Solid state lasers for ultrashort pulses – a diverse family

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Mode-locked solid state lasers of various kinds can generate light pulses with durations in the picosecond or femtosecond region, pulse energies from picojoules to several microjoules, and repetition rates between a few megahertz and many gigahertz. This article gives a short introduction to the technology of ultrashort pulse solid state lasers, and an overview on new developments.

Nanosecond pulses from Q-switched lasers are considered as short pulses, but the grade "ultrashort" demands pulse durations in the picosecond or femtosecond domain. Such pulses are usually generated in mode-locked lasers, which do have some features in common with Q-switched lasers, but differ significantly in the physical principles of pulse generation as well as in terms of the parameters of the generated pulses.

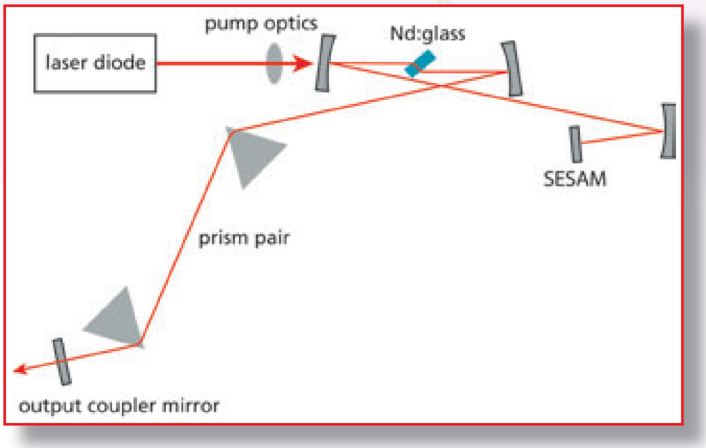

***Figure 1**: Schematic of a mode-locked diode-pumped Nd:glass laser with moderate output power (e.g. 100 mW) in 100-fs pulses. A prism pair compensates the dispersion, and a SESAM is used as the mode-locker*

1 Principle of active and passive mode locking

A fundamental feature of any mode-locked laser is that one or several ultrashort pulses are continuously circulating in the laser cavity. The various effects acting on the pulses during each round trip are in a balance so that the pulse parameters are essentially unchanged after each round trip. Each time when a pulse hits the partially transmissive output coupler mirror, a pulse is added to the output beam. The repetition rate is directly determined by the time required for a cavity round-trip and by the number of circulating pulses (which is usually one). The pulse duration is normally well below the round-trip time, often even by many orders of magnitude. Accordingly, the peak power can be far higher than the average power.

How is a laser made to generate a circulating ultrashort pulse, rather than emitting continuously? This can be achieved both with active and with passive methods [1]. In the former case, an electrically controlled modulator is used to modulate the optical losses at a frequency corresponding to the cavity round-trip time. The circulating pulse always traverses the modulator at the point in time when the losses are at their minimum. The pulse saturates the laser amplification such that it just compensates for the losses it experiences per round trip. For other arrival times, the losses are then higher than the laser gain, so that any additional pulse or any temporally constant background, which may initially also be propagating in the cavity, will eventually be eliminated. After many round-trips, there is a steady state for the parameters of the circulating pulse, where e.g. those effects increasing the pulse duration are in exact balance with those shortening the pulse. Typically, this leads to pulse durations of the order of 10 to 50 ps.

Significantly shorter pulses are obtained with *passive* mode locking, where the loss modulation occurs in a saturable absorber. The shorter the pulses become, the faster the resulting loss modulation. In addition, various other effects, in particular chromatic dispersion and nonlinearities, can contribute to the pulse shaping; depending on the situation, these can disturb or support the pulse formation. Currently, the most popular type of saturable absorbers are so-called SESAMs (semiconductor saturable absorber mirrors), small semiconductor optical elements with a Bragg mirror structure and a thin absorbing layer [2]. These SESAMs have turned out to be extremely versatile because their optical parameters can be tailored within wide regions by proper choice of the semiconductor material and the layer thicknesses. Perhaps surprisingly, SESAMs can even be used for lasers with very high output powers.

2 Typical laser setup

Although it is also possible to mode-lock semiconductor lasers, diode-pumped solid state lasers (**figure 1**) dominate in many applications. The latter are based on crystals or glasses as laser gain media, being doped with laser-active rare-earth ions (e.g. Nd^{3+}, Yb^{3+}, Er^{3+}) or certain transition-metal ions (Ti^{3+}, Cr^{2+}, Cr^{3+}, Cr^{4+}). Typical lasers of this kind operate in the 1-µm spectral region (with Nd- or Yb-doped crystals or glasses), are pumped with broad-area laser diodes, and emit average powers of about 0.1 to 2 W. A typical resonator length of e.g. 1 m leads to a pulse repetition rate of 150 MHz. Pulse durations are usually somewhere in the range from 1 to 10 ps for crystals and between 50 fs and 500 fs for glasses. For 1 W average power in 100-fs pulses at 100 MHz, one obtains peak powers of nearly 100 kW. Commercially available lasers

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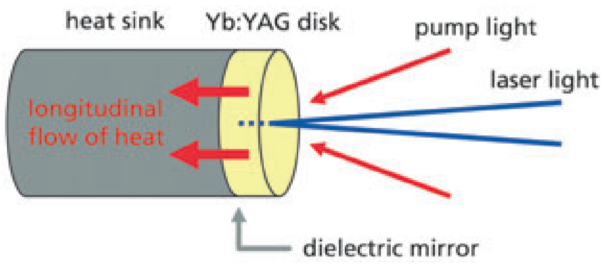

Figure 2: *Schematic of a thin disk laser head. The gain medium is an Yb:YAG disk with typically 100-200 µm thickness. The generated heat is extracted into the heat sink colinear to the beam axis. The cavity is arranged so that the pump light makes multiple passes through the disk (not shown)*

of this kind typically don't demand more from the user than simply turning a key.

Many further developments are still going on. New ytterbium-doped crystals allow similarly short pulse durations as glasses, while their better thermal properties allow for higher powers. Special designs lead to lasers which can be operated with small batteries and require very little space.

3 The shortest pulses

Lasers based on transition-metal-doped crystals, such as Ti:sapphire or Cr:LiSAF, are used for the shortest pulses. Pulse durations below 10 fs are presently routinely achieved with Ti:sapphire lasers, and the final limit seems to be around 5.5 fs [3]. In this regime, even the extremely large gain bandwidth of Ti:sapphire is hardly sufficient, and detrimental nonlinear effects become strong due to the high peak powers. Furthermore, it is difficult to precisely compensate the chromatic dispersion of the resonator over a very wide spectral range. For these very short pulses, special "double-chirped" laser mirrors have been developed, which significantly expanded the potential for ultrabroadband dispersion compensation.

For some applications, the relevant factor is not the extremely short pulse duration but rather the width of the spectrum of the laser output, which may be more than one octave. Using a microstructured fibre ("photonic crystal fibre"), it is also possible to broaden the initially narrower laser spectrum outside the laser cavity. Both methods allow the generation of self-referencing frequency combs [4], which are becoming very important particularly for applications in frequency metrology. They have recently obtained additional attention through the Nobel Prize in Physics, awarded in 2005 to Prof. Theodor W. Hänsch (MPI für Quantenoptik, Garching, together with two other winners).

4 High output powers

Initially, drastically increased output powers of mode-locked lasers appeared to be hardly achievable, because this leads to strong thermal effects in the laser gain medium, and it often didn't take many pulses until the SESAM was destroyed. A careful analysis revealed that one should not try to solve the latter problem by looking where the smoke comes from. It turned out to be better to optimise various parameters of the laser, in particular those of the resonator and the laser head, in order to operate the SESAM under optimised conditions. This has been demonstrated particularly with mode-locked thin disk Yb:YAG lasers (**figure 2**) [5], which, due to the cooling geometry of the thin disk laser head, allow for very high powers and can generate sub-picosecond pulses (this is because Yb:YAG has a fairly large gain bandwidth compared for example to Nd:YAG). After first attempts with 16 W average output power, 60 W and even 80 W have been achieved [6]. The pulse energy of these sub-picosecond pulses is now just above 1 µJ, and the peak power significantly above 1 MW – these lasers can be used directly for micro materials processing without the need for subsequent amplification. Much shorter pulses can be obtained by nonlinear pulse compression in a special kind of glass fibre with large mode area [7], while other wavelengths are accessible with nonlinear frequency conversion [8].

5 Higher pulse repetition rates

In order to obtain a higher pulse repetition rate, one can drastically reduce the cavity round-trip time by using a compact laser resonator. While the realisation of short cavities is physically not difficult, the consequence in the case of passively mode-locked lasers is unfortunately that the tendency for certain instabilities of the pulse energy (Q-switched mode locking [1]) becomes stronger and stronger. This effect initially limited the achievable repetition rates to a few GHz, so that such lasers were not usable for some applications where faster pulse trains are required, such as in fibre-optic communications and for certain measurement purposes. Once again, however, a detailed analysis of the phenomena and design constraints paved the way for drastic improvements. Nearly 160 GHz

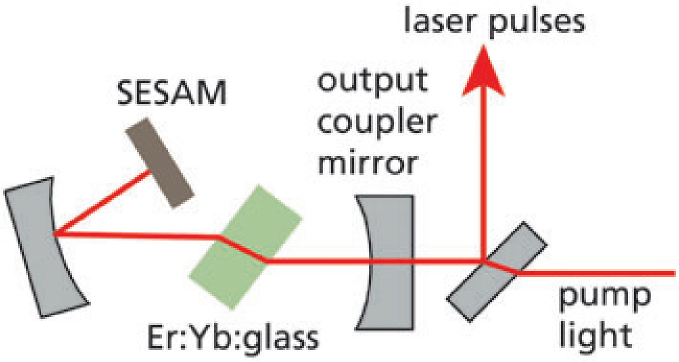

Figure 3: *Schematic of a miniature Er:Yb:glass laser for pulse repetition rates of 10 to 50 GHz. For 50 GHz, the resonator length (measured from the output coupler to the SESAM) is only about 3 mm*

have been achieved with Nd:YVO$_4$ lasers [9] around 1 µm wavelength, and 50 GHz in the 1.5-µm region [10] (**figure 3**) as used e.g. for fibre-optic communications. Although mode-locked diode lasers do allow for significantly higher repetition rates [11], the achievable average output powers of the solid state lasers are much higher (typically 10 to 50 mW), and the pulse quality is excellent. Furthermore, the approach of *passive* mode-locking may prove practical for many applications, as expensive multi-GHz electronics and modulators are not required.

6 New laser types

The optimisation either for high output powers or for multi-GHz pulse repetition rates leads into quite different directions. It turns out that the combination of both properties is very hard to achieve with conventional solid state lasers. Exactly this combination, however, is required for some future applications such as optical clocking of microprocessors or synchronous pumping of optical parametric oscillators. The challenge becomes even greater when sub-picosecond pulse durations are required in addition. This leads to requirements which can not be met by any laser crystals or glasses which are currently available.

6.1 VECSELs

In particular because semiconductor lasers have been very limited in terms of output power for some time, it is all the more surprising to learn that this type of laser is now starting to fill the gap. However, this new potential is realised not with a conventional diode laser, but rather with an optically pumped surface-emitting laser with external resonator (VECSEL, **figure 4**). Such lasers can generate high powers with excellent beam quality [12,13], and with a SESAM they can be mode-locked [14] without instabilities of the pulse energy, even at very high repetition rates. So far, e.g. 1.4 W average power in 6-ps pulses with 10-GHz repetition rate have been demonstrated [15]. Even the generation of 0.5-ps pulses is possible [16], even though not yet demonstrated with high average power. Within the next few years, combinations such as e.g. 3 W, 0.5-5 ps and 10-40 GHz should become feasible. Probably at some later time, similar lasers will be electrically pumped, and the saturable absorber could be integrated into the gain structure [17]. However, lower pulse repetition rates and higher pulse energies will probably remain the domain of conventional solid state lasers.

In terms of cooling geometry, the VECSEL is quite similar to the thin disk laser. However, the different microscopic parameters (in particular, the laser cross sections and upper-state lifetime) make it suitable for totally different parameter regions.

6.2 Fibre lasers and amplifiers

Yet another kind of laser is the fibre laser. Neodymium, ytterbium or erbium-doped fibres have a large amplification bandwidth, which is advantageous for the generation of ultrashort pulses. A fibre laser

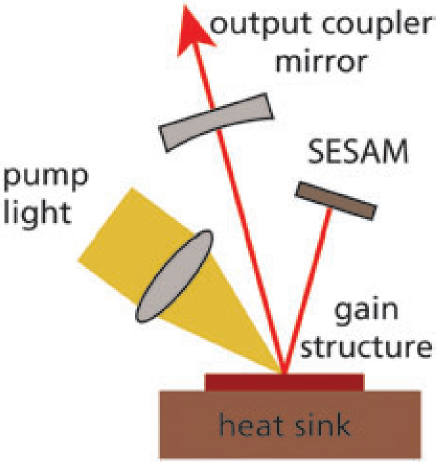

Figure 4*: Resonator setup of a mode-locked VECSEL. The gain structure is pumped with a high power laser diode. The resonator contains a SESAM as the mode-locker*

can also be passively mode-locked with a SESAM, or alternatively by exploiting the high nonlinearity of the fibres. For example, nonlinear rotation of the polarisation in combination with a polarising element in the resonator can be employed as a very fast "effective saturable absorber".

Mode-locked fibre lasers can be robust and have the potential to be very cost-effective sources of ultrashort pulses. However, peak power and pulse duration are limited by the strong fibre nonlinearity, and in order to achieve high pulse quality, long-term stability or high repetition rates, one often has to take somewhat sophisticated measures. The design of such lasers is thus a non-trivial task. It will be interesting to see to which extent fibre lasers can really replace other solid state lasers in the domain of pulse generation.

Active fibres are also interesting for the post-amplification of pulses from another laser. Extremely high average powers of hundreds of watts are possible [18], at least for high repetition rates, even though the conservation of pulse quality is not easy. Particularly for materials processing, however, such issues are irrelevant, and fibre amplifier systems may in the future play an important role in this domain.

7 Conclusions

There are rather different approaches for the generation of ultrashort pulses, each one covering a certain region of the huge parameter space. Competition between the different technologies only occurs where these regions overlap. In any particular case, it is essential to select the most suitable technology and realise its potential on the basis of a solid understanding of the underlying physics.

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