Widely tunable pulse durations from a passively mode-locked thin-disk Yb:YAG laser

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We demonstrate a passively mode-locked thin-disk Yb:YAG laser that generates solitonlike pulses with durations that are continuously tunable in a very wide range from 3.3 to 89 ps or from 0.83 to 1.57 ps. The average powers are typically ~12 W. Previously [Opt. Lett. **25,** 859 (2000)], only pulse durations in a narrow range near 0.7 ps could be obtained from such lasers because of the effect of spatial hole burning. We achieved this much wider range by constructing a laser cavity with two different angles of incidence on the thin disk, which greatly reduces the effect of spatial hole burning.

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Recently, we demonstrated a novel concept for femtosecond lasers with unprecedented output power levels.[1] The laser is based on a thin-disk Yb:YAG laser head[2] and a semiconductor saturable absorber mirror[3,4] (SESAM) for passive mode locking. The first experiment resulted in 700-fs soliton pulses with 16-W average power,[1] and the concept promises to allow for significant further advances of the power level. A notable observation was that stable mode locking was obtained only in a narrow range of pulse durations near 0.7 ps. This is a consequence of spatial hole burning (SHB), which inevitably occurs in thin-disk lasers. Recently, we developed a theoretical model that can quantitatively describe these effects and proposed a novel scheme to weaken the effect of SHB by use of a laser cavity in which the laser beam hits the thin disk under two different angles.[5] In this Letter we demonstrate for the first time the experimental implementation of this scheme, used in conjunction with an etalon, which now allows us to generate solitonlike pulses in a much wider range of pulse durations, extending from 3.3 to 89 ps. Without the etalon, we obtained pulses durations from 0.83 to 1.57 ps. The average output power was near 12 W. Obviously, this wide continuous tunability of pulse durations adds a lot of flexibility to this laser concept. For example, longer pulses are desirable for pumping certain nonlinear devices in which group-velocity mismatch limits the interaction length. Also the narrower bandwidth of longer pulses can be important for spectroscopic applications.

In a thin-disk laser head,[2] the gain medium consists of a thin disk of a laser crystal such as Yb:YAG. One side of the thin disk is coated for high reflectivity at the pump and laser wavelength and is directly attached to a cooling finger. Power scalability of this concept arises from the nearly one-dimensional heat flow in the axial direction. In this geometry, counterpropagating laser beams always form a standing-wave pattern in the gain medium, even if rather short pulses circulate in the cavity or if a ring cavity is used. This leads to SHB, i.e., to inhomogeneous gain saturation. The consequences of this were discussed in depth in Ref. 5 by use of a numerical model and are only briefly summarized here. The model assumes that the laser operates in the regime of negative group-delay dispersion, in which solitons are formed. The case of Yb:YAG turns out to be the most critical. For long pulses (with narrow spectra), a dip in the center of the saturated gain spectrum can be formed, which favors pulse breakup. However, short pulses also experience pulse breakup, because their spectra are clipped by the limited gain bandwidth. Therefore, stable mode locking is possible only in a short range of pulse durations near 0.7 ps.

To extend this range of pulse durations greatly, it is necessary to reduce the modulation of the standing-wave pattern in the gain medium. In Ref. 5 we proposed using a laser cavity in which the laser beam hits the thin disk at two different angles, corresponding to two different periods of the standing-wave pattern. If the angles are properly chosen, the pattern is largely wiped out. In a first approximation, the angles can be chosen so that the difference in phase of the standing-wave patterns, acquired over the whole crystal length, corresponds to half a standing-wave period. In this situation a node of one pattern near the nonreflecting end of the disk would coincide with an antinode of the other pattern. By increasing the difference in angle slightly further, one obtains an overall smoother intensity distribution and consequently a weaker SHB effect. For our laser head, with a 220-μm-thick Yb:YAG disk, we have chosen the external angles (in air) to be 2° and 4.8°, respectively. Even then, as the model of Ref. 5 predicts, the SHB effect is not totally eliminated, and pulse durations should be possible in the range of roughly 0.8 to 1.2 ps. With an additional etalon in the cavity, the free spectral range of which should be a couple of nanometers, a much wider range of pulse durations is predicted, beginning at a few picoseconds. The upper limit of the pulse duration in this case is determined not by SHB but by other factors such as the recovery time of the SESAM and the very weak soliton effects at long pulse durations.

Figure 1 shows the cavity design used in our experiment. Apart from small asymmetries in the arm lengths and the folding angles, the cavity is symmetric with respect to mirror M1. For this reason the stability range of the cavity with respect to thermal lensing is as large as for a simple cavity with only one double pass through the disk per round-trip.[6] The laser mode radius is calculated to be ≈ 440 μm in the thin-disk laser head and ≈ 320 μm on the SESAM. The thin-disk laser head is pumped by two fiber-coupled 30-W diode bars at ≈ 940 nm. The Brewster plate enforces a stable linear polarization. Negative group-delay dispersion (GDD) for soliton mode locking is obtained from a self-made Gires–Tournois interferometer (GTI). It consists of a high reflector and a fused-quartz plate (antireflection coated on one side) with a piezo-controlled air gap in between. The dispersion can be continuously tuned by variation of the piezo voltage. As an etalon, we use an uncoated 60-μm-thick fused-silica plate that exhibits a free spectral range of 5.9 nm. An end mirror with a transmission of 10% serves as an output coupler. For passive mode locking we use a SESAM as the other end mirror.

The SESAM, 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 a half-wave layer of GaAs on top of a Bragg mirror with 25 GaAs–AlAs layer pairs. The device has a small saturation fluence of ≈ 170 $\mu J/cm^2$, which allows operation with a relatively large spot for efficient heat removal. The modulation depth is relatively low ($\approx 0.7\%$) but sufficient to initiate and stabilize soliton mode locking. The recovery time is ≈ 90 ps. The nonsaturable losses of the device are $<0.4\%$. The SESAM is mounted on a heat sink kept at ≈ 20 °C. At full power, we operate the SESAM at roughly 10 times the saturation fluence. In this regime we observe no signs of damage, which typically occurs at 100 to 200 times the saturation fluence.

With the setup shown in Fig. 1, we obtain stable mode-locked operation in solitonlike pulses with durations that are continuously tunable from 3.3 to 89 ps and with average output powers near 12 W at a center wavelength of ≈ 1030 nm (Fig. 2). Mode locking is self-starting with a pulse repetition rate of 28 MHz. The beam quality is near diffraction-limited, with an M^2 value measured to be 1.2. The shortest pulses (3.3 ps) are close to the transform limit (time–bandwidth product, 0.34), whereas for longer pulses the time–bandwidth product increases steadily with the pulse duration to a value of 0.67 for the 89-ps pulses. We attribute the deviation from the ideal time–bandwidth product for soliton pulses (0.315) to the fact that the soliton pulse shaping becomes very weak for long pulses. In this regime, other effects such as the saturable absorption and any other perturbations can have a pronounced influence.

We measure the bandwidths of the pulses with durations ≥ 5 ps, using a scanning Fabry–Perot interferometer, since the resolution of a standard optical spectrum analyzer (0.1 nm) is not sufficient. For the longest pulses (89 ps), the bandwidth was 7.4 GHz or 0.026 nm (Fig. 2). Without the etalon, we obtain pulse durations within a tuning range from 0.83 to 1.57 ps and average output powers near 12.5 W (Fig. 3). In this case we used a SESAM grown with low-temperature molecular beam epitaxy to obtain a shorter recovery time (≈ 15 ps). For longer pulse durations, the above-described SESAM with longer recovery time is needed.

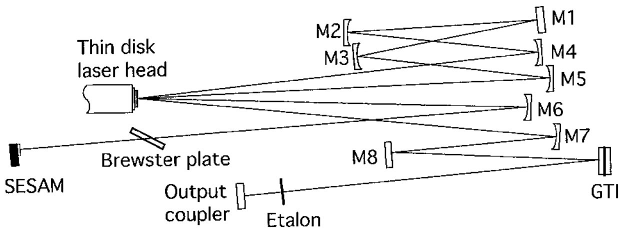

Fig. 1. Setup of the Yb:YAG thin-disk laser: M1, M8, flat mirrors; M2–M7, spherically curved mirrors.

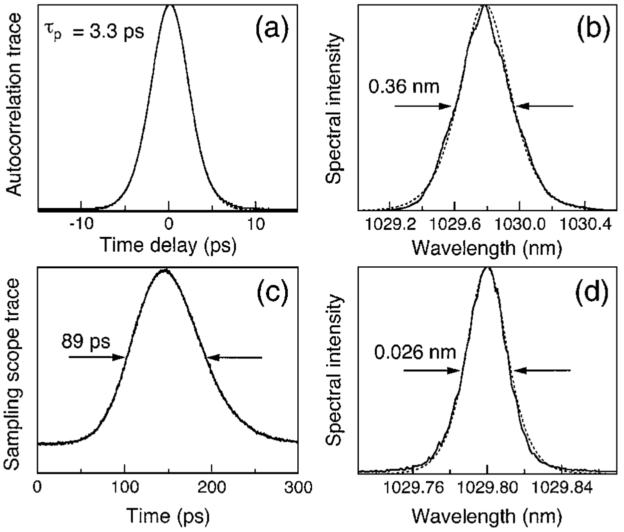

Fig. 2. Results obtained with the etalon, all at ≈ 12-W average output power: (a) intensity autocorrelation and (b) optical spectrum of the pulses with minimum pulse duration $\tau_p = 3.3$ ps. (c) Sampling scope trace and (d) optical spectrum of the pulses with maximum duration $\tau_p = 89$ ps. The dotted curves show fits assuming a soliton ($sech^2$) pulse.

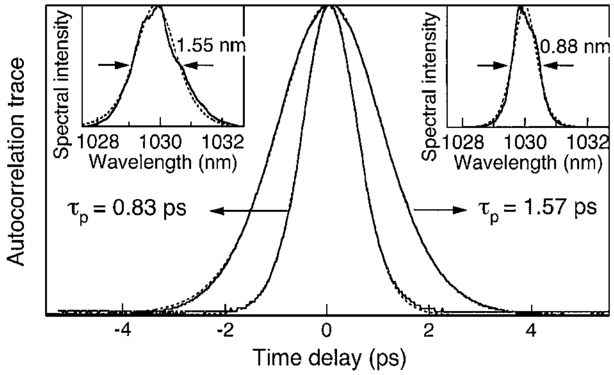

Fig. 3. Results obtained without the etalon: Intensity autocorrelation of the pulses with minimum and maximum duration, $\tau_p = 0.83$ ps and $\tau_p = 1.57$ ps, respectively. Insets, corresponding optical spectra. The dotted curves show fits assuming a soliton (sech^2) pulse.

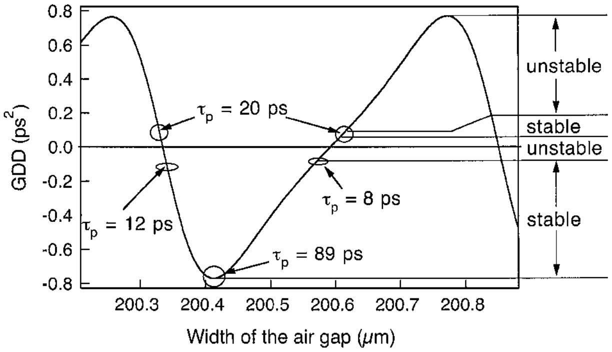

Fig. 4. GDD of the GTI versus the width of the air gap, in a range as required for the longest pulses. Several regimes of stability or instability are indicated.

We can tune the pulse duration simply by varying the voltage on the piezo that controls the air gap of the GTI (in a range of 12-μm width) and thus the negative GDD. Figure 4 shows the GDD as a function of the width of the air gap in a small range near 200 μm. In this case, the piezo allows us to vary the GDD in a range from -0.77 to $+0.77$ ps^2. Near the minimum we obtain the longest pulses (89 ps), and by varying the voltage to either side we obtain shorter pulses. The minimum pulse duration is 8 ps on the right-hand side (larger air gap) and 12 ps on the left-hand side (smaller air gap). For less-negative GDD, the pulses become unstable. The right-hand side allows for shorter pulses, probably because of the smaller third-order dispersion. For slightly positive GDD, we again observe cw mode locking, although it is less stable than soliton mode locking, with a nontunable pulse duration of $\approx$20 ps. Significantly shorter pulses with durations as short as to 3.3 ps are achieved when we reduce the width of the air gap to a value of 40 to 80 μm, using a translation stage for coarse adjustment.

In conclusion, we have demonstrated a novel configuration of a passively mode-locked high-power thin-disk laser, involving two different reflection angles on the thin disk. In good agreement with theoretical predictions, this configuration allowed us to generate solitonlike pulses in a very wide range of pulse durations, 0.83–1.57 ps or 3.3–89 ps, whereas a previously demonstrated laser[1] with a simpler cavity allowed stable mode locking only in a narrow range near 0.7 ps. In this way, we have greatly expanded the range of possible applications of passively mode-locked thin-disk lasers, which are based on a power-scalable concept and thus promise to generate by far the highest average output powers in both the femtosecond and the picosecond regimes.

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