Mode-locking Techniques and Principles

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20.1 Introduction

One of the most intriguing features of lasers is the possibility to generate ultrashort light pulses with durations on the picosecond or femtosecond scale. Such laser pulses find a wide range of interesting applications. Some of those directly make use of the ultrashort temporal durations. For example, with pump–probe measurement techniques, one can investigate in detail how a system evolves after the excitation with such a laser pulse; a second laser pulse, arriving at the sample with a variable short time delay, serves to probe the system. Another example is distance measurement with the time-of-flight technique, where a 1-ps pulse duration, for example, gives the potential for sub-millimetre accuracy even over large distances.

A wide variety of other applications make use of additional interesting aspects. For example, the typically rather high timing accuracy of ultrashort pulse trains makes them interesting as short-term timing references for optical clocks, and their coherence properties, which are the basis for so-called optical frequency combs, have opened a wide field of applications in optical metrology, particularly concerning measurements of time, frequencies and distances.

Another interesting aspect is that the concentration of a moderate amount of optical energy on extremely short timescales leads to enormously high peak powers. That in combination
with the high focusability of laser beams allows one to generate enormously high optical intensities, which can be used for laser material processing (the commercially most relevant field of application) but also in some hot topics of fundamental scientific research.

In most cases, ultrashort light pulses are generated with mode-locking techniques, where one obtains regular trains of usually coherent ultrashort pulses with relatively low energy, rather than single pulses. Pulse repetition rates are typically in the region of many megahertz or even gigahertz. There are various techniques for picking a single pulse out of such a pulse train (or making a pulse train with much lower pulse repetition rate), and then amplifying such pulses to much higher energy levels. That area, however, goes beyond the scope of this chapter.

The chapter is meant as an overview on that field, concentrating on the most common techniques and the most common types of lasers. The latter are treated in Sections 20.5–20.7. Rather than providing a complete overview on achieved performance figures, the chapter discusses which aspects of mode-locking techniques and which additional physical effects are particularly relevant in certain lasers, and what impact that has on the performance limitations.

Mode-locked lasers are also called ultrashort pulse lasers, picosecond lasers or femtosecond lasers; somewhat odd is the term ultrafast lasers, since certain processes, but not the lasers themselves are ultrafast.

### 20.2 Basic Principles of Mode-locking

#### 20.2.1 Origin of the Term “Mode Locking”

The term “mode locking” for techniques of ultrashort pulse generation resulted from an analysis of phenomena in the frequency domain. Each laser resonator has some number of modes, i.e. field configurations which are (in a certain sense) self-consistent when considering one complete resonator round trip; each mode has a certain resonance frequency. Typically, one considers only fundamental modes and ignores higher-order modes, having more complicated transverse intensity profiles and also different mode frequencies. For lasing on a single mode with constant power, the electric field corresponding to the laser output at a certain location is simply a sinusoidal oscillation. For simultaneous lasing on two modes, one obtains a beat note, i.e. an output with periodically modulated optical power. When combining several modes with equidistant frequencies, one can obtain a periodic train of well-separated short pulses (see Figure 20.1); however, that works only if the optical phases of the mode are “locked”, i.e. if those modes maintain a certain phase relationship over long times: with random phases instead of that phase locking, one would obtain a complicated temporal evolution rather than clearly separated pulses.

Special measures (mode-locking techniques) are required to fulfill that phase condition. Note that the frequencies of fundamental modes in a real laser resonator are not exactly equidistant, so that the mentioned phase condition would normally be lost within a short time; one requires some additional locking effect which can enforce the phase locking at least if the natural tendency for dephasing is not too strong.

Although the one can easily understand the importance of the phase condition in the frequency domain, the workings of different mode-locking techniques are normally more easily understood in the time domain. They are explained in the following sub-sections.

Typically, mode-locking leads to a situation where a single ultrashort pulse circulates in the laser resonator. (In some situations, achieved with harmonic mode-locking, one obtains multiple circulating pulses.) Each time when a circulating pulse hits the output coupler mirror, part of its energy is transmitted by that mirror, and one obtains an output pulse. Therefore, one obtains a regular pulse train, with the pulse spacing determined by the round-trip time of the laser resonator. The pulse repetition rate (i.e. the inverse pulse spacing) typically has a value of tens or hundreds of megahertz, sometimes a few or even many gigahertz.

![Synthesis of a pulse train by combination of an increasing number of fundamental modes in a laser resonator, where the relative phases are locked.](image)
Normally, stable mode-locking is possible only when lasing on higher order transverse resonator modes can be safely suppressed, because those would have different round-trip phase shifts and times than those of the fundamental modes, making a multimode pulse decay quite quickly.

### 20.2.2 Active Mode-locking

The basic idea behind active mode-locking is to provide a periodic loss modulation by inserting an electrically controlled optical modulator into the laser resonator – typically close to an end mirror of a linear resonator. The electronic driver signal is in some way synchronized to the resonator round trips, such that the circulating pulse can each time pass the modulator with the minimum amount of loss. The loss modulation has two different effects:

- Any other radiation circulating in the resonator would pass the modulator at a time where the losses are substantially higher. It would thus have a lower net round-trip gain. As the circulating pulse in the steady state saturates the laser gain such that its energy stays constant, the other radiation would have a negative round-trip gain and thus die out sooner or later. Therefore, the modulator “protects” the circulating pulse against competing other radiation.

- The temporal wings of the circulating pulse, being slightly outside the temporal loss minimum, experience a slightly negative round-trip gain. To keep the pulse energy constant, the pulse centre must have a slightly positive round-trip gain. Those effects in combination cause some pulse shortening in each round trip (see Figure 20.2). In the start-up phase of the laser, this is what leads to rapid formation of a pulse. In the steady state, that shortening effect just compensates other effects which tend to make the pulse temporally longer. (Typically, the limited gain bandwidth and sometimes also chromatic dispersion can lead to temporal pulse broadening.)

As the pulse duration gets shorter, the effectiveness of the pulse-shortening effect of the modulator becomes weaker and weaker. On the other hand, pulse-broadening effects such as those arising from the limited gain bandwidth of the laser crystal or from chromatic dispersion become more effective. For those reasons, active mode-locking is not suitable for generating very short pulses, even when the modulator has a rather high modulation depth. This matter has been quantitatively analysed by Kuizenga and Siegman 1970, who derived an equation for the achievable pulse duration if the gain bandwidth is the limiting factor.

Somewhat shorter pulses are obtained by operating the modulator with the frequency which is an integer multiple of the round-trip frequency of the laser resonator, but that has the side effect of creating additional time windows, where additional pulses could circulate. For suppressing those, one can use the combination of the fundamental and a harmonic modulation frequency.

The modulator drive frequency must remain in quite precise synchronism with the round-trip frequency of the pulses. In principle, a modulator driven at a slightly deviating frequency can “pull” the pulses to that frequency, but such a regime quickly leads into instabilities, since the achievable “pulling force” for the pulse timing is quite weak. In many cases, sufficiently precise synchronism would be lost already by thermal drifts of the laser resonator or the driver electronics, and stable operation then requires some kind of feedback loop. It is possible to use a fixed (or even slightly variable) drive frequency of the modulator and automatically regulate the resonator length (e.g. via a piezo actuator attached to a resonator mirror). Alternatively, one may use regenerative mode-locking, where the drive frequency is automatically adjusted to follow fluctuations of the resonator length.

![Figure 20.2](image-url) Temporal evolution of the pulse power and the losses at the modulator in an actively mode-locked laser. The temporal wings of the pulse experience higher losses than the central part and that leads to some pulse shortening. Under typical conditions with a low ratio of pulse duration to round-trip time, however, the pulse shortening effect may be quite weak.
20.2.3 Passive Mode-locking

20.2.3.1 Basic Principle

The inherent problem of active mode-locking concerning the achievable pulse duration is that the pulse-shortening effect obtained from the modulator rapidly becomes less effective as the pulses become shorter. That aspect is far more favourable for passive mode-locking, where the loss modulation is provided by a saturable absorber. Here, particularly the loss modulation on the leading front of the pulse becomes faster as the pulse gets shorter. Depending on the type of saturable absorber and the pulse duration, the loss recovery may be as fast as the decay of the pulse power – one would then have a fast absorber – or slower (for a slow absorber) with a fixed recovery time, which may be substantially longer than the pulse duration. Figure 20.3 shows the situation for a slow absorber.

Quite obviously, the use of saturable absorber allows for substantially stronger pulse-shortening effects even if the pulses become rather short. In the steady state, we may again have a situation where the pulse-shortening effect of the saturable absorber compensates pulse broadening effects, e.g. related to the finite gain bandwidth or to chromatic dispersion. However, there are also situations where the pulse duration is essentially determined by a balance of other effects (frequently, by soliton effects), while the saturable absorber has a negligible effect on the pulse duration. Its role is then only to initiate the pulse formation and to stabilize the circulating pulse. More details on soliton mode-locking are discussed in Section 20.4.

Similar to a modulator, a saturable absorber can also serve to suppress any other radiation circulating in the laser resonator. In that case, however, that suppression is not based on the other timing of the other radiation, but on the fact that the competing radiation is far less intense than the circulating pulse (e.g. in a typical solid-state laser, where the saturation energy of the gain medium is orders of magnitude higher than the pulse energy). According to the simple criterion formulated above, one should conclude that the pulses cannot be stable under such conditions. Indeed, that has been believed for many years, become most common, since essentially all of their parameters can be optimized through the choice of materials and the device design. (Of course, such optimization also requires a solid understanding of which absorber parameters are most appropriate for the task.) Although expensive fabrication equipment is required, the fabrication cost can be small if many devices are fabricated together on a single semiconductor wafer. In most cases, a SESAM is used as an end mirror in a linear laser resonator. The laser resonator design must provide a suitable spot size of the beam on the SESAM, such that the saturation parameter (the ratio of pulse fluence to the saturation fluence of the absorber) has a reasonable value (typically of the order of 3–10).

20.2.3.2 Stability of the Circulating Pulse

In passively mode-locked lasers, the pulse duration may often become so short that the pulse bandwidth becomes quite substantial and is no longer small compared with the gain bandwidth. This results in a substantial gain disadvantage of the pulse against any temporally long background radiation also present in the laser resonator. That situation can only be stable if the losses caused by the saturable absorber for that background radiation are high enough to over-compensate the gain disadvantage of the pulses: essentially, one should assume that we need a situation where the round-trip gain for the circulating pulse is higher than that for any other radiation in the resonator. Interestingly, however, that condition is not absolutely necessary, as discussed in the following paragraph.

A particular concern for stability of the pulses arises for a slow absorber, having a recovery time which is several times longer than the pulse duration. Here, the net gain just behind the pulse can be positive because the losses are still close to their minimum, while the laser gain is nearly constant, e.g. in a typical solid-state laser, where the saturation energy of the gain medium is orders of magnitude higher than the pulse energy. According to the simple criterion formulated above, one should conclude that the pulses cannot be stable under such conditions. Indeed, that has been believed for many years,
although practical experience actually showed that many lasers worked quite well even with pretty slow absorbers. An early explanation for that was limited to soliton mode-locked lasers (Kärtner and Keller 1995), because it was based on a mechanism which works only in such lasers, where chromatic dispersion causes a substantial temporal broadening of any noise behind the pulse. However, better than expected stability was observed even in simple picosecond lasers, where the effects of chromatic dispersion and the Kerr non-linearity are negligible. In fact, the same phenomenon of unexpected stability was also observed in numerical simulations and that finally led to the important finding that another effect, which had previously been overlooked, serves to stabilize the mode-locking: due to the decrease of losses during the pulse, the “center of gravity” of the pulse envelope is constantly shifted backwards, but the same does not happen for any noise behind the pulse. Therefore, the pulse is constantly shifted into that noise, which thus has only limited time to grow under the influence of the positive net gain. As a result, some significant amount of positive net gain can be tolerated without making the circulating pulse unstable. That allows for stable mode-locking even when the recovery time of the absorber is more than 10 times the pulse duration (Paschotta and Keller 2001). Of course, soliton effects and the like may provide some additional stabilization.

The previously mentioned analysis was done for the simplest situation, where the laser gain is temporally constant and only the limited gain bandwidth and the absorber action shape the pulse, while additional effects such as chromatic dispersion and the Kerr non-linearity are negligible. This is realistic for simple picosecond solid-state bulk lasers. Substantially more complicated situations arise for femtosecond bulk lasers and particularly for fibre lasers (see Section 20.6). Generally, the question of stability of a mode-locked laser, which can be a highly non-linear system, can be a highly non-trivial issue. It can depend on various details such as the required pulse energy and duration, the amount of chromatic dispersion and Kerr non-linearity, spectral filtering effects, etc.

20.2.3.3 Start-up Phase

In the start-up phase (directly after turning on the laser), there will always be some fluctuations of the laser power, e.g. arising from noise effects and from mode beating. Although the resulting peak power may be very small compared with the peak power of the pulse in the steady-state (because the final pulse is far shorter than initial power fluctuations), it causes some small amount of loss modulation at the saturable absorber. Even a small loss modulation of that type “favors” those parts of the circulating radiation which are more intense, since its net gain during each resonator round trip is slightly higher. Even if that process takes many thousands of round trips, for practical purposes, it often provides rapid self-starting of the mode-locking process. However, that self-starting feature may be inhibited by disturbing effects, particularly by parasitic reflections within the laser resonator. For example, even carefully anti-reflection-coated end faces of a laser crystal cause some amount of reflections, and those will be very disturbing unless the laser crystal is placed such that its surfaces are not exactly perpendicular to the laser beam. That rule also has to be observed for other optical surfaces in such a laser, except in some cases where an optical filtering effect from a sub-resonator needs to be employed, and the relevant optical surfaces have a small and stable distance from an end mirror.

For slow absorbers, the above-mentioned initial loss modulation is substantially stronger than for fast absorbers, essentially because for substantial absorber saturation, one does not require to reach the saturation energy within the short final pulse duration, but only within the much longer absorber recovery time. Self-starting mode-locking is thus tentatively more difficult to achieve, e.g. with Kerr lens mode-locking (KLM) (see Section 20.3.5), where the loss response is very fast. In many cases, such a laser will not automatically start mode-locking after being turned on, but will rather exhibit a noisy operation mode without ultrashort pulse generation. Mode-locking may then be started, e.g. by tapping one of the resonator mirrors, which introduces enhanced power fluctuations. Such requirements are obviously not ideal for commercial laser products.

Reliable self-starting of the passive mode-locking process is also tentatively more difficult to achieve in lasers with long laser resonators, leading to low pulse repetition rates. In such cases, the steady-state peak power of the pulse can be orders of magnitude higher than the power of initial random fluctuations. It is important to realize that one will usually have to optimize the absorber parameters such that they fit well to the steady-state conditions; the absorber will then have little effect on the initial phase.

20.2.3.4 Q-switching Instabilities

An inherent problem of passive mode-locking is that a saturable absorber influences the dynamical behaviour of a laser also on longer time scales. In particular, it tends to decrease the damping of the relaxation oscillations, as occurring in lasers with high saturation energies of the gain medium (e.g. solid-state lasers). If that effect becomes too strong, one obtains Q-switching instabilities, which usually lead to the regime of Q-switched mode-locking: the pulse energy is no longer stable, but undergoes strong oscillations, on a timescale of dozens, hundreds or more resonator roundtrips (Figure 20.4), depending on the system parameters. That regime is normally undesirable; it would in principle allow one to generate pulses of even substantially higher energy, but particularly when optimizing the parameters for a large enhancement of pulse energies, the operation becomes rather unstable. Therefore, one usually needs to adjust parameters such that one remains in the regime of stable mode-locking.

There is usually a well-defined transition between the regimes of stable mode-locking and the unstable regime. Frequently, a passively mode-locked laser is in the unstable regime below a certain value of the pump power, which is called the threshold power for stable mode-locking. In most cases, the value of that threshold power can be estimated based on a few system parameters, namely, the modulation depth of the absorber, its saturation parameter $S$, the saturation energy $E_{\text{sat}}$ of the gain medium and the intra-cavity pulse energy $E_p$. Stability can be expected if the following condition is fulfilled: $E_p > E_{\text{sat}} \Delta R/S$ (Kärtner et al. 1995, Hönninger et al. 1999).
(In the literature, the equation is often given in a modified form without the saturation parameter: $E_p^2 > E_{sat,a} E_{sat,a} \Delta R$, where $E_{sat,a}$ is the saturation energy of the absorber.) From that, one can conclude that the following measures are beneficial for avoiding Q-switching instabilities:

- One should avoid an unnecessarily strong modulation depth.
- The absorber saturation should be strong enough (e.g. $S > 4$ or even larger).
- One should have gain medium with low saturation energy (i.e. with high emission cross section at the laser wavelength and not too large beam area).
- A high intra-cavity pulse energy, e.g. achieved with a small output coupler transmission and small other intra-cavity losses, and with a long resonator, is also beneficial.

In some operation regimes, Q-switching instabilities are difficult to avoid and that may set limits to achievable performance parameters. In particular, this applies to lasers with very high pulse repetition rates, where it is difficult to achieve a high enough intra-cavity pulse energy, because that would correspond to a very high average power.

Note that Q-switching instabilities are not always easy to distinguish from other types of instabilities. For example, instabilities arising from a too slow saturable absorber may appear quite similarly in experimental tests.

### 20.2.4 Fundamental vs. Harmonic Mode-locking

In most mode-locked lasers, only a single ultrashort pulse circulates in the laser resonator. The obtained pulse repetition rate is then just the inverse of the round-trip time of the resonator. It has been mentioned above that shorter pulses can be obtained with active mode-locking if the modulator is driven at several times higher frequency, because that increases the last difference between the temporal wings and the power maximum of the pulse. At the same time, one obtains multiple temporal locations where a pulse can circulate and experience minimum losses at the modulator in every round trip. However, that does not automatically lead to clean harmonic mode-locking, i.e. multiple pulses with equal pulse energies and ideally perfect mutual phase coherence. For that, one requires additional measures which allow the circulating pulses to interact with each other such that their energies and phases are stabilized. That is typically achieved with some kind of sub-resonator within the laser resonator. A difficulty related to that concept is that the relative lengths of the involved resonators must be interferometrically stable.

Another motivation for harmonic mode-locking can be to achieve higher pulse-repetition rates. The resonators of fibre lasers, for example, can often not be made very short, because some length of active fibre is required in addition to various other components; on the other hand, multi-GHz pulse repetition rates are often required, for example, for telecom applications. One then requires harmonic mode-locking with a large number (hundreds or thousands) of pulses circulating in the laser resonator. Unfortunately, it is challenging to achieve long-term stability of operation under such conditions; at least, it requires a careful and relatively sophisticated device design. Therefore, a fundamentally mode-locked laser (possibly realized with a different technology) may be preferable.

### 20.2.5 Frequency Combs

The optical spectrum of a single ultrashort pulse shows a continuous distribution of power over the optical frequencies, the minimum (bandwidth-limited) width of which scales inversely with the pulse duration. For example, unchirped Gaussian-shaped pulses have a time–bandwidth product (the product of temporal and spectral width, both measured in terms of full width at half maximum) of $\approx 0.44$. Such a pulse with 100-fs duration at 1064-nm wavelength, for example, has a FWHM
bandwidth of 4.4 THz or 17 nm. For soliton pulses, the time–bandwidth product is smaller, \( \approx 0.315 \).

Optical spectra of regular and virtually infinite pulse trains, as obtained from mode-locked lasers, look entirely different due to the mutual coherence of subsequent pulses. The spectrum resembles a frequency comb, i.e. it consists of discrete lines (Figure 20.5), which in the absence of any noise would have a zero width. The comb lines are exactly equidistant, and their spacing corresponds to the pulse repetition rate \( f_{\text{rep}} \). The line frequencies can be formulated as \( \nu_j = \nu_{\text{ceo}} + j \cdot f_{\text{rep}} \), where \( j \) is an integer index and \( \nu_{\text{ceo}} \) is the so-called carrier-envelope offset frequency; the latter is determined by the carrier-envelope offset phase shift which the circulating pulse experiences in each resonator round trip.

Interestingly, the two parameters \( \nu_{\text{ceo}} \) and \( f_{\text{rep}} \) precisely determine the frequencies of all (possibly many thousands) lines of the frequency comb. This effect is very important for a number of interesting applications in frequency metrology. For example, a single broadband frequency comb source with carefully stabilized and precisely measured values of \( \nu_{\text{ceo}} \) and \( f_{\text{rep}} \) can be used for accurately measuring the optical frequencies of any optical signals within its bandwidth. In reality, the line spacing is normally much smaller, e.g. some hundreds of megahertz or some gigahertz.

Desirable properties of a frequency comb source are

- that it covers the optical frequency range of interest,
- that \( \nu_{\text{ceo}} \) can be measured accurately (typically with an \( f\)-\( 2f \) interferometer, requiring a large spectral width of the laser),
- that it generates the required comb lines with sufficiently high optical powers,
- that the influences of noise (both quantum noise and technical noise sources) are as weak as possible and
- that the comb parameters \( \nu_{\text{ceo}} \) and \( f_{\text{rep}} \) can be rapidly adjusted, for example, within a feedback loop.

For a slow absorber, the saturation fluence is the fluence of a short pulse required to reduce the saturable losses to \( 1/e \) times its unsaturated value; however, the loss for the pulse itself is still higher (\( (1 - e^{-1}) \) the initial loss), since that saturation value is only reached at the end (see Figure 20.6). For a given beam area on a saturable absorber, the saturation power is the saturation intensity times the beam area.

20.3 Saturable Absorbers for Mode Locking

20.3.1 Parameters of Saturable Absorbers

In analytical or numerical models, for example, of mode-locked laser operation, saturable absorbers are often described by a couple of parameters of simple analytical absorber models:

- The modulation depth is the maximum amount by which the losses (in a certain wavelength range) can be reduced by saturation. In case of reflecting devices such as SESAMs, the modulation depth is normally referred to as \( \Delta R \) (indicating the maximum increase of reflectivity).
- There are also often some non-saturable losses, which are normally undesirable but often to some extent unavoidable.
- For a fast absorber, the saturation intensity is the optical intensity required to reduce the saturable losses to half of their unsaturated value. For a given beam area on a saturable absorber, the saturation energy is the saturation fluence times the beam area.

Note that real absorbers will not always exhibit saturation characteristics as expected from simple absorber models. For example, they may not exhibit a simple exponential law for loss recovery after a pulse. Also, the reflectivity for pulses may not monotonically increase with increasing pulse fluence but eventually exhibit a roll-over, e.g. due to two-photon absorption. Therefore, a set of absorber parameters may not completely describe the actual characteristics. In addition, the transverse intensity variation of laser beam profiles, causing
a spatially variable degree of saturation, is often ignored in simple calculations.

The required values of absorber parameters depend very much on the circumstances:

- For many solid-state bulk lasers, a modulation depth of the order of 1% is fully sufficient, whereas fibre lasers often require a modulation depth of the order of 10%. For high-power operation of bulk lasers, one sometimes tries to work with less than 0.5% modulation depth.
- Non-saturable losses are no problem in some cases but can be critical for high-power operation (also for high pulse repetition rates) due to the involved heating. Tentatively, they are higher for absorbers with particularly fast loss recovery.
- Although a suitable saturation energy (assuming a slow absorber) can in principle be achieved for any saturation fluence just by choosing the appropriate beam area, it may be desirable to have a not too high saturation fluence because otherwise one requires inconveniently strong focusing, which may also cause thermal problems.
- An appropriate value for the saturation parameter (ratio of pulse energy to saturation energy) may be only 3 for some lasers, but it may have to be substantially higher in some cases, e.g. for suppressing Q-switching instabilities.
- An optical reflection spectrum of a SESAM, for example (see the following section), gives information on the contained Bragg mirror structure.
- A pump–probe measurement, ideally performed with shorter and longer pulses, shows how the losses evolve over time; one can measure both the modulation depth and the recovery time.
- For a closer inspection of the saturation characteristics, one often measures the reflectivity or transmittance of an absorber device as a function of the pulse energy (or fluence). From that, one obtains the saturation fluence. It is also possible to detect unusual features in the saturation characteristics, e.g. a roll-over at high pulse fluences.
- In some cases, damage measurements are performed. Here, one may gradually increase the incident pulse fluence until damage or degradation is observed, e.g. by observation of the reflection characteristics or increased levels of scattered light. However, it still remains challenging to characterize absorbers in terms of their long-term degradation, since such measurements are intrinsically quite time-consuming. (Test with accelerated aging could in principle be a solution, but one would first need to reliably establish how much the aging is accelerated under certain conditions.)

**20.3.2 Semiconductor Absorbers**

Although early experiments with passive mode-locking where often based on other types of absorbers, SESAMs are nowadays the most widely used absorbers for passive mode-locking.

In the simplest case, a SESAM structure consists of a semiconductor Bragg mirror, on top of which a single absorber

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**FIGURE 20.6** Saturation characteristics of a slow absorber mirror vs. pulse fluence with 1% modulation depth, 0.5% non-saturable losses and a saturation fluence of 100 $\mu$J cm$^{-2}$. Shown is the reflectivity for short pulses (with a duration well below the recovery time) as a function of the pulse fluence. After a pulse with the saturation fluence, the saturable absorption is reduced to $1/e$ times the initial value, but the average loss for the saturating pulse itself is still higher.
Mode-locking Techniques

The incident pulses are reflected on the Bragg mirror and experience some absorption losses essentially only in the absorber layer. Frequently, that absorber layer is so thin (e.g. 10 nm) that it acts as a quantum well. The absorption process moves some carriers from the valence band to the conduction band of the semiconductor material, and the absorption is substantially reduced once a substantial fraction of the carriers has been excited in that way. In the simplest case, recovery of the absorption would occur only through the return of carriers into the valence band; the recovery time would then simply be the carrier lifetime (which may, for example, be of the order of some tens or hundreds of picoseconds). However, particularly for femtosecond pulses, one frequently observes (e.g. in pump-probe measurements) a partial recovery of the absorption on a much shorter (sub-picosecond) time scale, which results from the thermalization of carriers in the conduction and valence bands. This effect can substantially support the use of such devices for the generation of femtosecond pulses, where a simple recovery with the recovery time of 50 ps, for example, would be too slow.

There are methods for making the recovery of SESAMs faster, as required for the generation of rather short laser pulses. One of them is to perform the growth of the semiconductor layers at significantly lower temperatures, so that a material with a higher density of certain microscopic defects is obtained. There are other methods to increase the defect density, e.g. the bombardment with high-energy heavy ions, which are then implanted into the material. Partly, an additional annealing process at higher temperature is required thereafter. It is common to those methods that while they can substantially speed up the loss recovery, they also tend to increase the level of non-saturable losses and possibly the tendency for short-term damage and long-term degradation. The optimization of such methods should thus be used to find a reasonable compromise between faster loss recovery and the negative side effects.

The choice of semiconductor materials largely depends on the required operation wavelength. For example, for the common wavelength region between 1 and 1.1 µm, one usually uses GaAs-based devices, i.e. with a GaAs substrate, a well lattice-matched AlGaAs-based Bragg mirror and an InGaAs-based absorber with higher indium content. The lattice mismatch caused by a high indium content tends to introduce material defects, which can be detrimental in terms of non-saturable losses and device lifetime but can also speed up the recovery, which can be beneficial for femtosecond pulse generation.

For a low saturation fluence, one typically places the absorbing layer in an anti-node of the optical field in the structure (i.e. at a location with high field intensities). If several absorbing layers are required for a higher modulation depth (e.g. for application in fibre lasers), one may place each one in a separate anti-node, or several of them (e.g. 3) close to one anti-node. The use of multiple absorbing layers increases the tendency for problems with deteriorated material quality due to the lattice mismatch.

Typically, the dimensions of the top layers are chosen such that the device is anti-resonant around the operation wavelength. One could achieve a lower saturation fluence with a resonant design, but this would have the disadvantage that the effective absorption would be lower at other wavelengths, possibly encouraging the laser to “escape” the absorption by some shift of wavelength. Also, the achievable values of the saturation fluence are usually small enough with anti-resonant designs – for example, of the order of 100 µJ cm⁻² or even significantly lower. Reasonable beam radii on the SESAM are then required for the typical intra-cavity pulse energies.

Although SESAMs for 1-µm lasers have been best developed, devices for other wavelength regions such as 0.8, 1.5 and 2 µm have also been developed based on adaptive semiconductor materials (e.g. InP for 1.5-µm devices).

The fabrication of SESAMs requires sophisticated and expensive clean-room equipment for methods such as MOCVD, MOVPE or MBE. The development of a new type of SESAM (e.g. for a new wavelength region) can be time-consuming and quite expensive. However, once the fabrication technique is established, many SESAMs (each one being only, e.g. 10 mm² large) can be fabricated from a single processed wafer; the cost per device is then quite low, not contributing much to the overall production cost of a laser. Also, quite reproducible performance can be reached.

### 20.3.3 Carbon Nanotubes and Graphene

Although semiconductor-based saturable absorbers were already well established particularly for mode-docking applications, since 2004, there have been various reports on saturable absorbers based on carbon nanotubes (Set et al. 2004). Such nanotubes essentially consist of graphene layers which are wrapped up in microscopic dimensions to form rather thin tubes with diameters in the nanometre region. Depending on the detailed structure, they can have rather different optical properties, related to semiconducting, metallic or semimetallic characteristics. The detailed composition, length

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**FIGURE 20.7** Structure of a simple SESAM (semiconductor saturable absorber layer).
spectrum, etc. depends on the growth method (e.g. a laser ablation technique followed by purification steps) and its details, which can thus be optimized to obtain certain optical properties. For saturable absorption, an excitonic absorption transition of semiconductor nanotubes, showing sub-picosecond recovery characteristics, can be used. Metallic nanotubes, which are also to some extent contained in the typically fabricated materials, might act as recombination centres for the semiconducting tubes, speeding up their loss recovery.

For a saturable absorber, one uses a thin layer of randomly oriented purified carbon nanotubes, which can be sandwiched between two glass plates, for example. If one of the plates contains a highly reflecting mirror, one obtains a reflecting saturable absorber device similar to a SESAM. It is also possible to place an absorbing layer between the ends of two optical fibres, resulting in a saturable absorber which can be operated in transmission within an all-fibre ring laser set-up. It is also possible to directly deposit carbon nanotube absorbers on fibre-end faces (Yamashita et al. 2004).

A disadvantage of using carbon nanotubes is that they are random in nature, and the influence of additional purification steps makes the fabrication overall not very reproducible. More controllable conditions are possible when using pure graphene sheets (Bonaccorso et al. 2010), which may either be used directly in transmission (e.g. after transfer to a fibre-end) (Bao et al. 2011) or in evanescent devices based on a side-polished fibre (Park et al. 2015) for obtaining a stronger absorption. Single or multiple graphene sheets may be used.

It is conceivable that graphene-based saturable absorbers will replace or complement more traditional semiconductor-based devices in some areas, particularly where the limitations of SESAMs are felt. For example, they may be useful for operation in some spectral regions for which well-developed SESAMs are not available. For mode-locking of fibre lasers, an advantage may be that a large modulation depth is possible (at least for evanescent devices) without negative side effects. There might also be other advantages, for example, concerning the lifetime, but the development is at a too early stage (at least for evanescent devices) without negative side effects.

20.3.4 Laser Dyes

In the early days of femtosecond pulse generation, dye lasers were often used, in contrast to many solid-state laser gain media which provide a rather large gain bandwidth. The gain medium is typically a dye solution in the form of a dye jet exposed to pump light. It was then common to use a second dye jet (without optical pumping) as the saturable absorber.

When using the same dye for the saturable absorber as for the laser gain medium, one may be concerned that gain saturation would be just as strong as the loss saturation, so that one would overall not achieve a modulation of net gain as required for ultrashort pulse formation. However, one can simply use the absorber dye jet in a correspondingly smaller beam focus of the laser resonator, so that effectively the absorber’s saturation energy becomes smaller than that of the gain medium.

Due to the inconvenience of using dye solutions, which are relatively maintenance-intensive and short-lived, and also because hazards due to their poisonous and partially even carcinogenic nature, dye lasers were more and more replaced with solid-state lasers.

20.3.5 Artificial Saturable Absorbers

There are several techniques for making devices with reduced transmission losses for high optical powers, as required for mode-locking, but without employing any absorption. In most cases, they are based either on the Kerr non-linearity or on the $\chi^{(2)}$ non-linearity of some non-linear crystal material:

- For KLM (Salin et al. 1991), one exploits non-linear self-focusing of an intense laser beam, in most cases within the laser crystal. In case of hard aperture KLM, the losses at a subsequent optical aperture are reduced for a non-linearly focused beam, comparing with a low-power beam. In case of soft-aperture KLM, one exploits the higher laser gain for a more strongly focused beam, passing the laser crystal with increased overlap with the more strongly pumped centre. Such techniques (most often soft-aperture KLM) are frequently used for Ti:sapphire lasers, particularly when requiring the shortest possible pulse durations well below 10 fs. For reaching a sufficiently high sensitivity to the non-linear lens, such a laser usually has to be operated close to the stability limit of its resonator – which unfortunately makes it relatively sensitive to length changes, thermal lensing and other effects.

- Additive-pulse mode-locking is a method where self-phase modulation of light in an additional passive resonator is exploited. A pulse coming from the passive resonator has a phase profile such that the return of its energy into the main laser resonator is favoured for the intense centre of the pulse, but not for the temporal wings. That technique can also be fairly effective, but it requires interferometric stabilization of resonators.

- In fibre lasers, one often exploits non-linear polarization rotation in combination with some polarizing effect, e.g. in a Faraday isolator. Here, the polarization evolution and thus the overall power transmission through the polarizing element are power-dependent due to the fibre non-linearity. Unfortunately, the polarization evolution also depends on poorly controlled influences like temperature changes; therefore, this method is less suitable for industrial devices, where one often prefers polarization-maintaining fibres, excluding the use of non-linear polarization rotation.

- There are non-linear fibre loop mirrors of Sagnac type, where the effective reflectivity becomes power-dependent due to the power-dependent relative non-linear phase shifts of counter-propagating pulses in an asymmetric device. For example, the input pulse is split into two pulses, traveling through the fibre ring in opposite directions, and one of them, being
amplified in an active fibre before going through a longer passive fibre, experiences higher non-linear phase shifts than the other. Such operation principles can be realized with polarization-maintaining fibres, leading to environmentally stable devices.

- For some bulk lasers, one uses the combination of a frequency-doubling non-linear crystal in combination with a dichroic mirror. For high optical powers, much of the incident light is frequency-doubled, then effectively reflected on the mirror and converted back to the original wavelength in the backward path. For lower optical powers, leading to less efficient frequency doubling, the mirror exhibits higher reflection losses.

In most cases, the achieved non-linear response of artificial saturable absorbers is very fast, which can be beneficial for generating very short pulses. Another advantage is that a high modulation depth (as required, e.g. for fibre lasers) can often be achieved without negative side effects. On the other hand, the effective absorber parameters are often not well known, because they depend on poorly controlled influences.

A frequently encountered problem is that self-starting mode-locking is tentatively more difficult to achieve with artificial saturable absorbers – for example, with KLM. That is essentially a consequence of the fast absorber response, as explained in Section 20.2.3.3.

### 20.4 Soliton Mode-locking

In many mode-locked lasers, the pulse shaping effect of the saturable absorber is only one of several strong effects acting on the circulating pulse. In particular, chromatic dispersion and optical non-linearities (most frequently the Kerr non-linearity) are often quite important. They can have seriously performance-limiting effects but can, in some cases, also be utilized. This is particularly the case for soliton mode-locking. Here, one has substantial soliton effects in the laser resonator, i.e. an interplay of (typically anomalous) chromatic dispersion with the Kerr non-linearity: the two effects can combine such that in total there is neither a temporal broadening nor a change of the optical spectrum. For that balance, the non-linear and dispersive parameters of the laser resonator need to be adjusted such that the fundamental soliton condition is approximately fulfilled for the wanted operation conditions. The circulating pulse, which will then automatically acquire the needed temporal and spectral shape, may be mainly shaped by those soliton effects, and the saturable absorber is needed only for initiating the mode-locking and stabilizing the pulse in the steady state. In particular, the absorber needs to safely suppress the rising of any low-power background radiation, which may have a gain advantage over the pulses due to its potentially smaller bandwidth, i.e. due to its better spectral fit to the gain spectrum.

Originally, soliton effects have been employed in fibre lasers (see Section 20.6) (Mitschke and Mollenauer 1987). Here, however, a problem is that soliton pulse energies in fibres are usually very small, and the achievable pulse duration is also quite limited due to the onset of instabilities. Therefore, other mode-locking mechanisms have been developed for fibre lasers, which offer much better performance.

On the one hand, the technique of quasi-soliton mode-locking has become very important for solid-state bulk lasers (Kärtner and Keller 1995). Many of those can be designed such that the amount of intra-cavity chromatic dispersion (e.g. controlled via dispersive mirrors or a prism pair) and Kerr non-linearity are suitable for forming a quasi-soliton pulse; that is, also based on the balance of chromatic dispersion and Kerr non-linearity, although here those two effects are not continually spread in the laser resonator. For quasi-soliton mode-locking to work, one does not only need the appropriate relative strength of dispersion and non-linearity but also an appropriate absolute strength of both effects, quantified, e.g. with a peak non-linear phase shift of the order of 100 mrad per round trip. Soliton effects are then strong enough to substantially contribute to the formation of pulses with the desired pulse duration (usually in the femtosecond domain) and with clean temporal and spectral shapes. For substantially stronger non-linear phase shifts, the discrete distribution of the chromatic dispersion and non-linearity would lead to strongly disturbed pulses and correspondingly unstable pulse evolution.

In some bulk lasers, the amount of anomalous intra-cavity dispersion can be varied, e.g. through the insertion of a prism into the beam path. One then typically finds that the pulse duration (for a given pulse energy) is proportional to the overall amount of anomalous dispersion; it is hardly dependent on absorber parameters, the gain bandwidth, etc. However, the pulses become unstable as soon as they would get too short. At this point, the overall non-linear phase shift and/or the gain filtering in the gain medium gets too strong for stable operation. Therefore, details like the gain bandwidth and absorber parameters indirectly determine the minimum possible pulse duration.

### 20.5 Mode-locked Solid-state Bulk Lasers

#### 20.5.1 Initial Remarks

Although a lot of initial work in the area of ultrashort pulse generation was made with dye lasers, solid-state lasers are nowadays dominating, since they are substantially more practical, not involving short-lived and poisonous liquid dye solutions. In this section, we consider only bulk lasers, i.e. lasers based on bulk pieces of some crystal or glass material; fibre lasers are discussed in the following section.

An important aspect of doped-insulator solid-state lasers is that the saturation energy of the gain medium is typically orders of magnitude larger than the achievable intra-cavity pulse energy. Therefore, gain saturation during a single pulse is negligible, and only the cumulative effect of many pulses can saturate the gain. This leads to a simple situation for a single pulse (temporally constant gain) but also to long-term gain dynamics (during many round trips) with relaxation oscillations – which in case of mode-locked lasers mean oscillations of the pulse energy. Through the effect of a saturable absorber,
those oscillations can even become undamped for passively mode-locked lasers, which imply the so-called Q-switching instabilities (see Section 20.2.3.4). The need to maintain sufficient damping of the relaxation oscillations can introduce substantial constraints on the laser design and the achievable performance, at least for gain media with particularly low-emission cross sections.

20.5.2 Picosecond Lasers

It is relatively simple to realize a picosecond laser by incorporating a suitable saturable absorber (e.g. a SESAM) in the laser resonator (see Figure 20.8), which also contains a usual kind of laser crystal (e.g. Nd\textsuperscript{3+}:YAG or Nd\textsuperscript{3+}:YVO\textsubscript{4}). Normally, such a device is used as an end mirror, and the resonator design is made such that the fundamental mode size on the absorber is suitable for achieving an appropriate strength of absorber saturation. Additional means such as dispersion compensation are not required in that operation regime. The pulse duration is often determined essentially by the balance of pulse shortening by the absorber and pulse broadening by the limited gain bandwidth. That means that an absorber with higher modulation depth allows the generation of shorter pulses; the pulse duration is inversely proportional to the square root of the modulation depth (Paschotta and Keller 2001), while the absorber recovery time has no significant influence on the pulse duration; it only needs to be short enough to obtain stable mode-locking. The pulse duration is also inversely proportional to the gain bandwidth.

20.5.3 Femtosecond Lasers

One might imagine that femtosecond pulses can be generated simply by using a laser crystal (or glass) with substantially broader gain bandwidth; there is a wide range of broadband crystalline and glass media with active ions such as Nd\textsuperscript{3+}, Yb\textsuperscript{3+}, Er\textsuperscript{3+}, Tm\textsuperscript{3+}, Cr\textsuperscript{2+}, Cr\textsuperscript{3+}, Cr\textsuperscript{4+} or Ti\textsuperscript{3+}. However, that alone would not work. First of all, pulse broadening by chromatic dispersion would become relevant. Even if chromatic dispersion would be totally removed by dispersion compensation (i.e. by inserting some dispersive elements with a dispersion opposite to that of other elements such as the laser crystal), self-phase modulation due to the Kerr effect would become problematically high due to the increased peak power of the circulating femtosecond pulse. However, there is a simple solution for both problems: quasi-soliton mode-locking (see Section 20.4) can be achieved if the overall chromatic dispersion per round-trip is adjusted to have a suitable value in the anomalous dispersion region. That works well, allowing for stable and clean pulse formation in a wide range of pulse durations, even where the pulse shortening action of the saturable absorber alone would be too weak.

It turns out that the strength of the Kerr non-linearity, which can to some extent be adjusted, e.g. via the length of the laser crystal, is quite suitable down to pulse durations of the order of 10 fs.

For even shorter pulse durations, a number of challenges need to be met. First of all, one requires a gain material with very large gain bandwidth; the most successfully used material is Ti\textsuperscript{3+}:sapphire. Second, careful dispersion compensation is required, not only considering second-order dispersion but also dispersion of higher orders due to the large relevant frequency range; double-chirped dielectric mirror designs (Kärtner et al. 1997) are often used. Of course, any intra-cavity components such as laser mirrors and a saturable absorbers also need to have a very high reflection bandwidth. Finally, a rather fast absorber is required; for the shortest pulse durations (around 5 fs) (Sutter et al. 1999), KLM is usually used – sometimes in combination with a semiconductor absorber for reliable self-starting.

20.5.4 High-power Operation

For many years, average output powers of more than a few watts from mode-locked lasers were difficult to achieve. A breakthrough has then been obtained by passive mode-locking of thin-disk lasers, which have a number of attractive properties:

- the ability of fundamental mode operation even at very high power levels (due to well-managed thermal effects),
- the high power conversion efficiency and
- the relatively large gain bandwidth of the most frequently used gain material Yb\textsuperscript{3+}:YAG (and the potential to use some other crystal materials like Yb\textsuperscript{3+}:Lu\textsubscript{2}O\textsubscript{3} or Yb\textsuperscript{3+}:Sc\textsubscript{2}O\textsubscript{3} with even substantially larger gain bandwidth).

Not too long after the first demonstration with 16 W average output power (Aus der Au et al. 2000), much higher powers of =60 W (Innerhofer et al. 2003) and later even powers well above 200 W (Saraceno et al. 2014) have been demonstrated; pulse durations were in most cases somewhat below 1 ps. With KLM, substantially shorter pulses were achieved (Pronin et al. 2001).

20.5.5 High Pulse Repetition Rates

Typical pulse repetition rates of such lasers are between 50 and 500 MHz, corresponding to a length between ~3 and 0.3 m of a linear laser resonator. For obtaining much higher repetition rates, the main challenge is not to build much smaller laser resonators but rather to avoid Q-switching instabilities (see Section 20.2.3.4). The highest pulse repetition rate of 160 GHz...
Mode-locking Techniques

20.6 Mode-locked Fibre Lasers

Fibre lasers are a special kind of solid-state lasers where the gain medium is an optical fibre doped with laser-active ions. Such active fibres have a number of attractive properties for ultrashort pulse generation, including a substantial gain bandwidth, good coverage of wide wavelength regions and the potentially low cost and ruggedness (provided that an all-fibre set-up can be realized). However, their substantial non-linearity (resulting from the relatively long length of the gain medium and the very small mode size) and partly their chromatic dispersion often constitute substantial challenges. Since the introduction of many kinds of photonic crystal fibres (Russell 2003), there is at least a much greater variability of fibre parameters.

In principle, soliton mode-locking would appear to be the most natural technique for handling problems with dispersion and non-linearities, and it has indeed been demonstrated long ago (Mitschke and Mollenauer 1987). However, soliton pulse energies in fibres are typically very small (in the picowatt regime), which results in low output powers. The average intra-cavity powers are normally smaller than the gain saturation power, so that operation only slightly above threshold is required, which itself is a problem. Also, for pulse durations well below 1 ps, the soliton period quickly gets shorter than the practical length of the active fibre and the desirable resonator length, quickly leading to Kelly sidebands (Kelly 1992) and eventually to instabilities.

For those reasons, alternative methods for handling the dispersion and non-linearity have been developed, mostly based on various methods of dispersion management. One of those is to build stretched-pulse fibre lasers (Tamura et al. 1993) containing fibre segments with normal and anomalous dispersion; at most locations in the laser resonator, the pulses are then strongly chirped, leading to a reduced peak power and thus to a reduced non-linear phase shifts. With such methods, one can achieve pulse energies in the nanojoule domain.

Other types of dispersion management in fibre lasers have been developed which resulted in further improved performance. Most notably, it has been realized that while pulse propagation in the anomalous dispersion regime (with soliton effects) is subject to serious limitations in the context of strong non-linearities, attractive possibilities arise in the normal dispersion regime. In a normal dispersion fibre with laser gain, one can obtain self-similar propagation of parabolic pulses (Fermann et al. 2000), where the pulse duration and bandwidth grow together with the pulse energy, and wave-breaking effects are avoided. That principle has been utilized for mode-locked fibre lasers (Chong et al. 2008, Renninger et al. 2012); here, the laser resonator must contain a bandpass filter for “resetting” the pulse bandwidth after the gain medium (or some other location), which (for strongly chirped intra-cavity pulses) also resets the pulse duration. Pulse durations far below 1 ps in conjunction with multi-nanojoule output pulse energies are achieved. In a landmark experiment (Baumgartl et al. 2012), an unusually high average output power of 66 W in pulses which can be compressed to a duration below 100 fs has been demonstrated, based on a photonic crystal fibre with very large mode area in a laser resonator containing several bulk-optical elements.

While the operation principle of a soliton fibre laser (similar to a quasi-soliton bulk laser) can be relatively easily analysed, the pulse evolution in many other mode-locked fibre lasers is rather complicated (with strongly non-linear dynamics), and the dependence of the steady-state pulse parameters and the pulse stability on various device parameters can often be calculated only with numerical simulations. Therefore, the development particularly of high-performance mode-locked fibre lasers is substantially more difficult and time-consuming than for a bulk laser, which can be operated with much lower non-linearity and therefore based on much simpler operation principles.

Most mode-locked fibre lasers are passively mode-locked. Saturable absorbers are often SESAMs (usually with higher modulation depth than those used for bulk lasers) based on semiconductors, but other materials such as carbon nanotubes and graphene can also be used (see Section 20.3.3). Alternatively, one can use non-linear polarization rotation (see Section 20.3.5): in a not polarization-maintaining fibre, the Kerr non-linearity can lead to power-dependent polarization evolution, which in combination with a polarizing element can provide an artificial saturable absorber. While that method is versatile (e.g. applicable in any wavelength region without requiring special parts), it typically leads to lasers which are environmentally not very stable, because the polarization evolution is also affected by bending of the fibre, temperature changes, etc.

Certain specific practical advantages of fibre lasers in terms of stability and robustness (e.g. immunity to dirt and dust) can be achieved only with all-fibre set-ups, where the light is everywhere contained in a fibre, thus being well protected against dust. That, however, strongly limits the choice of available components; in particular, in many of the record performance figures were achieved only with set-ups containing a fibre together with bulk-optical elements and would be hard or impossible to realize with an all-fibre set-up. On the other hand, fibre laser set-ups containing bulk optics are often even less robust than pure bulk lasers, since they involve air-to-fibre interfaces which are particularly sensitive to dust and misalignment. (Launching a laser beam into a single-mode fibre typically requires micrometre precision.)

In order to overcome the power limitations of mode-locked fibre lasers, they are often combined with one or several fibre amplifiers. Active fibres can provide a high gain with a substantial gain bandwidth and high average power; therefore, they may appear to be ideal for ultrashort pulse amplification. However, particularly, the limitations arising from
non-linearities are again quite severe. For example, a 100-nJ pulse with 100 fs duration, as can easily be generated in a mode-locked bulk laser, has a peak power of the order of 1 MW, while a peak power of only 1 kW already produces substantial non-linear phase shifts within a 1-m length of a fibre with standard mode area. Although the mode areas can be increased by roughly two orders of magnitude, that is not sufficient to avoid serious non-linear phase shifts in ultrashort pulse fibre amplifiers even for moderate pulse energies. In addition, there remains the hard limit set by non-linear self-focusing at a few megawatts peak power (independent of the mode area). To some extent, the principle of chirped pulse amplification can be used to mitigate such problems, but even then the peak power limitations are far more severe than for bulk devices.

20.7 Mode-locked Semiconductor Lasers

20.7.1 Mode-locked Diode Lasers

Semiconductor laser gain media, particularly when directly electrically pumped, obviously have important practical advantages and are in principle interesting for ultrashort pulse laser sources, which could be very compact, potentially cheap and would not require another laser as pump source. The gain bandwidth – typically, some tens of nanometres – is sufficient for pulse durations in the picosecond or high femtosecond regime, as is sufficient for many applications.

There are different ways of incorporating a mode-locking device into a diode laser. For active mode-locking (Bowers et al. 1989), different types of modulators can be implemented on a semiconductor platform; in the simplest case, one can just modulate the gain section. Alternatively, one can implement electro-absorption modulators, being quite similar to active gain sections.

Passive mode-locking of diode lasers is also possible by incorporating a saturable absorber section. Comparing with the gain section, such an absorber section usually does not require an electrical contact, and it should be prepared such that the carrier lifetime is reduced in that area, so that a sufficiently fast loss recovery is obtained. That can be achieved by irradiating the material with accelerated ions, for example. (Similar techniques are used for SESAMs.)

It is also possible to use a hybrid approach, where a saturable absorber section has an electrical contact through which the carrier density can be modulated with an external signal. That way, one can achieve the synchronization of the generated pulse train with an external signal while at the same time achieving shorter pulses than with active mode-locking only.

As the length of such a semiconductor device is typically quite small (e.g. a few millimetres), the laser resonator typically needs to be extended according to the desired pulse repetition rate; otherwise, extremely high repetition rates of possibly more than 1 THz are obtained (Arahira et al. 1996).

In an extended-cavity laser, the semiconductor gain medium (including absorber sections and the like) is then just one part of a longer resonator, which may either contain free-space optical elements just as in a solid-state bulk laser (with a doped-insulator gain medium) or can be made with optical fibre. (In the latter case, one should nevertheless avoid the term fibre laser since the fibre is used only for forming the resonator not as the laser gain medium.) Mode-locked external cavity diode lasers with a fibre resonator are most suitable for optical fibre communications (Sato 2002, Jiang et al. 2005) as far as the performance requirements can be met.

A serious limitation for the achievable output pulse energy arises from the very small gain saturation energies of gain and saturable absorption in a semiconductor waveguide; more than some tens of picoseconds is difficult to achieve. Particularly for pulse repetition rates well below 1 GHz (i.e. devices with a small duty cycle), the gain non-linearity limits the average output power to a value far below what would be possible in continuous-wave operation. This is remarkably different to ion-doped insulator gain media, which typically have saturation energies far larger than the pulse energies; they can thus easily store enough energy to amplify energetic pulses even at far lower repetition rates. Note that the saturation of gain and absorption in a semiconductor is also accompanied by significant non-linear phase changes (resulting in a kind of self-phase modulation), which must be dealt with, e.g. using certain chirp compensation techniques (Delfyett et al. 1992), at least in cases with relatively high pulse energies and/or short pulse durations. In that sense, boosting the output power with an external semiconductor optical amplifier (SOA) is less problematic; it can at least not disturb the mode-locking dynamics.

20.7.2 Mode-locked VECSELs

For a long time, only laser diodes were considered in the area of mode-locked semiconductor lasers. Only in the year 2000, the first mode-locked external-cavity surface-emitting semiconductor laser was reported (Hoogland et al. 2000). Such a mode-locked vertical external-cavity surface-emitting laser (VECSEL) (Keller and Tropper 2006) contains a semiconductor gain chip, which is most often optically pumped with radiation from a laser diode (e.g. from a diode bar), and is part of a laser resonator made of bulk optical elements (see Figure 20.9). The semiconductor gain chip is used as an end mirror or folding mirror. Due to its geometry, the term semiconductor disk laser has also become common. Indeed, there are strong similarities to thin-disk lasers based on doped-insulator laser crystals, including the potential for true power scalability, provided that an effective cooling method (e.g.
based on a strongly thinned wafer mounted on a cooled metal plate) is applied.

Passive mode-locking is achieved by incorporation of a SESAM (see Section 20.3.2). Although such lasers are in many respects similar to more traditional mode-locked bulk lasers based on an ion-doped insulator gain medium, they differ from those in some important aspects:

- The semiconductor gain medium has a far lower gain saturation energy, which makes it suitable for passive mode-locking at very high pulse repetition rates without Q-switching instabilities. On the other hand, it is less suitable for low pulse repetition rates, where gain saturation could be excessive, unless the average power is reduced accordingly.
- Although the fabrication of such semiconductor gain chips requires sophisticated and expensive equipment, devices can be relatively cheap if many gain chips are fabricated together on a common wafer.
- Semiconductor gain media can be tailored to a wide range of wavelengths, including some wavelength regions which are difficult to access with ion-doped gain media. Also, other properties such as the gain bandwidth can be tailored by device design.

On the other hand, this type of device also substantially differs from mode-locked diode lasers:

- The area used on a surface-emitting semiconductor gain chip can be scaled up according to the required pulse energy (at least for optical pumping) while maintaining transverse single-mode emission due to the (comparatively long) external resonator. Therefore, far higher pulse energies are possible than with laser diodes based on small-area semiconductor waveguides (which would become multi-mode when increasing the beam area too much). Output pulse energies of hundreds of picowatts and multi-watt average output powers have been achieved early on (Aschwanden et al. 2005), and even much higher pulse energies should be possible when using even larger beam areas in conjunction with a sufficiently effective cooling scheme.
- Optical pumping substantially simplifies the design and fabrication requirements of the gain chip; it has so far been used in most cases. On the other hand, electrical pumping as for a diode laser would obviously be attractive since one would no longer need a separate pump laser diode and the pump optics; the overall power conversion efficiency could then also be higher. However, it is difficult to implement electrical pumping for larger beam areas; for example, one cannot work with an electrode ring as in monolithic small-area surface emitting lasers (VCSELs) because carrier diffusion for obtaining a reasonable transverse gain distribution works only over limited areas. For such reasons, there have been some demonstrations of electrically pumped mode-locked VECSELs (Barbarin et al. 2011) but usually with much lower performance than optically pumped devices.

In conclusion, mode-locked VECSELs constitute a new type of ultrafast laser with average output powers similar to those from traditional diode-pumped ion-doped insulator lasers (if optical pumping is employed) while being better suited for higher (multi-GHz) pulse repetition rates and for other wavelength regions. Pulse durations are often in the picosecond regime, but much shorter pulse duration down to 60 fs (Quartermann et al. 2009) has also been demonstrated.

In order to simplify the optical set-up, VECSEL gain chips with integrated saturable absorber (called MIXSELs) have been developed which despite of the additional design and fabrication challenges have reached attractive performance figures (Maas et al. 2007, Wittwer et al. 2012). For example, multi-watt average output powers in picosecond pulse trains are possible.

### 20.8 Modelling of Ultrashort Pulse Lasers

The generation of ultrashort pulses in mode-locked lasers often involves a complicated interplay of various physical effects, including potentially strong optical non-linearities. Although at least a qualitative understanding of the pulse formation and shaping processes is normally possible, a comprehensive and quantitative understanding is often highly desirable for successful implementation and optimization of such laser devices.

In some cases, pulse formation is dominated by the interplay of two or three essential effects, which can be satisfactorily modelled based on reasonably simple analytical equations. An example for this is the active or passive mode-locking of simple solid-state picosecond lasers as described in the beginning of Section 20.5, where, for example, the expected pulse duration, the required absorber recovery time and the Q-switching threshold can well be estimated with some simple formulas. Another example is quasi-soliton mode-locking in similar solid-state lasers, where the pulse duration is essentially determined by only a few parameters and the stability limit can at least be roughly estimated based on the calculated soliton period. The key parameters of such a laser design can thus be determined based on a relatively simple analysis, and if some guidelines are followed (e.g. concerning a reasonable amount of absorber saturation or of non-linear phase shifts in a quasi-soliton laser), the results are fairly predictable in a wide parameter region. Only when exploring extreme parameter regions (e.g. concerning output powers or pulse repetition rates), somewhat more sophisticated analysis is required.

Particularly in mode-locked fibre lasers, where strong effects of optical non-linearities and chromatic dispersion lead to strongly non-linear dynamics, the pulse shaping processes are so complicated that they can only be vaguely “explained” with simple physical arguments, and reliable predictions are not possible based only on a couple of simple equations. For example, the pulse duration, spectral width and spectral shape of the output of a fibre laser operating in the all-normal dispersion regime have a complicated dependence on the pump...
power and various device parameters (also on the distribution of chromatic dispersion in the resonator), and it is not possible to reliably predict performance figures and the stability of parameter regimes on a simple basis. In such cases, numerical simulations are often the only way to achieve a comprehensive understanding of the workings of such a laser, and thus to reach optimum performance and stability. Essentially, this approach involves the numerical simulation of pulse propagation in the laser over many resonator round trips, taking into account various physical effects related to the laser gain, the saturable absorber, chromatic dispersion, non-linearities, etc. Such a model can reveal under which circumstances the pulse propagation approaches a stable steady state and how the steady-state pulse parameters depend on various system parameters. Even in numerical simulations, it is sometimes difficult to identify suitable parameter sets, but at least that is much less difficult than doing the same exercise experimentally, where it is much harder to try out different configurations; also (perhaps more importantly) from experimental failures one obtains much less information concerning possible causes.

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