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Sub-100-fs Kerr lens mode-locked Yb:Lu_2O_3 thin-disk laser oscillator operating at 21 W average power

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Abstract: We investigate power-scaling of a Kerr lens mode-locked (KLM) Yb:Lu_2O_3 thin-disk laser (TDL) oscillator operating in the sub-100-fs pulse duration regime. Employing a scheme with higher round-trip gain by increasing the number of passes through the thin-disk gain element, we increase the average power by a factor of two and the optical-to-optical efficiency by a factor of almost three compared to our previous sub-100-fs mode-locking results. The oscillator generates pulses with a duration of 95 fs at 21.1 W average power and 47.9 MHz repetition rate. We discuss the cavity design for continuous-wave and mode-locked operation and the estimation of the focal length of the Kerr lens. Unlike to usual KLM TDL oscillators, an operation at the edge of the stability zone in continuous-wave operation is not required. This work shows that KLM TDL oscillators based on the gain material Yb:Lu_2O_3 are an excellent choice for power-scaling of laser oscillators in the sub-100-fs regime, and we expect that such lasers will soon operate at power levels in excess of hundred watts.

1. Introduction

High-power ultrafast laser systems operating at MHz repetition rates are a versatile tool for numerous applications in science and industry [1]. Compared to amplifiers, oscillators generate usually close to transform-limited pulses in fundamental TEM_{00} mode operation without pre- or post-pulses and feature low noise levels, suitable for carrier-envelope-offset frequency stabilization. However, the currently achieved power levels decrease strongly as function of the minimum achieved pulse duration. In the last decade, numerous studies have been targeting to increase the achievable power levels of ultrafast laser oscillators operating in the sub-100-fs regime [2–4]. Sub-100-fs bulk oscillators based on Ti:sapphire are currently limited to 3.5 W of average power [5] (Fig. 1). In comparison, sub-100-fs oscillators based on Yb-doped bulk gain materials operate at a reduced quantum defect, enabling up to 12.5 W of average power [6]. However, even in this case thermal effects in the bulk gain material are the most severe challenge for further increase of the average power.

The thin-disk geometry is advantageous for further power increase of sub-100-fs laser oscillators, because it reduces the thermal effects in the gain material during laser operation [7]. Various techniques have been applied for efficient mode-locking of thin-disk laser (TDL) oscillators, e.g. by saturable absorber mirrors (SESAMs) [8], nonlinear polarization rotation [9], nonlinear mirror mode-locking [10] and Kerr lens mode-locking [11]. Among those techniques, the shortest pulse duration of a TDL oscillator was achieved by Kerr lens mode-locking [12].

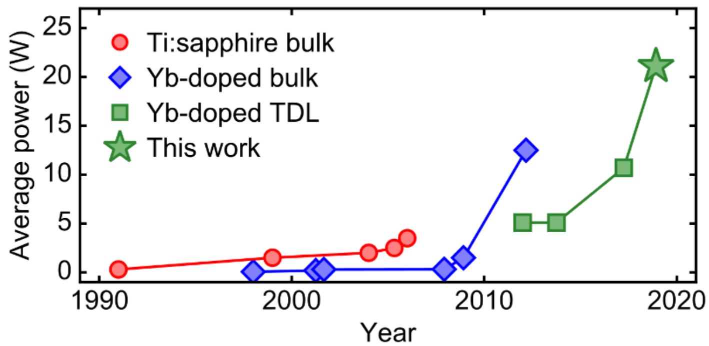

Fig. 1. Progress of the average power of ultrafast solid-state laser oscillators operating in the sub-100-fs pulse duration regime (Ti:sapphire [5,13], Yb-doped bulk [6,13–15], Yb-doped thin-disk laser (TDL) [16–18]).

In order to expand high-power operation of ultrafast TDL oscillators into the sub-100-fs regime [2], mode-locking of various broadband Yb-doped gain materials was investigated by several research groups [19–24]. The first TDL oscillators achieving sub-100-fs pulse durations were based on the broadband gain materials Yb:$LuScO_3$ and Yb:CALGO. Up to 5.1 W average power were demonstrated with an optical-to-optical efficiency amounting to 11% [16,17] (Table 1). Although their distorted crystalline structure is beneficial for a broad gain bandwidth, the resulting reduced thermal conductivity as well as the crystal quality of the available disks are limiting factors for achieving higher average powers. Currently, the highest average power of any ultrafast TDL oscillator based on disordered gain materials is limited to 28 W with 300-fs pulses [24].

Table 1. Selection of state-of-the-art ultrafast Yb-based laser oscillators.[a]

Type	Gain material	P_{ave}	τ_{pulse}	η_{eff}	Reference
Bulk	Yb:CALGO	12.5 W	94 fs	20%	[6]
Bulk	Yb:CALGO	3.3 W	45 fs	16%	[25]
TDL	Yb:$LuScO_3$	5.1 W	96 fs	11%	[16]
TDL	Yb:CALGO	5.1 W	62 fs	7%	[17]
TDL	Yb:YAG	155 W	140 fs	29%	[26]
TDL	Yb:YAG	3.5 W	49 fs	3.5%	[27,28]
TDL	Yb:Lu_2O_3	10.7 W	88 fs	5.8%	[18]
TDL	Yb:Lu_2O_3	21.1 W	95 fs	16.2%	This work

[a]P_{ave}: average power; τ_{pulse}: pulse duration; η_{eff}: optical-to-optical efficiency; TDL, thin-disk laser.

Ultrafast TDL oscillators based on the most mature gain material Yb:YAG have already reached average powers of 275 W, but operating at several hundred femtoseconds of pulse duration [29,30]. Kerr lens mode-locked (KLM) TDL oscillators demonstrated laser operation with 140-fs pulses at 155 W of average power and an optical-to-optical efficiency of 29% by fully exploiting the emission bandwidth of Yb:YAG [26]. Even shorter pulse durations of 49 fs were achieved by inserting nonlinear crystals for the generation of additional spectral components by self-phase modulation (SPM) in the cavity of a KLM Yb:YAG TDL oscillators. However, in this case the laser performance was limited to 3.5 W of average power at an optical-to-optical efficiency of 3.5% [27,28]. A gain material for high-power laser operation, which directly supports sub-100-fs pulse durations is Yb:Lu_2O_3. Yb:Lu_2O_3 provides a 60% broader emission bandwidth than Yb:YAG supporting the generation of 86-fs pulses at an even better thermal conductivity [2]. Although the gain material is still at an early stage of development, its suitability for high-power laser operation was already demonstrated by an ultrafast SESAM mode-locked TDL oscillator reaching 141 W of average power, albeit at pulse durations of several hundred femtoseconds [31]. In 2017, we demonstrated a KLM TDL oscillator fully

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exploiting the emission bandwidth of Yb:Lu_2O_3. The laser operated at 10.7 W of average power in 88-fs pulses with a modest optical-to-optical efficiency of 5.8% [18].

In this work, we investigate the impact of higher round-trip gain on the average power and the optical-to-optical efficiency of a sub-100-fs KLM Yb:Lu_2O_3 TDL oscillator. Folding the standing-wave cavity two times on the disk enabled an increase of the average output power by a factor of two and the optical-to-optical efficiency by a factor of three compared to our previous result [18]. We demonstrate that using this approach TDL oscillators based on the gain material Yb:Lu_2O_3 are suitable for the generation of sub-100-fs pulses at high average power with optical-to-optical efficiencies that are comparable to Yb-doped bulk oscillators (Table 1).

2. Cavity design

The performance of the Yb:Lu_2O_3 disk in continuous-wave (CW) operation and previous mode-locking results are published in [18]. Compared to these results, the presented cavity is modified by folding the standing-wave cavity a second time on the disk (Fig. 2). A second folding of the cavity on the disk is commonly used in high-power KLM TDL oscillators [26,30]. In this configuration, the gain propagation length of the laser beam per cavity round-trip amounts to the eightfold of the gain crystal thickness, resulting in a higher round-trip gain.

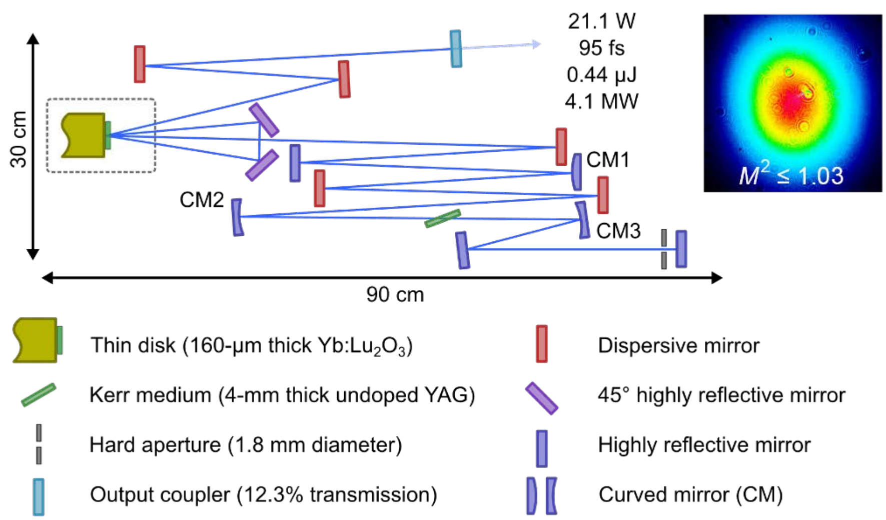

Fig. 2. Schematic of the Kerr lens mode-locked Yb:Lu_2O_3 thin-disk laser oscillator. (inset) Beam profile in mode-locked operation and M^2 beam quality factor. CM1, convex radius of curvature (ROC) of 2 m; CM2 and CM3, concave ROC of 250 mm.

Higher round-trip gain in the oscillator cavity enables laser operation at higher total cavity losses and, thus, the operation at a higher output coupler transmission (T_{OC}). Considering a constant intracavity performance, an increase in the T_{OC} should result in an increase of the output performance. However, higher round-trip gain also causes stronger gain narrowing which can reduce the spectral bandwidth and might prevent an exploitation of the gain bandwidth. The gain spectrum of Yb:Lu_2O_3 features a peak at a central wavelength of around 1033 nm with a full width at half maximum (FWHM) bandwidth of around 13 nm [Fig. 5(a)] [2,32]. Both parameters are nearly constant with the inversion level. Therefore, effects on the spectral gain properties for laser operation at a different inversion level can be neglected.

The mode radius in the cavity is calculated based on a formalism of ray transfer matrices for Gaussian beams (Fig. 3). We restrict the discussion to the sagittal plane which experiences a stronger Kerr lens due to the smaller beam radius in the Kerr medium (KM). The different mode radii in tangential and sagittal plane originate from the Brewster's angle under which the

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KM is placed. In mode-locked operation, the additional Kerr lens changes the mode radius compared to the CW operation.

The focal length of the Kerr lens (f_{KM}) is estimated for a given intracavity peak power by an iterative optimization routine. In the simplified model, f_{KM} is considered as a single lens in the center of the KM. In the routine, the cavity is calculated for an initially guessed focal length $f_{\mathrm{KM,guess}}$. For a stable cavity, the mode radius in the KM (w_{KM}) is retrieved and a resulting averaged focal length of the lens in the Kerr medium ($f_{\mathrm{KM,calc}}$) is calculated based on

$$f_{\mathrm{KM,calc}}^{-1} = \frac{4 n_2 d_{\mathrm{KM,eff}}}{\pi w_{\mathrm{KM}}^4} \cdot P_{\mathrm{peak,IC}} \quad ,$$

where n_2 is the nonlinear refractive index of the KM, $d_{\mathrm{KM,eff}}$ is the effective thickness of the KM under Brewster's angle, and $P_{\mathrm{peak,IC}}$ is the intracavity peak power [33]. A stable solution for f_{KM} can be found by an iterative optimization routine minimizing the difference between $f_{\mathrm{KM,guess}}$ and $f_{\mathrm{KM,calc}}$ for a given intracavity peak power. Once a stable solution is found, it enables an estimation of the mode radius in mode-locked operation (Fig. 3). In the presented cavity are two design aspects considered. First, the mode radius has to decrease at the position of the hard aperture (HA) to form a fast saturable absorber for self-amplitude modulation. Second, the mode radii at the position of the disk (DISK1, DISK2), have to increase for an optimized overlap with the pump spot. This increase affects the optical-to-optical efficiency and creates an additional soft-aperture self-amplitude modulation.

For efficient laser operation, the mode radius on the disk in mode-locked operation has to fit to the pump spot on the disk. An 80% overlap with the pump spot diameter of 2.8 mm was evaluated for highest optical-to-optical efficiency of the fundamental-mode in CW operation [18] (Fig. 3). The different mode radii on the disk originate from the concave 2.1 m radius of curvature of the disk. For improved overlap of both mode radii on the disk (DISK1, DISK2) the free space propagation distance between them (length b) was minimized, using two highly reflective mirrors optimized for 45° angle of incidence (Fig. 2). In contrast to our previous mode-locking results, a slightly elliptical beam profile is observed (inset of Fig. 2). We attributed the ellipticity to the larger angle of incidence on the disk of 9°.

Unlike to usual KLM TDL oscillators [11,34], an operation at the edge of the stability zone in CW operation is not required. Typically, KLM TDL oscillators are first optimized for fundamental-mode CW laser operation in the center of the stability zone and adjusted mode radius on the disk. Then, a 4-f imaging section is introduced into the cavity via two curved mirrors to create an intracavity focus without influencing the behavior of the laser in CW operation. The Kerr medium is placed in the vicinity of the intracavity focus for the formation of the Kerr lens in mode-locked operation. By increasing the distance between the curved mirrors, the cavity is shifted towards the edge of the stability zone in CW operation to promote Kerr lens mode-locking. In contrast, our cavity design has not been optimized for CW operation. The curved mirrors CM2 and CM3 form an intracavity focus without serving the purpose of a 4-f imaging section leading to different cavity dynamics. This allows for tailoring the mode size on the disk by adjusting the length e between CM2 and CM3 (Fig. 4). During the experimental optimization of the mode-locking performance for highest average power at sub-100-fs pulse durations the length e, the position and thickness of the KM, the HA diameter, the T_{OC} and the introduced group delay dispersion (GDD) were adapted.

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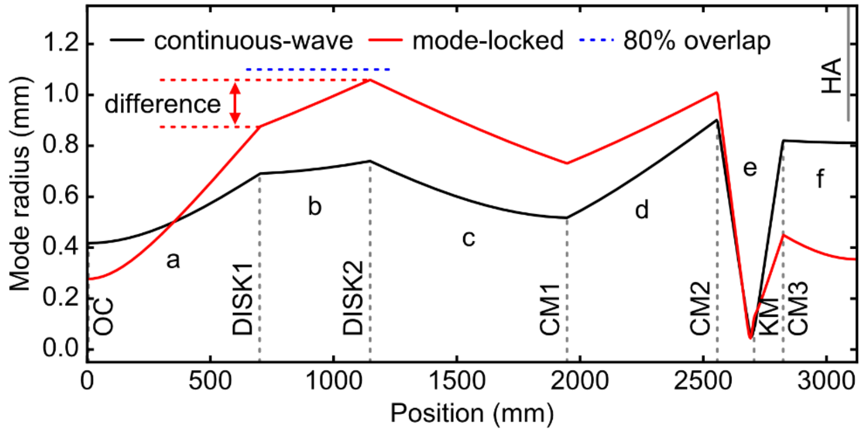

Fig. 3. Cavity design in continuous-wave and mode-locked operation shown for the sagittal plane. The mode radius is defined as the $1/e^2$ decay of the maximal intensity. In mode-locked operation, the effect of the Kerr lens in the Kerr medium (KM) is estimated for an intracavity peak power of 33 MW. Gray dotted lines indicate the position of the cavity components. In mode-locked operation, the mode radius on the disk (DISK1, DISK2) targets an 80% overlap with the pump spot (blue dotted). The different mode radii on the disk (red dotted) originate from the ROC of the disk. Cavity lengths in the simulation are a = 700 mm; b = 448 mm; c = 799 mm; d = 610 mm; e = 267mm; f = 300 mm. The distance between curved mirror CM2 and the KM is 149 mm. The hard aperture (HA, gray solid) is placed 30 mm before the cavity end mirror. In the experimental setup, the uncertainty of each length measurement towards the disk is ± 3 mm. The uncertainty of each length measurement between all other cavity components is ± 1 mm. OC, output coupler.

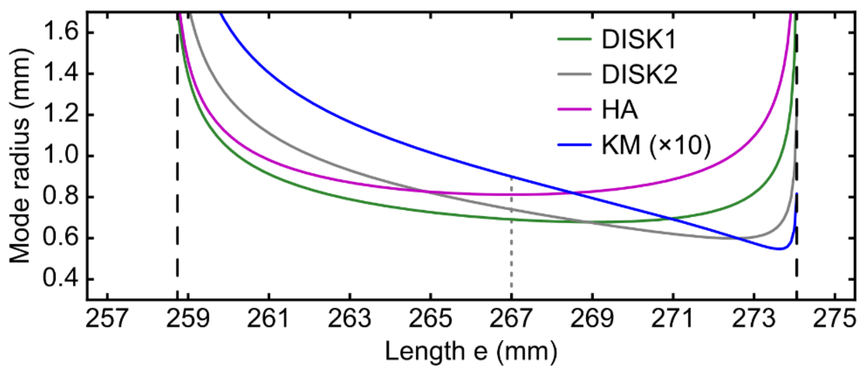

Fig. 4. Impact of the distance between the curved mirrors CM2 and CM3 in CW operation on the mode radii on the disk (DISK1; DISK2), in the Kerr medium (KM) and on the hard aperture (HA). Vertical black dashed lines indicate the edge of the stability zone for a stable cavity. The gray dotted line indicates the length e after the cavity optimization.

3. Performance in mode-locked operation

For mode-locked operation, –5400 fs^2 of GDD per cavity roundtrip are introduced by five dispersive mirrors (Fig. 2) at a T_{OC} of 12.3%. A 4 mm thick undoped YAG plate acts as KM and the diameter of the HA is 1.8 mm. The mode radii in the KM in CW operation were estimated by the cavity calculation to be 90 µm × 165 µm in sagittal and tangential plane, respectively. The start-up of the mode-locked operation follows the same procedure utilized in our initial laser result [18]. In the presented configuration, the formation of a single soliton in the cavity is achieved by setting the pump power to 160 W and knocking on the laser table. Afterwards, the pump power is reduced to 130 W to suppress a CW breakthrough visible in the

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optical spectrum. As Kerr lens mode-locking features discrete stable solutions for the pulse formation, residual energy is often extracted by CW lasing.

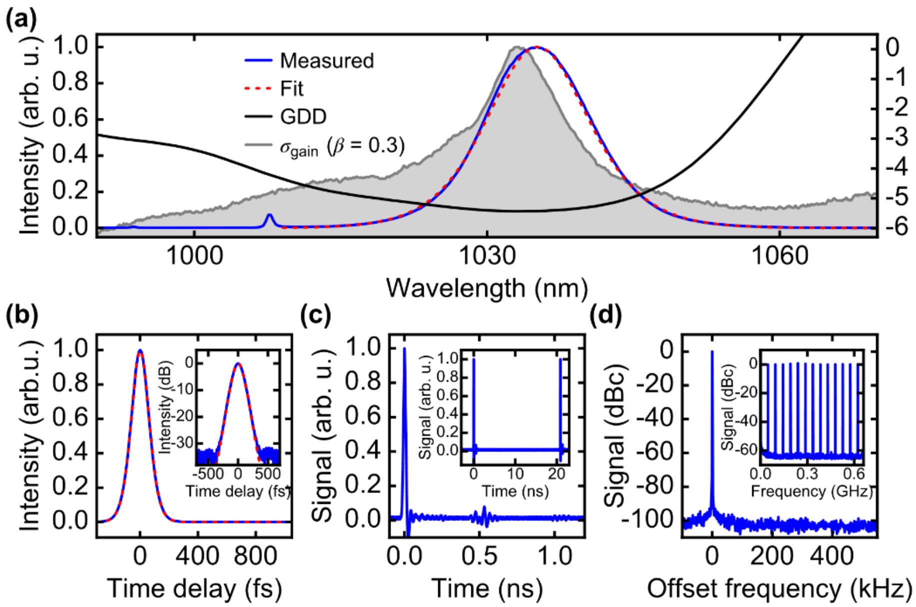

Fig. 5. (a) Optical spectrum of the laser output with sech^2 fit for soliton pulses, introduced group delay dispersion (GDD) per cavity roundtrip, and normalized gain cross-section of Yb:Lu_2O_3 for an inversion level β of 0.3 as reference (data taken from [2]). (b) Autocorrelation trace of the 95-fs pulses with sech^2 fit (measured in blue solid line and fit in red dotted line) in linear and (inset) logarithmic scale. (c) Sampling oscilloscope trace for 1 ns and (inset) 20 ns. (d) Radio-frequency spectrum of the fundamental repetition-rate frequency at 47.9 MHz and (inset) its harmonics at 100 Hz and 1 kHz resolution bandwidth, respectively.

In this configuration, the oscillator generates 95-fs pulses at an average output power of 21.1 W. The generated peak power is estimated to be 4.1 MW for soliton pulses at 0.44 µJ of pulse energy. The optical spectrum of the generated pulses [Fig. 5(a)] is centered at a wavelength of 1035.1 nm with a FWHM bandwidth of 12.3 nm. It is in good agreement with the sech^2 fit for soliton pulses. In comparison, the normalized spectrum of the gain cross-sections of Yb:Lu_2O_3 is plotted for an inversion level β of 0.3. Compared to the gain cross-sections, the central wavelength of the optical spectrum is shifted by 2 nm towards longer wavelengths. The shift is a result of the reflectivity and dispersion of the cavity components.

The pulse duration of 95 fs is measured by intensity autocorrelation [Fig. 5(b)] and has an ideal sech^2 shape for soliton pulses down to the measurement noise floor of –32 dB. The time-bandwidth product of 0.325 is close to the transform limit and 1.04 times the ideal value for sech^2 pulses. Single pulse operation was proven by a 180-ps scan with the autocorrelator and by observing the pulse train with an 18.5-ps-rise-time photodetector on a 40-GHz sampling oscilloscope [Fig. 5(c)]. Fluctuations at 0.5 ns and 1.0 ns are electronic reflections. The radio-frequency spectrum measured at the fundamental repetition frequency of 47.9 MHz shows no side peaks down to the measurement noise floor of –100 dBc and modulation-free higher harmonics confirm clean mode-locking [Fig. 5(d)]. The beam quality factor M^2 was measured to be ≤ 1.03. A summary of the parameters in mode-locked operation is given in Table 2.

For long-term operation, the pump power was slightly reduced to 126 W, decreasing the average power by 5% to 20.0 W. This suppressed a CW breakthrough that appeared during the warm-up of the system after several minutes. During a one-hour measurement in this condition, the average power and pulse duration showed no drift and fluctuated by less than 0.3% rms (Fig. 6).

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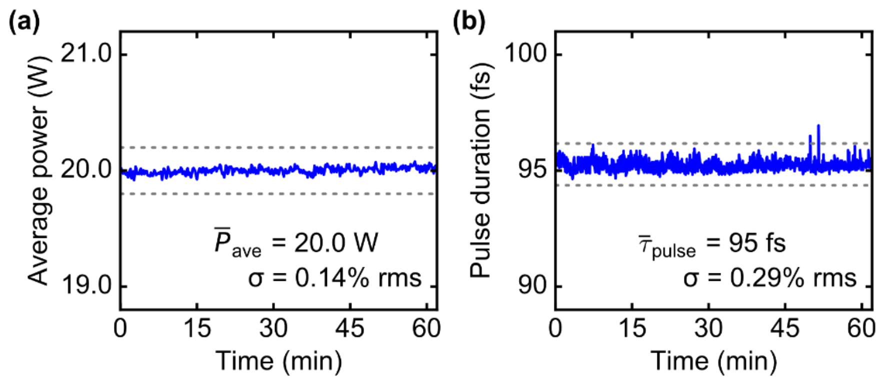

Fig. 6. (a) Average power and (b) pulse duration during a stability measurement of one hour. Corresponding averaged values are given with the root mean square (rms) error (σ). Gray dotted lines indicate the ± 1% margins of the average value.

Table 2. Summary of the mode-locking performance of the KLM Yb:Lu_2O_3 TDL oscillator for a single and double folding of the cavity on the disk.[a]

	Single folding	Double folding	Comparison
$w_{KM,CW}$	90 µm × 150 µm	90 µm × 165 µm	≈
τ_{FWHM}	88 fs	95 fs	≈
$N_{Disk,RT}$	4	8	2 × ↑
P_{ave}	10.7 W	21.1 W	2 × ↑
η_{eff}	5.8%	16.2%	3 × ↑
T_{OC}	4.6%	12.3%	3 × ↑
P_{peak}	1.8 MW	4.1 MW	2 × ↑

	Single folding	Double folding	Comparison
E_{pulse}	0.18 µJ	0.44 µJ	2 × ↑
$P_{peak,\ IC}$	39 MW	33 MW	≈
$E_{pulse,\ IC}$	3.9 µJ	3.6 µJ	≈
$P_{ave,\ IC}$	233 W	172 W	26% ↓
f_{rep}	61 MHz	47.9 MHz	21% ↓
GDD_{RT}	−2200 fs^2	−5400 fs^2	2 × ↑
d_{KM}	2 mm	4 mm	2 × ↑
$\lambda_{central}$	1037.6 nm	1035.1 nm	

[a] $w_{KM,CW}$: mode radius in the Kerr medium in continuous-wave operation; τ_{FWHM}: FWHM pulse duration; N_{Disk}: number of passes through the disk per cavity round-trip; P_{ave}: average power; η_{eff}: optical-to-optical efficiency; T_{OC}: output coupler transmission; P_{peak}: peak power; E_{pulse}: pulse energy; IC: intracavity; f_{rep}: repetition rate; GDD_{RT}: introduced group delay dispersion per cavity round-trip; d_{KM}: thickness of the Kerr medium; $\lambda_{central}$: central wavelength; ≈: comparable; ↑: increase; ↓: decrease.

The performance of the oscillator is compared to previous mode-locking results achieved with folding the cavity once on the disk (Table 2) [18]. In both configurations, the mode size in the KM in CW operation and the pulse duration are similar.

Doubling the number of passes through the disk per cavity round-trip enabled an increase of the average output power by a factor of two. Optical-to-optical efficiency and output coupler transmission were increased by a factor of almost three to 16.2% and 12.3%, respectively. Although peak power and pulse energy increased, the corresponding intracavity values remained comparable. This observation agrees with the geometrical scaling law of KLM TDLs [30] which relates the achievable intracavity peak power to the mode size in the KM in CW operation. As consequence of a similar intracavity peak power ($P_{peak,IC} \approx 0.88 \cdot E_{pulse,IC} / \tau_{FWHM}$), the 26% decrease in intracavity average power can be attributed to the reduced repetition rate ($E_{pulse,IC} = P_{ave} / T_{OC} \cdot f_{rep}$). The two times larger amount of introduced GDD per round-trip compensates for the stronger SPM (γ_{SPM}) in the two times thicker YAG KM plate ($E_{pulse,IC} \approx 2 \cdot 1.76 \cdot |GDD| / \gamma_{SPM} \cdot \tau_{FWHM}$). The stronger SPM is attributed to be required for the compensation of the gain narrowing caused by the increased T_{OC} to maintain the spectral bandwidth. The central wavelength is slightly shifted by 2 nm towards the gain peak in the cross sections of Yb:Lu_2O_3 at 1033 nm, which may contribute to the increased laser efficiency. We suggest that the different central wavelengths originate from the slightly different dispersion profiles of the dispersive mirrors used in both lasers.

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4. Conclusion and outlook

We demonstrated a KLM Yb:Lu_2O_3 TDL oscillator generating 95-fs pulses at 21.1 W average power. By folding the cavity two times on the disk, the average power was increased by a factor of two with an almost three times higher optical-to-optical efficiency of 16.2%, compared to our previous result [18]. We showed that KLM TDL oscillators based on the gain material Yb:Lu_2O_3 are suitable for the generation of sub-100-fs pulses at high average power with optical-to-optical efficiencies that are comparable to Yb-doped bulk oscillators. The presented TDL oscillator has been used as single-stage driving laser for broadband THz generation via optical rectification in GaP [35]. In this case, high-power laser operation with sub-100-fs pulse duration was beneficial for the generated THz spectral bandwidth that expanded up to 5 THz at 0.3 mW of THz average power.

The average power of SESAM mode-locked Yb:Lu_2O_3 TDL oscillators was scaled from initially 20 W up to 141 W [31,36]. We anticipate that similar power-scaling should be feasible for sub-100-fs KLM Yb:Lu_2O_3 TDL oscillators. We expect that further power-scaling of sub-100-fs KLM Yb:Lu_2O_3 TDL oscillators can be achieved by scaling the intracavity peak power via adapting the mode size in the Kerr medium [30], enlarging the pump spot diameter on the disk [7] and by further increasing the number of passes through the disk. By this, we anticipate that sub-100-fs KLM Yb:Lu_2O_3 TDL oscillators operating at more than hundred watt of average power are within reach.

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