Passively mode-locked Yb:YAG thin-disk laser with pulse energies exceeding 13 μJ by use of an active multipass geometry

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We demonstrate the generation of high-energy picosecond pulses directly from a thin-disk laser oscillator by employing a self-imaging active multipass geometry. Stable single-pulse operation has been obtained with an average output power in excess of 50 W, excluding a cw background of 8%, at a repetition rate of 3.8 MHz. Self-starting passive mode locking was accomplished using a semiconductor saturable absorber mirror. The maximum pulse energy was 13.4 μJ at a pulse duration of 1.36 ps with a time-bandwidth product of 0.34. Single-pass external frequency doubling with a conversion efficiency of 60% yielded >28 W of average power at 515 nm. © 2008 Optical Society of America

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Ultrashort laser pulses in the microjoule regime are of prime importance for many applications, including micromachining and direct pumping of parametric devices, as well as basic research, e.g., in high-field physics [1,2]. To some extent the pulse energies from an oscillator can be scaled by increasing the resonator length, e.g., by using passive multipass Herriott cells [2], or by cavity dumping [3]. As compared with external amplifiers, ultrafast oscillators are very attractive owing to their simplicity and compactness. In recent years the pulse energies obtained directly from thin-disk (TD) lasers have increased continuously, meanwhile surpassing the pulse energies of any other ultrafast laser oscillator [2]. High-power TD lasers exhibit major advantages compared with other solid-state laser geometries, i.e., their good thermal management combined with a small optical nonlinearity of the TD itself, owing to the small thickness of the gain medium versus the width of the pump and the laser mode [4]. The nonlinearity of air may therefore become the predominant source of nonlinearities. Hence, the highest pulse energies of 5.1 μJ [5] and up to 11.3 μJ [2] previously obtained had been generated with oscillators operated in helium to reduce self-phase modulation (SPM). The highest energy previously obtained from a laser operated in ambient atmosphere was only 1.75 μJ [6]. Since the low single-pass gain of a TD appears to call for low output coupling (OC), the intracavity energies of TD oscillators typically exceed the external energies by a factor of ten or more. One way to compensate for the low single-pass gain of a TD is to use multiple passes through the gain medium successively, thus multiplying the amplification within one round trip. This approach was used in solid-state laser amplifiers with low-gain rods [7], as well as in TD amplifiers [8]. In oscillators it allows for larger OC and hence lower nonlinearities inside the resonator. Previous mode-locked (ML) TD oscillators mostly used four passes through the disk per round trip (single-V configuration), with the exception of eight passes in [3,9].

Here we report on a passively ML Yb:YAG TD laser that delivered pulses with energies as high as 13.4 μJ from a resonator operated within ambient atmosphere. The experimental setup of the laser is shown in Fig. 1. The Yb:YAG disk had a thickness of only 60 μm, a diameter of 10 mm, and a wedge angle of 0.1°. The pumping chamber provided 20 passes through the gain medium leading to an estimated absorption of less than 60% for the fiber-coupled 940 nm pump power. As in previous ultrafast TD oscillators, passive soliton mode locking of the laser was started and stabilized with a semiconductor saturable-absorber mirror (SESAM) [2,5,6,9]. In soliton mode locking, pulses are formed by the influence of SPM, which in this setup mainly originated from the nonlinear refractive index of air [5], balanced by

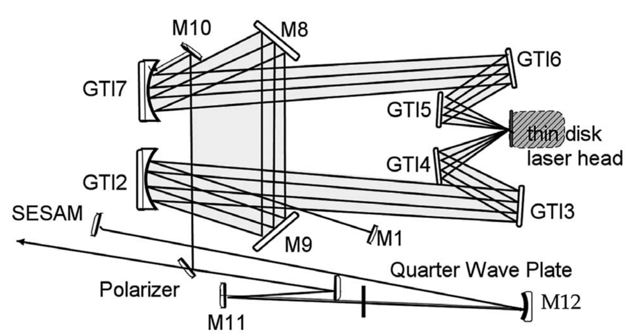

Fig. 1. Schematic design of the passively mode-locked Yb:YAG TD laser with angular multiplexing. For reasons of clarity, in this figure only four passes through the multipass cell (AMC) have been plotted. The actual experimental setup contained 11 passes through the AMC. Six Gires–Tournois interferometric mirrors (GTI2-7) are included in the design. All remaining mirrors are denominated with an "M."

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the negative group-delay dispersion (GDD) [10]. In contrast to [5,2], where the resonator length was increased by three passive 4-*f* telescopes and by a passive Herriot-cell, respectively, we used an active multipass geometry based on angular multiplexing of the gain element, such as apparently has not been used in an oscillator before. The active multipass cell (AMC) consisted of one pair of spherical mirrors that formed a telescopic image at the position of the TD, reproducing itself after each pass through the AMC, whereas in this setup 11 (corresponding to 44 passes through the gain medium within one round trip) have been realized. The drastically increased round-trip gain allowed for OC well above 50%, and represents the highest OC of any TD laser reported so far, to our knowledge. The ratio of intracavity pulse energy to external energy was thereby reduced such that helium flooding could be avoided. The footprint occupied by the AMC was 0.3 m × 1 m, including the TD laser head. The total length of the cavity was 39.93 m, corresponding to a repetition rate of 3.79 MHz. A commercial SESAM (Batop GmbH, Germany) with a nominal saturation fluence of 100 μJ/cm^2, a relaxation time of 1 ps, and a low modulation depth ΔR of only 1.3% was sufficient to initiate ML. In contrast, much larger values of ΔR between 10% and 30% are not uncommon in fiber oscillators with large OC [11]. A small beam radius of 350 μm on the SESAM was chosen in order to minimize thermal-lensing effects, however, leading to a strong saturation at the maximum internal pulse energy of approximately 23 μJ (compared with 113 μJ and >50 μJ in [2,5], respectively). Although no degradation of the SESAM (or any other optical component) was observed during several hours of operation, reliability has not thoroughly been evaluated, and the properties of the SESAM certainly leave room for further optimization. A total B-integral per round-trip of approximately 0.35 rad (corresponding to an SPM coefficient about 3 orders of magnitude lower than that reported in [11]) was estimated by integrating over the length of the beam path along the cavity and adding the contribution of the TD (8% of the overall SPM). To compensate for the overall SPM within the laser cavity, a total GDD of −191600 fs^2 has been introduced into the resonator (see Fig. 1). Stable linear polarization was achieved with an intracavity polarizer, and the OC was adjusted with an additional quarter wave plate.

At an average output power of 55 W, pulses with a duration of 1.36 ps and a spectral bandwidth of 0.88 nm (FWHM) at a center wavelength of 1030.3 nm were measured (Fig. 2). The resulting time-bandwidth product of 0.34 is within 10% of the transform limit of 0.315 for soliton pulses. At all pump powers the spectrum showed an additional cw background around 1027 nm and also small spikes within the main sech^2-shaped spectral distribution. With an integrated intensity of 8% compared with the entire spectrum, these contributions were smallest at 55 W. Subtracting an equal amount of the output power results in pulse energies of 13.4 μJ. At this power the OC was roughly 60%. While the achieved

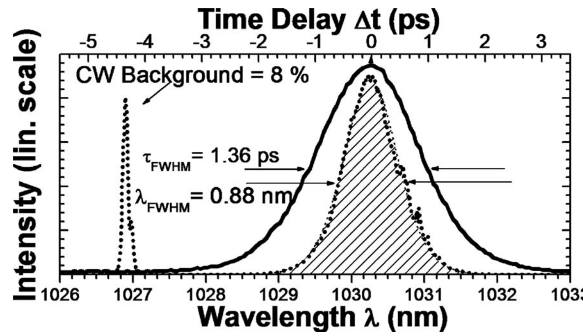

Fig. 2. Autocorrelation (AC) trace and optical spectrum of the laser output. The shaded area shows an ideal sech^2 fit of the optical spectrum with an optical bandwidth of 0.88 nm. The AC trace corresponds to a pulse with FWHM pulse duration of 1.36 ps, assuming a sech^2 pulse shape.

optical-to-optical efficiency of >30% with respect to the launched pump power of 170 W compares favorably with the values reported in [2,5], it could certainly be further increased by using a TD head with larger pump absorption. Relaxation oscillations were measured using a fast photodiode and an rf spectrum analyzer to be suppressed by 37 dBc (decibels relative to carrier), when operating the laser at an output power of 55 W (inset in Fig. 3). The beam quality measured at the maximum pulse energy with a commercial camera-based system was close to diffraction limited with $M^2 < 1.2$. Despite the large number of passes through the TD, the resonator was stable over the full range of pump powers, owing to the low thermal lensing of the disk. As shown in Fig. 3, the pulse duration was inversely proportional to the pulse energy, as expected for soliton ML. Single-pulse operation was observed in the autocorrelation trace that was taken within a time window of 100 ps. The output pulse train was also measured with a fast photo-

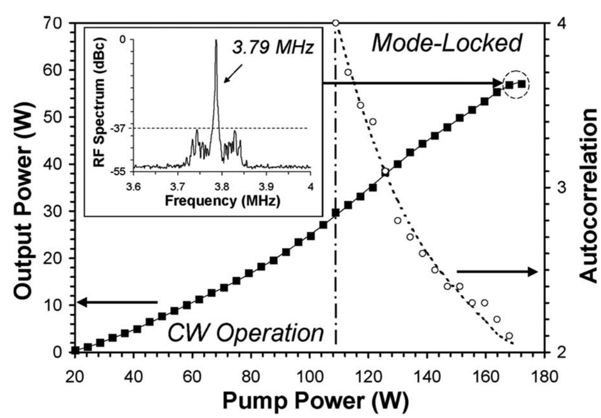

Fig. 3. Change of output power (squares) and autocorrelation width (open circles) with pump power. Single-pulse mode-locking (ML) behavior was observed for pump powers between 105 W and 170 W. The lines are visual aids, the dash-dotted line being inversely proportional to the solid line in the ML regime. For pump powers less than 105 W, ML ceases and the laser operates in continuous mode. The inset shows the measured rf spectrum for operation with maximum pulse energy and reveals relaxation oscillations suppressed to below 37 dBc with respect to the carrier at 3.79 MHz.

diode (rise time of 300 ps), showing single-pulse behavior. We exploited the high peak powers of the TD oscillator to generate pulses at 515 nm in a critically phase-matched, 3 mm long, uncooled beta barium borate (BBO) crystal with a beam diameter of 0.8 mm inside the crystal. The conversion efficiency of second-harmonic generation with 48 W of power incident on the BBO crystal (losses with respect to 55 W output due to imperfect beam delivery) was measured to be 60%. At externally attenuated power incident on the BBO crystal, the undepleted conversion efficiency agreed within a tolerance of 5% with numerical calculations [12], confirming single-pulse operation of the oscillator as in [5]. At 10 to 20 W higher pump-power double pulses were generated. With a separation of 20 ns, these pulses were easily resolved on the oscilloscope trace and as expected showed half the single-pulse conversion efficiency. The ML results are also in good agreement with numerical simulations, implementing an adapted version of the Haus Master equation [10]. However, the configuration does not allow application of the well-known "soliton area theorem," i.e., the simplified relationship between internal energy, linear dispersion, SPM, and pulse duration [10], because of the strong change of internal pulse energy within each round trip. By decreasing the OC in the numerical simulations and keeping the internal pulse energy constant, the simulation results merge with the soliton formula. The same behavior was observed experimentally when the OC was varied. ML instabilities, such as Kelly sidebands [13], were observed neither experimentally nor in the corresponding simulations. The pulse energy was therefore not limited by SPM but rather by double pulsing, which could be further suppressed with different SESAM parameters.

A low ΔR is beneficial for the suppression of Q-switched ML (QML): In our case the transition energy between QML and ML calculated according to [14] was about five times lower than the maximum pulse energy. At the corresponding pump powers, however, cw rather than pulsed operation was observed, which again can be attributed to the low ΔR. A tendency toward QML was observed for experimental situations with fewer passes through the TD, corresponding to less gain and a larger ratio of $\Delta R/\mathrm{OC}$. In that setup the cw background vanished and stable ML with pulse energies of $>5\ \mu\mathrm{J}$ was observed. For future micromachining applications of the frequency-converted output, on the other hand, a small cw portion at the fundamental wavelength should usually be irrelevant. A further increase in cavity length, e.g., by a passive multipass cell [5,6,9], might allow for even higher pulse energies. Additionally, owing to the power scalability of the TD concept [4–6], the pump diameter along with the laser mode area on the SESAM can be enlarged to allow for higher pump powers.

In conclusion, we have demonstrated the generation of ultrashort pulses from a passively mode-locked Yb:YAG TD laser with a repetition rate in the megahertz regime by use of a multipass geometry involving the active medium. This concept allowed for (i) an easy alignment of the components, (ii) enough GDD by only few dispersive mirrors to compensate for the SPM due to air, (iii) enough gain to overcome cavity losses, and (iv) a high OC and hence low intracavity pulse energies. We have obtained 13.4 μJ pulses of 1.36 ps duration while operating the TD laser in ambient atmosphere. To the best of our knowledge, this pulse energy exceeds all reported values for unamplified solid-state laser oscillators operated in ambient atmosphere by more than a factor of seven [15].

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15. Using a larger (2 mm) pump spot we meanwhile achieved energies up to 16 μJ at 54 W of average power without any cw background. Q switching was observed at average output powers below 8 W.