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Diode-pumped passively mode-locked lasers with high average power

R. Paschotta[1], **J. Aus der Au**[1], **G.J. Spühler**[1], **F. Morier-Genoud**[1], **R. Hövel**[2], **M. Moser**[2], **S. Erhard**[3], **M. Karszewski**[3], **A. Giesen**[3], **U. Keller**[1]

[1] Ultrafast Laser Physics, Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg – HPT, 8093 Zürich, Switzerland
(Fax: +44-1/633-1059, E-mail: paschotta@iqe.phys.ethz)
[2] Centre Suisse d'Electronique et de Microtechnique-Zürich, Badenerstrasse 569, 8048 Zürich, Switzerland
[3] Institut für Strahlwerkzeuge, Universität Stuttgart, Pfaffenwaldring 43, 70569 Stuttgart, Germany

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Abstract. We discuss challenges arising from the quest for high average powers from passively mode-locked diode-pumped lasers. The recently obtained detailed understanding of Q-switching instabilities in passively mode-locked lasers turns out to be a crucial element on the way towards higher powers. We give an overview on results achieved with Nd:YAG (10.7 W, 16 ps and 27 W, 19 ps), Yb:YAG (8.1 W, 2.2 ps and 16 W, 0.7 ps) and Nd:glass (1.4 W, 275 fs).

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Picosecond and femtosecond mode-locked lasers with high average output powers are required for many applications, in particular for those involving nonlinear wavelength conversion. With sufficiently high (multi-kW) peak powers we can achieve very efficient ($> 50\%$) wavelength conversion by single-pass interactions in nonlinear crystals. This results in mode-locked pulse trains with high average power in the visible, ultraviolet or infrared wavelength regime. Such sources can be expected to find very widespread applications.

In principle, high average powers can be obtained by combining a low-power laser oscillator with one or more amplification stages. However, particularly in the fs domain, high-gain amplifiers usually rely on complicated multi-pass arrangements. Thus it is clearly preferable to achieve high-power performance directly with a laser oscillator, not using amplification stages.

The most promising approach towards these goals is to develop passively mode-locked diode-pumped high-power solid-state lasers. Diode pumping is essential for efficient, compact and reliable devices. Passive (rather than active) mode locking using SESAMs (semiconductor saturable absorber mirrors [1–3]) leads to a simpler setup and also allows for shorter pulse durations and higher peak powers. However, until recently the average powers obtainable from passively mode-locked lasers were much lower than those from some continuous-wave lasers. Particularly in the pulse duration regime below 1 ps, average powers from diode-pumped lasers were typically well below 1 W. Sub-ps pulses with multi-watt average power have been obtained only from Ti:sapphire lasers, which however rely on a bulky, inefficient argon-ion pump laser or on an expensive frequency-doubled diode-pumped pump laser. In this paper we discuss the main challenges of high-power diode-pumped passively mode-locked lasers. We show that different solutions are required depending on the desired pulse duration (which limits the choice of gain media), and give an overview on recent achievements in three different pulse duration regimes.

1 Challenges

Here we discuss the main issues encountered in the development of high-power diode-pumped passively mode-locked lasers. It will become apparent that the issues discussed in the following subsections are interconnected in various ways, so that the overall optimization of a pulsed laser system is a nontrivial issue. In Sect. 2 we will show solutions in different pulse duration regimes.

1.1 Choice of gain medium

For continuous-wave high-power lasers, the gain medium should already meet quite a number of requirements. It should have a laser transition at the required emission wavelength, combined with a pump transition at a suitable wavelength (where powerful pump diodes are available). A small quantum defect as well as the absence of parasitic losses (resulting for example from strong quenching or upconversion processes) are important factors for good efficiency. A large product of emission cross-section and fluorescence lifetime is desirable as it allows us to achieve a low laser threshold. Other requirements are a high thermal conductivity (which generally favors crystals over glasses), a weak temperature dependence of the refractive index (to reduce thermal lensing), and a weak tendency for thermally induced stress fracture.

Mode locking, particularly in the sub-ps domain, introduces additional constraints. The more obvious one is that the amplification bandwidth must be sufficient to maintain the wanted pulse duration. This definitely excludes otherwise very favorable laser media (such as Nd:YAG) for the generation of sub-ps pulses. Diode-pumpable gain media with much larger amplification bandwidth are available: Yb:YAG is suitable for pulse durations around 1 ps or even down to 0.34 ps [4], and Nd:glass lasers [5] as well as Yb:glass lasers [6] have generated pulses as short as 60 fs. However, these gain media are typically less favorable in other respects. The quasi-three-level nature of Yb:YAG leads to high laser thresholds, whereas Nd:glass suffers from a relatively poor thermal conductivity. Both increases the tendency for thermal distortions in the gain medium (see Sect. 1.2). However, in Sects. 2.2–2.4 we show that special approaches still allow us to achieve relatively high average output powers with these gain media. Another challenge is that broadband gain media typically have low emission cross-sections which leads to a strong tendency for Q-switching instabilities (see Sect. 1.3) in passively mode-locked lasers [7]. (A notable exception is Ti:sapphire, for which however a high-power green diode laser as pump source is not yet available.) This shows that the search for new laser materials with the combination of a broad amplification bandwidth, large emission cross-sections and good thermal properties is very important. The search for such materials is under way, but in this paper we concentrate on some well-established gain media and discuss options to cope with their limitations.

1.2 Thermal effects in the gain medium

The power dissipated in the gain medium of a laser leads to an inhomogeneous temperature distribution. The main consequences of this are thermal lensing (possibly with strong aberrations), losses induced by stress-induced birefringence, and a tendency for stress fracture. Thermal lensing is a particular problem when a near-diffraction-limited output beam is required. This is generally the case for mode-locked lasers because the mode-locking process would be disturbed by the presence of higher-order transverse modes with resonance frequencies deviating from those of the fundamental longitudinal modes.

As long as pulses with > 5 ps duration are wanted, one can resort to gain media such as Nd:YAG or Nd:YVO$_4$ which have rather favorable thermal properties. Traditional rod geometries, used with either end pumping or side pumping, can then be used to generate fairly high output powers (see Sect. 2.1). Currently available diode-pumpable gain media with larger amplification bandwidth, however, require special solutions for high-power operation. Here we describe an approach which has been applied first to Cr:LiSAF [8] and has recently been proven to be successful with Yb:YAG [9] and Nd:glass [10] (see Sects. 2.2, 2.4). The spatial profile of the output of typical high-power diode lasers (with tens of watts) is very asymmetric in terms of beam size and mode quality: while M^2 is < 10 in one direction, it can be $\gg 1000$ in the other direction. Thus the generation of a focused circular spot without a significant loss of brightness requires the use of some beam shaper [11] which symmetrizes the beam quality in both directions. Our approach, however, involves focusing the beam with cylindrical lenses so that the confocal parameters for both directions are in the order of the absorption length of the crystal. The resulting strongly elliptical beam can be used to pump a gain medium with only ≈ 1 mm thickness or less. Such a thin gain medium can be cooled efficiently from the top and bottom sides (Fig. 1). This limits the maximum temperature rise. This is beneficial particularly for gain media such as Yb:YAG or Cr:LiSAF which are less efficient at elevated temperatures. Moreover, if the width of the pump beam is larger than the crystal thickness, the resulting heat flow is nearly one-dimensional, and the temperature profile roughly resembles the intensity profile of the pump beam. If the latter is relatively flat in the long direction, the focusing power of the thermal lens in this direction (which is the more critical one) is significantly reduced. Unlike cylindrical rod geometries, this geometry is in principle power scalable: doubling the power as well as the width of the pump beam leads to a four times weaker thermal lens, whereas the two times wider laser mode is four times more sensitive to thermal lensing. (The width of a cavity stability zone in terms of focal power of the thermal lens is proportional to $1/w^2$, if w is the beam radius in the laser medium [12].) Thus the width of the stability range of the cavity in terms of pump power can be increased together with the pump and output power.

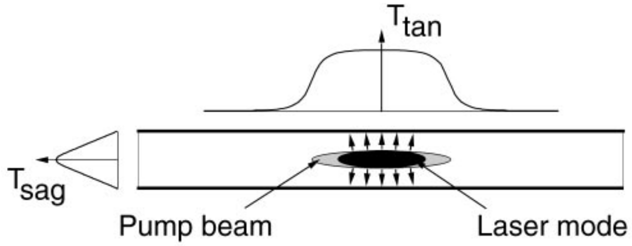

Fig. 1. Elliptical geometry for high-power lasers with thermally challenging materials. T_{tan} and T_{sag} denote the temperature variation in tangential (horizontal) and sagittal (vertical) direction

A totally different approach which looks very promising at least for a limited range of laser materials is the thin-disk concept [13, 14]. Here a circular rod geometry is used, however with a very small dimension (< 1 mm) in the axial direction and cooling through one end face (rather than transverse cooling). In this geometry, the temperature rise at a given distance from the symmetry axis is largely determined by the local pump intensity and the distance from the cooled end-surface. The pump intensity distribution can be controlled so that thermal lensing is reduced well below the level that is typical for conventional rod lasers. The pump absorption in a single pass through the thin disk is weak, but efficient pump absorption is achieved by 8 or more passes of the pump radiation through the disk [13]. The probably most crucial advantage of this laser head design is its power scalability: doubling the mode area in the gain medium allows for doubling of the pump and output power without making thermal problems more severe. Applied to Yb:YAG, this concept has lead to lasers with near-diffraction-limited performance at up to ≈ 100 W cw output power [15], and even higher powers seem to be feasible. We have recently demonstrated passive mode-locking of such a laser with 16 W of average power in 0.7-ps pulses [16–18] (see Sect. 2.3). In the near future, even significantly higher mode-locked powers should be achievable. Unfortunately, the thin-disk approach seems to be applicable only to gain media with good thermal conductivity, a small quantum defect, a relatively large product of upper-state lifetime and emission cross-section, and a potential for high doping density, as otherwise the temperature rise and temperature gradient are too strong. Although Nd:YAG has been used [19, 20] (though somewhat less successfully than Yb:YAG), the application to broadband gain media such as Nd:glass or Ti:sapphire seems not to be feasible. Here we currently see the elliptical mode geometry (as discussed above) as the best way to high powers.

1.3 Q-switching instabilities

In a passively mode-locked laser, the saturable absorber needed for mode locking also introduces a tendency for Q-switching instabilities. This can drive the laser into the Q-switched mode-locked regime with mode-locked pulses under a Q-switched envelope [21, 22]. Recently, we have investigated in detail the transition between the regimes of stable cw mode locking and Q-switched mode locking (QML) [23]. Here we discuss the impact of this issue on the development of passively mode-locked high-power lasers, which turn out to be more affected by this problem than most low-power lasers. For ps lasers, not operating in the soliton mode-locked regime, we found the condition [23]

$$E_p^2 > E_{L,sat} E_{A,sat} \Delta R, \tag{1}$$

for stable cw mode locking. Here E_p is the intracavity pulse energy, $E_{L,sat} = h\nu_L A_L / N\sigma_L$ is the effective saturation energy of the laser medium and A_L is the mode area in the laser medium. N is the number of passes through the gain medium per cavity round-trip. We assumed a slow absorber with modulation depth ΔR which is fully saturated by the intracavity pulse ($E_p > 3E_{A,sat}$). Here we rewrite this criterion by introducing the saturation parameter

$$S = E_p / E_{A,sat} \tag{2}$$

and obtain

$$E_p > E_{L,sat} \frac{\Delta R}{S} . \tag{3}$$

The pulse energy E_p enters this equation both directly and indirectly (via S), but this form of the equation is useful for the following discussion. The problem with many high-power lasers is that the ratio $E_p/E_{L,sat}$ is relatively small, mainly because the poor beam quality of the diode pump laser and/or the use of schemes such as side pumping tend to increase the laser mode area A_L more than the pulse energy. To some extent, QML can still be suppressed by using a small value of ΔR, just enough for mode locking, although this typically leads to longer pulses. Another option is to saturate the SESAM more strongly, i.e., to increase S. This can also affect the pulse duration, and eventually lead to SESAM damage (normally for $S > 100$). Typically we use $S \approx 3-5$ in low-power lasers, whereas the suppression of Q-switching instabilities has made it necessary to use values of up to $S \approx 27$ in high-power lasers [24]. Finally, for given values of ΔR and S we can increase the intracavity pulse energy E_p by using an output coupler with smaller transmission. This, however, will eventually compromise the laser efficiency and increase the dissipated power on the SESAM. An often better way of increasing E_p is to use a longer laser cavity with smaller repetition rate.

A somewhat unexpected result of our discussion is that the choice of laser material as well as the construction of the laser head has an indirect (but strong) effect on the problem of SESAM damage. This is because for a laser head with large saturation energy (i.e., with small cross-sections and/or large mode area) the need to avoid Q-switching instabilities can enforce the operation with high intracavity power (weak output coupling) and strong saturation of the SESAM. Partly for this reason it was essential for the results presented in Sects. 2.2–2.4 that we used optimized pumping geometries and laser cavity designs. Particularly in the domain of high powers, not every laser head is equally suitable for passive mode locking.

Another important finding is that operation in the soliton mode-locked regime (with negative overall cavity dispersion) substantially increases the stability against QML [23]. Basically this is because any increase in pulse energy of a soliton increases the bandwidth and thus reduces the effective gain because of the limited gain bandwidth. As most of the other measures against QML (as discussed above) have unwanted side effects, the additional option of reducing the QML tendency by operation in the soliton mode-locked regime (i.e., by adding appropriate level of negative dispersion to the cavity) is very welcome. While we only have to tolerate a slight increase of the intracavity losses (which can be rather small), we can typically further reduce the pulse duration. This technique was essential for stable mode locking of the Yb:YAG and Nd:glass lasers which we describe in Sects. 2.2–2.4.

1.4 Damage of the saturable absorber

In passively mode-locked high-power lasers, an important issue is to avoid damage of the saturable absorber. One possible cause for damage is that the absorber may become too hot. We note, however, that absorber damage can also be caused by non-thermal effects, particularly in the presence of Q-switching instabilities (see Sect. 1.3) which can lead to the generation of very intense pulses. We can expect non-thermal effects to be under control if we do not operate the absorber with an excessively high saturation parameter S and also manage to suppress Q-switching spikes. In Sect. 1 we have shown how this can achieved. Thermal effects will remain, and in this section we briefly discuss how to limit them. We do this discussion for semiconductor saturable absorber mirrors (SESAMs) [1–3], which have so far been used most successfully for mode locking of solid-state lasers, although some results would apply to other absorbers as well.

Each SESAM has both some saturable loss, which is needed for passive mode locking, as well as some unwanted nonsaturable loss. The latter tends to be increased by low-temperature semiconductor growth, which is often used to reduce the recovery time of the absorber. It has been shown, however, that the application of a suitable annealing procedure [25] or doping the semiconductor with beryllium [26] can help to obtain a fast time response and low nonsaturable losses at the same time.

Here we discuss thermal effects on a phenomenological level. If a pulse with energy E_p hits a SESAM, the dissipated part of the energy is

$$E_{dis} \approx E_{A,sat} \Delta R + (1 - R_{ns}) E_p , \tag{4}$$

provided that the SESAM is fully saturated: $E_p > 3E_{A,sat}$ where $E_{A,sat}$ is the saturation energy, ΔR is the modulation depth, and R_{ns} is the reflectivity in the fully saturated regime. Thus the heat dissipation is usually dominated by the nonsaturable loss if the SESAM is operated in the regime of strong saturation, which is often needed to reduce Q-switching instabilities (see Sect. 1.3). Particularly for high-power operation it is therefore desirable to have SESAMs with a small ratio of nonsaturable to saturable loss.

Of course, the maximum temperature on the SESAM also depends on the size of the laser beam on the absorber. As long as the Gaussian spot radius w_{A} is smaller than the thickness d of the absorber, the maximum temperature rise (in the center of the laser beam) is

$$\Delta T_{\max} \approx \frac{P_{\mathrm{dis}}}{(\sqrt{2\pi})Kw_{\mathrm{A}}} , \tag{5}$$

where P_{dis} is the dissipated average power and K is the thermal conductivity, for example $\approx 45\,\mathrm{W/(K\,m)}$ for GaAs. We have assumed that the whole back side of the absorber is kept at room temperature. Scaling up the output power of the laser usually involves a proportional increase of mode area πw_{A}^2 so that effectively $\Delta T_{\max}$ rises proportional to $\sqrt{P_{\mathrm{dis}}}$. At some stage, however, w_{A} becomes larger than d, and the nearly one-dimensional heat flow leads to

$$\Delta T_{\max} \approx \frac{dP_{\mathrm{dis}}}{K\pi w_{\mathrm{A}}^2} , \tag{6}$$

where $\Delta T_{\max}$ will no longer rise if the mode area is scaled up proportional to the laser power. The most advanced high-power mode-locked lasers just begin to get into this regime.

How large the mode radius w_{A} on the SESAM has to be depends not only on the intracavity pulse energy E_{p} but also on the saturation energy $E_{\mathrm{A,sat}}$ – in fact the mode-locking performance depends only on $E_{\mathrm{p}}/E_{\mathrm{A,sat}}$. Therefore it is advisable to use SESAM designs with a small saturation fluence – despite their typically lower damage fluence – and use an accordingly larger mode radius w_{A} in order to limit the temperature rise $\Delta T_{\max}$.

We see from this discussion that the problem of SESAM heating (or SESAM damage, to be more general) will – in contrast to a still widespread belief – not necessarily become more severe as the output power is scaled up, provided that suitable laser heads (with small gain saturation energy) and SESAMs with low saturation fluence (for a large mode area on the absorber) are employed. Therefore we expect SESAMs to remain very suitable for passive mode locking even of lasers with much higher average powers than demonstrated so far.

2 Solutions in three different pulse duration regimes

In this section we briefly review our latest achievements in high-power mode-locked lasers, discuss them in the context of the issues investigated in Sect. 1, and try to evaluate their potential for further improvements.

2.1 10-W *and* 27-W Nd*:* YAG ps *lasers*

Nd:YAG is a popular solid-state gain medium which has good thermal properties and is well suited for pumping with high-power diode bars at 808 nm. We decided on a side-pumping approach because of its simplicity and the lower demands on the pump beam quality. Potential disadvantages of side-pumping are that the good efficiency and beam quality of end-pumped lasers are usually not achieved. Also, it often leads to a larger beam in the gain medium and thus increases the tendency towards QML (see Sect. 1.3 and (3)). We have solved both problems by using a direct coupled pump (DCP$^{\mathrm{TM}}$, Lightwave Electronics) laser head [27], where the output of two diode bars is directly side-coupled into the cylindrical laser rod through slits in the crystal mount. The rod is laterally surrounded by a water-cooled metal block. A reflective coating allows for multiple passes of the pump radiation and thus for efficient pump absorption and a smooth profile of the inversion. In this way the DCP$^{\mathrm{TM}}$ concept leads to an excellent beam quality and good power efficiency while using a relatively small crystal diameter (and laser mode size). This reduces the tendency towards QML and thus makes the laser head particularly suitable for passive mode locking.

The laser cavity (Fig. 2) [24] contained two curved mirrors defining the mode radii in the DCP$^{\mathrm{TM}}$ head (300 μm) and on the SESAM (100 μm). The output coupler had 7% transmission. The maximum average output power in the mode-locked regime (for 41.7 W pump power) was 10.7 W (only slightly less than in the cw regime), and the output beam was diffraction-limited ($M^2 < 1.1$). The overall optical-to-optical efficiency of more than 25% (and the electrical-to-optical efficiency of 8.2%) is high for a side-pumped system. QML occurred only below ≈ 3 W average output power. The SESAM was operated with a relatively high saturation parameter $S \approx 27$; at this level, some (although not all) SESAMs showed signs of degradation within hours. The pulse duration was 16 ps and the repetition rate 88 MHz, resulting in a pulse energy of 120 nJ and a peak power of 7.2 kW. Such high peak powers and pulse energies are usually only obtained with amplifier systems and are for example high enough for efficient frequency doubling in a single pass through a nonlinear crystal.

A good alternative for the laser medium Nd:YAG might be Nd:YVO$_4$. Whereas the thermal properties of this medium are similar to Nd:YAG, the larger amplification bandwidth supports shorter pulses, and the ≈ 9 times higher emission cross-section would allow us to saturate the SESAM less strongly. This would not only relax the operation conditions of the SESAM, but also help to further decrease the pulse duration.

With the DCP$^{\mathrm{TM}}$ concept, applied either to Nd:YAG or Nd:YVO$_4$, it is feasible to further increase the mode-locked average power. Apart from developing DCP$^{\mathrm{TM}}$ (or similar) laser heads with somewhat more pump power, several of such laser heads can be combined in one laser cavity. We recently investigated this method of power scaling, using three DCP$^{\mathrm{TM}}$

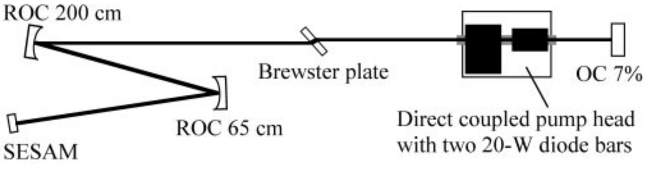

Fig. 2. Cavity setup of the 10-W ps Nd:YAG laser (ROC: radius of curvature; SESAM: semiconductor saturable absorber mirror; OC: output coupler)

heads, and obtained 27 W average power, 0.5 μJ pulse energy, and 23 kW peak power in 19-ps pulses [28]. The output coupler transmission was increased so that the intracavity average power was comparable to the laser with a single laser head. An increased modulation depth of the absorber is needed to maintain the short pulse duration and self-starting behavior, while a decrease of repetition rate helps to suppress Q-switching instabilities. SESAM damage was not observed. Additional laser heads could be used for external single-pass amplification because the obtained average output power is already high enough to saturate the gain.

2.2 8-W Yb*:* YAG ps *laser*

Yb:YAG is a very promising gain medium for short-pulse generation in the high-power regime. Its bandwidth allows for sub-ps pulses [7], and the small quantum defect makes it potentially very efficient. High-power diode bars at 940 nm are available as pump sources. Problems arise from the quasi-three-level nature, which leads to a high laser threshold (which significantly rises with crystal temperature). Moreover, the small cross-sections cause a strong tendency for QML. For these reasons, the concept used for the 10-W Nd:YAG laser (see Sect. 2.1) would not work with Yb:YAG. An end-pumped approach is necessary to keep the laser threshold at a reasonable level, and efficient cooling is essential. Note that despite the small quantum defect, thermal effects are strong in such a laser due to the high laser threshold.

We used the geometry with a strongly elliptical mode in the gain medium (Fig. 1), as discussed in Sect. 1.2. The laser cavity [9] is shown in Fig. 3. The mode area in the laser medium was similar to that in the 10-W Nd:YAG laser (Sect. 2.1), but the mode radii in horizontal and vertical direction were very different, ≈ 900 μm and ≈ 90 μm, respectively. A 1-mm-thin and ≈ 4 mm-long flat/Brewster-cut crystal was used, pumped with two polarization-coupled 40-W diode bars at 940 nm. A standing-wave laser cavity (with the gain medium not being located very close to one end of the cavity) has two stability zones, called zone I and zone II [12], where zone I is substantially less sensitive to misalignment. It turned out to be essential for our laser to be operated in zone I (by using a suitable cavity design), as this turned out to be less sensitive not only to misalignment but also to thermal lensing. (Note that adjustment of the pump beam can cause asymmetries of the thermal lens which have a similar effect to tilts of cavity mirrors.) The repetition rate of our laser was 63 MHz.

Compared to Nd:YAG, the cross-sections of Yb:YAG at the laser wavelength are roughly 11 times smaller. As the laser mode area was similar as for the Nd:YAG laser, this caused a strong tendency for QML. We could obtain stable mode-locked operation only by operation in the soliton mode-locked regime, generating negative dispersion with a Gires–Tournois interferometer (GTI). (A prism pair with a reasonable prism spacing could not provide sufficient negative dispersion for operation in the ps regime.) Apart from this, we had to reduce the output coupler transmission which significantly compromised the laser efficiency in the mode-locked regime compared to the cw regime where a stronger output coupler could be used. At full power (53 W incident on the crystal) we obtained 8.1 W of average output power and 52 kW peak power (in two beams). The pulse duration was 2.2 ps, limited by the bandwidth of the GTI. We think that around 1 ps should be possible with a better GTI, because a similar laser with one 40-W pump diode and a prism pair instead of the GTI generated a single beam with 1.0-ps pulses, 3.5 W average power and 74 kW peak power.

2.3 16-W *thin-disk* Yb*:* YAG *laser*

As we explained in the introduction, the thin-disk concept for the construction of a laser head has the very significant advantage of power scalability: starting with an initial design, we can double the output power by doubling the pump power and the mode area in the gain medium. This scaling procedure does not make thermal problems more severe: the stability range of a laser cavity with the doubled mode size is reduced by a factor of 4, but the focusing power of the thermal lens is reduced by the same factor.

Recently we have demonstrated passive mode locking of a thin-disk Yb:YAG laser [16–18]. We used a laser head that had generated ≈ 20 W of output power in a diffraction-limited beam, when operated in a simple cavity for continuous operation. This laser was passively mode-locked using a SESAM which was actively cooled from the back side. As the SESAM had a low-finesse design with a relatively low saturation fluence of ≈ 100 μJ, it could be operated with a relatively large spot radius of ≈ 600 μm, and thermal or non-thermal damage was not observed. The laser cavity also contained a GTI for operation in the soliton mode-locked regime. A remarkable detail is that due to the small thickness of the laser disk, spatial hole burning (SHB) led to a broadening of the effective gain bandwidth. For this reason, near-transform-limited soliton pulses as short as ≈ 0.7 ps were obtained despite the relatively small modulation depth of the SESAM (≈ 0.5%). The average output power was 15.8 W.

We emphasize that not only the thin-disk laser head concept, but the whole concept of the passively mode-locked thin-disk laser is power-scalable. For the laser head itself, we have explained this above. Moreover, as the mode diameter on the SESAM is significantly larger than the thickness of the substrate (450 μm), further power scaling (by increasing the mode area also on the SESAM) will not significantly increase the temperature rise on the SESAM. Finally, the tendency for Q-switched mode locking or for thermal or non-thermal SESAM damage will not be increased. (This relies on the fact that the ratio of intracavity average power and mode area on the thin-disk laser head is kept constant.) Therefore, we expect that our concept will allow passive mode locking of thin-disk lasers with even significantly higher powers, as long as near-diffraction-limited performance is possible (as demonstrated already for ≈ 100 W average power [15]). This demonstrates very clearly that SESAMs are suitable for lasers with very high powers, provided that suitable laser head and SESAM designs are used.

2.4 1.4-W Nd*:glass* fs *laser*

For pulse durations far below 1 ps, even Yb:YAG does not provide sufficient amplification bandwidth. Nd:glass allows for pulse durations as short as 60 fs [5], but suffers from

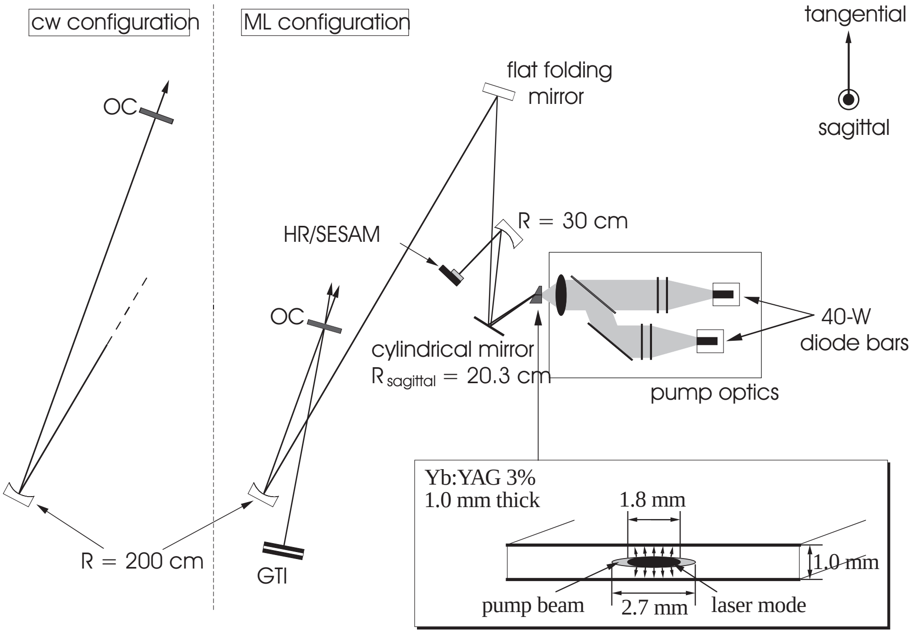

Fig. 3. Cavity setup of the 8-W ps Yb:YAG laser (SESAM: semiconductor saturable absorber mirror; OC: output coupler)

poor thermal properties (thermal lensing and stress fracture) which makes it difficult to obtain high powers. The elliptical mode concept (as discussed in Sect. 1.2) helps to cope with these problems. We used a cavity which was similar (in type and dimensions) to the one in Fig. 3. To prevent stress fracture, the output of a single 20-W diode bar was split in two beams and applied from opposite sides to the Nd:glass gain medium. As the emission cross-section of Nd:glass is around 1.7 times higher and the laser mode area was slightly smaller than in the Yb:YAG laser of Sect. 2.2, the QML tendency of the Nd:glass laser was somewhat weaker. We operated the laser in the soliton mode-locked regime, using a prism pair for dispersion compensation; this helped to avoid QML and was necessary anyway to obtain fs pulse durations. We obtained nearly bandwidth-limited soliton pulses of 275 fs duration with 1.4 W average power and 97 kW peak power. A similar result with 175 fs pulse duration and 1 W in two output beams has previously been published [10].

Although the peak power of these Nd:glass lasers is quite respectable, this concept can not compete in terms of average output power, if compared with the thin-disk approach as applied to Yb:YAG (see Sect. 2.3). Still we have demonstrated that power levels comparable to those from Ti:sapphire lasers are possible. For even higher average powers (> 10 W) with pulse durations far below 1 ps, one will probably rely on the development of new laser materials with a broad amplification bandwidth, large laser cross-sections and good thermal properties.

3 Conclusions

We have reviewed recent developments towards passively mode-locked lasers with high average powers and discussed the main challenges to be met on this route. In particular, the tendency for Q-switching instabilities requires careful optimization of such lasers. An important finding is that semiconductor saturable absorber mirrors (SESAMs) are suitable for operation at very high average power levels, provided that certain design guidelines, which involve properties not only of the absorber but also of the laser head, are observed. Although tens of watts of average power with pulse durations of about 10–20 ps can be obtained by passive mode locking of high-power Nd:YAG or Nd:YVO_4 lasers with quite conventional designs, different approaches are needed for shorter pulses. For pulse durations far below 1 ps we have demonstrated a Nd:glass laser with 1.4 W average power. Pulses with ≈ 0.7 ps duration and μJ pulse energies can now be obtained with very high average powers from passively mode-locked thin-disk lasers, and the scalability of this concept promises for the near future to allow for even higher average powers than previously possible in the domain of much longer pulse durations. The use of such lasers as pump sources for parametric oscillators should also lead to tunable high-power sources in the pulse duration regime far below 1 ps.

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