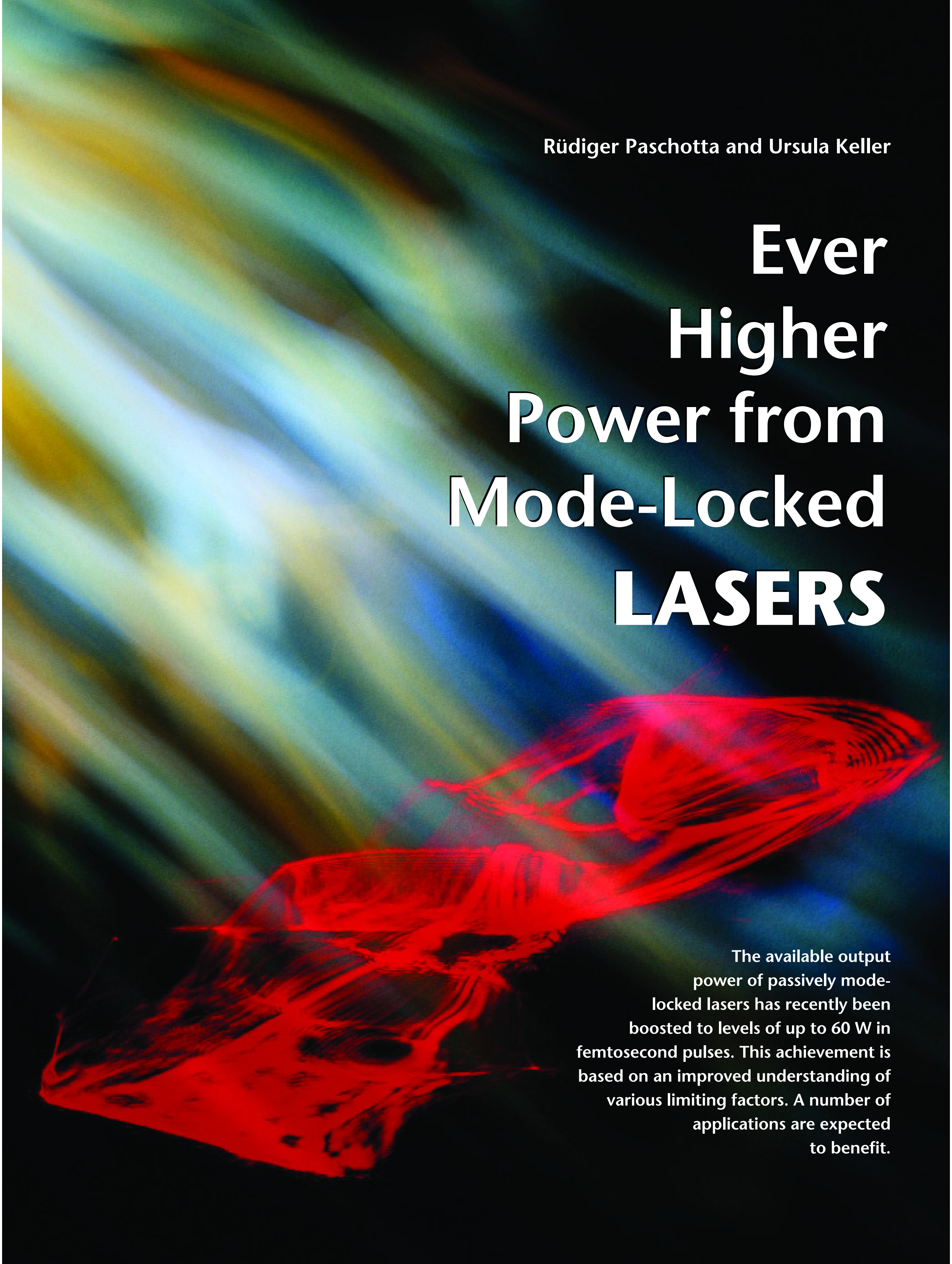

Rüdiger Paschotta and Ursula Keller

Ever Higher Power from Mode-Locked LASERS

The available output power of passively mode-locked lasers has recently been boosted to levels of up to 60 W in femtosecond pulses. This achievement is based on an improved understanding of various limiting factors. A number of applications are expected to benefit.

The use of passive mode locking to generate ultrashort pulses is a success story that began in the mid-1960s. Recently, mode-locked lasers capable of generating pulses with durations down to the order of 5 fs have been developed.[1] Previously, however, the average output power of mode-locked lasers had been limited to the order of 1 W, a level that was sufficient for many applications but certainly less than desirable for others. Mode-locked high-power lasers are needed, for example, for large-scale projection displays, an application in which mode-locked beams facilitate nonlinear wavelength conversion to generate high-average-power beams with red, green and blue color.[2] Although diode-pumped continuous-wave lasers were being used to generate hundreds of watts or even kilowatts of power in the early 1990s, at that time the output power of mode-locked lasers was still limited to the order of 1 W. It has only been in recent years that the limit has increased steeply to several tens of watts—today up to 60 W in femtosecond pulses.[3] The story of how this was achieved is an interesting one.

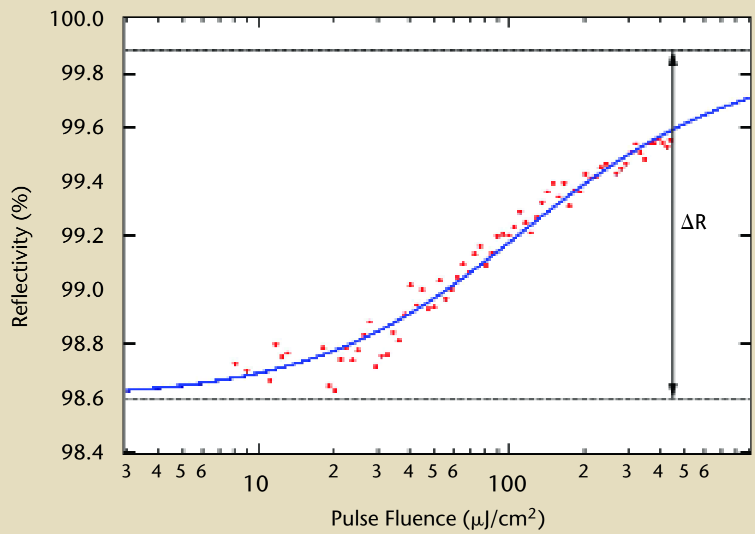

Figure 1. Typical saturation curve of a semiconductor saturable absorber mirror (SESAM). In a laser equipped with a SESAM, a pulse with sufficiently high energy suffers losses which are lower than those experienced by a continuous background.

The challenges

The initial attempts to obtain higher powers from mode-locked lasers met with an array of problems. Mode locking is possible only when a laser operates stably on a single transverse mode, i.e., with diffraction-limited beam quality. In high-power lasers, thermal effects—particularly in the gain medium—introduce wave-front distortions that can strongly affect beam quality, making mode-locked operation impossible. Particularly in the case of broadband gain media required for diode-pumped high-power femtosecond lasers, it took some time to understand and control these effects. Note that most broadband gain media are based either on glasses with poor thermal conductivity or on quasi-three-level laser transitions which necessitate operation at very high pump and laser intensities.

Even with these problems solved, mode locking such a laser was not a straightforward exercise. The most successful technique of passive mode locking is based on semiconductor saturable absorber mirrors (SESAMs).[4,5] Initially, however, many believed that SESAM damage—sometimes observed even at moderate power levels—would severely limit available output power. Other mode-locking techniques had their own problems. Q-switching instabilities,[6] linked to absorber damage in various ways and often more difficult to suppress in high-power lasers, constituted another challenge. Until a few years ago, the combination of all these problems made the outlook relatively bleak. In the late 1990s, however, solutions were found. The result was a generation of mode-locked high-power lasers characterized by extraordinary performance.

SESAM damage and Q-switching instabilities

In most passively mode-locked lasers, a SESAM initiates and stabilizes the mode-locking process. Use of this type of absorber introduces some loss of intracavity laser radiation; this loss is relatively large for low intensities but significantly smaller for a short pulse with high-peak intensity (Fig. 1). In effect, the circulating pulse saturates the laser gain to a level that is just sufficient to compensate the losses for the pulse itself, while any other circulating low-intensity light experiences more loss than gain and is thus deemed to die out during successive cavity round-trips.

But this process necessarily involves some absorption, which in turn causes heating of the absorber and possibly also nonthermal damage. Because early mode-locked lasers sometimes exhibited SESAM damage even at moderate power levels, many researchers deemed the technique unsuitable for high-power lasers. At the very least it appeared necessary to undertake the possibly tedious process of identifying SESAM materials and/or designs capable of allowing a significant increase in the damage threshold. For this reason, Kerr-lens mode locking (KLM)[7] appeared to many to be the technique with better potential for high-power operation. Here, the Kerr nonlinearity of the gain medium creates a lensing effect that improves the overlap of laser beam and pumped region only for high intensities. Because absorption of optical power is not involved, high powers can be handled. But for KLM to be sufficiently effective, pump beam and laser-cavity design must meet strict requirements, which is probably the reason why no one obtained more than a few watts of average output power with this technique.

By learning how to avoid SESAM damage, we were able to remove a major obstacle in the push toward higher powers. In fact, a more detailed look at this issue revealed that to avoid damage, apart from careful optimization of the whole laser, only minor changes to SESAM design were necessary. First, the peak intensities necessary to saturate the absorber are in a safe regime, well below the regime where damage is observed. Even for high laser powers, intensities can be limited by scaling up the mode area accordingly. Second, when the mode area is increased in proportion to the power, the resulting temperature rise increases only until the mode diameter is on the order of the thickness of the semiconductor substrate. For further increases of the mode area, the effective cooling area also increases. It turns out that, even for very high powers, the temperature increase can be limited to reasonable values if the modulation depth (the amount of saturable absorption) and the nonsaturable losses are kept reasonably low.

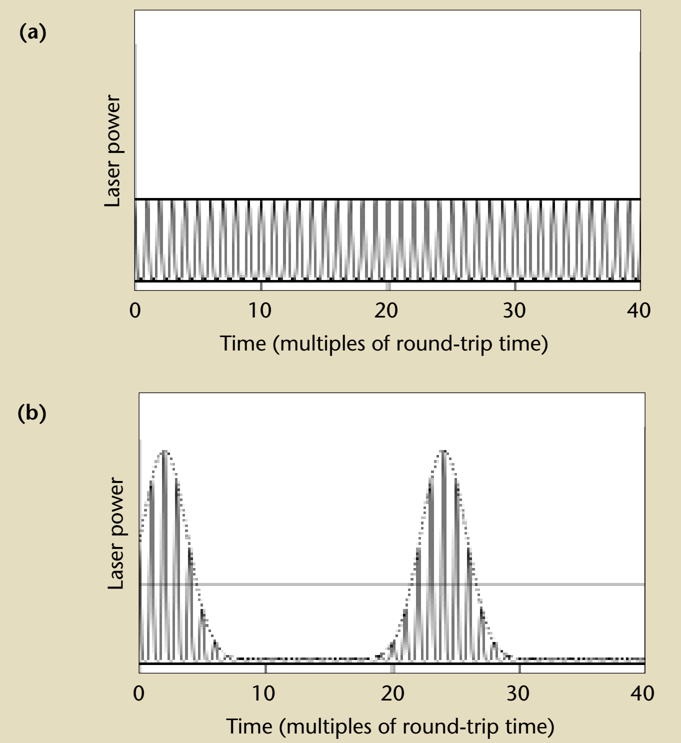

Figure 2. (a) Continuous-wave mode locking (cw ML) with constant pulse energy. (b) Q-switched mode locking (QML), where the pulse energy oscillates.

Q-switched mode locking

An unwanted effect of the saturable absorber is that it reduces the damping of the relaxation oscillations. If this effect is too strong, the relaxation oscillations become undamped and the pulse energy undergoes large oscillations. Such large oscillations characterize the regime of Q-switched mode locking, abbreviated as QML (Fig. 2). The QML issue is linked to SESAM damage in different ways. It is obvious that QML can lead to high peak intensities which can destroy the absorber layer. Not so obvious is the fact that the need to suppress QML can lead to a regime in which thermal and non-thermal SESAM damage is more likely; in particular, high intracavity power (with low-cavity losses) and strong absorber saturation (with a small mode area on the SESAM) tend to suppress QML but can cause absorber damage.

The way out of this dilemma is to improve the laser head rather than the SESAM: by choosing a gain material with high laser cross-sections and/or operating it with a small mode area, the QML tendency is reduced, which in turn allows for relaxation of the constraints placed on SESAM operation and thus helps to avoid damage. Another option is to use a relatively long laser cavity (as long as several meters), which also reduces the QML tendency, thus allowing more room for optimization of other laser parameters.

Passively mode-locked Nd-based lasers

The first attempts toward mode-locked lasers with multiwatt average output powers were based on the well-known laser medium Nd:YAG, which is suitable for diode-pumped high-power operation at 1064 nm. However, not every Nd:YAG laser head is equally suitable for mode locking. First, of course, the laser head and the laser cavity have to be optimized for single transverse mode operation. Second, the laser mode area in the gain medium must be sufficiently small. Many high-power laser heads tend to have rather large mode areas. This often results from the poor beam quality of high-power diode bars. While for many continuous-wave lasers this is not a problem, in a passively mode-locked laser it leads to an excessive QML tendency. For this reason we selected a so-called DCP laser head**, which is based on direct side pumping, without pump optics, through a small slit in the crystal mount. A reflective coating around the crystal allows for multiple passes of the pump radiation and thus for efficient pump absorption, homogeneous distribution of the excitation and, last but not least, a relatively small mode area. This mode area, together with the reasonably large laser cross-sections of Nd:YAG lasers, made it relatively easy to design a mode-locked laser with a SESAM without running into QML problems. The first laser of this type generated 10.7 W of average power in 16-ps pulses. Using three of these laser heads, we later generated 27 W in 19-ps pulses. Because of the higher gain in this configuration, we used an output coupler mirror with significantly higher transmission so that the circulating intracavity power was comparable to the one in the 10.7-W laser.

Based on this research, we concluded that mode locking without SESAM damage is possible at power levels far higher than those that had previously been demonstrated. We achieved this result

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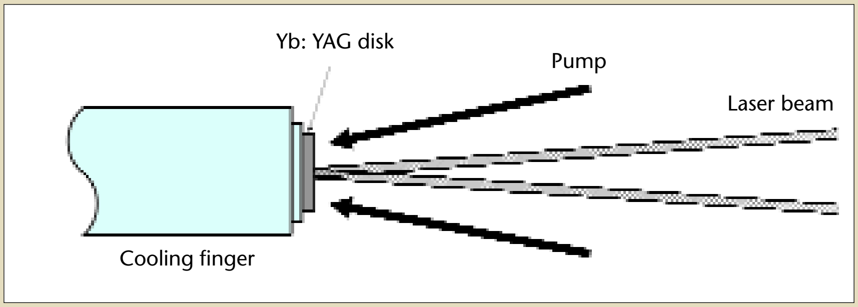

Figure 3. Thin-disk laser head (without multipass pump optics).

not by developing special SESAMs with a far higher damage threshold but rather by selecting an optimized laser head with a small laser-mode area and then optimizing the entire set of laser parameters.

While further increases in output power would appear feasible, the pulse durations are bound to be in the regime of multiple picoseconds because of the limited gain bandwidth of Nd:YAG. Some improvement may be achieved with Nd:YVO_4, which has about twice the gain bandwidth. Note, however, that mode-locked high-power lasers often generate somewhat longer pulses than do optimized low-power devices because the modulation depth of the SESAM has to be limited in order to avoid QML and/or SESAM damage.

Passively mode-locked thin-disk lasers

It was difficult to apply the results described above to femtosecond lasers. Although use of Nd-doped glass as a gain medium would offer a much higher gain bandwidth, because of the poor thermal conductivity it would lead to excessive thermal-lensing effects, making it very difficult to maintain the necessary beam quality at high power levels. On the other hand, some Yb-doped gain media, such as Yb:YAG for 1030 nm, have intermediate gain bandwidths sufficient for sub-picosecond pulse generation as well as favorable thermal properties. However, Yb-doped gain media are operated on a quasi-three-level laser transition with significant influence of ground-state absorption. For this reason, such media need to be operated at very high pump intensities, above the level which is usually realistic in the case of side-pumped lasers. Even with end-pumped lasers, thermal effects usually make it difficult to generate more than a few watts of output power with good beam quality.

The favorable properties of Yb:YAG (and similar media) can best be exploited with a so-called thin-disk laser head. This concept, developed in the mid-1990s in Germany by A. Giesen's group at the University of Stuttgart,[9] is based on use of a rather thin disk (of Yb:YAG, for example) which has a reflective coating on one side that is directly attached to a water-cooled mount; the other side has an antireflection coating (Fig. 3). By reducing the disk thickness to a value that typically ranges from 100 μm to 250 μm, thermal effects through refractive index changes and mechanical stress are minimized. Efficient pump absorption in a thin disk is achieved by use of multiple (e.g., 32) passes of the pump radiation. This can be arranged with a rather compact optical setup that uses the power either from beam-shaped diode bars with bulk optics or from fiber-coupled diode bars. A very important aspect is that the heat in the disk propagates in the longitudinal direction (i.e., along the laser beam). For this reason, only minor components of the temperature gradient are in directions transverse to the laser beam, and thermal-lensing effects are minimized. Furthermore, it can be shown that thermal lensing from the change of the refractive index does not become worse if the laser power is scaled up in proportion to the mode area (i.e., with constant pump intensity). Although the effects of thermal stress do increase with power, they can be minimized by use of a thin enough disk. The whole concept is therefore power scalable in a wide range of powers. The highest power demonstrated in continuous-wave operation with nearly diffraction-limited beam quality is approximately 100 W. Hundreds of watts should become possible within the next few years.

Overcoming design challenges

Early attempts to passively mode lock a thin-disk Yb:YAG laser failed because of problems with SESAM damage and QML. Only when QML[6] and several other issues had been better understood was it possible to develop designs that led to success. The first achievement was generation of 16 W of average power in 730-fs pulses,[10] far more than had ever been achieved before in the subpicosecond domain. It turned out that the effect of spatial hole burning, which inevitably occurs in thin-disk lasers because of the counterpropagating laser beams in the gain medium, has important effects on mode-locking dynamics: it is responsible for the surprising fact that such a laser operates stably only in a narrow range of pulse durations. The pulse duration is basically determined by the amount of negative dispersion in the laser cavity (e.g., from dispersive mirrors), together with the Kerr nonlinearity (for a given intracavity pulse energy), because both together define solitonlike pulses the shape of which is not strongly influenced by the SESAM. Yet the SESAM is very important for the stability of these pulses. To achieve stable mode locking by avoiding various types of instabilities, several parameters have to be carefully chosen.[11]

It is important to stress that not only the thin-disk laser head but also the whole concept of the SESAM-mode-locked thin-disk laser is power scalable: the main challenges (beam quality, QML, SESAM damage) do not become more severe if the power is scaled up according to certain scaling rules. To demonstrate power scalability, we used an improved laser head,[12] again supplemented with a SESAM, in a suitable laser cavity. So far we have achieved up to 60 W of average power in 810-fs pulses. Figure 4 shows the laser setup. Interestingly, the power is currently limited not by thermal effects in the laser head, QML or SESAM damage, but rather by thermal and nonlinear effects in the required dispersive mirrors. Both the high average intracavity power ($\approx$0.7 kW) and the high peak intensities (up to several GW/cm^2) can be handled with optimized high-reflectivity dielectric mirrors. The use of dispersive mirrors, compared to standard highly reflecting mirrors without dispersion, may lead, however, to problems with the handling of high-intensity pulses because of the higher optical intensities within the mirror structure.

To achieve even shorter pulses, it is necessary to employ a gain medium with broader bandwidth that at the same time meets all other requirements (especially in terms of thermal properties and laser cross-sections high enough to suppress QML). We have identified special tungstate crystals (KGW and KYW) which, in contrast to many other broadband Yb-doped media, are suitable in all respects. A thin-disk laser based on Yb:KYW has generated 22 W in 240-fs pulses.[13] If these pulses are still not short enough, nonlinear compression in a special optical fiber, combined with a dispersive prism pair, can be used to generate high-power pulses with durations far below 100 fs. For example, sub-40-fs pulses with 18 W average power have been achieved.[14]

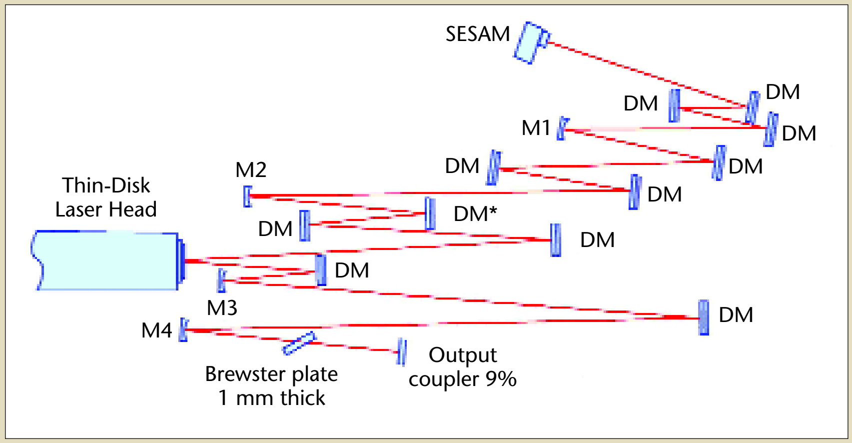

Figure 4. Cavity of mode-locked 60-W laser.
DM = dispersive mirror; M2, M3, M4 = highly reflecting mirrors;
SESAM = semiconductor saturable absorber mirror.

Applications

Apart from material processing, many applications of mode-locked high-power lasers involve nonlinear frequency conversion. A particularly interesting example is a very bright source of red, green and blue beams for use in a digital projection display system. For a large-scale cinema screen, at least a few watts per color are required, while more than 10 W (or even significantly more for outdoor displays) would be desirable. It seems feasible to construct a set of nonlinear wavelength converters which can generate 7-10 W per color starting with 60 W from a mode-locked infrared laser. Work in this direction is in progress.

Various high-power nonlinear conversion stages pumped with thin-disk lasers have already been demonstrated. The high peak power of the 16-W laser has allowed us to achieve 58%-efficient frequency doubling with a critically phase-matched LBO crystal. The advantage of critical phase matching is that the crystal can be operated at or near room temperature, eliminating the need for a temperature-stabilized crystal oven, thus making this source of green light more suitable for applications.

The high peak powers of thin-disk lasers have also allowed for construction of special high-gain optical parametric oscillators (OPOs) with a single-mode fiber in the cavity. Apart from compactness, this type of setup has important advantages, such as an unusual insensitivity to intracavity losses and mismatch of the cavity length. In several cases, nonlinear frequency conversion has been facilitated by the high peak powers now available. It can be expected that real-world applications will profit from this research as well.

Conclusions

Unprecedented output power levels of up to 60 W have recently been generated from passively mode-locked lasers, particularly those based on a thin-disk laser head and a SESAM for mode locking. Before this result could be achieved, a number of obstacles had to be overcome. The foundation was an improved understanding of certain key technical issues, including the design of laser heads, thermal effects, absorber damage and mode-locking dynamics.

The new technology provides very powerful pump sources (e.g., for nonlinear wavelength conversion devices), which are expected to find interesting applications.

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