

# Femtosecond thin-disk laser with 141 W of average power

Cyrril Roman Emmanuel Baer,<sup>1,\*</sup> Christian Kränkel,<sup>1,2</sup> Clara Jody Saraceno,<sup>1</sup> Oliver Hubert Heckl,<sup>1</sup> Matthias Golling,<sup>1</sup> Rigo Peters,<sup>2</sup> Klaus Petermann,<sup>2</sup> Thomas Südmeyer,<sup>1</sup> Günter Huber,<sup>2</sup> and Ursula Keller<sup>1</sup>

<sup>1</sup>Department of Physics, Institute of Quantum Electronics, ETH Zurich, Wolfgang-Pauli-Strasse 16, 8093 Zurich, Switzerland

<sup>2</sup>Institute of Laser-Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

\*Corresponding author: cbaer@phys.ethz.ch

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We present a semiconductor saturable absorber mirror mode-locked thin disk laser based on Yb:Lu<sub>2</sub>O<sub>3</sub> with an average power of 141 W and an optical-to-optical efficiency of more than 40%. The ideal soliton pulses have an FWHM duration of 738 fs, an energy of 2.4 μJ, and a corresponding peak power of 2.8 MW. The repetition rate was 60 MHz and the beam was close to the diffraction limit with a measured  $M^2$  below 1.2. © 2010 Optical Society of America  
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Femtosecond laser sources with high average powers are important tools for industrial and scientific applications. An increased average power can reduce the processing time for cutting or drilling applications and, in high field physics, it allows one to drive experiments at higher repetition rates leading to an increased signal-to-noise ratio or a higher photon flux [1]. This is particularly interesting in frequency conversion processes, such as high harmonic generation [2]. To date, semiconductor saturable absorber mirror (SESAM) [3] mode-locked thin disk lasers based on Yb:YAG deliver 80 W of average power [4] and pulse energies of up to 11.3 μJ with the thin disk gain element in a single folding mirror configuration [5] and up to 25.9 μJ in an active multipass cavity [6]. Higher average powers have only been obtained from more complex setups, such as fiber chirped-pulse amplifier systems [7] or slab amplifiers [8].

However, the pulse duration from Yb:YAG thin disk lasers is limited to about 700 fs due to the relatively narrow emission bandwidth compared to other Yb-doped materials [9]. The shortest pulse duration so far reported from a thin disk laser has been achieved with a Yb:LuScO<sub>3</sub> thin disk laser that delivered 227-fs-long pulses with an average power of 7.2 W [10]. However, the thermal conductivity of this mixed material [3.6 W/(m · K)] is much lower than for its individual constituents Sc<sub>2</sub>O<sub>3</sub> and Lu<sub>2</sub>O<sub>3</sub> [11]. The latter has a thermal conductivity of 12.5 W/(m · K), which is significantly higher—also higher than for YAG [11 W/(m · K)]—and remains, in contrast to YAG, almost unaffected when doped with Yb ions [12]. The emission bandwidth is not as broad as for Yb:LuScO<sub>3</sub> but still has about twice the width of Yb:YAG. Yb:Lu<sub>2</sub>O<sub>3</sub> shows an absorption maximum at 976 nm (zero-phonon line) with an absorption cross section that is about four times higher than for Yb:YAG [13], which is typically pumped at 940 nm. Pumping at 976 nm instead of 940 nm reduces the quantum defect by about 40%. Yb:YAG could also be pumped at the zero-phonon line at 969 nm, where it shows almost the same absorption cross section as at 940 nm. However, both materials show only a narrow absorption bandwidth of below 2.9 nm at the zero-phonon line, which requires a wavelength-stabilized and narrow-linewidth pump diode. Three years ago, the first mode-locked thin-disk laser based on Yb:Lu<sub>2</sub>O<sub>3</sub> was presented [14]. It achieved the highest

optical-to-optical efficiency of 43% for mode-locked thin-disk lasers. In the meantime, an average power of 63 W and pulses as short as 329 fs at an average power of 40 W have been demonstrated [15]. The higher absorption cross section, which allows for the use of thinner disks, the lower quantum defect, and the better thermal conductivity clearly favor the choice of Yb:Lu<sub>2</sub>O<sub>3</sub> over Yb:YAG for high-power applications.

Here, we report on successful power scaling of a femtosecond Yb:Lu<sub>2</sub>O<sub>3</sub> thin disk laser oscillator to an average power of more than 100 W. The simplicity of this high-power cavity is the same as for low power cavities, and no additional amplifiers after the laser oscillator are required. We achieved an average power as high as 141 W, which is, to the best of our knowledge, the highest average power so far reported from any passively mode-locked laser oscillator. Figure 1 shows the development of the average power of mode-locked thin disk lasers since their first demonstration in 2000.

SESAM mode-locked thin-disk lasers are a very successful technology to reach high output powers [16]. The key components, the thin disk as a gain medium and the SESAM for passive mode locking, are used in reflection and can be cooled efficiently through the back side. To increase the output power, we can increase the pump power by the same amount as the pump area on the disk and the laser mode area on the SESAM. This procedure keeps all critical parameters, such as the pump power density and the saturation parameter of the

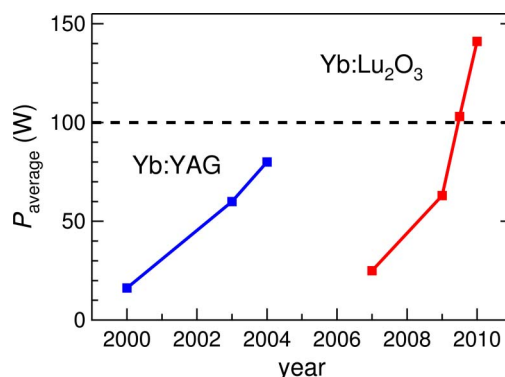


Fig. 1. (Color online) Evolution of the average power from mode-locked thin-disk lasers based on Yb:YAG and Yb:Lu<sub>2</sub>O<sub>3</sub>.

SESAM, constant. However, according to Magni [17], the stability zone regarding a thermal lens of the gain medium [ $\Delta(1/f_{\text{disk}})$ , where  $f_{\text{disk}}$  is the focal length of the disk] decreases inversely proportional to the mode area on the disk. This means that a larger laser mode on the disk leads to a more sensitive cavity with respect to a thermal lens. On the other hand, the focal power of the disk resulting from a thermal change of the refractive index ( $dn/dT$ ) decreases for an increasing pump spot. Although these two effects counteract each other, the design of a fundamental mode cavity can become more challenging for larger pump spots, as there are other thermal-induced effects, such as stress, bending, or bulging. This underlines the importance of the thermal properties of the gain material.

In comparison to previous reported results [15], we increased the pump spot from 1.9 to 2.6 mm in diameter. We placed the two end mirrors on linear translation stages, which allowed us to continuously adapt the cavity to the change of the thermal lens and, therefore, maintain efficient fundamental mode operation over the total pump power range. Figure 2 shows a picture of the real setup with a sketch and a description of the components underneath. We used a 2 at. %  $\text{Yb}^{3+}$ -doped  $\text{Lu}_2\text{O}_3$  crystal that was grown by the heat exchanger method at the ILP in Hamburg [18]. The crystal was cut and polished to a thickness of 250  $\mu\text{m}$  and a wedge of 0.05° to avoid interaction of residual reflections with the main beam. The back side of the disk is coated with a high reflective (HR) coating for both pump and laser wavelength, whereas the front side has an antireflective (AR) coating for the same spectral range. The HR side of the disk is soldered with indium–tin onto a water-cooled copper heat sink. The disk was pumped with a fiber-coupled laser diode emitting at 976.4 nm. Wavelength stabilization and the necessary narrow emission bandwidth of the diode have been achieved with a volume Bragg grating [19], resulting in an emission bandwidth of 0.6 nm (FWHM). The pump module was aligned for 24 passes of the pump light through the disk and a spot of 2.6 mm in diameter. The output coupler mirror had a transmission of 9%. A key element in high-power oscillators is dispersion management. For stable soliton mode locking, one has to find the ideal balance between self-phase modulation (SPM) and negative group delay

dispersion (GDD) [20]. A SESAM mode-locked thin disk laser offers good control over the SPM in the cavity, as all components are used in reflection (see Fig. 2). The amount of SPM introduced from the gain material is small, as the laser mode size is in the order of the pump spot size (2.6 mm diameter) and the thickness of the crystal is only 250  $\mu\text{m}$ . We typically add extra SPM by introducing a fused silica plate at Brewsters angle. However, in the current resonator with an average intracavity power of up to 1.6 kW, the SPM contribution of the ambient air becomes significant and the Brewster plate can be omitted. We estimated the total phase shift in air to be about 40 mrad and compensated for it with a set of nine GTI-type dispersive mirrors introducing, in total,  $\approx 9900 \text{ fs}^2$  of negative GDD per cavity roundtrip. The SESAM had a standard low-finesse design, consisting of a 30-pair GaAs/AlAs Bragg reflector and one 10 nm InGaAs quantum well absorber layer. To reduce the electric field in the absorber structure, and therefore increase the saturation fluence, a dielectric top coating—consisting of two layers  $\text{Ta}_2\text{O}_5$  with a thickness of 251 nm and 126 nm with one 178-nm-thick layer  $\text{SiO}_2$  in between—has been added. The final SESAM had a saturation fluence of 61  $\mu\text{J}/\text{cm}^2$ , a modulation depth of 0.5%, and negligible nonsaturable losses ( $< 0.1\%$ ). The SESAM was operated with a maximum saturation parameter of about 33. In the final configuration, the resonator had a total length of 2.5 m, corresponding to a repetition rate of 60 MHz. We obtained stable mode-locked operation with an average power starting from  $\approx 65 \text{ W}$  up to 141 W. To keep the efficiency high while increasing the average power from 65 to 141 W, we adapted the cavity length. Altogether, we moved the SESAM toward a shorter cavity by approximately 20 cm and simultaneously enlarged the distance between the output coupler and the first mirror by roughly 15 cm. The maximum output power was achieved with an incident pump power of 349 W, which corresponds to an optical-to-optical efficiency of 40.4%. At a lower output power of 114 W, we achieved an even higher optical-to-optical efficiency of 43.8%, which is, to the best of our knowledge, the highest efficiency reported from a mode-locked thin disk laser so far. Given the drop in efficiency of 7.8% and a pump power density of 6.6  $\text{kW}/\text{cm}^2$  for the highest output power, we did not want to risk damage of the crystal by further increasing the pump power without adapting the pump spot diameter, too.

A second-harmonic autocorrelation trace and the optical spectrum of the measured output pulses are shown in Fig. 3. The pulses had an FWHM duration of 738 fs and a spectral bandwidth of 1.7 nm (FWHM). The time-bandwidth product of 0.352 is close to the ideal theoretical value of 0.315. The pulses had an energy of 2.35  $\mu\text{J}$  and a peak power of 2.8 MW. The output beam was close to the diffraction limit with a measured  $M^2 < 1.2$ . Single-pulse operation has been confirmed with scanning of the autocorrelator for nearby cross correlations (scanning range 80 ps) and a sampling oscilloscope with a 25 ps photodiode. We observed a stable linear polarized output of the laser, which was most likely due to stress or tension in the disk. However, for better control over the polarization state, a Brewster plate could be added, for instance, as in [15].

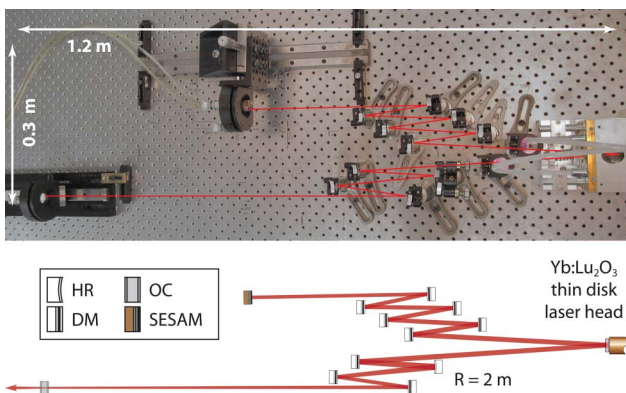


Fig. 2. (Color online) Top, photo of the laser cavity fitting on a footprint of 0.3 m by 1.2 m. Bottom, schematic view of the photo above: SESAM, semiconductor saturable absorber mirror; HR, curved high-reflective mirror with 2 m radius of curvature; DM, GTI-type dispersive mirror; OC, output coupler mirror.

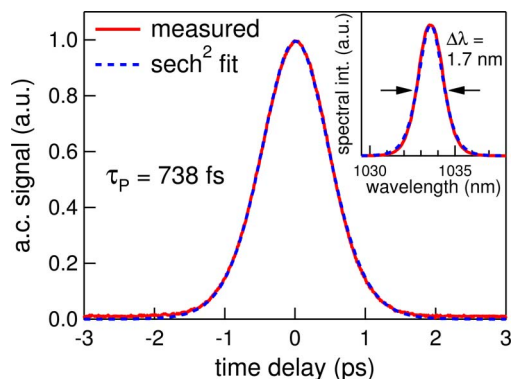


Fig. 3. (Color online) Second-harmonic autocorrelation and optical spectrum (inset) of the measured pulses (solid red line) with fit curves assuming ideal  $\text{sech}^2$  pulses (dashed blue line). The pulses had an FWHM duration of 738 fs and a spectral bandwidth of 1.7 nm (FWHM) centered near 1034 nm.

Except for the size of our disk, we did not observe any limiting factors for a further increase of the average power by applying the scaling laws for mode-locked thin-disk lasers. We believe that with an optimized cavity and dispersion management, 500-fs-long pulses like in previous reported results should be possible. The disk used in the experiment was soldered with indium–tin onto a copper heat sink, as is usually done for preliminary tests. State-of-the-art mounting on diamond heat sinks should significantly increase the heat dissipation, reduce the thermal lens, and therefore reduce the need to shift the end mirrors.

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