius of curvature (ROC) and ≈0.1 mm thickness. The pump source was a fiber-coupled, 1 kW diode laser operating at 940 nm. The pump spot was ≈3.3 mm in diameter. After an initial characterization, the cavity was rearranged with the aid of a second pair of flat folding mirrors to exhibit three reflections on the thin disk. All other parameters of the cavity, except for the output-coupler transmission, were intentionally kept unchanged. The so obtained triple-pass cavity is illustrated in Fig. 1. Adding further passes via flat folding mirrors became unfeasible due to spatial constraints as well as a growing difference in mode size among the passes.

Mode-locked operation of this oscillator was possible even for an output coupling rate of 30% and resulted in a slight performance improvement over the configuration with two passes. The mode-locking procedure was the same for both folded configurations, requiring a perturbation of one of the cavity optics in continuous wave (CW) operation. The performance comparison between the configurations is given in Table 1.

After this successful experiment, an increased number of thin-disk passes was realized with an imaging concept called active multipass cell (AMC) [17]. The AMC concept did already demonstrate 11 reflections on the thin disk (44 passes through the gain medium per round trip) in a SESAM mode-locked oscillator [13]. A potential non-imaging alternative to it can be found in reference [18].

Table 1. Performance of the Realized Oscillators with Multiple Thin-Disk Passes Based on Flat Mirrors

Reflections on TD	OC [%]	τ [fs]	$P_{Average}$ [W]	P_{Peak} [MW]
2	20	200	92	14
3	30	220	130	18

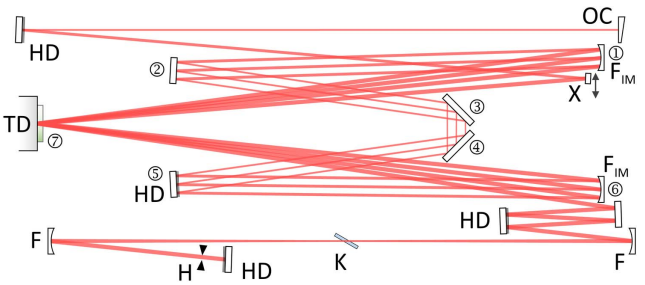

Fig. 2. Schematic of the KLM thin-disk oscillator with an active multipass cell (AMC). The AMC is formed by the distance 7-1, concave mirror F_{IM} at 1, distance 1-2-3-4-5-6, concave mirror F_{IM} at 6, distance 6-7, and one reflection on the thin disk. Horizontal displacement of the pick off mirror X adjusts the number of passes through the AMC. OC, output coupler; HD, high-dispersion mirror; TD, thin disk; F, concave mirror of the Kerr telescope; H, hard aperture; K, Kerr medium. Non-labeled components are highly reflective mirrors. Mirrors 3 and 4 are 38.1-mm mirrors.

In our experiment, using the AMC approach, up to four reflections on the thin disk (16 passes through the gain medium per round trip) were realized with the oscillator sketched in Fig. 2. Its fundamental cavity had the same basic dimensions as the cavity in Fig. 1. The number of imaged reflections in this particular oscillator was rather low due to the 25.4 and 38.1 mm optics of the 4f-telescope in the AMC and the laser mode size on these optics. The number of these additional, imaged passes could be varied between zero and three by horizontal displacement of mirror X (see Fig. 2). This is a very advantageous feature, because it allows to change the number of passes through the disk systematically, without affecting the main cavity mode, as can be inferred from Fig. 3.

The focus for the Kerr medium was again formed by two concave mirrors with 1.0 m radius of curvature. Similar to the configuration in Fig. 1, a 3.0 mm thick sapphire plate under Brewster's angle was used as the Kerr medium. Again, a standard thin disk with ≈16 m ROC and ≈0.1 mm thickness was used. The pump spot had a diameter of ≈3.4 mm. For the

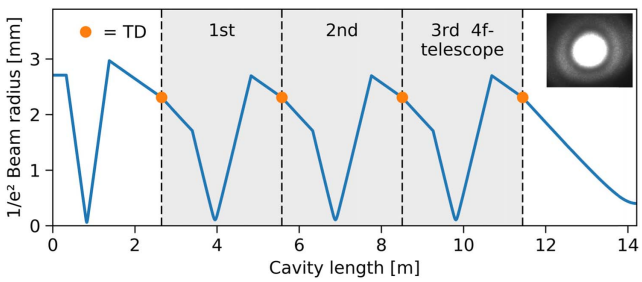

Fig. 3. Estimated beam radius evolution along the cavity in CW operation based on ray transfer matrix formalism. Each 4f-telescope contains one reflection on the thin disk. The laser beam at the beginning and end of each 4f-telescope is the same. The fourth reflection on the thin disk is part of the fundamental cavity, which is plotted over white background. Inset: emitted laser beam in pure mode lock without external beam cleanup on a detector card.

water-cooled hard aperture, a diameter of 4.4 mm was empirically found to optimize the intracavity peak power. The initial cavity (5.4 m long) together with three passes through the AMC (each 2.9 m long) resulted in a repetition rate of 10.6 MHz. Concave mirrors (F_{IM}) with focal lengths of 0.75 m were used in the AMC. The length of the 4f-telescope in the AMC was chosen such that it compensated a typical residual curvature of the thin disk [19]. As seen in Fig. 3, the passes through such an AMC do not affect the original cavity mode, because the AMC preserves the complex beam parameter. For the sake of mechanical and thermal stability, the oscillator was housed within a massive but transportable aluminum housing with a footprint of 70 cm × 140 cm.

It was possible to mode lock this oscillator with an output coupling rate as high as 50%. This is the first time that a KLM thin-disk oscillator was mode-locked with such a high output coupling rate. Anomalous group delay dispersion (GDD) was introduced by means of highly dispersive (HD) mirrors with −3000 fs^2 per reflection in order to compensate the nonlinear phase shift arising from the sapphire plate, the thin disk, and air. The locations of the HD mirrors are shown in Fig. 2. One of them is simultaneously serving as an AMC mirror. The total GDD per round trip was only −39000 fs^2, which is eight times less than in publication [13], even though the maximum internal peak power achieved in the present work is nearly twice as high. The so obtained pulses had an energy of 13.2 μJ and a pulse duration of 290 fs, which results in 40 MW external accessible peak power. The 140 W of average power were produced with an optical-to-optical efficiency ($\eta_{\mathrm{O\text{-}O}}$) of 27%. The measured spectrum and intensity autocorrelation are shown in Fig. 4. The resulting time-bandwidth product is 0.351, which indicates a slight chirp, as predicted by simulations [20].

Kerr-lens mode-locked operation with multiple reflections at the disk is therefore not prevented by thermal issues in intracavity optics or the gain medium. However, during oscillator startup, a behavior somewhat similar to thermal lensing is observed. Mode-locked operation is initiated at 200 W intracavity power with a pronounced CW feature. By increasing the intracavity power to 280 W, the CW feature vanishes. This transition is most likely caused by varying thermal lenses within the cavity, which modify the position of the cavity in the stability diagram and influence the SAM [15]. No additional studies were made to identify these suspected thermal lenses.

The emitted laser beam was surrounded by a faint circular pattern (see inset in Fig. 3), which seems to stem from diffraction at the hard aperture within the cavity. This pattern can easily be removed by the placement of an additional copper aperture around the emitted beam. This external aperture transmitted 92% of the power. The beam quality after this

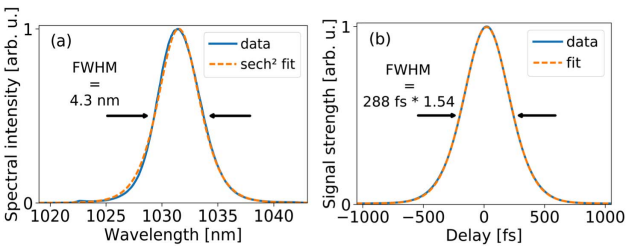

Fig. 4. (a) Emitted spectrum with its sech^2-fit (b) Intensity autocorrelation of the emitted pulses and its fit.

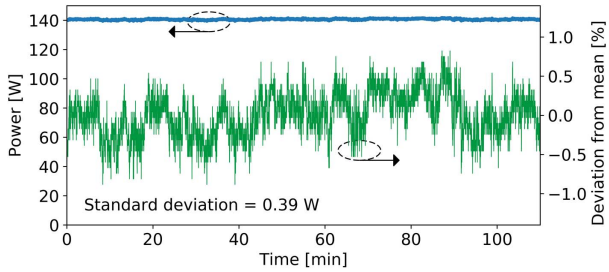

Fig. 5. Recording of the average output power and its deviation from its mean value over 110 min. The standard deviation is 0.4 W (0.3%).

additional aperture was measured with a commercial M^2-meter (CINOGY Technologies GmbH). The measurement resulted in $M_u^2 = 1.09 \pm 0.02$ and $M_v^2 = 1.06 \pm 0.01$ with the stated 140 W average and 40 MW peak power. Single-pulse operation of this KLM oscillator was confirmed with an optical spectrum analyzer and a home-built long scan autocorrelator and by observing the pulse train with a 175-ps-rise-time photodiode on a 3.5 GHz oscilloscope.

The integrated relative intensity noise of the oscillator was measured with an RF spectrum analyzer and amounted to 0.055% RMS in the range from 10 Hz to 1.25 MHz. The underlying power spectrum was recorded with 10 Hz resolution bandwidth, averaged 10 times, and normalized to the electrical power derived from the measured DC voltage. The long-term stability in Fig. 5 was measured with a thermopile power sensor (LaserPoint s.r.l.) and resulted in 0.3% standard deviation for 110 min of measurement time with 4 Hz sampling rate. No damages or degradation of performance occurred during one year of daily operation.

With these properties, this system delivers the highest peak power of any oscillator operated in ambient air, as summarized in Table 2.

It is noticeable that the pulse duration of this KLM oscillator did not increase considerably with growing losses (output coupling rate), nor did it systematically change with the growing number of thin-disk passes (see Table 3). The same applies to the internal peak power. This promising behavior might be explained by an increased SAM coefficient related to an overall increase in the soft-aperture Kerr-lens effect. The increase of the soft-aperture Kerr-lens effect should happen due to the increase in the number of passes through the thin-disk gain medium.

According to [21], the pulse duration scales as

$$\tau = \frac{1}{\Omega g}\sqrt{\frac{l}{R}}$$

Table 2. Overview of Thin-Disk Oscillators with the Highest Emitted Peak Powers Operated in Ambient Air

ML Type	OC [%]	GDD [−fs^2]	T [fs]	P_{Peak} [MW]	References
SESAM	72	346 500	1112	32	[13]
SESAM	40	16 800	780	22	[8]
KLM	21	48 000	330	38	[14]
KLM	50	39 000	290	40	This work

Table 3. Oscillator Performance Evolution for Growing Number of AMC Passes and OC Rate After Spatial Filtering

Reflections on TD	OC [%]	GDD [$-fs^2$]	τ [fs]	$\eta_{O\text{-}O}$ [%]	$P_{Peak.\text{-}Internal}$ [MW]
1	21	21 000	325	21*	34*
2	21	27 000	250	28*	71*
3	21	33 000	250	23*	75*
4	21	39 000	265	19*	74*
4	29	39 000	265	27*	77*
4	40	39 000	265	27*	83*
4	50	39 000	290	27	80

* = retrospectively corrected for beam cleanup.

where Ωg is the FWHM gain bandwidth, l are the linear losses, and R is the modulation depth (SAM coefficient) of the mode locker. In other words, in our case, the increase in the SAM coefficient compensates the increased losses, keeping the pulse duration nearly constant. On the other hand, this simple interpretation fails to explain the experimental data (see Table 3). Other factors such as alignment reproducibility including the telescope alignment, thermal lens variations for different configurations (different pump powers and intracavity power levels), and different inversion levels in the pumped disk should be considered in a more accurate and systematic study.

The demonstrated oscillator configuration uses a rather small number of passes through the gain medium. A larger number of passes, as in Ref. [13], is possible by the use of larger mirrors in the multipass section and should enable even larger output coupling rates. A reduction in pulse duration might be possible by combining the AMC concept with the concept of distributed KLM [22] and by further dispersion optimization. A variation of the Kerr medium thickness might optimize the peak power to some extent.

Besides being a peak-power scaling approach, the AMC concept provides a way to increase the round-trip gain in KLM thin-disk oscillators in general. The transfer of this concept to thin-disk gain media with significantly lower emission cross sections and doping concentrations such as Ho:YAG [23] or Yb:CALGO [24] holds promise to improve their performance significantly.

In conclusion, we successfully combined Kerr-lens mode locking with the AMC concept, which enabled the highest output peak power from a mode-locked oscillator in air so far. Advantageously, the pulse duration of the KLM oscillator stayed nearly constant despite of the increased round-trip losses. Under the assumption that this concept can be integrated into the already demonstrated oscillators operated in vacuum [4], peak powers on the order of 200 MW directly from oscillators would become reality. Furthermore, in combination with the free-space multipass spectral broadening approach [25,26], this peak-power level could easily be boosted by a factor of 10, making 2 GW peak-power oscillators feasible.

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