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Powerful 100-fs-scale Kerr-lens mode-locked thin-disk oscillator

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We have recently demonstrated a simple power scaling procedure for Kerr-lens mode-locked thin-disk oscillators. Here we report on the extension of this scheme to a broadband high-peak-power thin-disk oscillator, delivering 140-fs pulses with a peak and average power of 62 MW and 155 W, respectively. This result shows that reaching the emission bandwidth of the gain material in Kerr-lens mode-locked thin-disk oscillators is feasible without sacrificing output power, efficiency, or stability by relying on high intracavity nonlinearities. © 2016 Optical Society of America

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The state of the art of high-power ultrafast oscillators is currently demonstrated by mode-locked thin-disk lasers with average output powers of several hundred watts, pulse energies of tens of microjoules, and peak-powers approaching 100 MW [1–3]. These power levels obviate the need for further amplification for many applications, offering compact, reliable, and cost-effective solutions. Supplemented by extracavity pulse compression and carrier-envelope phase stabilization [4], the technology even offers a viable alternative to femtosecond Ti:sapphire oscillators. With the mature and reliable Yb:YAG gain material being a de facto industry standard for high-power thin-disk lasers, the average output power from oscillators has so far not been a limiting factor. With multi-kilowatt average power in the fundamental mode from a single thin-disk significant improvements can be expected in the future [5]. In contrast to this exceptional power scalability the reported mode-locked pulse durations achievable directly from the laser oscillator are relatively long and their spectral bandwidth far from the fluorescence bandwidth of the gain material. This applies generally to Yb:YAG as well as other broader-band gain materials, especially when semiconductor saturable absorber mirrors (SESAMs) are used for mode-locking [6–11]. The reported pulse widths have been dictated by the interplay of self-phase modulation (SPM) and group delay dispersion (GDD) and also strongly influenced by self-amplitude modulation (SAM) responsible for start-up and stabilization of the soliton-like pulse formation. In general, mode-locking techniques that combine a fast response time with high modulation depth are preferred to exploit the emission bandwidth of the laser material [12–14]. Mode-locked high-power operation has so far only been shown for SESAM ([2,15]), nonlinear polarization rotation ([16]), or Kerr-lens mode-locking (KLM, [3,17]), the latter of which has the clear advantage of high modulation depth of the order of up to several percent as well as ultrafast (femtosecond) response time and nearly no wavelength dependence. For these reasons KLM is the method of choice for generating the shortest pulse durations from both low- and high-power oscillators.

In this Letter we report on a Kerr-lens mode-locked thin-disk oscillator based on Yb:YAG that combines high average as well as high peak power and at the same time exploits the full emission bandwidth of the gain material. The broad bandwidth also improves the prerequisites for further, extracavity, pulse compression [18,19].

As shown in [3], the peak power in linear-cavity KLM thin-disk oscillators can be scaled by increasing the mode area inside the Kerr medium and 330-fs pulses with a peak power of 38 MW outside and 180 MW inside the cavity have been reported. For the present experiment a linear cavity was designed, similar to the one in [3] (see Fig. 1). The amplifying medium is a nearly flat Yb:YAG thin-disk, which acts as an active mirror and is pumped in the broad absorption band around 940 nm. A double pass over the thin-disk is realized without imaging optics, resulting in eightfold transmission of the beam through the laser-active volume each round trip with an average $1/e^2$ mode diameter of 2.4 mm. The dispersion is controlled by four reflections off highly dispersive 15-nm-bandwidth mirrors per round trip, introducing a total GDD of −12.000 fs^2 [20]. This is a significantly smaller value than reported in [3]. The reduced negative GDD along with a reduced output coupler transmission of 15% support shorter pulses [21]. Further

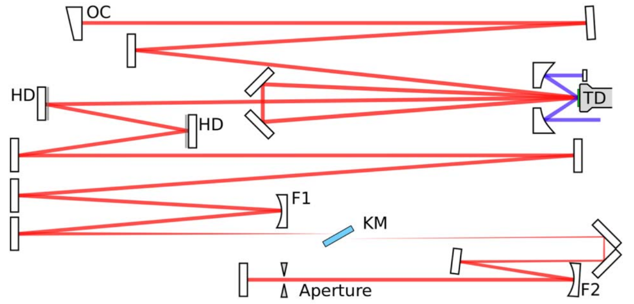

Fig. 1. Schematic of the KLM thin-disk laser cavity used in the experiment. OC, 15% output coupler; TD, thin-disk with pump optics; HD, highly dispersive mirror with −3000 fs^2 GDD; F1 and F2, 2000 mm concave focusing mirror; KM, 5 mm sapphire Kerr medium. Not marked components are highly reflective mirrors.

reduction of the negative GDD was prevented by the onset of instabilities such as extreme sensitivity to external perturbations, the pumping level, alignment, or complete failure to mode-lock.

A focusing arrangement consisting of a concave mirror pair produces the desired small mode size in the focal region, designed to have a $1/e^2$ diameter of approximately 600 μm at the center of the stability zone (see Fig. 2). The radii of curvature of the curved mirrors were chosen as 2000 mm compelling to fold the focusing section two times due to the space restraints imposed by the laser housing. The total length of the resonator is 9.6 m, which results in a 15.6-MHz repetition rate of the generated pulses.

In order to enable KLM operation the cavity is adjusted to the edge of its stability zone (Fig. 2) [22,23]. A 5-mm-thick sapphire plate was inserted in the focus under Brewster's angle as a Kerr medium, corresponding to a fivefold increase in material thickness as compared to the previous configuration [3]. The large focal spot is accompanied by a long Rayleigh range of several centimeters. Relative to the thickness of the Kerr medium this increases the interaction length of the focused oscillator mode with atmospheric air. As a result the contribution of air to the accumulated nonlinear phase shift in the oscillator becomes comparable to that of the sapphire plate.

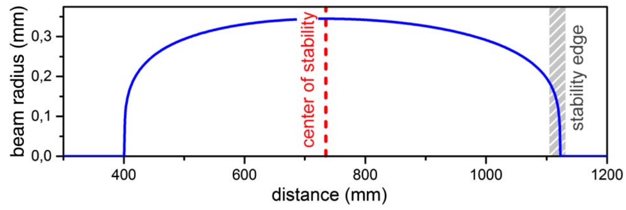

Fig. 2. Simulation of the cavity mode radius at the Kerr medium for the distance between F1 and KM (see Fig. 1). The "center" and the edge of the stability zone (where the oscillator is mode-locked) are indicated.

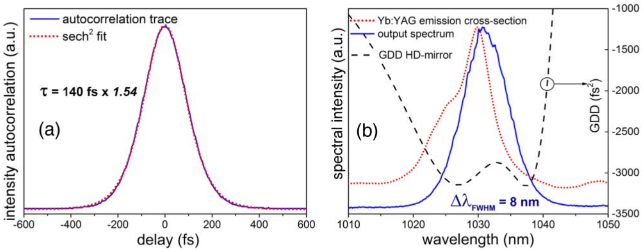

Fig. 3. (a) Intensity autocorrelation trace of the output pulses and sech^2 fit. (b) Output spectrum with GDD design curve of the HD mirrors and emission spectrum of Yb:YAG (from [27]).

This has several implications. First, convection-induced atmospheric pressure variations in the beam path translate to noise in the optical spectrum and beam pointing due to SPM and self-focusing. Second, the Kerr lens induced by air also has a negative impact on the SAM and output power. To escape these unfavourable conditions the housing of the oscillator has been evacuated to 140-mbar residual air pressure. The use of the relatively high residual air pressure makes a buffer gas unnecessary [24].

In addition to the soft aperture of the gain profile the loss modulation is aided by a hard, water cooled, copper aperture. Notwithstanding the large focus in the Kerr medium, mode-locking can be initiated reliably by moving the mirrors on the translation stage between KM and F2 (Fig. 1).

The output spectrum and intensity autocorrelation trace shown in Fig. 3 demonstrate unchirped output pulses with 140-fs duration, 8-nm optical bandwidth, and a time-bandwidth product of 0.315. Single-pulse operation was confirmed with a 15-ps autocorrelator, a 2.6-ns long-range autocorrelator and with a fast 100-ps photodiode and 3.5-GHz sampling oscilloscope. The output optical bandwidth is matching the width of the peak in the fluorescence spectrum of Yb:YAG (see Fig. 3). The emission peak experiences a peak-power-dependent redshift, which is often observed in mode-locked lasers [25,26]. According to [26] such shifts are most likely caused by Raman scattering in sapphire or reabsorption in the gain material. Another possible cause of this redshift could be the influence of the HD mirrors that are operated at the limits of their bandwidth [Fig. 3(b)]. At these pulse durations the average output power was 155 W with an optical-to-optical efficiency of 29%. This corresponds to a pulse energy of 10 μJ and a peak power of 62 MW. The M^2 beam quality factor was measured (following the ISO 11146 procedure) to be 1.1.

Tuning the air pressure inside the oscillator chamber has a substantial influence on the intracavity peak power as can be seen in Fig. 4. Due to the choice of a very low, optimized GDD level, the pulses become unstable for pressures higher than 500 mbar. While evacuating down to a critical pressure of 130 mbar the peak power increases with nearly constant pulse duration as expected from the solitonic energy scaling with SPM. However, we observe a sharp increase in pulse duration as well as a drop in pulse energy below this critical pressure. A possible explanation for this strong decline in output power is increased heating of the dispersive mirrors due to reduced convection cooling at lower pressure. The dispersive coating is most sensitive to the thicknesses in the multilayer structure wherefore thermal expansion from excessive heating could shift the GDD curve away from the central wavelength and consequently reduce the peak power of the pulses.

Although the initial state of the cavity is close to unstable with high losses owing to bad mode overlap with the pump and aperture, the mode in pulsed operation is modified by the Kerr lens toward a more stable configuration, which allows for low

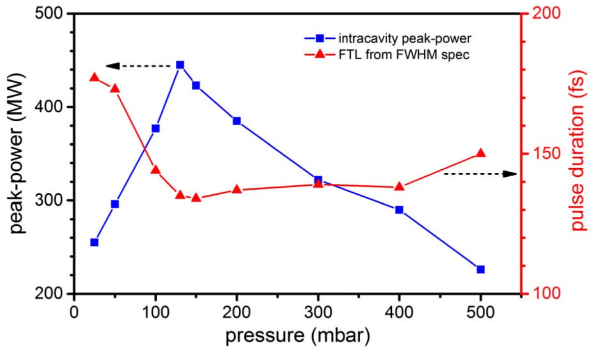

Fig. 4. Pressure dependence of the intracavity peak power and pulse duration. The pulse durations were estimated from the FWHM spectral bandwidth, assuming unchirped sech^2 pulses. The curves are reversible, which excludes damage to the oscillator optics as a possible cause for the peak power drop at low pressures.

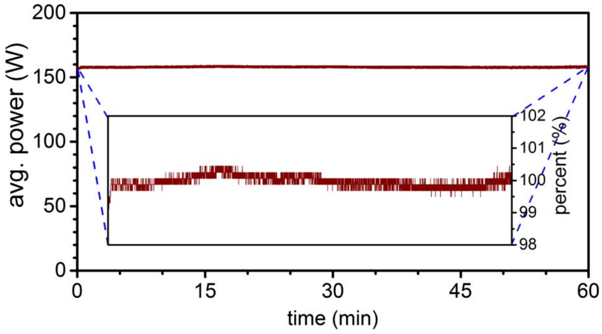

Fig. 5. Long-term stability of average power. Small power variations of <1% are attributed to drifts in cooling-water temperature.

noise figures. The RMS beam-pointing noise was measured over 10 min staying below 1 µrad, corresponding to 0.2% of the $1/e^2$ beam radius at the position of measurement. The intensity noise on a Si photodetector was <0.5% RMS in a 1 Hz–16 MHz window. The unstabilized average output power was logged over the course of an hour and is shown in Fig. 5. Only very little power variations with an amplitude of less than 1% are discernible and correspond to drifts in the cooling water temperature (~1°C). The demonstrated power stability makes this oscillator a promising candidate for carrier-envelope phase stabilization [4].

In Fig. 6 the intracavity peak power of this oscillator is compared with the results from [3]. On first sight this graph seemingly confirms the linear scaling behavior with the mode radius in the Kerr medium. However, the large variance of the peak power with air pressure makes a direct comparison difficult. We estimate the coefficient of self-phase modulation, γ_{spm}, to be 0.012 MW^{-1}, which would result in a total nonlinear phase shift of ~5 rad per round trip due to SPM. By virtue of this strong SPM the spectral narrowing caused by the gain is counteracted, allowing for the broad spectral bandwidth of the pulses. From experience with other KLM experiments we expect the effect of a thicker Kerr medium to change the mode-locking threshold with a minor increase in spectral bandwidth. The broadening observed in this oscillator may be attributed to stronger saturation of SAM in combination with the ~1.7 times larger γ_{spm} from the Kerr medium as compared to our previous experiments [3,17].

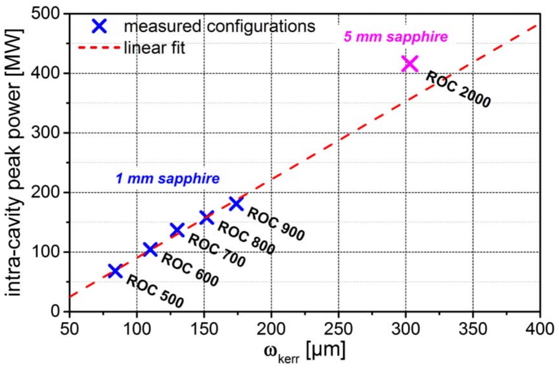

Fig. 6. Intracavity peak power for different beam sizes ω_{kerr} in the Kerr medium. ω_{kerr} is estimated with the ABCD matrix formalism at the center of the stability zone.

We have demonstrated an Yb:YAG thin-disk oscillator producing 140-fs pulses at intracavity and extracavity peak power levels of more than 0.4 GW and 62 MW, respectively. Together with the measured low-intensity noise and good stability this performance is a further demonstration of the unique capabilities of the Kerr-lens mode-locking technique in thin-disk oscillators. No obvious technical limitation was found that would prevent a further increase in peak power. Gain-bandwidth-limited pulses with more than 100-MW output peak power may be expected in the near future.

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