

# Generation of 35-fs pulses from a Kerr lens mode-locked Yb:Lu<sub>2</sub>O<sub>3</sub> thin-disk laser

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**Abstract:** We investigate Kerr lens mode locking of Yb:Lu<sub>2</sub>O<sub>3</sub> thin-disk laser oscillators operating in the sub-100-fs regime. Pulses as short as 35 fs were generated at an average output power of 1.6 W. These are the shortest pulses directly emitted from a thin-disk laser oscillator. The optical spectrum of the 35-fs pulses is almost 3 times broader than the corresponding emission band of the gain crystal. At slightly longer pulse duration of 49 fs, we achieve an average power of 4.5 W. In addition, 10.7 W are obtained in 88-fs pulses, which is twice higher than the previous power record for ultrafast thin-disk lasers generating pulses shorter than 100 fs. Our results prove that Kerr lens mode-locked Yb:Lu<sub>2</sub>O<sub>3</sub> thin-disk lasers are a promising technology for further average power and pulse energy scaling of ultrafast high-power oscillators operating in the sub-100-fs regime.

**OCIS codes:** (140.4050) Mode-locked lasers; (140.3538) Lasers, pulsed; (140.7090) Ultrafast lasers; (140.3615) Lasers, ytterbium.

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## 1. Introduction

Following the demonstration of the first mode-locked thin-disk laser (TDL) oscillator more than fifteen years ago [1], tremendous progress in the area of power scaling has been achieved [2]. In this period, the field of mode-locked TDLs has evolved into being the leading technology for high power and high pulse energy ultrafast laser oscillators. State-of-the-art ultrafast TDLs emit up to 275 W of output power [3,4] and 80  $\mu$ J of pulse energy [5] with several hundred femtoseconds pulse durations. Such performance has enabled TDLs to directly drive applications which previously required the use of complex amplifier systems [6–8]. However, reducing the pulse duration of high-power oscillators is a major

challenge. The first TDL emitting sub-100-fs pulses has been demonstrated only in 2012 [9] and even today, the power levels in this regime are limited to 5 W [9,10] (see Fig. 1). Therefore, external nonlinear pulse compression is applied for many applications in areas such as high field science and frequency comb generation. This introduces an additional stage of complexity to the system which may reduce the beam quality, power level and temporal pulse profile. Overcoming the trade-off between output power and pulse duration by providing compact and simple laser oscillators delivering hundreds of watts and tens of micro-joules in sub-100-fs pulses will simplify many existing experiments and open new application areas.

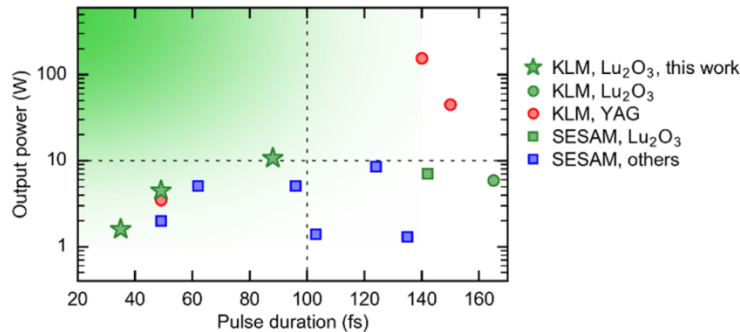


Fig. 1. Overview of sub-170-fs mode-locked thin-disk lasers based on Yb-doped materials [9–17]. The results presented in this article are highlighted with star symbols. The green area spotlights the desired performances of ultrafast oscillators to directly drive applications such as high field science and frequency comb generation.

Initially, all ultrafast TDLs were passively mode-locked using a semiconductor saturable absorber mirror (SESAM, [18]). Besides self-starting pulsed operation and simplicity of the cavity design, the combination of TDLs and SESAMs enables power scalability of the mode-locked performance of the laser [2]. Following the demonstration of the first Kerr lens mode-locked (KLM) TDL [19], similar scaling laws were demonstrated for this alternative mode locking technique resulting in average output powers up to 270 W in 330-fs pulses utilizing Yb:Y<sub>3</sub>Al<sub>5</sub>O<sub>12</sub> (Yb:YAG) [4]. Recently, 140-fs pulses were generated directly from a KLM Yb:YAG thin-disk oscillator at an average output power of 155 W and an optical-to-optical efficiency of 29% [17]. This pulse duration is more than three times shorter than any Yb:YAG SESAM mode-locked TDL [2]. Mode locking of TDLs via the Kerr lensing mechanism enables high modulation depth as well as instantaneous response time of the self-amplitude modulation. While Yb:YAG may be the best choice for high (average) output power, its gain bandwidth of 9 nm (FWHM) does not support pulses shorter than 120 fs. In order to achieve mode-locked operation with pulse durations shorter than 100 fs, numerous TDL using Yb-doped laser materials with broader gain bandwidths have been developed [20]. In this way, the minimum pulse duration was successfully reduced from initially hundreds of femtoseconds to 49 fs, which were obtained from a SESAM mode-locked Yb:CaGdAlO<sub>4</sub> (Yb:CALGO) TDL [10,14]. Most of the recently demonstrated Yb-based broadband gain materials are still in an early phase of thin-disk development, suffering from growth defects and non-optimized disk processing technologies. Moreover, many of them exhibit comparably low thermal conductivity due to their disordered nature. All of these factors hinder further power scaling at the moment. Until recently, all TDLs generating record-short pulses were based on SESAM mode locking. In 2015, pulses as short as 49 fs with 33 nm optical bandwidth have been obtained from a KLM Yb:YAG TDL [15]. This result relied on spectral broadening of the pulses utilizing additional spectral components generated due to SPM well beyond the gain limitation [21]. Although the output power of 3.5 W was moderate, this result clearly indicates that KLM is a promising approach for achieving even

shorter pulses from TDLs based on Yb-gain materials with broader emission bands than Yb:YAG.

Yb:Lu<sub>2</sub>O<sub>3</sub> is an excellent candidate to push the performance of ultrafast TDLs towards high-power and short pulses. The cubic host lutetia (Lu<sub>2</sub>O<sub>3</sub>) features a high thermal conductivity of 12 Wm<sup>-1</sup>K<sup>-1</sup>, which is nearly independent on the doping concentration, while the thermal conductivity of Yb:YAG drops by nearly a factor of two to 7 Wm<sup>-1</sup>K<sup>-1</sup> at the Yb<sup>3+</sup>-doping concentrations required in the TDL configuration. When doped with Yb<sup>3+</sup>, Lu<sub>2</sub>O<sub>3</sub> exhibits a 30% broader gain bandwidth than Yb:YAG, amounting to 12 nm (FWHM) and directly supporting sub-100-fs pulse formation. The absorption cross sections at the zero-phonon line around 976 nm are more than a factor of 3 higher than those of Yb:YAG. Pumping at this wavelength brings also the advantage of an increased Stokes efficiency and thus a lower amount of generated heat compared to Yb:YAG, which is typically pumped at 940 nm or 969 nm [22]. The high melting point exceeding 2400 °C makes the growth of lutetia very challenging, but the heat exchanger method has proven to be a viable technique for growing high quality crystals [23]. The beneficial properties of this gain material supported very high optical-to-optical efficiencies exceeding 70% in continuous wave operation. In the bulk geometry, an Yb:Lu<sub>2</sub>O<sub>3</sub> oscillator emitted 71 fs pulses [24] while in SESAM-mode-locked TDL operation, it generated more than 140 W of average output power with sub-ps pulses [25] and supported pulses as short as 142 fs [11]. Recently, the first KLM Yb:Lu<sub>2</sub>O<sub>3</sub> TDL was presented delivering 5.9 W with 165-fs pulses [16]. Figure 2 presents a timeline of the minimum achieved pulse duration from ultrafast Yb:Lu<sub>2</sub>O<sub>3</sub> bulk and thin-disk lasers.

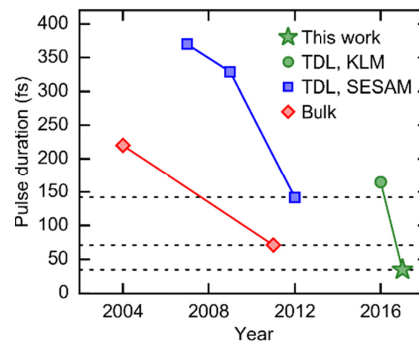


Fig. 2. Overview of the minimum achieved pulse duration from ultrafast oscillators based on the Yb:Lu<sub>2</sub>O<sub>3</sub> gain material in bulk and thin-disk geometries [11,16,24,26–28]. The presented work is highlighted with a star symbol.

Here we demonstrate that the use of the broadband gain material Yb:Lu<sub>2</sub>O<sub>3</sub> in the TDL configuration in combination with KLM technique is well-suited for the generation of pulses shorter than 100 fs. We achieved the shortest pulses as well as two times higher average power in the sub-100-fs domain than from any TDL.

## 2. Laser characterization in continuous-wave operation

The laser experiments were performed with a 12-mm-diameter Yb(3%):Lu<sub>2</sub>O<sub>3</sub> disk. The crystal boule has been grown at the Institut für Laser-Physik (Universität Hamburg) and was afterwards cut and polished to a thickness of 160 μm. The disk exhibits a wedge of 0.1° in order to avoid interaction between the residual reflections and the main beam. The front surface is anti-reflection (AR) coated while the back surface is coated to be highly reflective (HR) for laser and pump wavelengths. The disk is contacted onto a diamond heat sink and has a concave radius of curvature (RoC) of 2.1 m. Water-cooling of the diamond from the backside allows for efficient removal of the heat generated in the active material. A fiber-coupled volume-Bragg-grating (VBG) stabilized 400-W diode laser system pumps the

gain material at the zero-phonon line at a wavelength of 976 nm with a spectral width below 0.5 nm. The disk is placed in a TDL head designed for 36 passes of the pump through the gain material in order to achieve high pump absorption. The pump spot is set to a diameter of 2.8 mm.

The disk was initially tested in continuous-wave (cw) operation in a linear multi-mode (MM) cavity consisting of a flat output coupler (OC) with a transmission  $T_{OC}$  of 1.8% and the HR coated backside of the disk, separated by  $\approx 7$  cm. The beam radius of the fundamental mode on the gain crystal was estimated to be  $360 \mu\text{m}$ , thus the laser operation was highly multi-mode given the pump spot diameter of 2.8 mm. In such a configuration, highest efficiencies can be expected due to an improved overlap of the top-head pump profile and the laser beam compared to a diffraction limited Gaussian beam. As shown in Fig. 3, a cw output power of 137 W was obtained under 209 W of incident pump power. The optical-to-optical efficiency amounted to 66% and the slope efficiency was 81%. These values are close to the best reported results with this gain material in the thin-disk configuration [22]. In order to avoid damage, we limited the pump intensity on the disk to  $\approx 3.5 \text{ kW/cm}^2$  even though no hints for degradation of the laser efficiency were observed even at highest pump powers.

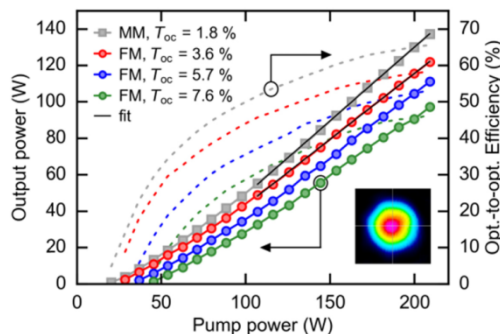


Fig. 3. Output power (solid) and optical-to-optical efficiency (dashed) as a function of the pump power for a multi-mode linear cavity (MM, output coupler transmission  $T_{OC} = 1.8\%$ ) and a fundamental transverse mode cavity folded over the disk (FM,  $T_{OC} = 3.6 - 7.6\%$ ), thus experiencing two times higher gain; The black solid lines show the linear fits used for the calculation of the slope efficiencies. Inset: near-field mode profile of the laser at 122 W of output power at a  $T_{OC}$  of 3.6%.

In the next step, we built a 3 m long linear cavity supporting fundamental transverse mode (FM) operation following a similar design as the one reported in [25]. The disk and a concave curved mirror (CM) (RoC = 3 m) are placed between two flat end mirrors, of which one is partially transmissive and used as an OC. In this configuration where the disk is used as a folding mirror, the laser beam passes four times per roundtrip (RT) through the gain crystal which leads to a twice higher gain and consequently a twice larger optimal output coupling rate compared to the multi-mode cavity. The lasing performance in cw operation was evaluated for different output coupling rates (see Fig. 3). The estimated laser mode to pump diameter ratio was around 80% and the beam quality factor  $M^2$  was measured to be below 1.2 in all experiments, confirming fundamental mode operation of the laser. At  $T_{OC} = 3.6\%$ , 122 W were emitted with an optical-to-optical efficiency approaching 60% and a high slope efficiency of 70%. The near field mode profile of the laser at this output power is depicted in the inset of Fig. 3. These results reveal that this particular disk exhibits high growth and manufacturing quality and is well suited for further mode-locking experiments.

### 3. Results of the laser experiments in mode-locked operation

For mode-locked operation, we modified the cavity similar to [19] in order to favor pulsed operation by applying the Kerr effect as depicted in Fig. 4. A 2-mm-thick undoped YAG plate

is placed under Brewster's angle in the focal region between the two concave mirrors (CM2 and CM3), which have both a RoC of 400 mm. This Brewster plate (BP) ensures linear polarization of the laser beam and serves as the Kerr medium for the mode-locking mechanism. The beam spot radius inside the BP is estimated to be  $90 \mu\text{m} \times 150 \mu\text{m}$  in sagittal and tangential planes. A water-cooled pinhole placed in front of an end mirror serves as a hard aperture for KLM. The intra-cavity group delay dispersion (GDD) is adjusted by several dispersive mirrors for the soliton formation. The pulsed operation is generally initiated by a gentle knock on the laser table. The cavity length of the resonator is 2.5 m, which results in a 61 MHz repetition rate of the generated pulses. The resonator is operated in ambient air and has a footprint of only  $80 \text{ cm} \times 40 \text{ cm}$ .

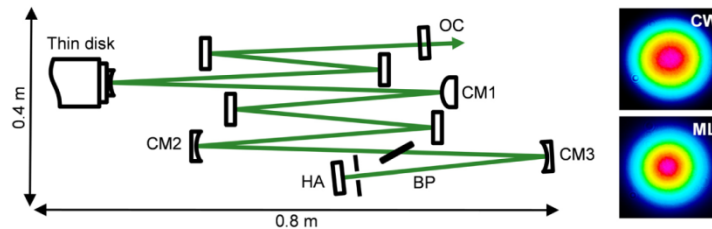


Fig. 4. Schematic of the cavity used for mode locking operation. CM1, convex RoC of 2 m; CM2, CM3 concave RoC of 400 mm; BP, Brewster plate; HA, hard aperture; OC, output coupler. All other mirrors are highly reflective or dispersive depending on the configuration. A difference in the size of the beam profile was between cw and ML operation (data shown for the 35-fs operation).

In our work, we focused on optimizing the laser for shortest pulse duration and highest average output power in the sub-100-fs regime. For this purpose, we studied the influence of critical laser parameters in one general cavity configuration, keeping the cavity design and the concave mirrors around the Kerr element constant. We investigated the mode locking performance for varying output coupling rate, intra-cavity dispersion, and hard aperture diameter. For each configuration, the pump power was set to the level delivering the minimum pulse duration in stable fundamental mode locking. At slightly higher pump power, a cw breakthrough was typically observed in the optical spectrum. In this way, stable mode locking was obtained for a large variety of laser parameters. The transverse beam quality  $M^2$  was measured in several mode-locked configurations and was always below 1.05. Table 1 summarizes the mode-locked performance and laser parameters for a few representative configurations.

**Table 1. Mode locking performance and laser parameters for the presented configurations with pulse durations of 35 fs, 49 fs and 88 fs.**

Configuration	35 fs	49 fs	88 fs	Configuration	35 fs	49 fs	88 fs
Output power (W)	1.6	4.5	10.7	GDD per RT ( $\text{fs}^2$ )	-1000	-1100	-2200
Peak power (MW)	0.7	1.3	1.8	Hard aperture diameter (mm)	1.9	2.0	2.0
Pulse energy ( $\mu\text{J}$ )	0.03	0.07	0.18	Repetition rate (MHz)	61	61	61
Central wavelength (nm)	1028.8	1031.5	1037.6	Output coupling rate (%)	0.9	2.7	4.6
FWHM bandwidth (nm)	33.9	24.1	14.4	Pump power (W)	76	96	186
Time bandwidth product	0.332	0.330	0.353	Opt-to-opt efficiency (%)	2.1	4.7	5.8

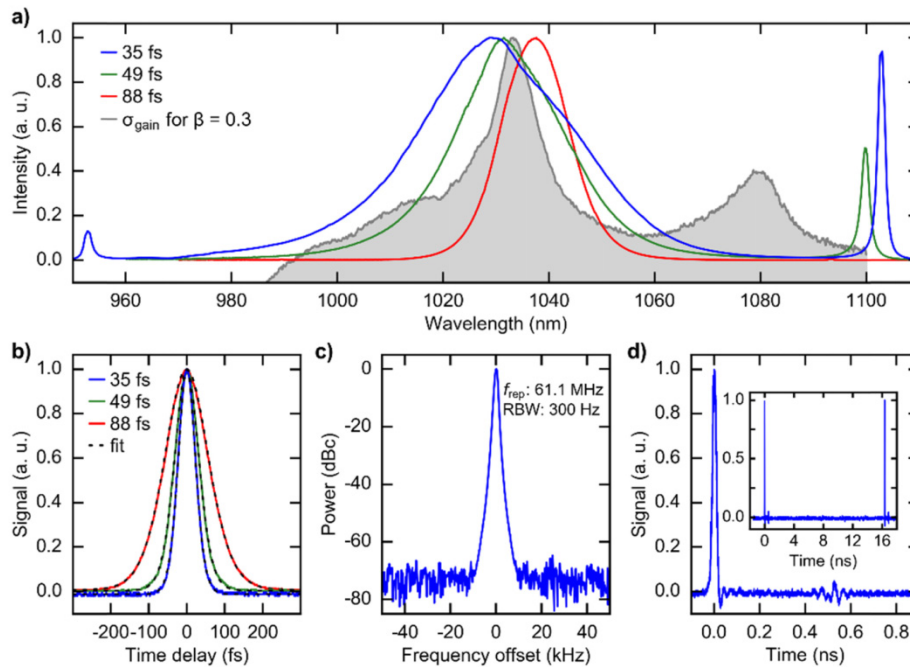


Fig. 5. (a) Optical spectra of the 35-fs, 49-fs and 88-fs laser configurations. The normalized gain cross section  $\sigma_{\text{gain}}$  of Yb:Lu<sub>2</sub>O<sub>3</sub> for an inversion level  $\beta$  of 0.3 is shown for reference (data taken from [20]). (b) Intensity autocorrelation traces with fit to the autocorrelation of a  $\text{sech}^2$ . (c) Radio frequency spectrum of the 35-fs pulses measured with a resolution bandwidth RBW of 300 Hz. (d) Sampling oscilloscope trace in 1 ns and (inset) 20 ns for the 35-fs pulse train confirming the single pulse operation of the mode-locked laser. The weak ringing in the signal trace at 0.5 ns is an artefact due to the electronics of the detection setup.

Figures 5(a) and 5(b) show the optical spectra and the gain at an inversion level of 0.3 for reference, as well as the intensity autocorrelation traces with the corresponding fit to the autocorrelation of a  $\text{sech}^2$  function for the three configurations. The side peaks observed in the spectra of the short pulses carry only a minor fraction of the power and are associated with dispersive waves, similar to the sidebands observed in previous work [14,24]. Moreover, the output coupler transmission increases by more than a factor of two at the edges of the spectrum. The radio frequency spectrum and sampling oscilloscope trace of the shortest pulses are shown in Figs. 5(c) and 5(d). The 88-fs and 49-fs configurations achieve an average power of 10.7 and 4.5 W, respectively. The shortest pulse duration of 35 fs has been achieved at an output power of 1.6 W. For this pulse duration measurement, an extra-cavity dispersive mirror with negative group delay dispersion of  $-250 \text{ fs}^2$  was used to compensate for the material dispersion of the output coupler mirror and for the propagation in air. For all configurations, we confirmed fundamental single pulse mode-locked operation of the laser with a 180-ps long-range autocorrelation and a fast 18.5-ps photodiode in combination with a 40-GHz sampling oscilloscope as shown in Fig. 5(c).

This result demonstrates pulses 4 times shorter than previously achieved from a SESAM mode-locked Yb:Lu<sub>2</sub>O<sub>3</sub> TDL [11] and 50% shorter than obtained in bulk geometry with the same gain material [24]. For reaching shorter pulse durations, we observed general trends in agreement with previous reported studies on mode-locking with fast saturable absorbers [17,29,30]. Operating at a moderate level of introduced negative dispersion of  $-1000 \text{ fs}^2$  up to  $-2000 \text{ fs}^2$  per roundtrip enabled shortest pulse durations. Pulses became unstable at lower GDD values, while for higher values, the minimum achievable pulse duration increased. Other critical parameters are output coupling rate and hard aperture

diameter. To optimize pulse durations, it was important to reduce the output coupling rate while at the same time decreasing the aperture size. This allows maximizing the modulation depth of the self-amplitude modulation, enabling stable mode-locking operation even in a regime with strong gain narrowing of the pulses. In this context, it should be noted that the optical bandwidth of the 35-fs pulses is almost 3 times broader than the FWHM of the emission cross section of the gain crystal.

#### 4. Conclusion and outlook

We studied the minimum pulse durations achievable in soliton mode-locking with a TDL based on the broadband gain material Yb:Lu<sub>2</sub>O<sub>3</sub> and KLM for various configurations of output coupling rate, intra-cavity dispersion, and hard aperture diameter. This work presents the shortest pulses and the highest power with sub-100-fs pulses directly emitted from a thin-disk laser oscillator. In order to reach shortest pulse durations, the total negative intra-cavity dispersion needs to be minimized and the modulation depth of the saturable absorber has to be maximized by selecting a low degree of output coupling and adapting the hard aperture diameter. The efficiency in mode-locked operation is currently below 10% but we expect that further optimization of the cavity design in combination with mode-locking parameters for lower non-saturable losses should enable higher values. Furthermore, in 2014, Brons *et al.* showed that scaling the intra-cavity peak power is feasible by enlarging the spot size on the Kerr medium [4], eventually leading to a significant increase of the output power of the laser. As a next step towards power scaling of sub-100-fs lasers, we will perform a similar study on an Yb:Lu<sub>2</sub>O<sub>3</sub>-based KLM oscillator. We expect that an increase of the spot size in the Kerr medium in combination with a larger pump area on the disk and multi-pass on the laser crystal will enable significantly higher output powers and pulse energies, making this source even more attractive for numerous experiments. Our work shows that Yb:Lu<sub>2</sub>O<sub>3</sub> is one of the most promising gain materials for power-scaling of sub-100-fs TDL oscillators towards several hundred watts of output power.

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