275 W average output power from a femtosecond thin disk oscillator operated in a vacuum environment

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Abstract: We present an ultrafast thin disk laser that generates an average output power of 275 W, which is higher than any other modelocked laser oscillator. It is based on the gain material Yb:YAG and operates at a pulse duration of 583 fs and a repetition rate of 16.3 MHz resulting in a pulse energy of 16.9 µJ and a peak power of 25.6 MW. A SESAM designed for high damage threshold initiated and stabilized soliton modelocking. We reduced the nonlinearity of the atmosphere inside the cavity by several orders of magnitude by operating the oscillator in a vacuum environment. Thus soliton modelocking was achieved at moderate amounts of self-phase modulation and negative group delay dispersion. Our approach opens a new avenue for power scaling femtosecond oscillators to the kW level.

OCIS codes: (140.7090) Ultrafast lasers; (140.4050) Mode-locked lasers.

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1. Introduction

Semiconductor saturable absorber mirrors (SESAM) modelocked thin disk lasers (TDLs) currently set the frontiers of ultrafast oscillators in terms of pulse energy and average power. The combination of the outstanding heat removal capabilities of the thin disk geometry [1] and the design flexibility of SESAMs [2] results in a power scalable concept that has enabled steady progress both in terms of average power and pulse energy since their first demonstration in the year 2000 [3] (Fig. 1). Currently, modelocked TDLs reach pulse energies > 40 μJ [4] and average powers > 140 W [4, 5], which is higher than any other femtosecond oscillator technology. This places modelocked TDLs among the main leading ultrafast technologies that enable high-energy femtosecond sources with MHz repetition rates. Other successful approaches include chirped pulse amplification using fiber amplifiers [6] and Innoslab amplifiers [7].

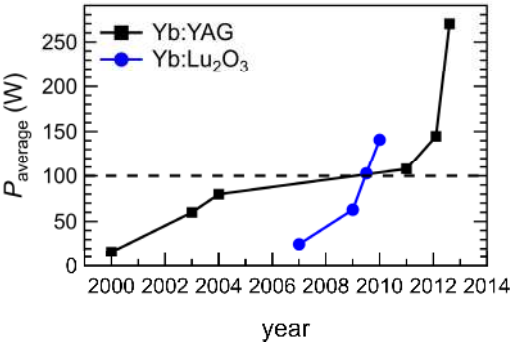

Fig. 1. Evolution of the average power of high power modelocked lasers. Since their first demonstration in the year 2000, modelocked thin disk lasers (TDLs) have achieved the highest average power compared to any competing oscillator technologies. The gain materials Yb:Lu$_2$O$_3$ and Yb:YAG exhibit both excellent properties for power scaling in the thin disk geometry.

Most of the power and energy scaling of modelocked TDLs was achieved with the well-established gain material Yb:YAG (Fig. 1). Using this material, a record-high pulse energy of 41 μJ at an average power of 145 W and a pulse duration of 1.1 ps was demonstrated [4]. Furthermore, the first Kerr-lens modelocked TDL based on Yb:YAG was recently reported with 200-fs pulses at a moderate average power of 17 W [8]. In the current work, we use Yb:YAG for power-scaling because thin disks with sufficiently large diameters and excellent quality are commercially available. However, numerous other promising materials for TDLs are currently being investigated in the thin disk geometry [9–12], in particular materials with broad emission bandwidths for the generation of short pulses [13]. An important example is the family of cubic sesquioxides [14–16] such as Yb:Lu$_2$O$_3$. This material exhibits a higher thermal conductivity than Yb:YAG (κ (10 at.%) = 6.6 Wm^{-1}K^{-1} for Yb:YAG and κ (5at.%) = 11.7 Wm^{-1}K^{-1} for Yb:Lu$_2$O$_3$ for an equivalent doping concentration of 1.4×10^{21} cm^{-3}) and supports shorter pulse durations with a larger emission bandwidth ($\Delta\lambda$ = 9 nm for Yb:YAG and $\Delta\lambda$ = 13 nm for Yb:Lu$_2$O$_3$). The excellent properties of this material were confirmed with the demonstration of a modelocked TDL with 141 W and 738-fs pulses [5]. This was, for several years, the highest average power achieved with modelocked TDLs (Fig. 1). In another experiment using Yb:Lu$_2$O$_3$, pulses as short as 142 fs were demonstrated at 7 W of average power showing the potential of this material for short pulse generation in the thin disk geometry [17]. Furthermore, the first TDL with sub-100 fs pulse duration was recently demonstrated using the broadband mixed sesquioxide material Yb:LuScO$_3$ [18].

So far several issues have limited further scaling of modelocked TDLs to higher average power and pulse energy levels. These issues are discussed in detail in [19, 20]. One of the most crucial limitation for high power modelocking is an excessive nonlinear phase shift that can destabilize modelocked operation in the soliton modelocking regime [21, 22]. Most modelocked TDLs use the disk as a single folding mirror in the cavity, resulting in 4 passes through the disk per cavity roundtrip. Due to the small thickness of the disk, the resulting gain is low and optimal output coupling rates are typically < 10%. Therefore the intracavity levels are substantially higher than the output and can reach average powers in the kW range [5], pulse energies larger than 100 μJ, and peak powers exceeding 100 MW [23]. Thus the intracavity self-phase modulation (SPM) introduced by the ambient air in the cavity can become the main contribution to the total soliton phase shift [24]. In order to compensate for this phase shift and obtain stable soliton modelocking, large amounts of negative group delay dispersion are required. Furthermore, if these phase shifts become too large, the pulse formation mechanism is destabilized limiting power and energy scaling.

Different approaches have been suggested to overcome this limitation. In reference [23], an intracavity pulse energy of > 110 μJ was demonstrated by operating the oscillator in a helium atmosphere. The required dispersion to generate the 791-fs pulses was, in this case, −20’000 fs^2. In reference [4], multiplying the gain passes through the thin disk and increasing the outcoupling rate to more than 70% allowed for record-high output pulse energies while keeping the intracavity pulse energy below 60 μJ. However, in this approach, the resulting system has a relatively high complexity, and still significant amount of dispersion (−346’500 fs^2) was required to compensate for the accumulated nonlinear phase shift in air.

In this paper, we demonstrate a different approach for power scaling of high power femtosecond TDLs. We operate the oscillator in a vacuum environment, therefore reducing the nonlinearity of the ambient environment by several orders of magnitude. In this way, only a reasonable amount of dispersion is required even at very high intracavity pulse energies. Furthermore, high average power and pulse energies can be achieved in simple oscillator geometries with a low number of passes through the gain medium. Moreover, operating the oscillator in a vacuum environment keeps all intracavity components clean over a long operation period. With this approach, we were able to demonstrate a TDL with an average power of 275 W at a pulse duration of 583 fs using the well-established gain material Yb:YAG. The laser operates at a repetition rate of 16.3 MHz resulting in a pulse energy of 16.9 μJ and a peak power of 25.6 MW. To our knowledge, this is the highest average power ever demonstrated from a passively modelocked oscillator and represents an important milestone towards kW level femtosecond oscillators.

2. Experimental setup and results

The gain element is a commercial Yb:YAG thin disk glued on a water-cooled diamond heatsink (TRUMPF GmbH). The disk showed no significant thermal lensing over the whole pump power range used throughout the experiment (approximately 850 W of pump power corresponding to a pump power density of 5.1 kW/cm^2). This allowed for robust single mode operation without any readjustment of the resonator length [19, 25]. The thin disk head was arranged for 24 pump passes through the disk and a pump spot diameter of 4.7 mm. The pump diode used for this experiment can deliver up to 1.2 kW of power at a central wavelength of 940 nm. However, in our experiment, we only used 70% of the available pump power (≈850 W). In order to match the 940 nm absorption line of Yb:YAG at this operation point, we adjusted the temperature of the diode with an external chiller.

A schematic of the fundamental-mode cavity used for the modelocking experiment is presented in Fig. 2(a). Throughout the experiment, we used an output coupler with 11.4% transmission. The optimum outcoupling rate was experimentally determined in multimode operation to be $T_{oc} \approx 7\%$. However, we employed a higher degree of output coupling in order to reduce the intracavity power, but at the expense of a lower optical-to-optical efficiency. A lower intracavity power simplified the cavity design because it allows for smaller spot sizes on the SESAM (in our experiment, the laser beam on the SESAM had a radius of ≈1.23 mm) and reduces thermal distortions from intracavity elements such as dispersive mirrors. We obtained 340 W of continuous wave power at an optical-to-optical efficiency of 39.2% (Fig. 2(b)) with a diffraction-limited beam ($M^2 < 1.05$).

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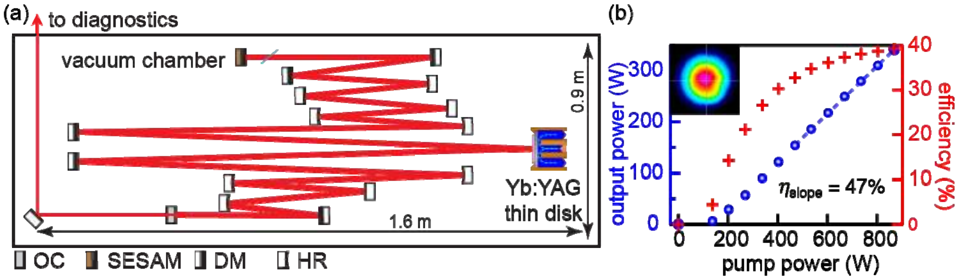

Fig. 2. (a) Schematic setup of the 16.3 MHz pulse repetition rate fundamental transverse mode cavity used for the high power modelocking experiment. (b) Output power and optical-to-optical efficiency in cw fundamental transverse-mode operation using the same output coupler as for the modelocking experiment. For the presented slope, we used only highly reflective mirrors as cavity mirrors and did not control the polarization of the laser. Inset: Picture of the laser mode at the maximum CW output power.

In order to obtain soliton modelocking, we introduced a set of five dispersive mirrors in the cavity that introduced approximately −8’100 fs^2 of negative group delay dispersion (GDD) per roundtrip. A fused silica plate with a thickness of 700 µm was introduced at Brewster’s angle at a position in the cavity where the beam has a large radius of ≈1.3 mm. This controls the laser polarization with minimal phase shift introduced by the Brewster plate. Fine control of the total SPM was achieved by changing the pressure in the vacuum chamber by introducing small amounts of nitrogen.

The SESAM used in this experiment was designed for high damage threshold and high power modelocking following the guidelines presented in reference [26]. It consists of a distributed Bragg reflector and 3 InGaAs quantum wells as absorbers in an antiresonant configuration. A dielectric topcoating that consists of 3 quarter-wave pairs of SiO_2/Si_3N_4 was deposited by plasma enhanced chemical vapor deposition. This top section reduces the field in the structure, resulting in a high saturation fluence and damage threshold. We measured the nonlinear saturation response of this SESAM using a high precision nonlinear reflecivity setup [27] seeded by an Yb:YAG TDL delivering 2 µJ, 1-ps long pulses at 3.9 MHz and at a central wavelength of 1030 nm. The measurements yielded a saturation fluence F_{sat} = 140 µJ/cm^2, a modulation depth ΔR = 0.95% and nonsaturable losses ΔR_{ns} = 0.1%. Furthermore, we measured a recovery time $\tau_{1/e}$ = 67 ps using a standard pump-probe setup with a Yb:YAG bulk laser delivering 1-ps long pulses at a repetition rate of 38 MHz and an average power of 150 mW.

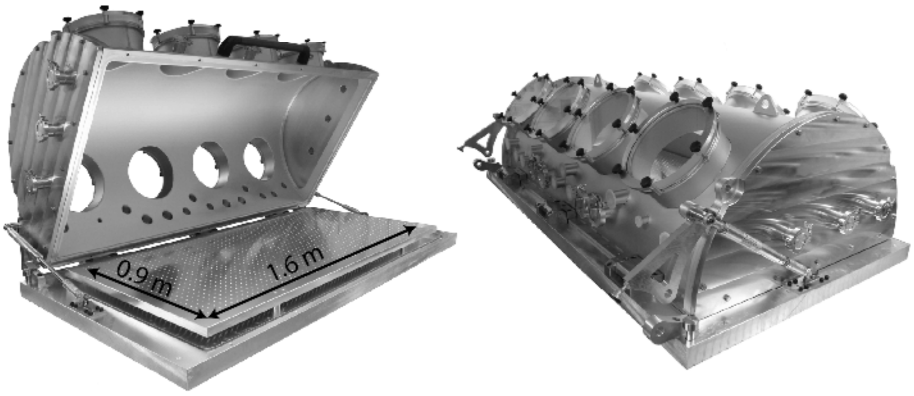

Fig. 3. Picture of the vacuum chamber in which the modelocked laser was built.

For the modelocking experiment presented here, the vacuum chamber (Fig. 3) was operated at constant pressure of 0.5 mbar. Stable cw modelocking was obtained for average powers ranging from 135 W to 275 W. At the highest power level, the optical-to-optical efficiency decreased (by approximately 1%), but no modelocking instabilities were observed. In order to avoid possible damage of the thin disk, the pump power was not further increased. At the maximum power of 275 W, the pulse duration was measured to be 583 fs (Fig. 4(a)). The optical-to-optical efficiency was 32.4%, corresponding to an incident pump power of 839 W. The pulses had a time bandwidth product of 0.329 (ideal sech^2 0.315) determined with the measured spectral bandwidth of 2 nm (Fig. 4(b)). The obtained nearly transform limited pulses confirm stable modelocking in the soliton regime. The repetition rate of the pulses was 16.3 MHz (Fig. 4(c)) resulting in a pulse energy of 16.9 μJ. The corresponding peak power of the pulses is 25.6 MW. Single pulsed operation was confirmed using a fast photodiode (25 GHz) and a sampling oscilloscope. Furthermore, the delay of the autocorrelator (80 ps) was scanned in search for cross-correlations of potential parasitic pulses with the main pulse. The beam at the maximum modelocked average power level was nearly diffraction limited with an $M^2 < 1.05$.

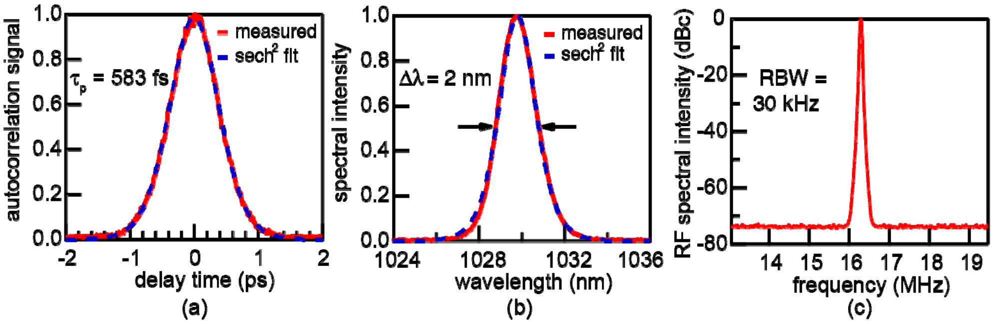

Fig. 4. (a) Autocorrelation trace of the pulses at the maximum power of 275 W (b) Optical spectrum of the pulses (c) Radio frequency spectrum of the pulses (resolution bandwidth RBW = 30 kHz)

Inside the oscillator, the circulating pulses had an energy of 146 μJ, and a peak power of 220 MW. In contrast to previous high-power modelocked TDLs, the nonlinearity of the ambient environment was not the main contribution to the total SPM phase shift required for soliton modelocking. Assuming soliton pulses, the dispersion introduced in our cavity compensates for a nonlinear phase shift of approximately 75 mrad at the maximum power and for the obtained pulse duration. The atmosphere in the cavity only contributes ≈8 mrad to this total phase shift. This value was calculated assuming a linear behavior of the nonlinear refractive index of air with the pressure in the vacuum chamber [28]. The Brewster plate accounts for ≈17 mrad and the thin disk for ≈3 mrad. The remaining phase shift (≈47 mrad) seems to originate from nonlinearities due the high intensities on the different cavity mirrors. In our current setup, some of the dielectric mirrors used in the cavity withstand intensities > 50 GW/cm^2. At these high peak intensities, even a small penetration depth can lead to a significant phase shift. However, in order to precisely evaluate the contribution of each mirror to the total phase shift, the exact structure and material composition of these commercial mirrors needs to be precisely known which is currently being investigated.

In spite of these very high intracavity intensities, no damage was observed on the SESAM. The main limitation to higher average powers in our current configuration was thermal effects and even damage that occurred in the dispersive mirrors. Improved dispersive mirror designs with better thermal properties will allow for higher average power in the future.

3. Conclusion and outlook

We demonstrated a femtosecond Yb:YAG TDL with 275 W of average power and 583 fs pulse duration. To the best of our knowledge, this is the highest average power ever obtained from a passively modelocked oscillator. The obtained laser performance combines femtosecond pulses, high pulse energy (16.9 µJ) and record high average power. In order to reach this performance, the oscillator was operated in a vacuum environment. This represents a new promising approach that opens the door to power scaling of modelocked oscillators to the kW range.

In the near future, we expect to reach pulse energies in the 100 µJ range by increasing the length of the resonator using a Herriott-type passive multi-pass cell [23, 29] and average powers in the 500 W range by increasing the spot sizes on the disk and on the SESAM and by improving the thermal properties of the dispersive mirrors.

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