Laser Sources for Ultrashort Pulses

Oscillators and Amplifiers for Various Applications

Ultrashort light pulses are nowadays used for a wide range of applications including metrology, communications, spectroscopy, terahertz science, ophthalmology, and material processing. Given this great diversity, it is not surprising that the required pulse parameters such as pulse energy and duration, repetition rate and wavelength are spread over a huge region of the multidimensional parameter space.

In addition, applications may demand other properties such as compactness, reliable operation over years, energy efficiency, low cooling requirements, high beam quality, and a low price. For these reasons, there is a wide range of very different laser sources for ultrashort pulses. This article is intended to give an overview on the most important technologies and to briefly discuss their potentials.

Picosecond and Femtosecond Lasers

Ultrashort pulses are in most cases generated with mode-locked lasers [1]. Here, a single picosecond or femtosecond pulse, or sometimes a regularly spaced train of such pulses, circulates in the laser cavity (Fig. 1). Various effects act on the circulating pulse(s), but usually such a laser is operated in a steady state where the pulse parameters are more or less constant, or at least are reproduced after each completed cavity round trip. Each time when a pulse hits the partially transmissive output coupler mirror, a pulse is emitted as a useful output, and the output pulses form a regularly spaced pulse train.

Active and passive techniques can be used to enforce the emission of such pulses, rather than e.g. continuous-wave light. Active mode locking uses an intracavity modulator, which periodically modulates either the losses or the phase shift in synchronism with the cavity round trips. While the limited speed of active loss modulation usually allows only for pulse durations of tens of picoseconds, much shorter pulses are possible with passive loss modulation in a saturable absorber, e.g. a so-called SESAM = semiconductor saturable absorber mirror. In extreme cases, pulse durations of just a few femtoseconds are achieved. Particularly for very short pulses, dispersive and nonlinear effects in the laser cavity are important and introduce a number of critical design issues.

Mode-locked solid state bulk lasers based on rare-earth-doped laser crystals or glasses (e.g. Nd:YVO_4, Nd:glass, Yb:YAG, Yb:KYW) or on transition-metal-doped crystals (e.g. Ti:sapphire) typically operate with a single circulating pulse and have a cavity round-trip time between 1 ns and 100 ns (nanoseconds), leading to pulse repetition rates of tens or hundreds of MHz. With typical average output powers of the order of 1 W, this leads to pulse energies around 1 to 100 nJ. Higher energies of e.g. several microjoules are possible with mode-locked high power thin disk lasers, generating a much higher average power. Another strategy is to realize lower pulse repetition rates, but this tends to result in impractically long laser cavities and in strong nonlinear effects in the cavity.

Mode-locked fiber lasers can also generate picosecond or femtosecond pulses, sometimes with significant wavelength tunability, and in most cases with repetition rates below 100 MHz or even 10 MHz. With sophisticated additions for harmonic mode locking, multi-GHz repetition rates are also possible.

Other laser gain media allow to reach other parameter regions, for example very high pulse repetition rates (with low pulse energies) from semiconductor lasers, or other (e.g. visible) wavelengths from dye lasers. However, ion-doped solid state gain media dominate lasers for scientific and industrial applications, except for telecommunications.

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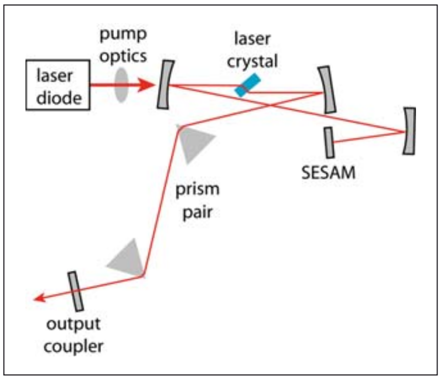

FIGURE 1: **Cavity setup of a diode-pumped femtosecond bulk laser, passively mode-locked with a SESAM. A prism pair in the resonator is used for dispersion compensation.**

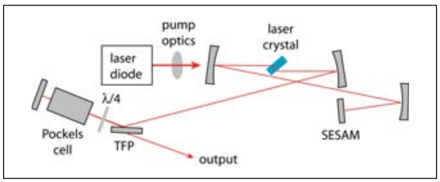

FIGURE 2: **Setup of a cavity-dumped picosecond laser. The cavity dumper contains a Pockels cell, a quarter-wave plate, and a thin film polarizer (TFP).**

Cavity Dumping for Microjoule Pulses

Even micromachining with strongly focused laser beams normally requires higher pulse energies than can be generated with most mode-locked lasers, while a lower pulse repetition rate (and thus a moderate average power) is often acceptable. This can be a case for using a cavity-dumped mode-locked laser, containing an electrically controlled optical switch (e.g. a Pockels cell and a thin film polarizer). For most of the time, the cavity losses are kept as low as possible, so that an intense pulse builds up in the cavity. With a repetition rate of some fraction of the round-trip frequency (e.g. 100 kHz or 1 MHz), the switch is operated to extract most of the energy of the circulating pulse to the output. One can thus obtain multiple microjoules. One should, however, not consider the cavity dumper as a simple add-on to any mode-locked laser; for example, the additional nonlinearity and dispersion introduced with that device, together with the temporally varying intracavity pulse energy, can totally change the pulse shaping process, and it can become difficult e.g. to reach stability and very short pulse durations.

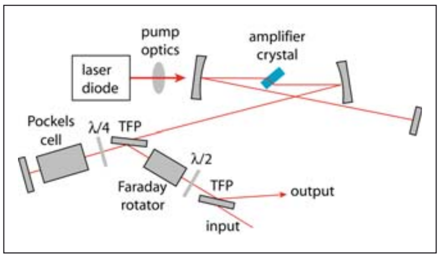

FIGURE 3: **Regenerative amplifier. A Pockels cell, combined with a quarter-wave plate and a thin-film polarizer (TFP), acts as an optical switch. The Faraday rotator allows to separate input and output pulses.**

Bulk and Fiber Amplifiers

A conceptually simpler approach for higher pulse energies is to amplify the whole output at the full laser repetition rate to obtain a higher average power (Alternatively, one may reduce the pulse repetition rate with a pulse picker, placed after the seed laser). A high amplification factor from a device based on a solid state bulk crystal will usually require an arrangement for multiple passes through the crystal. (Particularly for femtosecond amplifiers, the single-pass gain is fairly limited.) In this respect, a fiber amplifier is simpler, as it can generate a high gain in a single pass combined with a gain bandwidth broader than that of most crystals. Here, however, the dispersion and particularly the strong nonlinearity of a long fiber can have serious detrimental effects on the pulses, such as strong broadening or even pulse break-up. Such effects are particularly strong for short pulses, and can seriously limit the achievable pulse energies. Therefore, such fiber amplifiers are often operated with high repetition rates of e.g. tens or hundreds of MHz, and their strength is more the average power than the pulse energy. The essential limitation is that of peak power; significant nonlinear effects within a few meters of fiber occur already for 1 kW in fibers with standard mode area, or for some tens of kW in large mode area fibers. A possible solution is chirped-pulse amplification (see below).

Regenerative Amplifiers

Pulse energies of many millijoules or even several joules are compatible with still moderate average powers of e.g. a few watts or a few tens of watts if the pulse repetition rates are below 10 kHz. Such low repetition rates can easily be realized e.g. with an electro-optic pulse picker behind a mode-locked laser. For amplifying such pulses, one normally uses a regenerative amplifier. Such a device contains a resonator essentially like a bulk laser, but with one or two optical switches (normally of electro-optic type) for injecting a seed pulse and extracting the amplified pulse after a chosen number of cavity round trips. Using hundreds or thousands of round trips, very high gains can be easily achieved even with a relatively low-gain bulk laser crystal. This principle can be combined with chirped-pulse amplification (see below) if the peak powers in the amplifier would otherwise become too high.

Compared e.g. to a cavity-dumped system, a regenerative amplifier can reach much higher pulse energies since the processes of pulse formation and amplification are decoupled from each other. The requirement of a separate seed laser can be seen as a reasonable price for achieving superior performance while avoiding various serious technical challenges as would usually be associated with "all-in-one" approaches.

Chirped-Pulse Amplification

Peak power is a limiting factor particularly in fiber amplifiers, but also in regenerative amplifiers. An often used solution is chirped-pulse amplification. Here, one first uses a dispersive element (e.g. a grating pair) to stretch the pulses to durations of e.g. several nanoseconds before they enter the actual amplifier. After the final amplifier stage, one then applies another element with essentially the opposite dispersion, thus temporally recompressing the pulses. This means that the peak power within the amplifier is reduced by orders of magnitude, as compared to the output peak power.

Chirped-pulse amplification is nowadays widely used in bulk amplifier systems for millijoule or even joule-level pulse energies in femtosecond pulses, as required for certain areas of fundamental research (e.g. high intensity physics). It is in principle also well suited for fiber devices. However, the use of bulk grating compressors in such systems partially eliminates the practical advantages of a fiber system, as the pulses are partially propagating in air, and relaunching them into a fiber requires precise alignment. Therefore, there are attempts to eliminate all bulk elements, possibly except the final compressor grating pair. Dispersive pulse stretching is then e.g. done in a fiber Bragg grating, and the pulses stay within the fiber from the first amplifier stage (or perhaps even the seed laser, if it is a fiber laser) up to the output of the final stage. Even the final compressor gratings may be replaced with a hollow-core photonic crystal fiber, if the pulse energies are not too high. Currently, however, the technology of such all-fiber chirped-pulse amplifier systems is not yet fully developed.

Parametric Oscillators, Generators, and Amplifiers

Partly for obtaining other wavelengths of interest, various kinds of parametric devices can be used. An optical parametric oscillator, synchronously pumped with pulses from a mode-locked laser, can provide widely wavelength-tunable picosecond or femtosecond pulses. In some cases, one can even omit the oscillator cavity to obtain a parametric generator as a very simple device. Particularly interesting are parametric amplifiers, offering very high gains in a single pass through a nonlinear crystal, and a wide amplification bandwidth. In combination with chirped-pulse amplification (see above), such amplifiers are nowadays used even for generating terawatt peak powers. The strong pulse stretching within the amplifier also allows to use powerful Q-switched lasers as pump sources. There is a wide range of interesting options, many of which are not yet utilized with commercial devices – sometimes maybe just because the required technical expertise is not yet very wide spread.

Conclusions

We have seen that a wide range of different sources for ultrashort pulses exists not only because a great choice of laser gain media, but also because of very different approaches e.g. for realizing high pulse energies. As a rule of thumb, one will typically obtain nanojoule pulses directly from mode-locked lasers, microjoules from cavity-dumped lasers, and millijoules or joules from regenerative amplifiers. For moderate pulse energies combined with high average powers, fiber-based amplifier systems can be interesting. Extremely high output peak powers require chirped-pulse amplification in combination with a bulk amplifier system, while parametric devices can provide a wide range of wavelengths but also simple high-gain pulse amplification.

References

[1] Articles in the „Encyclopedia of Laser Physics and Technology“ (http://www.rp-photonics.com/encyclopedia.html) on ultrafast lasers, mode locking, cavity dumping, regenerative amplifiers, fiber amplifiers, chirped-pulse amplification, etc.