High-power 200 fs Kerr-lens mode-locked Yb:YAG thin-disk oscillator

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We demonstrate a power-scalable Kerr-lens mode-locked Yb:YAG thin-disk oscillator. It delivers 200 fs pulses at an average power of 17 W and a repetition rate of 40 MHz. At an increased (180 W) pump power level, the laser produces 270 fs 1.1 μJ pulses at an average power of 45 W (optical-to-optical efficiency of 25%). Semiconductor-saturable-absorber-mirror-assisted Kerr-lens mode locking (KLM) and pure KLM with a hard aperture show similar performance. To our knowledge, these are the shortest pulses achieved from a mode-locked Yb:YAG disk oscillator and this is the first demonstration of a Kerr-lens mode-locked thin-disk laser. © 2011 Optical Society of America

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Since the invention of thin-disk technology, substantial progress has been made in power and energy scaling of mode-locked disk oscillators. These advances culminated in an average output power of 140 W [1] and pulse energies of 30 μJ [2,3] at pulse durations of 700–1000 fs. These pulse widths are larger than dictated by the gain bandwidth limit. Much effort has been dedicated to manufacturing and mode-locking broadband materials, yet the sub-200-fs regime could only be accessed with the broadband gain material Yb:LuScO$_3$ [4]. Although the emission band of Yb:YAG supports sub-200-fs pulses (Fig. 1), it has been understood that high-power operation is limited to 700 fs pulses. This limitation applies to mode locking with semiconductor saturable absorber mirrors (SESAMs) and relates to a higher saturated gain and reduced gain bandwidth due to a high inversion level at high-power operation [5]. In contrast, Kerr-lens mode locking (KLM) of an Yb:YAG slab oscillator resulted in 35 fs pulses [6]. This remarkable performance came at the expense of dramatically reduced output power and efficiency, achieved by spectral filtering that shifted the central wavelength from 1030 nm toward 1060 nm (see Fig. 1), limiting the output power to ~100 mW.

In this Letter, we demonstrate the feasibility of highly efficient near-gain-bandwidth-limited pulse generation from a thin-disk Yb:YAG oscillator via KLM [7]. KLM, the method of choice for sub-10-fs few-cycle pulse generation from Ti:sapphire oscillators [8], has been successfully applied for the first time, to our knowledge, to a power-scalable diode-laser-pumped thin-disk laser, opening the route to the development of user-friendly femtosecond oscillators at unprecedented power levels.

Yb:YAG is a well-established solid-state laser material commercially available in excellent optical quality and large crystal sizes. It has a broad absorption line at 940 nm, as well as a zero-phonon line at 969 nm suitable for pumping by wavelength-stabilized high-power diodes. As a result of its low quantum defect, absence of excited-state absorption, high thermal conductivity, and good thermomechanical properties, Yb:YAG constitutes a premium gain material for use in disk oscillators.

Our experimental setup, sketched in Fig. 2, includes a 220 μm thin wedged Yb:YAG disk of 7% doping. A disk head (Dausinger+Giesen GmbH) is aligned for 24 passes of the pump beam through the gain medium with a pump spot diameter of 3.2 mm. The Yb:YAG thin disk is used as one of the folding mirrors in a standing-wave cavity pumped by fiber-coupled diodes centered at a wavelength of 940 nm. The cavity is a convex–concave type designed for providing large mode sizes over its entire length, in order to minimize nonlinear propagation effects in air and the risk of damage to optical components. The average mode radius inside the cavity is 1.2 mm, the beam radius on the disk is 1.3 mm, and is 1 mm on the end mirror incorporating a SESAM. Owing the large mode size on the disk and its low thickness, KLM calls for a separate nonlinear medium and a cavity section, resulting in a tightly focused beam (R1–R2 in Fig. 2) with a

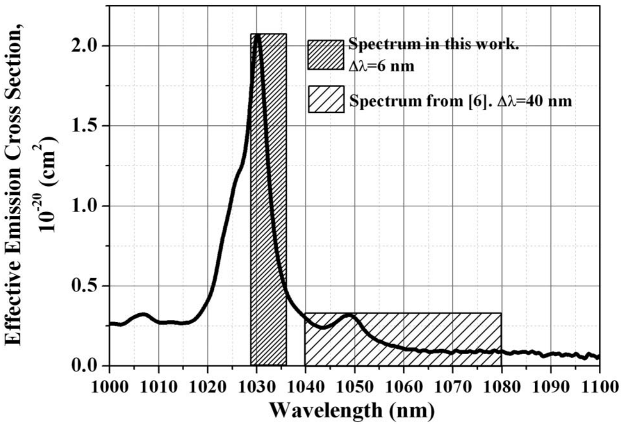

Fig. 1. Emission spectrum of Yb:YAG gain medium. The shaded areas show the spectra (FWHM) generated in the present work and in [6].

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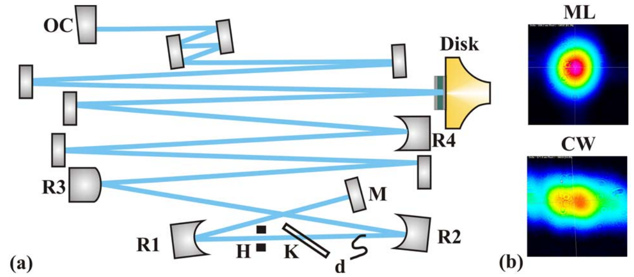

Fig. 2. (Color online) (a) Schematic of the Kerr-lens mode-locked Yb:YAG disk oscillator. All flat mirrors except for M are high-dispersion mirrors with ≈ – 1200 fs^2 per bounce; OC, an output coupler with 5.5% or 14% transmission; R1 and R2, concave mirrors with 0.3 m radius of curvature; R3, –4 m; R4, 4 m; K, 1-mm-thick fused silica plate placed in the focus at the Brewster angle; H, hard aperture (a pinhole); M, flat mirror or SESAM. The pulse repetition rate is 40 MHz. The oscillator is placed inside a box of size ×1 m × 0.4 m. (b) Beam profile in mode-locked regime and in CW regime (after mode locking has been interrupted).

beam waist of approximately 50 μm inside the Kerr medium.

In general, the cavity stability zones depend on both the length d and the thermal lens of the gain medium [9]; however, our cavity has been designed to minimize the influence of the disk thermal lensing. The KLM self-amplitude modulation depth is maximized by operating the laser near the stability zone boundary, corresponding to a maximum separation of mirrors R1 and R2. We found that this stability edge can be used for both soft- and hard-aperture KLM. Seven flat high-dispersion mirrors introduce a total round-trip negative group-delay dispersion of –22000 fs^2 (nine bounces, see Fig. 2) at the expense of a loss of 0.04% per bounce [10]. Since the total amount of the dispersion of intracavity materials is negligible (≈200 fs^2), the dispersion introduced by the mirrors serves only for balancing the nonlinear phase shift induced by the disk, air, and Kerr medium. A 1-mm-thick fused silica plate is used as the Kerr medium. Fused silica has a high optical damage threshold and is available in excellent optical quality. Its nonlinear index of refraction is comparable to that of sapphire and 1 order of magnitude smaller than that of SF57 glass, which was previously used for KLM [11]. Our cavity was designed to maintain both acceptable misalignment sensitivity and little influence of the disk thermal lens. A detailed analysis of the cavity design will be published elsewhere.

For approximately the same cavity configuration, we experimentally studied three different regimes of operation: pure SESAM mode locking, soft-aperture SESAM-assisted KLM, as well as pure KLM implemented with a hard intracavity aperture. The results with a pure SESAM mode-locked oscillator were reported in [12] with 100 W output power and 700 fs pulses. This operation suffered from frequent appearance of a CW background and frequent damage to the SESAM. Both KLM operational modes resulted in much shorter pulses than SESAM mode locking. However, SESAM-assisted KLM was less sensitive to the cavity misalignment and demonstrated better performance on a daily basis, as well as self-starting operation (though not fully reproducible). SESAMs used to be the intracavity element most susceptible to damage in high-power systems, typically via self-Q-switching or relaxation oscillation spikes during the pulse buildup process. Moreover, it also exhibits two-photon absorption (TPA) [13], which tends to give rise to breakup into multipulsing and limits both the achievable intracavity pulse energy and minimum pulse duration. To eliminate these shortcomings, we applied a dielectric top coating on a SESAM with a similar structure to that reported in [14]. An 8-nm-thick InGaAs single quantum well was incorporated into the SESAM structure characterized by the following (measured) parameters (without the top dielectric coating): saturation fluence, $F_{\text{sat}} = 50\ \mu\text{J/cm}^2$; modulation depth, $\Delta R = 0.7\%$; nonsaturable loss, $\Delta R_{\text{ns}} = 0.4\%$. The top reflective dielectric coating consists of six alternating layers of Ta_2O_5 (128 nm) and SiO_2 (178 nm). The coating reduces the intensity level in the SESAM by a factor of 9. As a consequence, the SESAM modulation depth drops by the same factor to $\Delta R < 0.1\%$ and the saturation fluence rises to $F_{\text{sat}} > 400\ \mu\text{J/cm}^2$, which leads to a reduced TPA and to increased damage threshold [14]. Because of the small modulation depth, this SESAM alone cannot result in stable mode locking. Nevertheless, it can reliably start KLM operation, with good day-to-day reproducibility. SESAM-assisted KLM has peak-to-peak amplitude fluctuations <3% within the 1 s measurement time, which is comparable to the pure SESAM mode-locked case. No measures were taken for acoustic insulation of the laser box. Being mode locked once, the oscillator remains stable all day. To our knowledge, this is the first demonstration of such a low-modulation-depth single-quantum-well SESAM used as a starter and mode-locking stabilizer for KLM operation [15,16]. It should be noted that this overcoated SESAM had never been damaged during our experiments.

Similar performance has been achieved through the use of pure hard-aperture KLM. The SESAM in position M (see Fig. 2) was replaced by a high-reflection mirror, and aperture H was inserted in the form of a pinhole. In this case, the mode-locking was initiated by translating

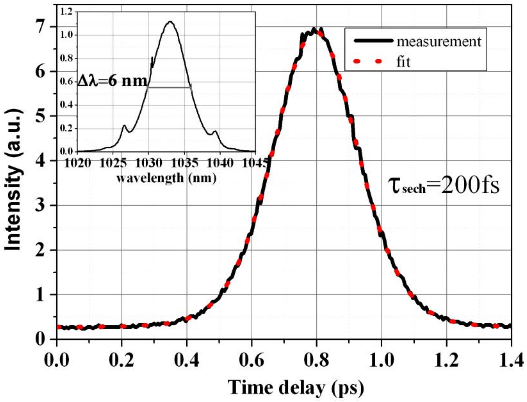

Fig. 3. (Color online) Autocorrelation and the spectrum (inset) at 17 W of output power and 5.5% output coupler (measured with an APE Pulse Check autocorrelator). The time–bandwidth product is 0.34 (sech^2, ideal 0.315). Kelly sidebands are visible in the spectrum wings. This measurement was performed for the SESAM-assisted KLM.

the cavity mirror R1. The power fluctuations were similar to those measured for a SESAM-assisted KLM.

The oscillator has been successfully operated with two different output couplers of 5.5% and 14%. With the low output coupling, we achieved 17 W of average power at 110 W of pump power, which corresponds to an optical-to-optical efficiency of 15%. Under these conditions, we measured a pulse duration of 200 fs (assuming a sech^2 pulse shape) with a spectral width of 6 nm (FWHM); see Fig. 3. With high output coupling, we could achieve stable operation up to pump power levels of 180 W, resulting in an average output power of 45 W, corresponding to 1.1 μJ pulses and 25% optical-to-optical efficiency. The autocorrelation and spectrum shapes were similar to those shown in Fig. 3 with a pulse duration of 270 fs. In both operational regimes, the intracavity pulse energy was approximately 8 μJ. Our attempts to reach higher energy led to the onset of multipulsing or cw background. Self-Q-switching instabilities used to appear only during the alignment of the oscillator. The suppression of Q-switching is very likely caused by saturation of the KLM self-amplitude modulation.

KLM of disk lasers appears to be most promising in terms of further power/energy scaling. Obvious advantages of KLM over pure SESAM mode locking include (i) much faster response of the self-amplitude modulation mechanism, leading to the shortest pulses demonstrated so far, (ii) absence of nonsaturable losses and TPA, and (iii) much higher resistance to damage. The theory [17] predicts that even higher energies may be attained in proportion to (i) increase of the anomalous intracavity group-delay dispersion and/or (ii) decrease of the nonlinear phase shift in the Kerr medium. Stable operation with higher energy *and* shorter pulses was also predicted in the case of larger modulation depth of hard-aperture KLM. We expect that optimized KLM might allow generating shorter pulses than those set by the emission bandwidth of Yb:YAG. Another conventional route for generating shorter pulses with higher energies in KLM thin-disk lasers is the use of more broadband materials (Yb:$\mathrm{Lu_2O_3}$, Yb:$\mathrm{LuScO_3}$, Yb:CALGO).

In conclusion, we have demonstrated a Kerr-lens mode-locked Yb:YAG thin-disk oscillator delivering 1.1 μJ of pulse energy, 45 W of average output power, and 270 fs pulses. Even shorter 200 fs pulses were generated at a lower average power of 17 W. We realized stable operation of the oscillator in spite of operating with a large intracavity mode, as well as with a pronounced thermal lens in the gain medium. Free of TPA and resistant to high intracavity intensities, our approach is power/energy scalable. The KLM technique applied, for what we believe is the first time to a thin-disk oscillator, reveals a hidden potential of the Yb:YAG material for supporting 200 fs pulses with a potential for further improvements with improved KLM modulation.

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