High-power diode-pumped passively mode-locked Yb:YAG lasers

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We obtained 74-kW peak power and 3.5-W average output power in 1-ps pulses from a diode-pumped Yb:YAG laser at 1030 nm that was passively mode locked with a semiconductor saturable-absorber mirror. Another laser produced 57-kW peak power and as much as 8.1-W average output power in 2.2-ps pulses, split into two nearly diffraction-limited beams ($M^2 < 1.2$). To our knowledge, these are by far the highest reported peak and average output powers from a diode-pumped mode-locked laser in this pulse-duration regime. © 1999 Optical Society of America

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Picosecond solid-state lasers with multiwatt average powers and multikilowatt peak powers are required for numerous applications such as UV generation for lithography and pumping of optical parametric oscillators. In the past few years laser diode bars as pump sources with cw output powers of 60 W or more have become commercially available. Therefore the limiting factor for the average output power of diode-pumped mode-locked solid-state lasers is no longer the available pump power but rather the occurrence of strong thermal effects in the gain medium, particularly because operation with a diffraction-limited output beam is normally required for stable mode-locked operation. A $Nd:YVO_4$ laser pumped by a fiber-coupled diode bar[1] generated 7-ps pulses with 4.5-W average power and 7.6-kW peak power. 10.7-W average power and 7.8-kW peak power in 16-ps pulses were obtained from a Nd:YAG laser with a direct-coupled pump laser head.[2] In this Letter we demonstrate lasers with ≤2.2-ps pulse duration, average output powers of as much as 8.1 W, and peak powers of as much as 74 kW. These parameters should allow for very efficient nonlinear frequency conversion to visible, UV, or tunable infrared wavelengths. These short pulse durations were achieved by use of Yb:YAG,[3] a laser medium with a very broad emission spectrum that has been used at a lower power level for generation of pulses with durations as short as 340 fs.[4] In addition, Yb:YAG is potentially a very efficient laser medium because of its small quantum defect; cw output powers as high as 346 W and optical efficiencies of up to 58% at room temperature were demonstrated by use of the so-called thin-disk concept.[5]

The quasi-three-level nature of the Yb:YAG medium requires an end-pumped configuration; the typically larger mode areas in side-pumped lasers would cause a very high threshold and too strong a tendency for Q-switched mode locking (QML).[6] We use a configuration with a strongly elliptical pump beam and laser mode[7] (inset of Fig. 1). This approach is well adapted to the poor beam quality of commercially available high-power low-brightness diode bars. Simply focusing the pump beam to a circular spot would not be favorable because the minimum spot size would be determined by the poor beam quality in the tangential direction, whereas the much better beam quality in the sagittal direction would not be exploited; the resulting pump intensity would be too low. The use of a beam shaper,[8] which would equalize the beam qualities in both directions, would solve this problem. However, we simply focus the pump beam with cylindrical lenses, generating a strongly elliptical pump beam so that the confocal parameter approximately matches the crystal length in both directions. This

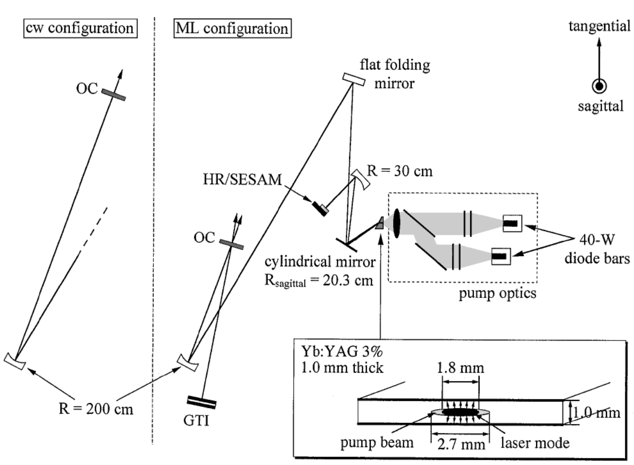

Fig. 1. Schematic of the high-power Yb:YAG laser pumped by two polarization-coupled 40-W diode bars: ML, mode-locked; R's, radii of curvature of the concave spherical mirrors; R_{sagittal}, radius of curvature of the cylindrical mirror; SESAM, semiconductor saturable-absorber mirror; HR, highly reflecting mirror; OC's, output couplers; GTI, Gires–Tournois interferometer. Inset, pump beam and laser mode at the flat end of the 1.0-mm-thick Yb:YAG slab.

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geometry allows us to use a very thin (1.0 mm) laser crystal and thus to remove the heat more efficiently; this is essential for efficient operation of a quasi-three-level laser. Another advantage of our pump geometry is the nearly one-dimensional heat flow, which reduces the effects of thermal lensing and stress-induced birefringence.

The laser (Fig. 1) is pumped by two polarization-coupled 40-W diode bars at 940 nm (DILAS Diodenlaser GmbH, Germany). Each diode has a cylindrical microlens attached to the output face, forming a nearly collimated beam in the sagittal direction. Two more cylindrical lenses for each diode are used to further collimate the sagittal as well as the tangential direction of the beam. After polarization coupling of the two beams with a thin-film polarizer, we use a pair of two closely spaced spherical doublets to focus the beams into the crystal, resulting in a beam with ${M_{\mathrm{sag}}}^2 \approx 10$ in the sagittal direction and ${M_{\tan}}^2 \approx 2800$ in the tangential direction. The focused pump spot radius is 1.36 mm × 0.10 mm. We obtained a maximum pump power of 53 W at the location of the laser crystal and a pump intensity of ≈12 kW/cm^2 (transparency intensity at 1.03 μm, 1.4 kW/cm^2).

The Yb:YAG crystal is flat Brewster cut and has 3-at. % Yb doping, resulting in an absorption length of ≈3 mm at the pump wavelength of 940 nm. The flat surface is antireflection coated for the pump wavelength and coated for high reflectivity at the laser wavelength. For efficient heat removal we have chosen the thickness of the Yb:YAG crystal to be only 1 mm. The crystal is mounted between two copper heat sinks that are attached to thermoelectric coolers. Because of the chosen pump and cooling geometry, the heat flow is nearly one dimensional, which reduces the effects of thermal lensing and stress-induced birefringence.

We match the laser mode to the highly elliptical pump mode, using a cylindrical cavity mirror next to the crystal. To reduce thermal aberrations, which strongly affect the beam quality of the laser, we make the tangential laser mode radius inside the gain medium (0.9 mm) somewhat smaller than the pump-beam radius (1.36 mm) (inset of Fig. 1). This overpumping leads to improved beam quality, with a measured $M^2 < 1.2$ for both axes in the mode-locked configuration, even at maximum pump power. Folding the cavity mode in the crystal results in a doubled small-signal gain per round trip and further reduces the tendency of the laser toward QML.[6]

At multiwatt power levels thermal effects are strong despite the small quantum defect of Yb:YAG and the cooling geometry used. These strong thermal effects can make the alignment of such lasers very difficult, particularly because the alignment toward higher output power often leads to local maxima with significantly lower power than in the global optimum, which is difficult to find. Magni[9] has shown that standing-wave resonators usually have two stability zones, I and II, where resonators operating in zone I are significantly less sensitive to misalignment. Magni considered misalignment caused by a tilt of cavity mirrors; inhomogeneities of the pump profile can show similar effects by causing asymmetries of the thermal lens. Indeed, we have found that our laser resonator, which was designed to operate in zone I, is much easier to align than earlier resonators, which we operated in zone II.

Soliton mode locking[10] is started and stabilized with a SESAM.[11,12] One of the main problems in passive mode locking of high-power solid-state lasers is that the saturable absorbers introduce a tendency of the laser toward QML. This tendency increases with increasing laser mode area in the gain medium. This area is typically quite large in high-power lasers because of the poor beam quality of the pump diodes. Also, the problem is more severe for gain media such as Yb:YAG with low emission cross sections and thus a high gain-saturation fluence. Therefore we had to take a number of measures to obtain stable cw mode locking. First, the laser mode area was kept as small as possible. Second, we used a SESAM with a small modulation depth (≈0.15%) and operated it in the strongly saturated regime (8× the saturation fluence). We kept the output coupler transmission low to increase the intracavity intensity. Finally, Hönninger *et al.*[6] have shown that the tendency toward QML can be substantially reduced if the laser is operated in the soliton mode-locked regime. Indeed, we achieved stable cw mode locking only in this way, generating negative dispersion with a GTI in the cavity.

The metal-organic chemical-vapor deposition–grown SESAM consists of a 15-nm-thick $In_{0.25}Ga_{0.75}As$ quantum well embedded in an antiresonant Fabry–Perot cavity formed by a GaAs–AlAs Bragg mirror with 25 layer pairs, a 70-nm AlAs spacer layer, a 70-nm GaAs spacer layer, and a dielectric top reflector with ≈70% reflectivity. The device has a modulation depth of ≈0.15%, a saturation fluence of ≈385 μJ/cm^2, and a recovery time of ≈60 ps.

In a cw configuration, in other words, without the GTI in the cavity and with the SESAM replaced with a highly reflecting mirror, we obtained an average output power of 10.2 W for a pump power of 53 W incident upon the crystal (Fig. 2). The output coupler had a transmission of 16.8% at the lasing wavelength of 1.03 μm. The threshold power and the slope efficiency with respect to the incident pump power were measured to be 16.5 W and 35%, respectively. At high

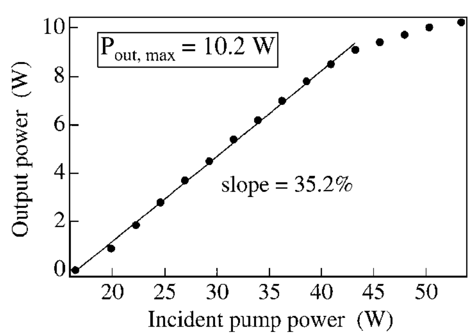

Fig. 2. Measured output power in cw operation at 1.03 μm as a function of incident pump power.

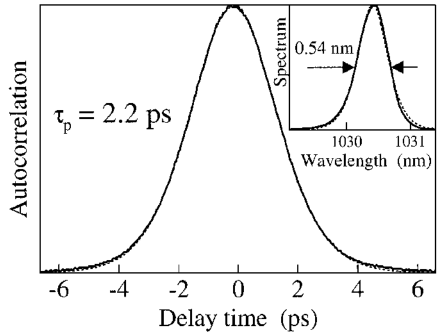

Fig. 3. Intensity autocorrelation trace and spectrum (inset) of the 2.2-ps pulse obtained from the soliton mode-locked Yb:YAG laser. The total output power (in two beams) was 8.1 W. Dotted curves, fits assuming an ideal $sech^2$ pulse.

pump powers, a roll-off in output power can be observed (Fig. 2). We attribute this degradation in efficiency to insufficient cooling of the crystal at high pump powers and to a change in laser mode size owing to thermal effects. The measured M^2 factors are 1.2 in the sagittal direction and 1.6 in the tangential direction.

For stable mode-locked operation we had to reduce the total output coupling per round trip to 8.4%. (A significant increase of output coupler transmission, an increase of the modulation depth of the SESAM, or a decrease of pump power would lead to Q-switching instabilities.) We obtained pulses as short as 2.2 ps (Fig. 3), with an average output power of 8.1 W and a pulse repetition rate of 63 MHz. The laser output was split into two nearly diffraction-limited beams ($M^2 < 1.2$ in the sagittal and the tangential directions), each with $\approx$4-W average power and $\approx$29-kW peak power. This decrease in the M^2 value in the tangential plane could be due to the stronger absorption of the SESAM in the wings of the beam, where the absorber is bleached to a lower extent. A single output beam with full power could be generated by use of a GTI with smaller dispersion as a folding mirror so that the output coupler would be the end mirror. The obtained 2.2-ps pulses were almost transform limited (time–bandwidth product, 0.34). Even shorter pulses should be achievable with a GTI with a broader bandwidth. A similar laser with a single 40-W diode bar and a prism pair instead of the GTI generated 1.0-ps pulses in a single output beam, with 3.5-W average power and as much as 74-kW peak power.

In conclusion, we have demonstrated diode-pumped passively mode-locked Yb:YAG lasers with as much as 8.1-W average power and 2.2-ps pulse duration or 3.5-W average power and 1.0-ps pulse duration. Peak powers of as much as 74 kW were generated. These are, to our knowledge, the highest reported average and peak output powers in this pulse-duration regime. We have achieved these results by using Yb:YAG in a pump geometry with a highly elliptical mode and unidirectional heat flow. Such lasers will allow for very efficient nonlinear frequency conversion to visible, UV, or tunable infrared wavelengths, even if two or more nonlinear processes have to be cascaded.

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