16.2-W average power from a diode-pumped femtosecond Yb:YAG thin disk laser

J. Aus der Au, G. J. Spühler, T. Südmeyer, and R. Paschotta

Ultrafast Laser Physics, Institute of Quantum Electronics, Swiss Federal Institute of Technology,
ETH Hönggerberg–HPT, CH-8093 Zürich, Switzerland

R. Hövel and M. Moser

Centre Suisse d'Electronique et de Microtechnique–Zürich, Badenerstrasse 569, 8048 Zürich, Switzerland

S. Erhard, M. Karszewski, and A. Giesen

Institut für Strahlwerkzeuge, Universität Stuttgart, Pfaffenwaldring 43, 70569 Stuttgart, Germany

U. Keller

Ultrafast Laser Physics, Institute of Quantum Electronics, Swiss Federal Institute of Technology,
ETH Hönggerberg–HPT, CH-8093 Zürich, Switzerland

Received February 15, 2000

We demonstrate a power-scalable concept for high-power all-solid-state femtosecond lasers, based on passive mode locking of Yb:YAG thin disk lasers with semiconductor saturable-absorber mirrors. We obtained 16.2 W of average output power in pulses with 730-fs duration, 0.47-μJ pulse energy, and 560-kW peak power. This is to our knowledge the highest average power reported for a laser oscillator in the subpicosecond regime. Single-pass frequency doubling through a 5-mm-long lithium triborate crystal (LBO) yields 8-W average output power of 515-nm radiation. © 2000 Optical Society of America

OCIS codes: 140.3480, 140.4050, 140.5680, 190.2620.

In recent years there has been great interest in passively mode-locked lasers with high average output powers. At present, the frontiers in the picosecond regime are slightly below 30 W,[1–3] whereas in the femtosecond regime average output powers of a few watts have been demonstrated.[4–7] The need for mode-locked high-power lasers is driven by many applications, particularly those involving nonlinear wavelength conversion, which is facilitated by the high peak powers of such lasers. For example, RGB laser displays can be built if at least a few watts of average output power can be generated at red, green, and blue wavelengths. In this Letter we demonstrate a power-scalable concept for femtosecond lasers with high average power. It is based on a Yb:YAG thin disk laser,[8] which we have passively mode locked for what is believed to be the first time, using a semiconductor saturable-absorber mirror (SESAM).[9,10] We obtained 16.2 W of average power in pulses with 730-fs duration, 0.47-μJ energy, and 560-kW peak power. This is by far more average power than ever demonstrated in the subpicosecond domain. So far, subpicosecond pulses with multiwatt average power have been obtained only from Ti:sapphire lasers,[5,6] which, however, rely either on a bulky, inefficient argon-ion pump laser or on an expensive frequency-doubled diode-pumped pump laser. In the near future our concept should allow for even significantly higher average powers.

Yb:YAG is a very interesting material for diode-pumped high-power femtosecond lasers because of its excellent thermal properties, its wide absorption band at 940 nm, and its broad amplification bandwidth. Pulses as short as 340 fs have been demonstrated in a low-power laser.[11] However, a major drawback of Yb:YAG concerning mode locking is its small emission cross section. In a passively mode-locked laser the saturable absorber needed for mode locking introduces a tendency of the laser toward Q-switching instabilities. This tendency can drive the laser into the Q-switched mode locking[12] (QML) regime, with mode-locked pulses under a Q-switched envelope. This problem is particularly severe for gain media such as Yb:YAG, which have low laser cross sections and thus a high gain-saturation fluence.[12] However, we succeeded in suppressing QML with a combination of measures. First, the thin disk laser head allows for operation with a high laser intensity and small spot size in the gain medium, i.e., a reduced gain-saturation energy. Second, we used a SESAM with relatively small modulation depth ($\approx$0.5%). Third, we designed a laser cavity with a low repetition rate (34.6 MHz). Finally, operation in the soliton mode-locked regime[13] (with negative overall cavity dispersion) substantially increases the stability against QML.[12] Basically this is because any increase in the pulse energy of a soliton increases the bandwidth and thus reduces the effective gain because of the limited gain bandwidth of the laser medium. This technique was essential for stable mode locking of our Yb:YAG thin disk laser.

The thin disk laser head consists of a 220-μm thin Yb:YAG disk, used as the gain medium, which is mounted with one face on a heat sink. This allows us to apply quite high pump-power densities to the disk. The cooled face of the disk is coated for high reflectivity for the laser and pump wavelengths, and the other side has an antireflection coating. As the diameter of the pump beam ($\approx$1.2 mm) is larger than the thickness of the disk ($\approx$220 μm), the heat flux is

0146-9592/00/110859-03$15.00/0

nearly one dimensional and is directed along the optical axis of the laser mode. This leads to a nearly homogeneous temperature profile within the pumped region in the radial direction and thus to only weak thermal lensing and low stress-induced birefringence. Efficient pump absorption is achieved with 16 passes of the pump radiation through the disk.[14] A more detailed description of the thin disk concept is given in Ref. 8. The thin disk laser head that we use is pumped by two fiber-coupled 30-W diode bars at ≈940 nm. The slightly wedged disk eliminates residual reflections, which might disturb the mode-locking process. In a simple cw cavity the laser head generated 20 W of output power near room temperature in a nearly diffraction-limited beam. This output power is lower than that obtained from similar lasers without wedges, from which ≈30-W output has been achieved with the same pump power. The reason for this is probably related to strain in the wedged disk. The focal length of the thermal lens of the thin disk at maximum pump power was estimated to be ~ -1 m. The negative focusing power can be explained by bending of the disk as a result of thermal expansion.[15]

Spatial hole burning[16] (SHB) has a strong effect on mode-locking performance because it leads to inhomogeneous gain saturation. In cw operation of our laser, spatial hole burning leads to laser oscillation on several lines simultaneously, separated by as much as 0.7 nm because of the small thickness of the Yb:YAG disk (220 μm). When we initially set the intracavity dispersion for the generation of pulses with several picoseconds, we observed two (or even more) mode-locked pulses circulating in the cavity with slightly different center wavelengths, corresponding to the different lines observed in cw operation. The reason for this is that the bandwidth of a single pulse is not sufficient to saturate the whole gain. This regime suffers from a lack of stability of pulse energies and timing. However, by reducing the negative intracavity dispersion, we obtained mode locking with a single pulse in the cavity. This led to a pulse duration of ≈0.7 ps and an increased optical bandwidth of 1.5 nm, broad enough to saturate the whole gain. In this regime, spatial hole burning is even beneficial because it effectively flattens the gain spectrum and thus allows for a reduced pulse duration.

The laser cavity (Fig. 1) is designed to operate near the middle of stability zone I (Ref. 17) to provide good alignment stability. The laser mode radius is calculated to be ≈500 μm in the thin disk laser head and ≈600 μm on the SESAM. We insert a Brewster plate into the cavity to enforce stable linear polarization. Without the Brewster plate, the laser is only partially polarized (~80%) along a preferred direction, which is determined by mechanical strain in the disk (from the fabrication process). Negative group-delay dispersion is obtained by use of a self-made Gires–Tournois interferometer (GTI) that consists of a high reflector and a fused-quartz plate (antireflection coated on one side) with a piezo-controlled air gap of ≈30 μm in between. We can continuously tune the dispersion by varying the piezo voltage.

The SESAM, which was grown by metal-organic chemical-vapor deposition, consists of a single 8-nm-thick $In_{0.26}Ga_{0.74}As$ quantum well embedded in an antiresonant low-finesse Fabry–Perot cavity. This cavity is formed by a GaAs–AlAs Bragg mirror with 25 layer pairs and the Fresnel reflection from the GaAs–air interface. Because of the low-finesse design, the device has a small saturation fluence of ≈100 μJ/cm^2, which allows operation with a relatively large spot for efficient heat removal. The modulation depth is relatively low (≈0.5%) but sufficient to initiate and stabilize soliton mode locking. The nonsaturable losses of the device are <0.3%. The back side of the SESAM is actively cooled to ≈20 °C. When the laser is at full power, we operate the SESAM at only ≈7 times the saturation fluence. In this regime we observed no signs of damage, which typically occurs at 100 to 200 times the saturation fluence.

With the cavity shown in Fig. 1 and an output coupler with 5.5% transmission at 1030 nm, we obtain a mode-locked average output power of 16.2 W for a maximum pump power of 57.5 W. To our knowledge, this is by far the highest reported average output power for a femtosecond laser. The pulse duration is 730 fs (Fig. 2), as expected for soliton pulses if the dispersion introduced by the GTI is ~3700 fs^2 per round trip. The repetition rate is 34.6 MHz, which results in a pulse energy of 0.47 μJ and a peak power of 560 kW. The pulses are almost transform limited (time–bandwidth product, 0.32), and the beam quality is measured to be not far from the diffraction limit ($M^2 < 1.5$). We normally had to readjust the voltage of the GTI every few minutes to compensate mainly for the drift of the piezo actuator. This drawback could be eliminated by use of monolithic GTI structures (or

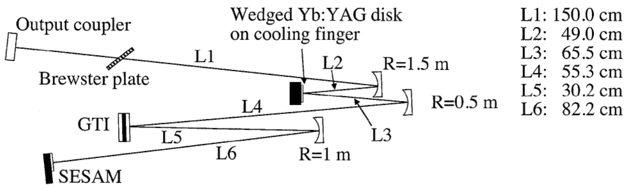

Fig. 1. Schematic of the Yb:YAG thin disk laser cavity: R's, radii of curvature of the concave spherical mirrors; L1–L6, arm lengths. See text for other definitions.

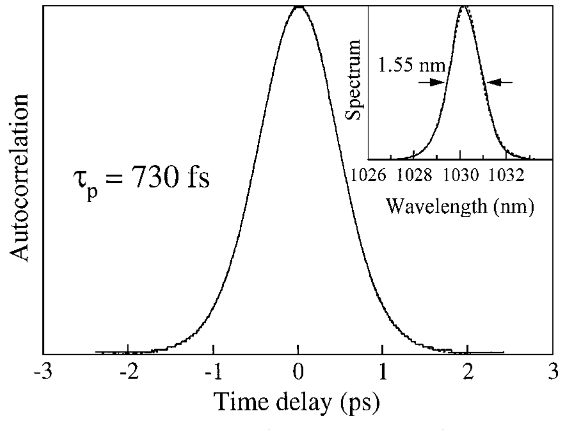

Fig. 2. Intensity autocorrelation trace and spectrum (inset) of the 730-fs pulses obtained from the soliton mode-locked Yb:YAG thin disk laser at full output power of 16.2 W. Dotted curves, fits assuming an ideal sech^2 pulse.

chirped mirrors) with a fixed negative dispersion. For the optimized setting of the GTI voltage, the onset of QML instabilities could be suppressed to average output powers of ~6 W, which is in agreement with the theory presented in Ref. 12.

With a longer cavity (repetition rate, 15 MHz) we obtained pulses as short as 680 fs.[18] In this case the laser output was split into two nearly diffraction-limited beams ($M^2 < 1.2$), each with 7.9-W average power and 680-kW peak power. The pulse energy was $2 \times 0.53\ \mu J$.

Frequency doubling in a single pass through an external 5-mm-long antireflection-coated lithium triborate (LBO) crystal yielded 8-W average output power at 515 nm. The high peak power of the laser allowed us to use critical phase matching at room temperature. (Efficient conversion with significantly longer pulses would require noncritical phase matching in an oven at elevated temperatures.) The 13.8 W of incident fundamental light was focused to a beam radius of ≈60 μm in the LBO crystal.

We emphasize that the whole concept of passively mode-locked thin disk lasers has the crucial advantage of power scalability. For example, we could double the output power of the thin disk laser by doubling both the pump power and the mode areas on the disk. Owing to the unchanged intensity and the one-dimensional heat flow, the temperature in the disk will not increase, if the cooling system is capable of removing the waste heat. Therefore the efficiency of the laser should not be decreased even at high output power. The same scaling law applies to the SESAM, as the mode diameter on the SESAM (≈1.2 mm) is larger than the thickness of the substrate (450 μm). The effect of thermal lensing will not be increased either, so that the good beam quality can be maintained. Finally, the tendency toward Q-switched mode locking or toward thermal or nonthermal SESAM damage will not be increased. Therefore we expect that our concept will lead to even significantly higher mode-locked powers.

In conclusion, we have demonstrated what is to our knowledge the highest average power reported for a laser oscillator in the subpicosecond regime. It is based on a Yb:YAG thin disk laser that we passively mode locked with a SESAM. We obtained pulses as short as 730 fs with 16.2 W of average output power at a repetition rate of 34.6 MHz. External frequency doubling through a 5-mm-long LBO crystal yielded 8-W green radiation. The scalability of this concept promises for the near future to allow for even higher average powers. The use of such lasers as pump sources for parametric oscillators should also lead to tunable high-power sources in the subpicosecond pulse-duration regime.

The authors thank L. Gallmann for helpful discussions. This work was supported by the Swiss Priority Program in Optics II and the European Grant in Biomed 2. J. Aus der Au's e-mail address is ausderau@iqe.phys.ethz.ch.

References

1. G. J. Spühler, T. Südmeyer, R. Paschotta, M. Moser, K. J. Weingarten, and U. Keller, "Passively mode-locked high-power Nd:YAG lasers with multiple laser heads," Appl. Phys. B (to be published).
2. D. Burns, T. Südmeyer, M. Hetterich, A. I. Ferguson, E. Bente, and M. D. Dawson, in *Advanced Solid-State Lasers*, H. Injeyan, U. Keller, and C. Marshall, eds., Vol. 34 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2000), p. 254.
3. J. Aus der Au, S. F. Schaer, R. Paschotta, C. Hönninger, U. Keller, and M. Moser, Opt. Lett. **24,** 1281 (1999).
4. J. Aus der Au, F. H. Loesel, F. Morier-Genoud, M. Moser, and U. Keller, Opt. Lett. **23,** 271 (1998).
5. T. Beddard, W. Sibbett, D. T. Reid, J. Garduno-Mejia, N. Jamasbi, and M. Mohebi, Opt. Lett. **24,** 163 (1999).
6. Z. Liu, S. Izumida, S. Ono, H. Ohtake, and N. Sarukura, Appl. Phys. Lett. **74,** 3622 (1999).
7. J. D. Kafka, M. L. Watts, and J. W. Pieterse, J. Opt. Soc. Am. B **12,** 2147 (1995).
8. A. Giesen, H. Hügel, A. Voss, K. Wittig, U. Brauch, and H. Opower, Appl. Phys. B **58,** 363 (1994).
9. U. Keller, D. A. B. Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, Opt. Lett. **17,** 505 (1992).
10. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, IEEE Sel. Top. Quantum Electron. **2,** 435 (1996).
11. C. Hönninger, R. Paschotta, M. Graf, F. Morier-Genoud, G. Zhang, M. Moser, S. Biswal, J. Nees, A. Braun, G. A. Mourou, I. Johannsen, A. Giesen, W. Seeber and U. Keller, Appl. Phys. B **69,** 3 (1999).
12. C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, J. Opt. Soc. Am. B **16,** 46 (1999).
13. F. X. Kärtner, I. D. Jung, and U. Keller, IEEE Sel. Top. Quantum Electron. **2,** 540 (1996).
14. S. Erhard, K. Contag, I. Johannsen, M. Karszewski, T. Rupp, C. Stewen, and A. Giesen, in *Advanced Solid State Lasers*, M. M. Fejer, H. Injeyan, and U. Keller, eds., Vol. 26 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 1999), p. 38.
15. M. Karszewski, S. Erhard, T. Rupp, and A. Giesen, in *Advanced Solid-State Lasers*, H. Injeyan, U. Keller, and C. Marshall, eds., Vol. 34 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2000), p. 378.
16. B. Braun, K. J. Weingarten, F. X. Kärtner, and U. Keller, Appl. Phys. B **61,** 429 (1995).
17. V. Magni, J. Opt. Soc. Am. A **4,** 1962 (1987).
18. J. Aus der Au, G. J. Spühler, R. Paschotta, U. Keller, M. Moser, S. Erhard, M. Karszewski, and A. Giesen, in *Conference on Lasers and Electro-Optics* (Optical Society of America, Washington, D.C., 2000), paper CMQ1.