Diode-pumped passively mode-locked Nd:YAG laser with 10-W average power in a diffraction-limited beam

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Received January 19, 1999

We present a passively mode-locked Nd:YAG laser with 10.7-W average output power in a diffraction-limited beam. Stable self-starting mode locking with a pulse duration of 16 ps and a pulse energy of 120 nJ is obtained with a semiconductor saturable-absorber mirror. The laser is directly side pumped with two 20-W diode bars. Single-pass frequency doubling in an external 5-mm-thick KTP crystal yields 3.2-W average power at 532 nm. © 1999 Optical Society of America

OCIS codes: 140.3480, 140.3530, 140.4050, 190.2620.

Picosecond high-power diode-pumped solid-state lasers with good beam quality are attracting growing interest because of numerous applications in medicine, material processing, and nonlinear frequency conversion. For example, multiwatt operation of cw mode-locked neodymium-doped lasers with kilowatt peak powers allows for efficient frequency conversion into the visible and ultraviolet regime.

For high peak powers, passive mode locking seems to be favorable because of the typically shorter pulse durations and the simpler setup than those of actively mode-locked lasers. However, the average power of passively mode-locked lasers in the 1-μm region has so far been limited. An average power of 3.4 W was obtained from a nonlinear-mirror mode-locked[1] Nd:YVO_4 laser,[2] and an average power of 4.5 W was obtained from a Nd:YVO_4 laser mode locked with a semiconductor saturable-absorber mirror (SESAM).[3] Both lasers were end pumped by fiber-coupled diode bars and showed beam qualities that were at least 1.6 times diffraction limited. In this Letter we demonstrate more than 10 W of average power and 7.8 kW of peak power from a passively mode-locked diffraction-limited Nd:YAG laser based on a compact laser head and a SESAM. Scaling to even higher powers seems realistic with our side-pumping approach.

The main difficulty in passive mode locking of a high-power solid-state laser is to overcome the tendency of the laser toward Q-switched mode-locking (QML) instabilities,[4] introduced by the saturable absorber, that increase with increasing laser mode area in the gain medium. This area is typically quite large in high-power lasers, because the poor beam quality of high-power pump diodes and thermal effects in the gain medium set limits on tighter focusing. As the threshold for QML depends on the saturation energy of the gain medium as well as the saturation energy of the saturable absorber and its modulation depth,[4] a proper choice of pump source and geometry, laser material, and mode-locking technique is essential for high-power mode-locked laser operation.

Side pumping of the laser medium (instead of end pumping) has advantages for high-power lasers, namely, easier delivery of pump power with reduced demands on pump beam quality and ease of combining several pump heads, which result in a widely scalable approach. However, the good efficiency and beam quality of end-pumped lasers are usually not achieved with side-pumped lasers.[5] Additionally, side-pumping geometries often imply large beam radii in the gain medium, and therefore a large saturation fluence of the gain, which itself lowers the stability against QML.[4]

These problems of side pumping are solved by use of a direct-coupled pump (DCP; Lightwave Electronics) laser head[6] (Fig. 1), in which the output of two longitudinally displaced laser diode bars is directly coupled into the cylindrical laser rod without any transfer optics. The diode bars are mounted in close proximity to the rod. The rod is laterally surrounded by a water-cooled metal block that contains two slits that allow the pump light to enter. The diameter of the rod is smaller than the absorption length, and a reflective coating on the metal block leads to multiple passes of

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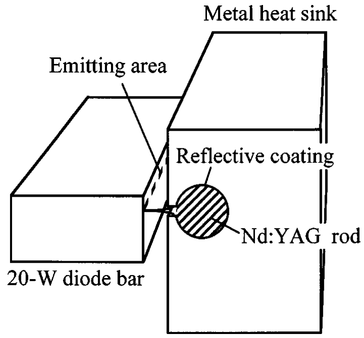

Fig. 1. Schematic of the DCP laser head, with only one of two diode bars shown.

the pump radiation. In this way we achieve a trap for the pump radiation and thus efficient pump absorption and spatially homogeneous inversion density. The induced thermal lens is weak, only weakly aberrative, and nearly spherical because of homogeneous pump distribution, a 90° angle between the orientation of the pump diodes, and efficient heat removal. These advantages result in good efficiency and excellent beam quality. The pump diodes are mounted upon the same water-cooled heat sink as the laser rod. As the absorption length of the pump is not critical in this configuration, the diode temperature does not need to be controlled actively. The DCP concept allows us to use relatively small crystal diameters (compared with those of other side-pumped approaches) because of the combination of pump radiation trapping and efficient heat removal. Therefore the laser mode size and thus the saturation energy of the gain can be kept relatively small (here a 300-μm radius), which is beneficial for stability against QML.

As gain material we chose Nd:YAG because of its good thermal conductivity (e.g., three times better than Nd:YVO_4) and high stress-fracture limit. The long absorption length of Nd:YAG is no disadvantage, as the pump light is trapped, resulting in a smooth pump distribution.

The use of a SESAM (Refs. 7 and 8) as a mode locker in conjunction with the relatively small laser mode in the gain medium leads to stable self-starting mode locking. The combination of adjustable device structure and material parameters of the SESAM provides us with sufficient design freedom to choose the key macroscopic parameters, such as modulation depth, recovery time, and saturation fluence, and therefore is well suited for application in a large variety of lasers. In this Letter we demonstrate that the SESAM is also well suited for mode locking of high-power lasers.

The cavity is shown in Fig. 2 and consists of only four mirrors (including the SESAM), a Brewster plate, and the laser head. With the compact DCP head, no complicated transfer optics or beam-shaping techniques are needed for the pump, making the system very simple and compact. The two curved mirrors allow us to control the mode radii in the laser head and on the SESAM in a simple manner. For our cavity, these mode radii are calculated to be 300 and 100 μm. Linear polarization is enforced by a Brewster plate, which causes only 0.3% depolarization loss at maximum pump power, because the temperature distribution in the rod is very smooth. The SESAM consists of one 25-nm-thick $In_{25\%}Ga_{75\%}As/GaAs$ quantum well in an antiresonant Fabry–Perot cavity formed by a GaAs-AlAs Bragg mirror with 25 layer pairs, AlAs and GaAs spacer layers, and a dielectric top reflector with 72% reflectivity. The device has a recovery time of 26 ps, a modulation depth of 0.5%, nonsaturable losses of 0.4%, and a saturation fluence of 200 $\mu J/cm^2$. To keep the tendency for QML weak enough we chose the spot on the SESAM to be rather small. This means that the SESAM is operated quite far above saturation energy (27 times at full pump power). The SESAM is simply mounted upon a copper heat sink, but no active cooling is applied. The dissipated heat energy per bounce originates from the saturation of the SESAM (saturation energy times modulation depth) and the nonsaturable losses (intracavity pulse energy times nonsaturable loss). Here ~95% of the total dissipated power of 0.6 W originates from nonsaturable loss, as we operate the SESAM far above the saturation energy. This high power is expected to cause a temperature rise of the order of 50 K.

With the cavity shown in Fig. 2 and an output coupler with 7% transmission we obtain a slope efficiency of more than 40% (Fig. 3). For a maximum pump power of 41.7 W, 10.7-W average output power is obtained. The overall optical–optical efficiency of more than 25% (and the electrical–optical efficiency of 8.2%) is high for a side-pumped system. At maximum pump power there is a slight roll-off of the output power, indicating that thermal effects become important at this point. QML occurs below

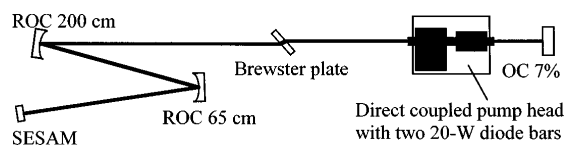

Fig. 2. Schematic of the laser cavity: ROC, radius of curvature; OC, output coupler.

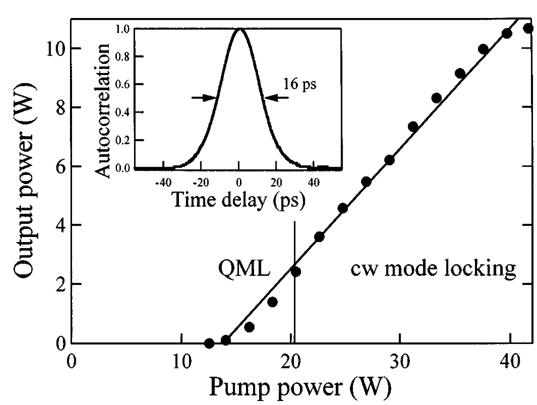

Fig. 3. Output power versus launched pump power. Self-starting cw mode locking is obtained for more than 20.4-W pump power. The autocorrelation of the 16-ps pulses at 10.7-W output power is shown in the inset.

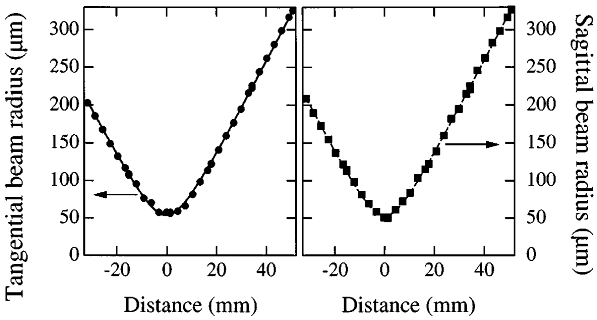

Fig. 4. Longitudinal cross section through the focused output beam. Left, tangential beam radius; right, sagittal beam radius; curves, ideal Gaussian beam. The beam profile yields M^2 of less than 1.05.

3-W output power (corresponding to 20.4-W pump power), in good agreement with the calculated QML threshold of 3.3 W [Eq. (13) of Ref. 4]. The pulse duration is 16 ps (see the inset of Fig. 3), and the repetition rate is 88 MHz, resulting in a pulse energy of 120 nJ and a peak power of 7.8 kW. Mode-locked picosecond pulses with peak powers and pulse energies of this order are usually obtained only with amplifier systems.

Frequency doubling in a single pass through an external 5-mm-long type II–cut KTP crystal yielded 3.2-W average power at 532 nm. The crystal was temperature stabilized, and phase matching was achieved by means of angle tuning. The fundamental light was focused to a beam radius of 22 μm (corresponding to a Rayleigh range of 2.6 mm) in the KTP crystal. The peak power of the second-harmonic light was still high enough for us to obtain 120 mW of ultraviolet radiation by means of subsequent frequency doubling in a temperature-stabilized 7-mm-long type I–cut BBO crystal.

The beam profile of the focused (fundamental) output beam for maximum power is shown in Fig. 4. The measured M^2 factor is smaller than 1.05. With the measured M^2 and the calculated spot size in the laser head, the Rayleigh range is 27 cm, which is significantly more than the length of the laser head assembly. Therefore only minor changes in the cavity design would allow us to insert another DCP head into the cavity and thus scale the power to even higher levels.

After 40 h of continuous operation we found an increase of the threshold for cw mode locking from 20.4-W pump power up to the maximum available pump power, whereas the output power remained unchanged. This indicates some change of the SESAM parameters. Along with the peak optical field strength, the thermal load might have an influence on aging of the SESAM. The latter can be reduced by use of a low-finesse SESAM (without a top reflector) with the same modulation depth but correspondingly lower saturation fluence. In this way the mode size on the SESAM can be kept larger for the same intracavity pulse energy (and laser performance), without changing the QML threshold. Then, the same heat is deposited on a larger spot, which leads to a more favorable thermal situation. Since such a SESAM is not available at this time we used the high-finesse SESAM described above. Another way to reduce the load of the SESAM is to choose a different gain material with a larger emission cross section and a correspondingly lower saturation fluence, which would allow for a larger spot on the SESAM while keeping the QML threshold low. A good candidate for this material is Nd:YVO_4, which also allows for shorter pulse durations owing to its broader emission bandwidth. However, Nd:YVO_4 suffers from poorer thermal properties.

In conclusion, we have demonstrated a method for obtaining higher powers from diode-pumped passively mode-locked lasers. We used a novel compact side-pumped Nd:YAG laser head with relatively small mode size in the gain medium in connection with a SESAM so that stable passive mode locking without Q-switching instabilities became possible. With this approach we obtained 10.7-W average output power in a diffraction-limited beam and peak powers as high as 7.8 kW. External frequency doubling yielded 3.2-W green and 120-mW ultraviolet radiation.

This research was supported by the Swiss Priority Program in Optics II and the European Grant in Biomed 2. G. J. Spühler's e-mail address is spuehler@iqe.phys.ethz.ch.

References

1. K. A. Stankov, Appl. Phys. B **45,** 191 (1988).
2. A. Agnesi, C. Pennachio, and G. C. Reali, in *Conference on Lasers and Electro-Optics*, Vol. 6 of 1998 OSA Technical Digest Series (Optical Society of America, Washington, D.C.), paper CTuM43.
3. B. Ruffing, A. Nebel, and R. Wallenstein, in *Conference on Lasers and Electro-Optics*, Vol. 11 of 1997 OSA Technical Digest Series (Optical Society of America, Washington, D.C.), paper CWB2.
4. C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, J. Opt. Soc. Am. B **16,** 46 (1999).
5. T. Kojima and K. Yasui, Appl. Opt. **36,** 4981 (1997).
6. J. D. Kmetec, "Solid-state laser with trapped pump light," U.S. patent 5,774,488 (June 30, 1998).
7. U. Keller, D. A. B Miller, G. D. Boyd, T. H. Chiu, J. F. Ferguson, and M. T. Asom, Opt. Lett. **17,** 505 (1992).
8. 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 J. Sel. Topics Quantum Electon. **2,** 435 (1996).