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Passively mode-locked high-power Nd:YAG lasers with multiple laser heads

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Abstract. We discuss power scaling of passively mode-locked lasers using multiple laser heads in the resonator. We experimentally compared two different approaches for the cavity design, both using three side-pumped Nd:YAG laser heads. We obtained a record-high average output power of up to 27 W with close to diffraction-limited beam quality, a pulse duration of 19 ps, a pulse energy of 0.5 μJ, and 23 kW peak power. Single-pass second-harmonic generation in a 10-mm-long LBO crystal yields 16.2 W of 532-nm radiation.

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Passively mode-locked lasers with high average power and good beam quality are interesting for numerous applications, particularly those involving nonlinear frequency conversion. Peak powers in the multi-kW regime allow for efficient frequency conversion in a single pass through a nonlinear crystal, and therefore for simple generation of visible and UV wavelengths. These lasers can also be used to synchronously pump high-power OPOs, generating other wavelengths as for example required for RGB displays.

Flashlamp-pumped actively mode-locked Nd:YAG and Nd:YLF lasers have been used to obtain more than 10 W of average power with typically around 100 ps and 30 ps pulse durations, respectively. The development of higher average-power diode lasers has stimulated a strong interest in diode-pumped solid-state lasers. Diode laser pumping provides dramatic improvements in efficiency, lifetime, size, saturation energy, and other important laser characteristics. However before 1990, all attempts to passively mode-lock solid-state lasers resulted in Q-switching instabilities which at best produced stable mode-locked pulses within longer Q-switched macropulses (i.e. Q-switched mode locking). Novel semiconductor saturable absorber mirrors (SESAMs) [1, 2] allowed for the first time self-starting and stable passive mode locking of diode-pumped solid-state lasers with an intracavity saturable absorber. For high peak powers, passive mode locking is favorable because of the typically shorter pulse durations and the simpler set-up compared to actively mode-locked lasers. However until recently, the output power of passively mode-locked lasers has been limited to less than 1 W [2]. Then several schemes were presented to reach power levels in the Watt and multi-Watt regime. A nonlinear mirror mode-locked [3] Nd:YVO$_4$ laser yielded 3.4 W average output power [4]. More output power was obtained using intracavity SESAMs for passive mode locking. A more detailed review of the different SESAM designs with their different advantages and trade-offs is given in a recent book chapter [5]. With this approach, 4.5 W were obtained from a Nd:YVO$_4$ laser [6]. A side-pumped Nd:YVO$_4$ laser has recently been presented yielding 4.4 W average power [7]. Using Yb:YAG as gain material in an elliptical mode geometry, Aus der Au et al. presented an 8.1-W laser with significantly shorter pulses (2.2 ps) [8]. Recently, we have demonstrated more than 10 W average power from a passively mode-locked, diffraction-limited Nd:YAG laser [9].

In this paper, we demonstrate the scaling to significantly higher powers by the use of three laser heads in one cavity. The paper is organized in the following way: in Sect. 1 we discuss the challenges for building a passively mode-locked high-power laser, for which solutions are given in Sect. 2. In Sect. 3 we address the cavity design for a laser with multiple laser heads. We present the experimental results in Sect. 4 and discuss the question of scalability of our approach in Sect. 5.

1 Challenge of passively mode locking a high-power solid-state laser

First, a laser head suitable for high-power cw operation with TEM$_{00}$ transverse beam quality is required. Discussing the details of such a laser head is beyond the topic of this paper. Instead, we focus on the topic of how to passively mode-lock it. The main challenge in passively mode locking a high-power solid-state laser is to overcome the tendency of the laser towards Q-switched mode locking (QML) instabilities introduced by the saturable absorber. The threshold for the intracavity pulse energy E_p, above which stable cw mode locking is achieved in ps lasers, is [10]

$$E_\text{p}^2 > F_{\text{sat,L}} A_\text{L} F_{\text{sat,A}} A_\text{A} \Delta R \,. \tag{1}$$

Below this threshold the mode-locked pulse train is underneath a Q-switched envelope, resulting in large variations of peak power and pulse energy. This regime of operation is usually unwanted.

There are three main parameters which can be optimized in order to suppress QML. First the choice of the gain material is important, as the QML threshold is directly proportional to the saturation fluence of the gain medium $F_{\mathrm{sat,L}}$. In a standing wave cavity the saturation fluence of the gain is given as $F_{\mathrm{sat,L}} = h\nu/2\sigma_{\mathrm{L}}$, where $h\nu$ is the laser photon energy and σ_{L} the emission cross section of the gain. Therefore, ps laser materials with large σ_{L} such as Nd:YVO$_4$ and Nd:YAG result in a lower threshold for cw mode locking than broadband fs laser materials. Second, the absorber parameters (saturation fluence $F_{\mathrm{sat,A}}$, modulation depth ΔR) play an important role in the QML threshold, and thus the mode locking technique and the saturable absorber have to be chosen carefully. The third important point is the cavity design and pump geometry: the laser mode areas A_{L} in the gain medium and A_{A} in the saturable absorber should be small in order to get a small QML threshold. Finally, a low repetition rate f_{rep} makes it easier to achieve a high pulse energy E_{p} and therefore to overcome the QML threshold.

Laser head design with the aim of a small laser mode radius is crucial for passively mode-locked high-power lasers. Many high-power laser heads have a rather large A_{L} because of limitations of the brightness of the high-power diode pump lasers or the pump geometry and possibly because of thermal limitations. To some extent, this can be compensated for by using a small mode area A_{A} on the absorber, i.e. by operating the absorber in a strongly saturated regime. However, this might result in multiple pulsing of the laser [11] or in absorber damage (see Sect. 2.3).

2 Approaches to overcome Q-switched mode locking

2.1 Laser head

Side pumping of the laser medium (instead of end pumping) has advantages for high-power lasers, namely the easier delivery of pump power with reduced demands on pump beam quality, and the ease of combining several laser heads, which results in a widely scalable approach. However, the good efficiency and beam quality of end-pumped lasers is usually not achieved with side-pumped lasers [12]. Additionally, side-pumping geometries often imply large beam radii in the gain medium and therefore a large saturation energy of the gain, which itself lowers the stability against QML.

These problems of side pumping are solved by using direct-coupled-pump (DCP, Lightwave Electronics) laser heads (Fig. 1) [13], which consist of a flat–flat cut, AR-coated 37-mm-long Nd:YAG rod embedded in a water-cooled metal block with two slits that allow the pump light to enter. Two 20-W diode bars per head are mounted longitudinally displaced in close proximity to the rod. Their output is directly coupled into the rod, without any transfer optics. The diameter of the rod is smaller than the absorption length, and a reflective coating on the metal block leads to trapping of the pump radiation. This results in efficient pump absorption and a spatially homogeneous inversion density. The induced thermal lens is only weakly aberrative and nearly spherical due to the homogeneous pump distribution, a 90° angle between the orientation of the pump diodes, and the efficient heat removal. These advantages result in good efficiency and beam quality and allow us to scale up the power of the laser by using several laser heads per cavity (see Sect. 5). As the absorption length of the pump is not critical in this configuration, the diode temperature does not need to be actively controlled. The pump diodes are mounted on the same water-cooled heat sink as the laser rod leading to a further simplified system. The DCP concept allows the use of relatively small crystal diameters (compared to 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 which is beneficial for stability against QML.

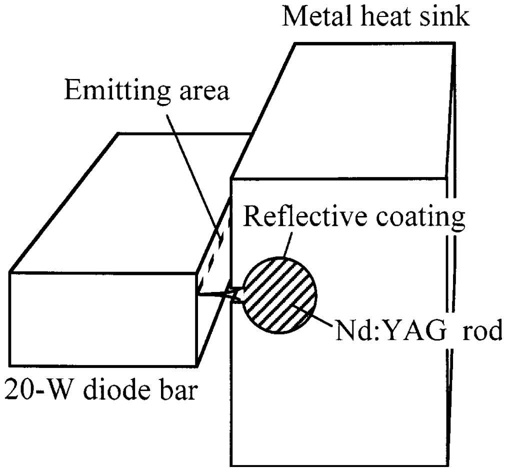

Fig. 1. Schematic of a direct-coupled-pump (DCP) laser head, with only one of two diode bars shown

2.2 Gain material

As gain material Nd:YAG is used because of its good thermal conductivity (for example, 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 and results in a smooth pump distribution. In order to further reduce the QML threshold and the demands on the SESAM, Nd:YVO$_4$ with its significantly larger emission cross section could be used.

2.3 Mode locking technique

With a SESAM as a passive mode-locker we benefit from absorber parameters which can be custom designed in a large range. Equation (1) serves as a guideline and suggests the use of a small modulation depth ΔR and a small saturation fluence $F_{\mathrm{sat,A}}$. A small ΔR also reduces the thermal load, but can compromise the self-starting ability and may lead to longer pulses [14]. Typical values that we use in high-power lasers are $0.5\% < \Delta R < 2\%$ and $F_{\mathrm{sat,A}} \approx 100\ \mu\mathrm{J/cm}^2$. The saturation parameter S of the SESAM is defined by $S = F_{\mathrm{A}}/F_{\mathrm{sat,A}} = E_{\mathrm{p}}/(F_{\mathrm{sat,A}}A_{\mathrm{A}})$, where F_{A} is the pulse fluence on the SESAM. S should not be much larger than 20 to

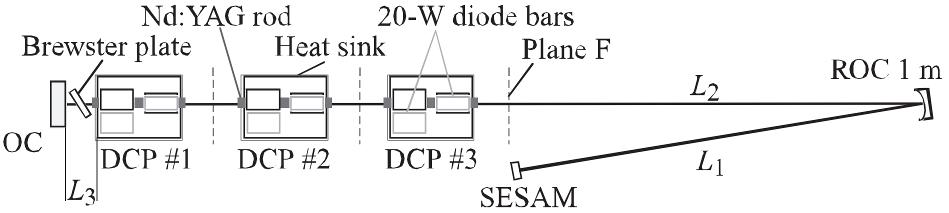

Fig. 2. Non-periodically extended cavity containing three direct-coupled-pump (DCP) laser heads. The *dashed lines* indicate the planes confining the simple flat–flat cavities. Plane F is 1 : 1 imaged to the SESAM by the relay optics L_1, ROC 1 m, L_2. OC, output coupler; ROC, radius of curvature; SESAM, semiconductor saturable absorber mirror

avoid multiple pulsing instabilities [11] and SESAM damage. Also a small saturation fluence $F_{\mathrm{sat,A}}$ is beneficial for high-power lasers because it allows for a larger mode area on the absorber and thus reduces the thermal load.

The SESAM, used as an end mirror in the high-power lasers described below, is grown by metal organic chemical vapor deposition (MOCVD). The growth temperature of the mirror structure and the absorber structure was 750 °C and 690 °C, respectively. The device contains a strained single 25-nm-thick $\mathrm{In_{25\%}Ga_{75\%}As/GaAs}$ quantum well in a low-finesse design. It has a modulation depth of 1.7%, nonsaturable losses of 1.4%, a saturation fluence of 60 $\mu\mathrm{J/cm^2}$, and a recovery time τ_{A} of 26 ps.

3 Cavity-design considerations

3.1 Basic requirements for a cavity containing multiple laser heads

For designing a cavity containing several laser heads, the focusing power of the thermal lens of each laser head must be precisely known. We determined the focal length of the three DCP heads at maximum pump power under lasing conditions to be 14 cm, 15 cm, and 18 cm, respectively. These three laser heads have then been used in two different laser cavities in order to get a high-power passively mode-locked laser.

The laser resonator has to meet several requirements. The mode radii in all laser heads should have the optimum size in a range of pump powers as large as possible. In the case of the DCP heads this is on the order of 290 μm. A larger size leads to clipping of the mode (hard aperture), with the consequence of loss of power, whereas a smaller mode size leads to oscillation on competing higher order transverse modes, which degrades the beam quality and can obstruct the mode locking process. The mode radius on the SESAM has to be chosen so as to obtain the wanted saturation parameter, depending on intracavity power and repetition rate. Obviously these parameters should meet the criterion for stable cw mode locking (1). Other desired features are a low alignment sensitivity and some flexibility to adjust parameters such as mode sizes and repetition rate. In the following we discuss two basic design approaches to construct a cavity fulfilling these conditions.

3.2 Non-periodic extension of simple cavity

If the thermal lens of the used laser heads is symmetric (same focal length for tangential and saggital direction, as it is for the DCP laser heads), a very simple single head flat–flat cavity can be built, with the laser head in the middle (this cavity is always in stability zone II [15] with diverging alignment sensitivity for low pump powers). The length of this cavity is then for each laser head experimentally optimized for maximum output power at full pump power. This leads to a resonator length on the order of the focal length of the thermal lens of the laser head, i.e. a few tens of cm in the case of the DCP heads. These single-head cavities for the different laser heads can then be arranged in series, leading to a simple approximately periodic resonator (the mode sizes of the single-head cavities on the end mirrors are sufficiently close to each other). However, this simple extended resonator is too short and the spot size on the end mirrors is too large to meet the conditions for saturating a typical SESAM and suppressing QML. But simple cavity extensions can be designed, that do not affect the mode sizes in the laser heads (at full pump power) but adjust the saturation parameter by changing the cavity length and the spot size on the SESAM. This can be achieved by imaging the mode at one end mirror of the simple original cavity to a new end mirror (which will later be replaced by the SESAM) using relay optics with the desired magnification factor and optical path length. A simple version of such an extended cavity is shown in Fig. 2.

A cavity extended in such a non-periodic way gives the flexibility to adjust repetition rate and mode sizes with only small changes of the resonator (for example changes of L_1, L_2, and L_3 in Fig. 2). The laser heads do not need to be readjusted during changes of repetition rate and mode size on the SESAM, just the relay optics. On the other hand, such cavities typically do not operate at stationary points for the mode sizes, so that suitable mode sizes are obtained only in a small range of pump powers. However, if the thermal lenses of the laser heads are precisely known, the width of this stability regime is large enough to support stable operation at full power.

3.3 Periodic extension of optimized resonator

A totally different design approach to meet the criteria of Sect. 3.1 is to use periodic resonators. The basic idea – to concatenate cavities with a single laser head each – has been discussed in [16]. The most important fact about this approach is that the width of the stability range of the obtained cavity (in terms of pump power) is scaled together with the laser power. Here we apply this principle to a passively mode-locked laser. If the single-head cavity fulfills the requirements for passive cw mode locking, the concatenated cavity does so too, if the output coupling and the modulation depth of the SESAM are scaled up proportionally to the small-signal gain.

But then, the single-head cavity to start with must fulfill more requirements than for the approach discussed in Sect. 3.2. It must have the right optical length (to achieve the desired repetition rate) and spot size on the end mirror, which will be replaced by the SESAM. Additionally, we want it to

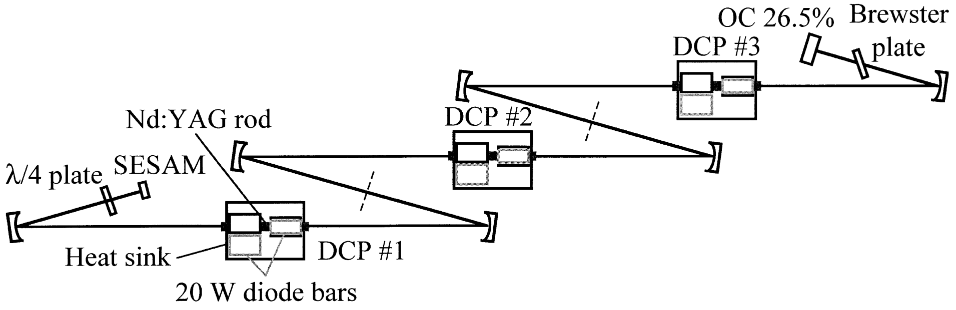

Fig. 3. Periodically extended cavity containing three direct-coupled-pump (DCP) laser heads. The *dashed lines* indicate the planes confining the identical single-head cavities. OC, output coupler; SESAM, semiconductor saturable absorber mirror

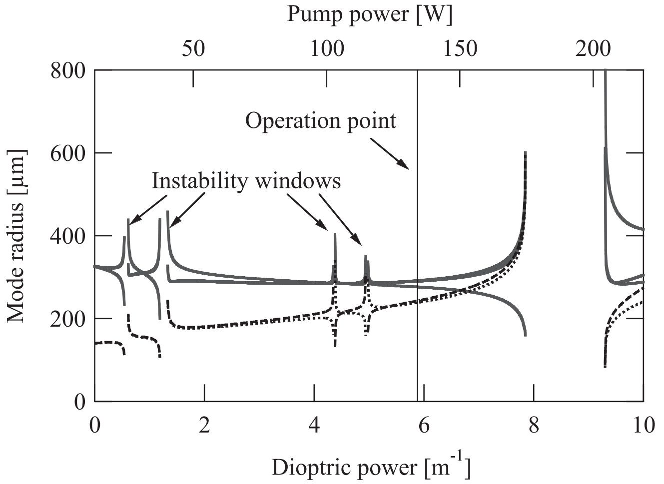

Fig. 4. Calculated mode radii in the DCP laser heads (*solid*), on the SESAM (*dashed*), and on the output coupler (*dotted*), as a function of the dioptric power of the thermal lens of the laser heads (and the pump power, respectively) for the cavity shown in Fig. 3. The axis scale on the bottom corresponds to the thermal lens of the head DCP #3. The lenses of the other heads are varied proportionally. The narrow windows of instability induced by the difference of the laser heads are indicated

operate in a regime where the mode size in the laser head depends only weakly on the focusing power of the thermal lens. Preferably, we like the cavity to operate in stability zone I [15] which has a significantly reduced alignment sensitivity. To obtain a sufficient number of parameters that allows us to meet all these requirements, one needs a somewhat more complicated cavity than used in [16] (Fig. 3).

A possible (but not serious) problem of periodic resonators, discussed already in [16], is that deviations from perfect symmetry create gaps in the stability region. Figure 4 shows four small instability regions which result from the difference in thermal lens power between the three laser heads. The cavity design could in principle be corrected for these differences, but the gaps in the stability range are so small that they are even hard to detect in the experiment. (Note that for example, a slight reduction of output power, caused by deviations from the ideal mode sizes, can modify the thermal lens so as to bring the cavity back to stability.)

Compared to the non-periodically extended cavity the stability is increased by operation in zone I [15]. The drawback is that there is no simple cavity parameter accessible which allows some experimental fine tuning of the mode sizes. Additionally, the initial single-head cavity can not as easily be optimized experimentally in terms of power. A change of repetition rate or of the mode sizes would require a complete reconstruction of the whole laser cavity. Note that in principle one could apply a non-periodic extension as in Sect. 3.2 for such corrections, but one would then lose the specific advantages of the periodic resonator, as discussed above.

4 Experimental systems, results

We experimentally compared laser cavities designed according to the two strategies discussed in Sect. 3, using three DCP laser heads as described in Sect. 2.1. One of those is the same head as used in [9] having plane AR-coated end faces. A slight angle between the laser mode axis and the symmetry axis of the rod is necessary to eliminate disturbing residual reflections. The other two DCP heads have slightly wedged end faces of the Nd:YAG rods, and yield slightly less power in a simple flat–flat configuration.

The periodically extended cavity that we used is shown in Fig. 3. The dashed lines indicate the planes confining the identical single-head cavities. In Fig. 4 the stability against variation of the thermal lens power of the laser heads is shown. The optimized mode radii of 290 µm in the laser heads are nearly constant over the whole range of available pump power. The mode radius on the SESAM is 230 µm. The cavity contains a Brewster plate to enforce linear polarization and a quarter-wave plate to reduce the stress-induced depolarization losses [17] from 1.2% to 0.5%.

At a total pump power of 136 W from the six diode lasers in the three laser heads and with an output coupler transmission of 26.5%, we obtain stable self-starting fundamental cw mode locking with an average output power of 24.2 W. The repetition rate is 50 MHz, the pulse energy 0.48 µJ, the pulse duration 25 ps (Fig. 5), and the peak power 17 kW. Although the laser is not operated far above the QML threshold, which is at 22.8 W output power, cw mode locking is very stable over days and the relaxation oscillations are suppressed to -73 dBc in a resolution bandwidth of 300 Hz. This is shown in the rf spectrum of the laser in Fig. 5, where the peaks resulting from the relaxation oscillations are only slightly above the noise floor. The M^2 of the output beam was measured to be less than 1.05. This was done with a CCD beam analyzer measuring the output beam radii (based on the second moment of the power distribution) over a distance of more than the confocal parameter (Fig. 6).

At full power, about 1.4 W is dissipated in the SESAM, approximately 95% of which originates from the nonsaturable losses of the device, because it is operated 19 times above saturation energy. The SESAM is soldered to a copper plate, actively kept at 14 °C. The maximum temperature

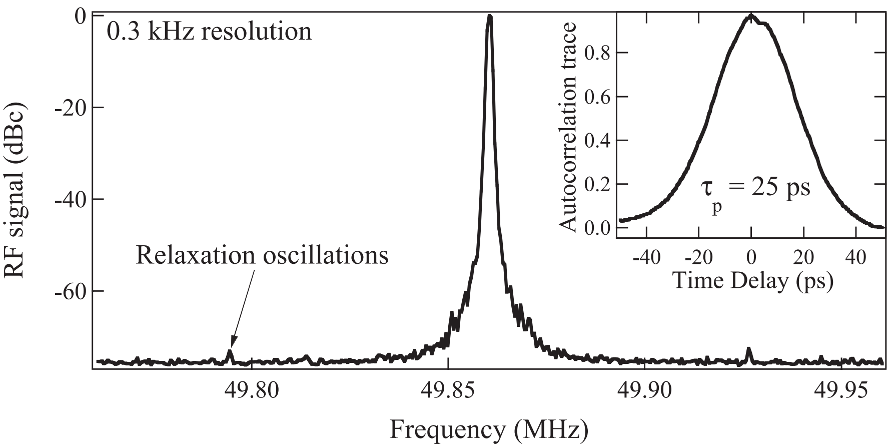

Fig. 5. rf spectrum of the mode-locked laser measured with a resolution of 300 Hz. The relaxation oscillations are suppressed to more than −73 dBc. The autocorrelation of the 25-ps pulses at 24.2 W output power is shown in the inset

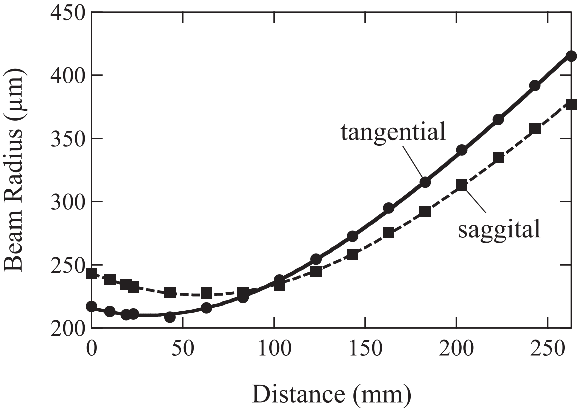

Fig. 6. Longitudinal cross section through focused output beam of the periodically extended cavity. *Bullets*: tangential beam radius; *squares*: saggital beam radius; *lines*: ideal Gaussian beam. The beam profile yields a M^2 of less than 1.05

rise in the SESAM compared to the heat sink temperature is estimated to be about 55 K. However, this heat load as well as the close proximity to the QML threshold does not affect the SESAM and the performance of the laser at all. This laser can be switched on and used without any realignment of the cavity being necessary over many days. We contribute this to the robustness of the cavity against misalignment and small changes in the cavity parameters due to the type-I design [15].

Figure 2 shows the non-periodically extended resonator, designed as discussed in Sect. 3.2, again containing the three laser heads. The dashed lines indicate the simple flat–flat single-head cavities. The length of these cavities has been experimentally optimized for output power at the beginning. As described in Sect. 3.3, plane F is imaged to the SESAM with the following relay optics: free space of length $L_2 (\approx 1\,\text{m})$, a mirror with radius of curvature of 1 m and another free-space section (length $L_1 \approx 1\,\text{m}$). The calculated mode radii are 270 μm in the laser heads, and 205 μm on the SESAM. Changes of the lengths L_1, L_2, and L_3 allow for slight changes of the mode sizes in the laser heads and thus for simple experimental optimization of the output power. Also in this cavity (Fig. 2) a Brewster plate enforces linear polarization, but we do not use any compensation for the stress-induced polarization rotation, as the induced losses at the Brewster plate are less than 1%. The insertion of a quarter-wave plate into this cavity induces mode distortions and only slightly increases the output power. The low stress-induced depolarization losses indicate a smooth temperature distribution in the laser heads.

At a full pump power of 139 W, this laser yields a passively mode-locked average output power of 27 W, which is the highest reported value to our knowledge. The repetition rate is 55 MHz and the pulse duration 19 ps (Fig. 7). The output pulse energy is 0.5 μJ and the peak power 23 kW. Therefore, this oscillator reaches a regime, which usually has been covered only with amplifiers. Stable, self-starting

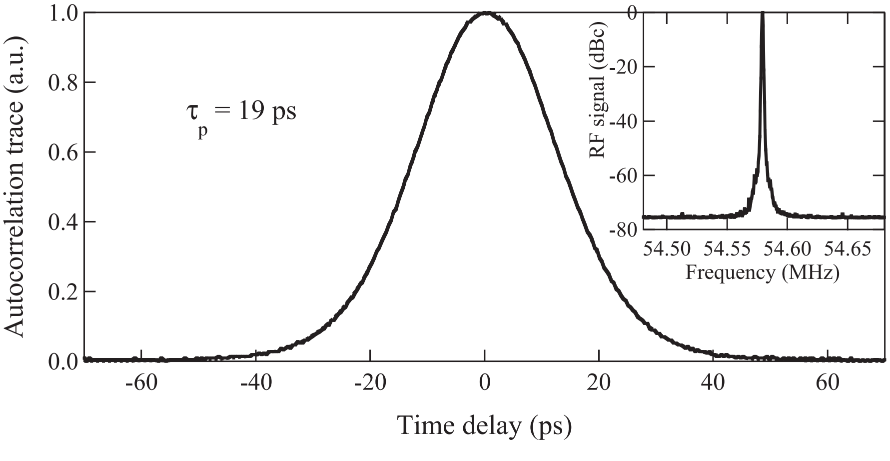

Fig. 7. Measured autocorrelation trace (*solid*) and autocorrelation of an ideal 19-ps sech^2 pulse (*dotted*) at 27 W average power. The rf spectrum of the mode-locked laser measured with a resolution of 300 Hz is shown in the inset

fundamental passive mode locking without any Q-switching instabilities is achieved using the same SESAM as in the periodically extended cavity. At full pump power, about 1.5 W is dissipated in the SESAM which is operated 23 times above saturation. The maximum temperature rise in the SESAM compared to the heat sink, which is kept at 19 °C, is ≈ 65 °C. The laser operates very reliably over many days. No degradation, ageing or damage of the SESAM is visible at any point. The output beam of the high-power oscillator is close to diffraction limited. We determined a M^2 of 1.05 in the tangential direction and 1.15 in the saggital direction, measuring the output beam radius with a knife-edge method over a distance corresponding to 8 times the confocal parameter (Fig. 8). Thus the beam quality is slightly reduced compared to the periodically extended cavity, which might be due to the reduced beam radii in the laser heads.

In order to prove the suitability of the laser for nonlinear frequency conversion, we have performed second-harmonic generation. A single pass through a 10-mm-long AR-coated LBO crystal, cut for type-I non-critical phase-matching at 150 °C, results in an average power of 16.2 W of second-harmonic radiation (532 nm). This corresponds to a conversion efficiency of 60%, close to the theoretical expectations. For this, the output of the oscillator is focused to a radius of ≈ 20 μm in the LBO crystal.

We contribute the fact that we extracted more power out of the non-periodically extended cavity to its facility to experimentally access important cavity parameters. This allows for power optimization by change of the effective mode size in the laser heads under lasing conditions by small changes of some cavity parameters. But once the optimum mode sizes are determined experimentally, a periodically extended cavity can be designed, which should be able to achieve the same performance. Additionally, such a cavity is much more robust. In fact, for commercial applications we would suggest the use of periodically extended cavities. Besides their increased stability, the different laser heads do not need to be characterized as accurately as for the non-periodically extended cavity, as the stability range against variations of the thermal lens is much wider. This allows the use of the same cavity despite the different thermal lenses of the different laser heads.

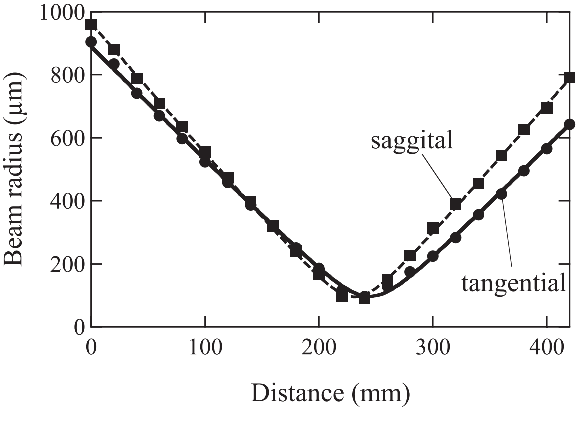

Fig. 8. Focused output beam of the 27-W 19-ps oscillator. *Bullets*: tangential beam radius; *squares*: saggital beam radius; *lines*: fitted Gaussian beams corresponding to a M^2 of 1.05 and 1.15

5 Scalability

It is an important observation that the approach of using multiple laser heads in a passively mode-locked laser leads to power scalability. This means that by applying the scaling procedure as described below, one can construct a laser with increased power without making the following problems more severe: thermal lensing (limited range of pump powers for stable operation), heating (or non-thermal damage) of the SESAM, and the Q-switching tendency.

We now discuss the scaling procedure for doubling of the output power. Obviously we have to double the number of laser heads in the cavity and maintain the mode size in the laser heads. Also we double the output coupler transmission so as to maintain the original intracavity laser power. Moreover we double the cavity length, the mode area on the SESAM, and the modulation depth of the SESAM, while keeping the saturation fluence of the SESAM unchanged. As a result, we obtain a doubled intracavity pulse energy without changing the saturation parameter of the SESAM. Equation (1) shows that also the QML tendency is then not affected as both sides get multiplied by 4. The increased effect of gain narrowing is compensated by the higher modulation depth, so that the pulse duration should stay the same. The mode locking start-up behavior is not affected because the higher modulation depth compensates for the larger mode area. The stability range in terms of pump power is doubled if a periodic resonator is used, as discussed in Sect. 3.3. Moreover, the power dissipated on the SESAM is doubled (assuming that doubling the modulation depth also doubles the nonsaturable losses), whereas the temperature rise on the SESAM is not increased because of the increased area. (We assume that the SESAM substrate thickness is smaller than the mode diameter, so that the heat flow is nearly one-dimensional.) Finally, non-thermal SESAM damage is also not more likely as the saturation parameter stays unchanged and the Q-switching tendency stays under control.

We see that indeed the main challenges are not made more severe when the laser power is scaled up in the discussed way. A remaining problem might be the beam quality (due to the aberrative parts of the thermal lenses), but this problem was still well under control in our experiments. Also the number of small instability regions, caused by asymmetries, for example in the thermal lenses, might be a problem for a very large number of laser heads in the cavity. Apart from this we note that a much increased modulation depth of the SESAM, to be achieved with increased thickness of the absorber layer, may require designs with additional strain-compensating layers, or possibly the use of several SESAMs in one laser.

Comparing the results presented in Sect. 4 with the single-head cavity in [9], we see that essentially the discussed scaling law was applied. We use three laser heads instead of one (with the additional heads being slightly less powerful), and a SESAM with three times higher modulation depth. The pulses are only slightly longer, and the output power is increased by a factor of 2.5. The cavity length was actually less than tripled, leading to a higher QML threshold.

We also consider a modified scaling procedure where we double the laser power by doubling the number of laser heads and the output coupler transmission, while we keep the cavity length unchanged (assuming that there is enough space for all heads), as well as keeping constant the mode area on the SESAM, the modulation depth, and the saturation fluence of the SESAM. In this way we do not alter the QML tendency, the risk of SESAM damage, or the mode locking start-up behavior. The laser efficiency is even slightly increased (because of a more favorable ratio of output coupling and other losses), although we expect to obtain longer pulses, because the increased effect of gain narrowing is no longer compensated in any way.

In other words, for a given power we can reduce the pulse duration by increasing the modulation depth of the SESAM; then we need a longer cavity in order to avoid QML, and a larger mode area on the SESAM to keep the saturation parameter unchanged. These changes do not modify the start-up behavior or the temperature rise on the SESAM, but somewhat decrease the laser efficiency.

We note that external single-pass amplification, i.e., the use of some of the laser heads as extra-cavity amplifiers, is a simple alternative to increasing the number of laser heads in the laser cavity, as soon as the laser power in the amplifier heads is at least several times the saturation power. Then, the laser power is high enough to sufficiently saturate the gain of the amplifier and thus maintain the power efficiency. Although beam quality degradation and beam profile changes have to be taken into account for both approaches.

The saturation power is approximately 6 W for a DCP head, so that more than three of such heads in one laser cavity would not seem to make sense. Similar DCP heads based on Nd:YVO_4 (instead of Nd:YAG) would have nearly half the saturation energy, so that only two heads in the cavity would be sensible. On the other hand, laser heads with broader amplification bandwidth for shorter pulses, based for example on Yb:YAG, typically have a higher saturation power, so that here it would be more important to generate a high average power directly from the oscillator, or alternatively use a multipass amplification scheme, which however usually increases the complexity and cost of the system.

6 Conclusion

We have discussed in detail how the output power of passively mode-locked lasers can be increased by using multiple laser heads in the resonator. We found that this leads to a power-scalable concept in the sense that the laser power can be increased without making the fundamental challenges of high-power operation as well as of passive mode locking more severe. Indeed we were able to demonstrate a side-pumped passively mode-locked Nd:YAG laser with a record-high average output power of 27 W, a pulse duration of 19 ps and a peak power of 23 kW, and a similar device with improved cavity stability and larger range of allowed pump powers, based on a different cavity design strategy. Key elements are in both cases three side-pumped laser heads which allow for a relatively small laser mode size in the gain medium, the use of a SESAM as a mode locker with optimized parameters, and a cavity design with suitable mode sizes and repetition rate.

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