Modelocked Thin-Disk Laser Oscillator with 550 W of Average Output Power

Moritz Seidel*, Lukas Lang, Christopher R. Phillips and Ursula Keller
Institute for Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland
**seidelm@phys.ethz.ch*

Abstract: We present an ultrafast thin-disk laser oscillator providing a record power of 550 W with 100-µJ, 852-fs pulses at a repetition rate of 5.5 MHz. This is enabled by a six-pass replicating-cavity multipass scheme and ion-implanted sapphire-bonded SESAMs.

1. Introduction:

High average-power laser sources find many applications in research and industry, both in continuous-wave (cw) and ultrafast operation. The thin-disk laser (TDL) technology is a main driver in this field of applications, both in laser oscillator and laser amplifier architectures. Efficient heat removal enabled by the thin-disk architecture makes it the best choice for achieving high output powers directly from an ultrafast oscillator. The most recent published papers for high-average-power oscillators achieve up to 4 kW in cw [1] and 350 W in modelocked operation [2] and are both based on the thin-disk architecture. Here we present the average power scaling of a modelocked thin-disk laser oscillator achieving 550 W of average output power with a repetition rate of 5.5 MHz, peak power of 103 MW and pulse energy of 100 µJ. This is, to the best of our knowledge, the highest average output power and highest pulse energy ever achieved from any modelocked oscillator and highest peak power from a SESAM-modelocked oscillator.

2. Laser design and results

A schematic view of the TDL oscillator presented here is shown in Fig. 1 a). A 100-µm thick, Yb-doped disk with a nominal cold radius of curvature of -3.84 m bonded onto a diamond heat sink (TRUMPF Scientific Lasers) is used in a 44-pass head and pumped into the 940-nm absorption band. The pump spot is adjusted to a radius of 3.7 mm, while the cavity is designed such that the single mode spot size on the disk is 2.7 mm. Using GTI-type dispersive mirrors, $-57200\ \mathrm{fs}^2$ of nominal round-trip group-delay dispersion (GDD) is introduced. Fig. 1 b) shows the mode radius evolution along the cavity, including six reflections on the thin-disk (12 reflections per round-trip) via the replicating-cavity active multi-pass arrangement depicted in Fig. 1 a). This setup is expanded from an earlier intermediate result which used a four-pass setup to achieve 420 W of average output power [3].

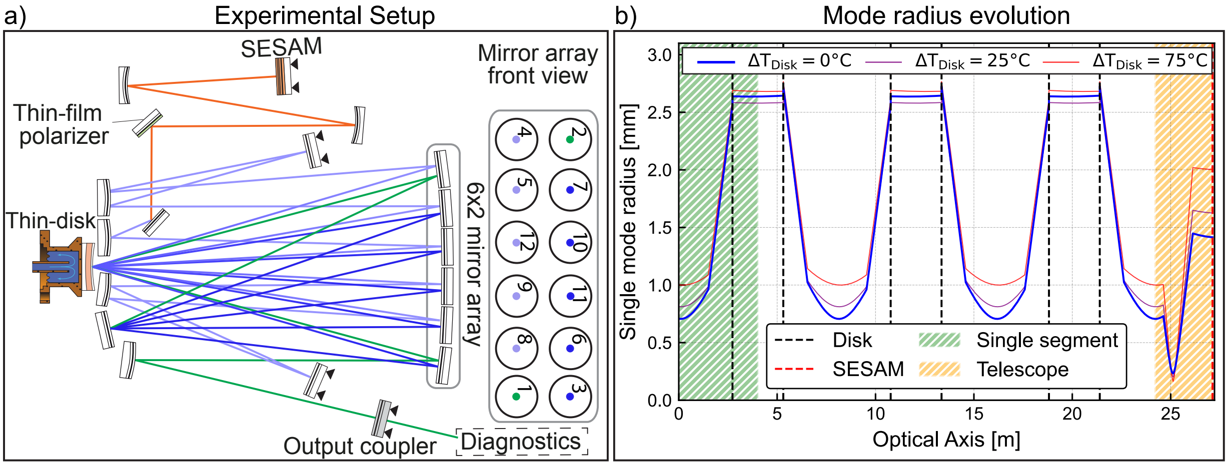

Fig. 1: Laser cavity design. (a) Beam path in the cavity. The shade of blue indicates the height above the optical table of the beam. The mirrors in the mirror array are numbered in sequence of hits if traced starting from the output coupler. Some mirrors (symbolized with two triangles on the backside in the schematic) are motorized with piezo actuators for automatic alignment of the laser passes onto the disk. The first segment as well as the telescope to the SESAM are color coded green and orange, respectively, corresponding to the shaded color in b) where the laser mode radius evolution throughout the cavity is shown. Three different power points parametrized by the change in disk temperature are shown. The nominal cold cavity mode is shown in blue, with cavity mode simulations for hotter disks depicted in purple and red.

During operation, the alignment optimization of the cavity is automated by the motorized mirrors highlighted in Fig. 1 a). This provides enough degrees of freedom to move all passes into the middle of the pump spot by maximizing the output power of the laser. Using six reflections on the disk per round-trip allows the use of a high

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output coupling rate of 40%, which keeps the intracavity power as low as possible without compromising efficiency. In modelocked operation at 550 W average output power the optical-to-optical efficiency of the laser is 35%.

For modelocking, we utilize a semiconductor saturable absorber mirror (SESAM) with a two-layer-pair semiconductor top-coating. This top-coating reduces the electric field inside the absorber region of the device and thus the SESAM can handle higher fluences before the reflectivity begins to decrease due to inverse saturable absorption. The SESAM including the quantum well region is grown at high temperatures to achieve low defect density. Post growth, the quantum well region is oxygen ion implanted and annealed to induce defect sites to obtain a tailored slow recovery time of 4.2 ps. Lastly, this SESAM is bonded onto a 1-mm-thick wedged sapphire window using the silicate bonding technique [4]. This window is a-cut to avoid thermal depolarization effects, is uncoated on the bonded facet, and AR-coated on the other facet. As discussed in [4], the sapphire bonding reduces the thermal lens of the SESAM, and thus provides for a larger cavity stability region with respect to the incident power on the SESAM. Here for the first time, we use SESAMs that have been silicate bonded under pressure and in vacuum (5 MPa for 8 hours), which improves bonding quality and longevity of the bond noticeably, possibly due to a thinner bonding interface.

We use a replicating cavity design, in which the width of the cavity stability zone with respect to the disk's thermal lens does not depend on the number of passes on the disk. This concept was first proposed in 2017 and was demonstrated in cw operation but only up to an output power of 90 W [5]. To power scale our configuration, we first investigated the influence of thin-disk aberrations on the performance of laser oscillators using a full-field simulation approach [6]. In the presented laser, modelocking could be initiated at an average output power of 85 W at ambient pressure and was sustained up to the reported 550 W average output power at 33 mbar of residual air pressure. This high power is reached by increasing the pump power and reducing the air pressure simultaneously to keep the pulse length around 700 fs – 1000 fs, which is the optimal operation point for such an oscillator due to spatial hole burning in the Yb:doped gain medium. The modelocking diagnostics at the 550 W operation point are shown in Fig. 2. We check single-pulse operation by scanning the range of the autocorrelator (200 ps) as well as in the RF spectrum.

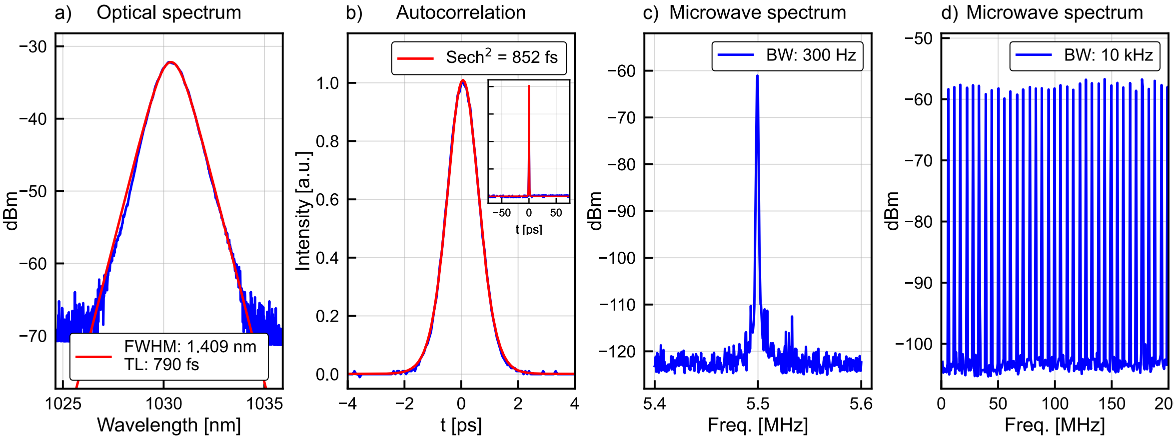

Fig. 2: Modelocking diagnostics at 550 W of average output power: a) Optical spectrum indicating a FWHM of 1.409 nm and transform limit (TL) of 790 fs, b) Autocorrelation trace providing pulses of 852 fs length, c) Microwave spectrum indicating a repetition rate of 5.50 MHz with 300 Hz resolution bandwidth (RBW) and d) Microwave spectrum over a large frequency spectrum with a RBW of 10 kHz.

The output parameters of this oscillators make it very interesting for applications in strong-field physics such as high-harmonic generation and attosecond science at high repetition rates, especially when combined with the established multipass-cell pulse compression technology. Furthermore, such an oscillator is well suited for industrial applications such as micromachining of metals, glasses and semiconductors.

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