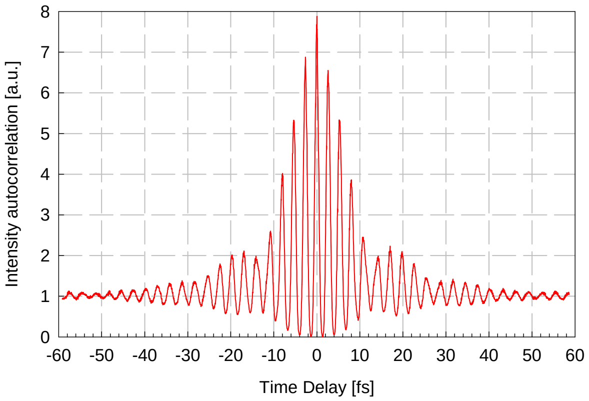
Femtosecond Ti:sapphire laser

Praktikum für fortgeschrittene Physikstudenten
(English version, 2013)



Alexander Apolonskiy, LMU München

Contents

1 Introduction

Nowadays almost all the research laboratories, dealing with high-resolution spectroscopy and non-stationary processes, use femtosecond lasers. Ti:Sa laser is the most popular among them. The goal of this Exercise (Praktikum) is twofold: to show students why this laser is so popular and to let students become familiar with it. The next exercises will be offered: i) adjustment (optimization) of the laser with aim to maximize its average power; ii) start of the Kerr-lens mode-locking regime and optimization of the output spectra; iii) measurement of the dependence of the spectra on the intra-cavity dispersion; iv) measurement of the duration of sub-40 fs pulses with autocorrelator.

The goal of this Exercise is twofold: to show students why this laser is so popular and to let students become familiar with it. The Exercises will include: i) adjustment (optimization) of the laser with aim to maximize its average power; ii) start of the Kerr-lens mode-locking regime and optimization of the output spectra; iii) measurement of the laser parameters.

The text below is based on material shown in references [1-10] on page 18. It is recommended to read one of the cited books (or other covering the topics of the Exercise). There is an additional paper to this text attached to this Exercise that helps students to familiarize themselves with the terminology and necessary laser basics. For example, introduction to terms “Gaussian beam”, “laser cavity”, “cavity modes” and “dispersion”, “mode-locking mechanisms” etc. can be found there. The paper can be downloaded with the password provided by Dr. A. Apolonskiy.

Today, Ti:sapphire laser is the most widely used commercially available tunable laser. The lasing ion in Ti:sapphire is an octahendrally coordinated $Ti3^+$ ion in $3d^1$ configuration. The laser is based on 4-level energy scheme, Fig.1; for details see, for example, [4,7]. The tuning curve of such a laser in a continuous wave regime (cw) spans the wavelength range of over 400 nm between 670 and 1050 nm (Fig.1). It means that in an optimized mode-locked (ML) regime the laser can emit pulses having such a broad spectrum. The spectrum in Fig.1 corresponds to approximately 4 fs pulse; in experiments performed so far, 5 fs pulses have been realized.

Ti:sapphire laser was invented by Moulton in 1982. Femtosecond Kerr-lens mode-locked (KLM) Ti:sapphire laser was realized by Sibbett in 1991. This laser possesses a favorable combination of properties which are up to now the best among all known broadband laser materials. First, the active medium is solid-state, that means long operational time and laser compactness. Second, sapphire has high thermal conductivity, exceptional chemical inertness and mechanical resistance. Third, a very broad generated spectrum.

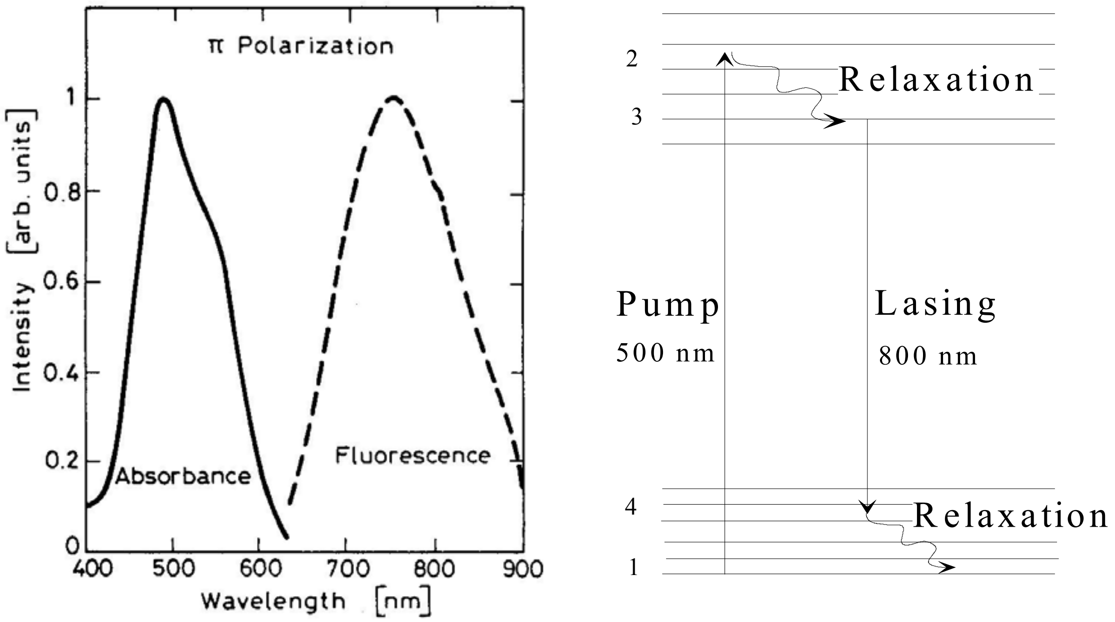


Fig.1. Absorption and emission bands of Ti:sapphire (left) and energy level scheme of the laser operation (right).

Laser in general, continuous wave regime (cw)

Each laser consists of an amplifier (gain medium) with pump, and a feedback system (an optical cavity). The amplifier gain (so-called small-signal gain g_0) must be greater than the loss in the feedback system. These are the necessary prerequisites to start the laser operation. As lasing starts, and the pump grows, the gain g becomes saturated: $g=g_0/(1+P/P_{sat})$, where P - intracavity light power and P_{sat} – so-called saturation power dependent on the medium. The gain in operating laser is equal to its total losses.

2 Mode-locking

The term “mode-locking” originates from the description of the laser in the frequency domain. In a free-running laser, the phases of a comb of equally spaced longitudinal modes (with frequency spacing Δ) can be a set of random numbers. The time domain transformation of such a frequency spectrum is an infinitive series of identical bursts of incoherent light, spaced in time by $t_r=2\pi/\Delta$, which is the time needed to complete a cavity round trip. Forcing all the modes to have equal phase – a procedure called "mode-locking" – implies in the time domain that all the waves of different frequency will add constructively at the point, resulting in a very intense and short burst of light, see Fig.2.

If the laser generates N equidistant longitudinal modes, separated by the frequency interval Δ, one can expect the pulse duration τ around $\tau\sim(N\cdot\Delta)^{-1} = D^{-1}$, where D is the spectral width.

Short pulses can be generated due to a couple of different mode-locking mechanisms. They fall into 2 different categories: **active** mode-locking and **passive** mode-locking.

Active mode locking includes amplitude or phase modulation at the repetition rate of the laser c/2L. Amplitude modulation is usually provided by standing-wave acoustooptic modulator. It periodically modulates the intracavity losses so that spontaneous optical bursts can be gained inside the "temporal window" , in such a way building up a stable optical (usually 10^{-10} – 10^{-9} s) pulse. Shorter pulses can be generated only on a base of **passive** mode-locking mechanisms. In this case a saturable absorber plays a role of a modulator. Its absorption becomes saturated (i.e. transmission becomes higher) under intense pulses, thus allowing them to survive inside the cavity. There are known several saturable absorbers: dyes, semiconductors. To generate sub-20 fs pulses, one has to rely on Kerr-lens mechanism (see below), which works as a very fast saturable absorber.

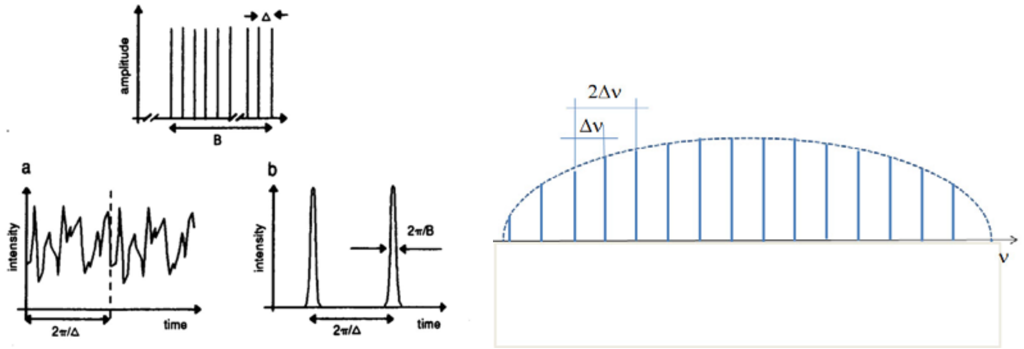


Fig.2. Left: A set of equally spaced modes (top), and the inverse Fourier transform of that spectrum. In (a), the modes have a random phase distribution. In (b), all modes are "locked" to the same phase. Right: The number of longitudinal modes of the laser cavity having optical frequencies ν is defined by the gain-loss curve (dashed line), with their spacing determined by the cavity repetition rate Δν. Though optical frequencies can not be measured with the current electronics, the difference Δν between them lies in the range of 10^7-10^8 Hz and can be measured with fast electronics present at this Praktikum.

In the steady state, the laser gain can be saturated to a level which is just sufficient for compensating the losses for the circulating pulse, whereas any light of lower intensity which passes through the Kerr medium and the aperture at other times will experience losses which are higher than the gain, see Fig.3.

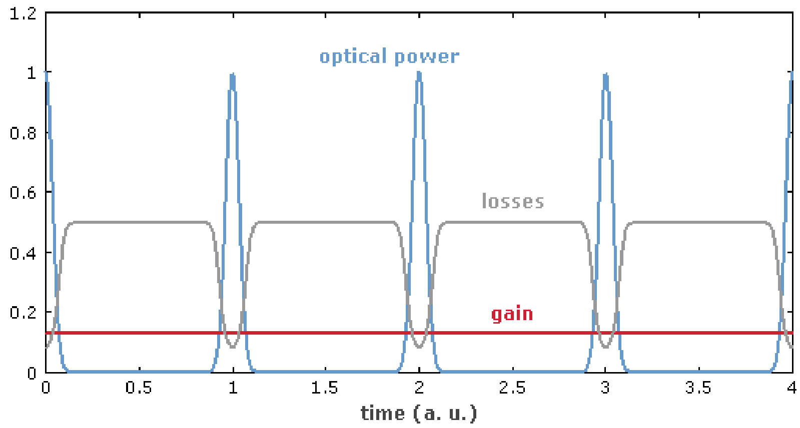


Fig.3. Temporal evolution of optical power and losses in a passively mode-locked laser with a Kerr-lens medium. The shorter the pulse becomes, the faster will be the loss modulation. The gain stays approximately constant.

3 Basics of a femtosecond laser

There are a few basic elements essential to a mode-locked laser:
- a broadband gain medium
- a laser cavity
- an output coupler
- a dispersive element
- a phase modulator
- a gain /loss process controlled by the pulse intensity or energy.

A relevant schematic representation of a fs laser is shown in Fig.4. The items listed above refer more to a function than to physical elements. For instance, the gain crystal in a Ti:sapphire laser can cumulate the functions of gain (source of energy), phase modulator (through the Kerr effect), loss modulation (through self lensing, see chapter 5 Fig.8), and gain modulation.

The signal from any free-running laser (oscillator) originates from noise. This is not different with the radiation from a femtosecond oscillator. Then several compression mechanisms will bring the noise spike into the ps or fs (1 fs $=10^{-15}$ s) range. First, a loss (saturable absorption) and gain (gain saturation) mechanism will steepen the leading and trailing edge of the pulse, reducing its duration down to few ps. Dispersive mechanisms, such as self-phase modulation – take over from the ps to the fs range. There are mechanisms of pulse broadening that prevent pulse compression from proceeding indefinitely in the cavity. The most obvious arises from the bandwidth limitation of the cavity. Other limitations arise from high-order dispersion of optical components and nonlinear effects. The pulse evolution in a cw pumped laser leads generally to a “steady state” in which the pulse reproduces itself after each cavity round trip. The pulse

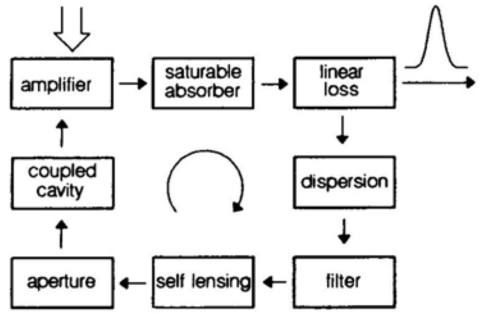


Fig.4. Schematic representation of a fs laser

parameters are such that gain and loss, compression and broadening mechanisms balance each other.

4 Characteristics of light pulses

Electromagnetic waves are fully described by the time and space dependent electric field. In the semiclassical treatment the propagation of such fields and the interaction with matter are governed by Maxwell's equations with the material response given by a microscopic polarization. The electric field can be written (in a simple form suitable for many-cycle pulse, see Fig.5) as a product of an amplitude function $\mathcal{E}$(t) and a phase term as

$E=\mathcal{E}(t)\cdot e^{i\Gamma(t)} = \mathcal{E}(t)\cdot e^{i\varphi(t)}\cdot e^{i\omega_0 t}$,

where $\varphi(t)$ is the time dependent phase and $\mathcal{E}(t)$ the field envelope and ω_0 a central

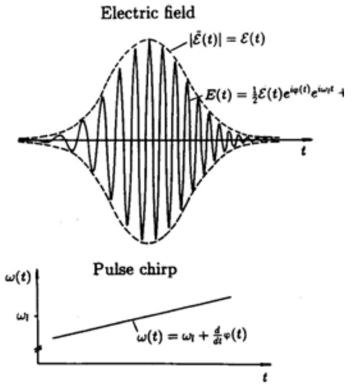


Fig.5. Electric field and time dependent carrier frequency of a chirped pulse

frequency of the pulse, respectively. The first derivative of the phase factor $\Gamma(t)$ in the equation above establishes a time dependent carrier frequency (instantaneous frequency):

$$\omega(t) = \omega_0 + \frac{d}{dt}\varphi(t).$$

For $d\varphi/dt=b=const$, a non-zero value b just means a linear correction of the carrier frequency. For $d\varphi/dt=f(t)$, the carrier frequency varies with time and the corresponding pulse is said to be frequency modulated or chirped, see Fig.5. **.** Chirp-free pulses ($d\varphi/dt=b=const$) are also called “bandwidth limited” or “Fourier limited” because the product $\tau\cdot D=\beta$ is minimal. Parameter β depends on the pulse shape. Chirp-free pulses exhibit the shortest possible duration at a given spectral width and pulse shape. If there is a frequency variation across a pulse, its spectrum will contain additional spectral components.

When a chirp-free pulse of duration τ_0 propagates through any (dispersive) medium, it becomes broaden:

$$\tau(z)=\tau_0\left(1+\zeta\frac{\phi''}{\tau_0^{\ 2}}\right)^{1/2}, \qquad (1)$$

where ϕ'' is so called group delay dispersion, defined as the derivative of the group delay of a certain spectral component with respect to the angular frequency (has units fs^2); ζ is a coefficient.

The shorter the light pulse the more it is sensitive to the dispersion. In the laser cavity, the pulse propagates through air, glass (prisms, wedges etc.) and thus becomes longer (chirped). Chirp mirrors (see below) help to keep it short.

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5 Femtosecond Ti:sapphire oscillator: Principle of operation

Schematic of femtosecond Ti:sapphire oscillator is shown in Fig.6. Green pump (at 532 nm) is tightly focused into Ti:sapphire crystal of several mm length.

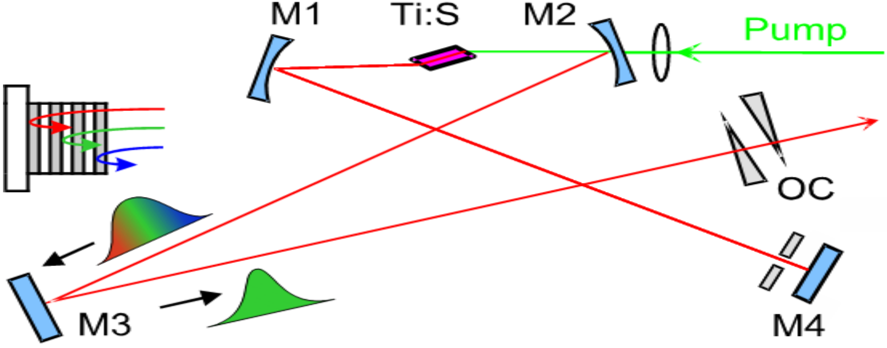
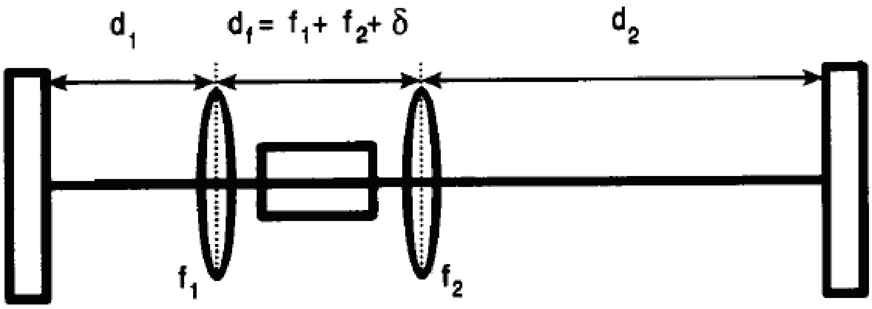


Fig.6. A schematic of femtosecond Ti:sapphire laser. The layout is based on chirped mirrors (inlet; see mirror 3).

Effectively, a linear laser cavity of Ti:sapphire oscillator can be described as a 2-mirror- and 2-lens scheme shown in Fig.7. The effective distance d_f between the 2 focusing mirrors M1 and M2 must be close to the value $d_f = f_1 + f_2 + \delta$. Here δ is a stability parameter. The range of values δ for which the resonator is stable is divided into two separate regions I and II as indicated in Figs. 7a and 7b.



Schematic of a tightly focused four-mirror laser cavity.

Fig.7. Another representation of the cavity shown in Fig.6 [10].

When the distance M1-M2 (Fig.6) is varied, the laser power has 2 maxima (so-called stability zones), see Fig.8a. The gap width between them depends on the parameter of the cavity asymmetry $\gamma = \frac{f_1^2}{f_2^2}\frac{d_2 - f_2}{d_1 - f_1}$. The larger γ, the broader the gap between the zones. Another representation of the nonmonotonic dependence of the laser parameters on the M1-M2 distance detuning is the mode size shown in Fig. 8b. The variations in the mode size in Fig.7b explain the variations in the laser power in Fig.7a.

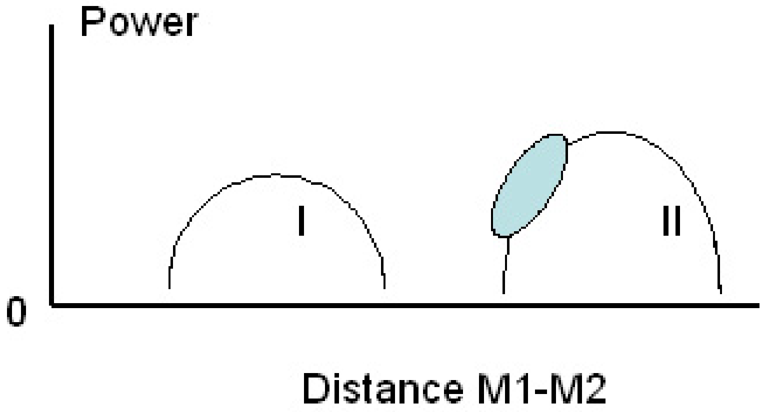
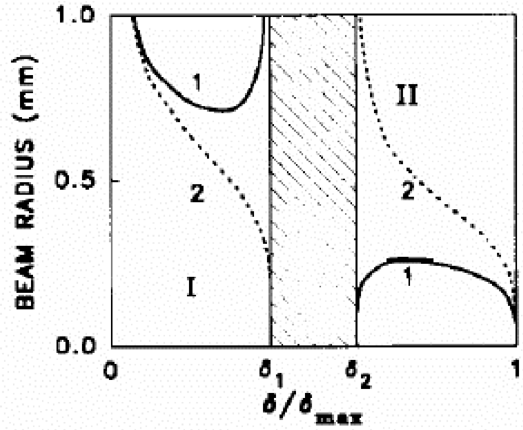


Fig.8a. Average laser power as a function of the distance between mirrors M1 and M2 at Fig.6. The marked area shows the range where mode-locking can be started.



Variation of the laser mode-spot sizes at the cavity ends versus the stability parameter δ for the representative case of $f_1 = f_2 = 6$ cm, $d_1 = 65$ cm,$d_2 = 120$ cm, and $\gamma = 1.54$. Plots 1 and 2 depict the spot sizes at the cavity ends corresponding to d_1 and d_2, respectively. The results have been obtained neglecting the effect of gain guiding.

Fig.8b. Qualitative representation of stability zones of continuous wave (cw) operation of the oscillator shown in Figs. 6 and 7. The appearance of zones is related to different length of oscillator's arms M2-M3-OC and M1-M4. Marked area: the mode size is not defined [from Ch. Spielmann et al. Ultrabroad femtosecond lasers. *IEEE J. Quant. Electron.* **30** 1100 (1994)*].*

In the Exercise, the two zones overlap and only slight gap can be resolved.
The term mode-locking means that there are certain phase relations between the cavity modes. In frequency domain mode-locking corresponds to a frequency comb of equally spaced synchronized modes. In time domain it corresponds to a light pulse traveling inside the laser cavity. A short pulse corresponds to a broad frequency comb.

Among other mechanisms that lead to mode-locking, KLM is the most effective to generate femsosecond (fs) pulses. The physical mechanism of KLM is shown in Fig.9. It uses nonlinear effect of self-focusing. This effect produces an intensity-dependent change in the refractive index of a Ti:sapphire crystal : $n=n_0+n_2I$, where n_0 is well known static refractive index of the material, n_2 is nonlinear part of refractive index and I is the pulse intensity inside the crystal. Thus, for a Gaussian-shaped beam passing through a material with the beam more intense at the center than the edge, the index of refraction of the material will become higher at the center than at the edges of the beam, thereby effectively creating a lens that in turn slightly focuses the beam within the material. In KLM, the self-focusing effect is used to preferentially select the pulsed mode-locked set of modes that generate short pulses rather than a single steady-state cw mode. One can describe the cavity mode losses α as $\alpha = \alpha_0 - kP$, where α_0 – fixed losses, P is the

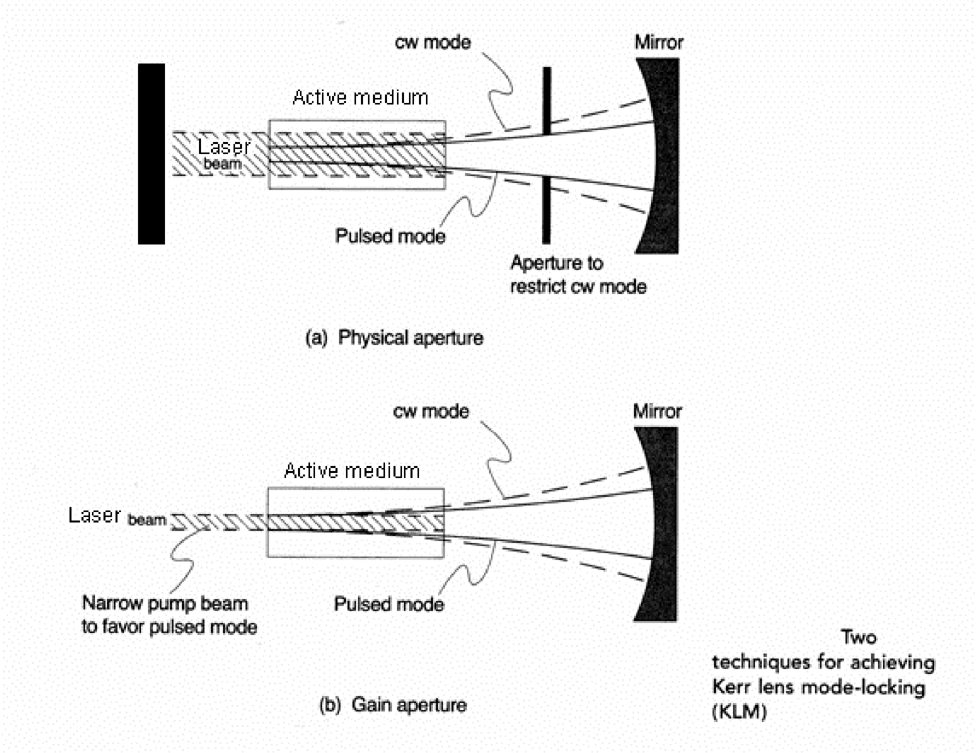


Fig.9. KLM: hard aperture (a) and soft aperture (b) [4]

intracavity power and *k* is the nonlinear loss coefficient. Fig. 9 shows two possible realization of this idea. Fig.9a demonstrates so-called KLM on hard (real) aperture. The aperture, placed between the laser gain medium and the mirror, is small enough in diameter to provide a relatively high loss for the cw mode. However, if a light pulse with higher intensity than the cw beam is generated within the gain medium, thereby providing a more favorable environment for a pulsed laser than for a cw laser. The same aperturing effect can be achieved by making a smaller-diameter laser beam than the cw mode size, as shown in Fig.9b (so-called soft aperture).

Nonresonant Kerr-lens effect is very fast (~1 fs) and can be considered as the fastest available saturable absorber.

6 Chirped mirrors

In details, principle of operation of chirped mirrors is described in Praktikum Kr 2 “Multilayer Dielectric Coatings. Mirror Characterization”. In comparison to standard dielectric multilayer mirrors, chirped mirrors provide not only high reflectance over a broad spectral range (up to 1 octave), but also precise control over the delay of different spectral components of the incident radiation (i.e. dispersion control). A properly designed chirped mirror allows to compensate for the material dispersion (Fig.10) which

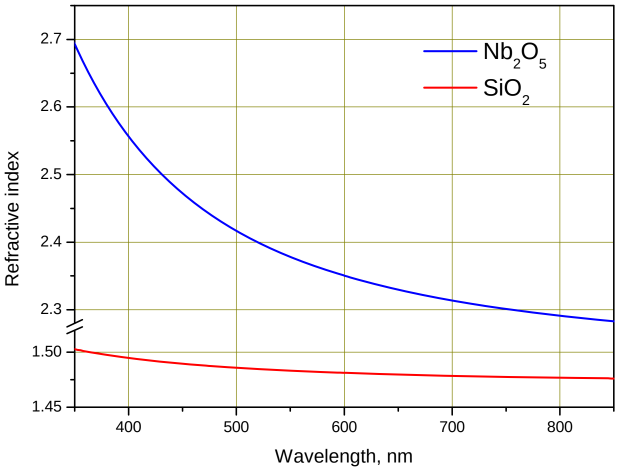


Fig.10. Dispersion of some materials (used for coating). In the visible spectral range, the pulse blue component travels with lower velocity than the red because of different phase velocity c/n

leads to pulse broadening due to the wavelength-dependent group velocity. In order to control the group delay, a combination of layers with high and low refractive indexes must have very carefully selected thicknesses, which, however, tend to increase from the surface of the mirror to the substrate. Such a structure provides different penetration depths for different spectral components and thus their different relative delays, see Fig.11. Typical coatings consist of 2 alternating materials of high and low index of refraction shown in Fig.10.

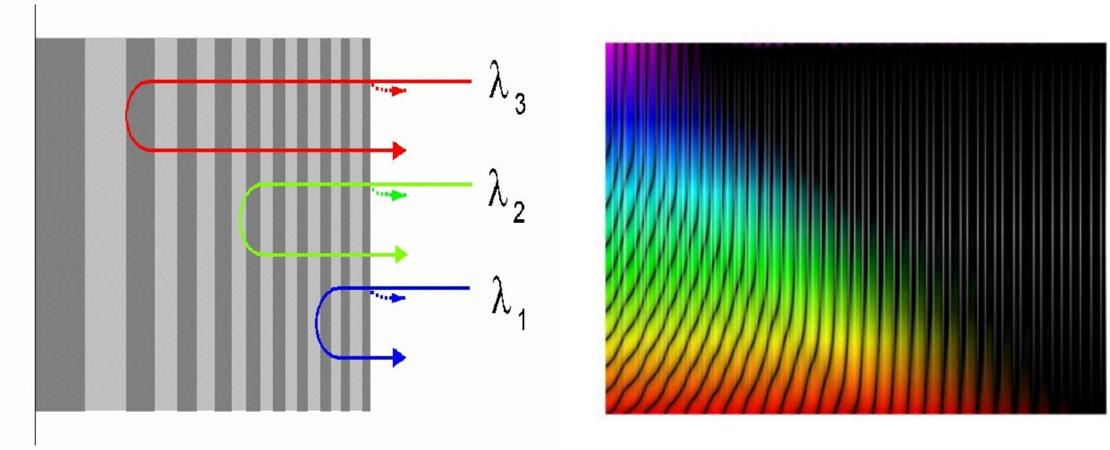


Fig.11. Schematic of a chirp mirror (left). Red components of incident radiation penetrate deeper into the structure in comparison to blue ones. Right: numerical

simulation of a real broadband chirped mirror with the electromagnetic field inside. White vertical lines: border between the layers.

Chirped mirrors were invented in 1994. Nowadays they are indispensable for producing and transporting sub-20 fs pulses. In a laser cavity, chirped mirrors have to compensate air (~20 fs^2/m), Ti:sapphire crystal (58 fs^2/mm) and fused-silica (FS) elements (wedges, OC; ~35 fs^2/mm).

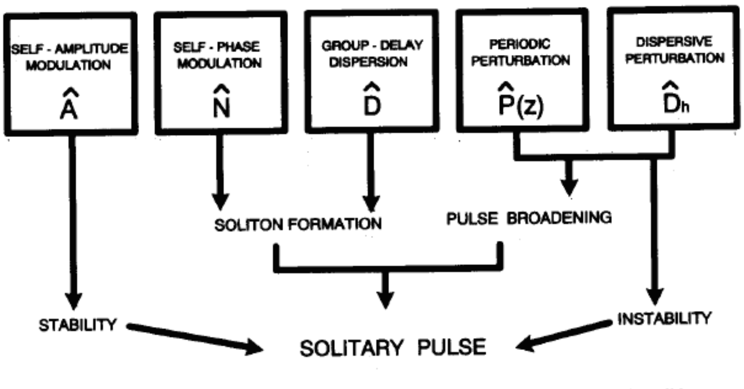
7 1) Femtosecond KLM Ti:sapphire oscillator: regime of solitary pulses [9,10]

A soliton pulse formation can be successfully performed in a **negative dispersion regime**. This regime allows to generate as short as 5 fs pulses directly in Ti:sapphire oscillator.

The main mechanism of a solitary pulse formation in negative dispersion regime include mainly self-phase modulation and net group delay dispersion. Self-amplitude modulation stabilizes the pulse. A list of all relevant mechanisms involved in the pulse formation is shown in Fig.12.

A steady-state pulse duration (full width at half maximum, FWHM) is given by [10]

$$\tau = \frac{3.5|\phi''|}{\gamma E}, \tag{2}$$



Summary of the various processes that influence the generation and evolution of femtosecond pulses in solid-state systems. Since the influence of SPM is usually much stronger than SAM, pulse formation is dominated by a soliton-like interplay of SPM and negative GDD. The primary role of SAM as the steady state is approached is to provide stabilization for the modelocked pulse against perturbations arising from higher-order dispersion and the separated action of SPM and GDD.

Fig.12. (from [10])

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[1] The chapter for advanced students

where ϕ'' – the group delay dispersion (GDD, measured in fs^2) value of the cavity, $\gamma = \frac{n_2\omega_0}{cA_{eff}}$ – the nonlinearity coefficient (where A_{eff} – the effective beam area inside the crystal, c - speed of light, ω_0 - central angular frequency), l- the effective crystal length, E – intracavity pulse energy. For realistic values ϕ''=-200 fs^2, $\gamma l \approx 10^{-6}$ W^{-1} and E~50 nJ (intracavity energy), we obtain 14 fs.

From (2) it follows that with aim to decrease the pulse duration, one has to keep the intracavity dispersion close to zero. From (1) we can also conclude that for higher pulse energy we have to increase the absolute value of the dispersion at the fixed pulse duration. It is worth noting once more that the soliton is stable only due to proper combination of such parameters as negative GDD, self-phase modulation and self-amplitude modulation (see Fig.12). The pulse duration can be estimated by using spectral width of the radiation: $\tau = k/\Delta$, where k is the coefficient that depends on the spectral shape, and Δ- the spectral width. The true value of the pulse duration can be extracted by only using information about the spectral phase. This information is available with FROG or SPIDER. The energy limitation of the regime is the area of the soliton (1) for given cavity dispersion and pulse duration. The limitation corresponds to ~1 W of average power from the oscillator (for ~ 20 fs pulses). It corresponds to ~ 5 W of intracavity average power and 2x10^{12} W/cm^2 of the intensity inside the crystal.

8 Experimental setup

A schematic of a Ti:sapphire femtosecond laser oscillator for this Exercise is shown in Fig.13; see also photos in Figs.14, 15. It consists of an oscillator head, oscillator mirrors and pump laser. The laser head (a blue box in Figs 14,15) contains 3 mm Ti:sapphire Brewster-cut crystal sitting on a cooled plate, a 50 mm focusing lens (L) and 2 focusing mirrors M1, M2 of radius of curvature (ROC) =-50 mm. A solid-state laser (Verdi, Coherent) is used as a pump laser. The output power of the laser can be varied between 0 and 10 W by the wheel on the front panel of the electronic block.

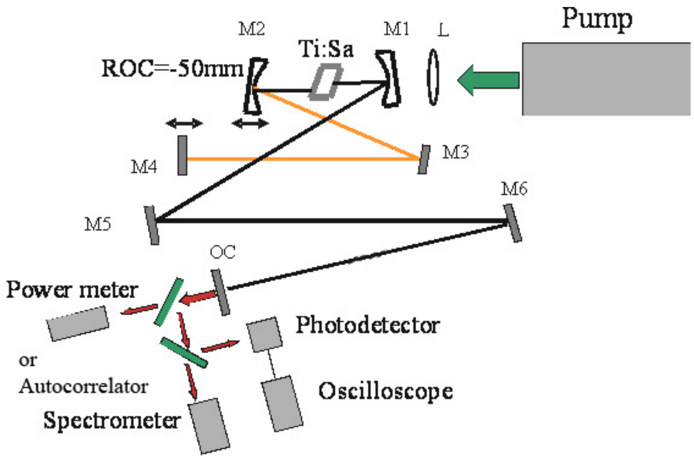

Fig. 13. A principal scheme of the Ti:sapphire laser oscillator. OC – output coupler. For details, see the text.

All the mirrors inside the laser cavity are chirped except OC (chirped mirrors: see below). The polarization of a laser beam is parallel to the optical table due to orientation of the Brewster-cut crystal surfaces. To avoid the accumulation of heat in the Ti:sapphire crystal, the supporting mount is cooled by running water. The accumulated heat leads to lensing in the crystal; the lens is not symmetric in tangential and sagittal planes and it is hard to compensate it by cavity readjustment.

Fig.14. Left: Photo of the femtosecond Ti:Sa oscillator together with Verdi pump laser and the computer for detecting spectra and the pulse train. Right: Verdi power supply (right), spectrum analyzer for recording the beat signals at the harmonics of the laser repetition rates (left bottom) and oscilloscope to record the pulse train.

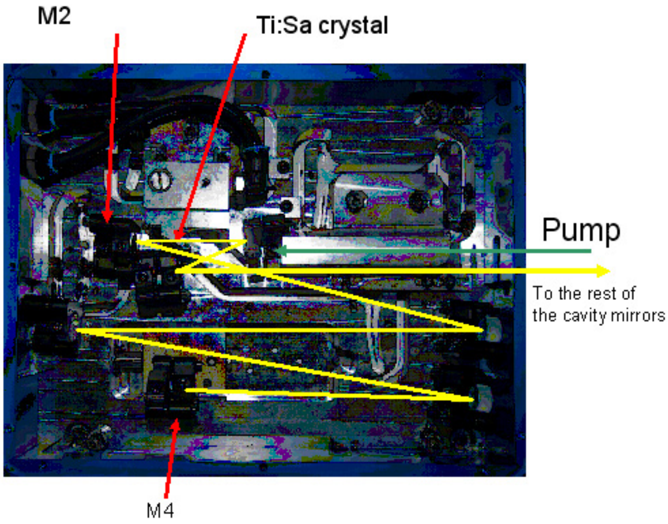

Fig.15. The Ti:Sa laser head and the beam pathway shown by yellow.

To start the oscillator in a cw mode, one has to switch on the pump and wait 1 hour until 3 W power is reached. Then, if no lasing, one has to adjust the cavity by the end mirror (output coupler, OC). For that, to switch almost all the light around to be able to see fluorescence from the crystal. On a piece of matt paper ("screen") behind the OC, one has to observe two fluorescence beams: one produced in the crystal and followed by mirrors M5, M6 to the screen, and another reflected back to another end mirror of the cavity through mirrors M6, M5, M1-M4 and returned back to the screen. The fluorescence beams have to be of similar size. For lasing, the beams have to overlap. If still no lasing, mirror M2 has to be moved along the axis M1-M2 (see Fig.13). When lasing appears, to adjust it to the maximum of cw power by tilting first OC, then synchronously OC and M4. Check the spectrum of cw regime and its central wavelength.

To start KLM, the end mirror M4 has to be slightly pushed on its translational stage (see Fig.13). After a short build-up time (~µs), the KLM regime is formed. In this regime the spectrum must be broad, at least 40 nm. If KLM does not start, mirror M2 has to be moved closer to the crystal and one more try with pushing mirror M4 to be done. Measure the spectrum (an example of the spectrum is shown in Fig.15), output power and the stability of the pulse train together with the period of the pulse train.

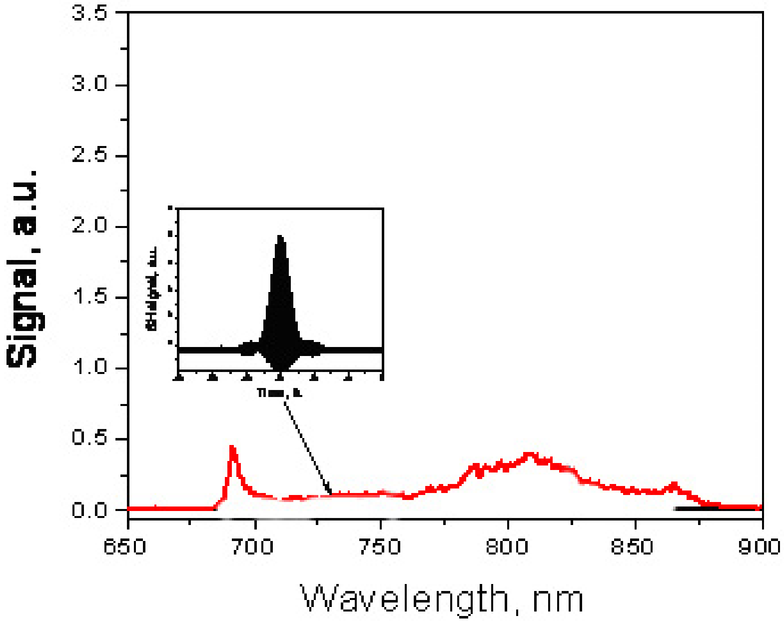

Fig. 16. Laser spectrum (red). Inlet: Autocorrelation trace corresponding to the spectrum.

To generate sub-50 fs pulses in negative dispersion regime, one has to rely on so-called soliton regime (see above). This regime can be realized only if the cavity dispersion is of proper value within the generated spectral range, in our case from 650 nm to 900 nm. The dispersion control is governed by chirped mirrors of the cavity.

9 Detection techniques

Fast photodetector and fast oscilloscope Tektronix are used to monitor the pulse train. This technique allows one to measure the pulse-to pulse stability and to control the presence of additional pulses inside the cavity, if these pulses are well separated from the main pulse (at least at 1 ns). NB: The bandwidth of the photodetector and oscilloscope are not enough to resolve the temporal structure of the pulse.

Spectrometer Ocean Optics S2000 is used to monitor the output spectrum in a range 300-1100 nm. The spectrum can be recorded on a computer. NB: the spectral resolution of the spectrometer is about 10 nm, much worse than the linewidth of the cavity modes.

Power meter Master Field (Coherent) is used to measure the output power of the laser radiation.

Spectrum analyzer Agilent in combination with fast photodetector is used to measure the pulse repetition rate $\Delta\nu$ of the oscillator and its harmonics $n\Delta\nu$ (see Fig.2, right). This detection technique is based on so-called heterodyne technique, see for first reading http://en.wikipedia.org/wiki/Heterodyne

10 Exercise

(Prior to the Exercise, please read safety rules in Appendix I)

10.1 Data to be retrieved from the experiments

What to be measured. Items 1-2 in mode-locked regime, 3, 5 – in cw, 4 – in cw and mode-locked.

1. A. The pulse period (Oscilloscope). Save the data to the notebook connected to the oscilloscope. First, organize your file directory there.
   B. The repetition rate of the pulses with a RF spectrum analyzer. Do it at the fundamental repetition rate of the oscillator (which can be determined from exercise 1) and at all its harmonics detectable with the setup. A hint: the “marker” helps to determine the frequency. Press the button “marker ” and rotate then the wheel on the panel of the spectrum analyzer until it will overlap with the signal peak.
2. Spectral width as a function of pump (Spectrometer) for 2.7, 3.2 and 3.7 and 4.2 W. The pump power can be varied by rotating the wheel on the front panel of the power supply, see Fig.14, right Save the data into the files. A hint: When the spectrum becomes periodically modulated at high pumps, save the data and see item 3 in the next section “What to be reported” while preparing the final report.
3. Output power of the laser P_{out} as function of pump power P_{pump} (cw regime) (Power meter). A hint 1: the power has to be measured between 0 and 10 W; the consequent steps between 6 and 10 W are to be 1 W and have to be done within 2 minutes to reduce the thermal effects in the active medium. A hint 2: for the whole curve one has to measure at least 20 points.

4. P_{out} as function of position of a mirror M2 in cw regime (Power meter). A hint: in the current setup, the two ranges shown in Fig.8a are overlapped and hardly resolvable. A hint: For the whole curve one has to measure approximately 20 to 40 points. One rotation ("12 hours") of the screw that varies the position of the mirror, corresponds to 0.5 mm of the mirror shift. At each point near the optimum KLM regime, please check a) whether KLM still exists and b) can be re-started.
5. To measure the current cavity layout with a measuring tape. The cover of the laser head (blue box in Fig.14 and Fig.15) has to be removed. NB: The pump laser is blocked or switched off!

Data in exercises 1 and 2 can be saved directly to the notebook as files. For that, open the intranet connection of the oscilloscope with computer (marked on the desktop as "TDS") by clicking on the icon, modify the data if necessary and go to "data" for saving. In the opened window, chose the oscilloscope channel from which the data will be saved, then modify the format to "spreadsheet", press "get" and save it into your newly opened directory at the desktop with the extension .txt. To save data from the spectrometer, click in the program menu at the button "floppy disk". For further processing, send the data saved to your e-mail address using the same notebook which is connected to Internet, or use your memory stick.

What to be reported.

0. Do not repeat the text. Write only the experiment you have done, exercise evaluated data and the results/conclusions. For each measurement 1-7 please estimate the measurement errors. The report length is expected to be ~10 pages.
1. Plot the pulse train. Determine the pulse period and the cavity length. The error bars of the measurements should be estimated and shown.
2. Determine the repetition rate and its harmonics with the data from a RF spectrum analyzer. What determines the highest detectable harmonics? Why high harmonics become less intense? Determine how accurate the repetition rate is preserved for the fundamental repetition rate and all the harmonics. Check whether there is a signal in cw regime. If not, why?
3. Plot the spectra. Pulse duration as function of pump (estimated from the spectral width, IN ABSOLUTE UNITS, fs!). Which dependence is expected from theory. "Periodically" modulated spectrum visible at high pump levels, mean a pair of close femtosecond pulses. Can you reconstruct the time interval between the pulses by using the modulation period of the spectrum?
4. Plot the data P_{out} vs P_{pump}. The threshold power: why it is not zero? What one can expect at very high pump? What type of power dependence one can expect at lower transmission of the output coupler?
5. Output power as a function of the position of a mirror M2. Please indicate the area on the curve "the signal vs the mirror displacement", where mode-locking still exists and can be re-started. What is the accuracy of the positioning of a mirror M2? In the graph show the direction to the crystal. Why displacement of M2 is so critical to the output power of the laser? (*a difficult question*).
6. From exercise 5 you have to determine why one needs so many chirped mirrors in the cavity.
7. From exercises 1, 2 and 5, you have to compare the cavity lengths. Are these lengths the same from the physical point of view?

10.2 Questions which will be asked during the final colloquium

1. Why Ti:sapphire laser is of worldwide use?
2. Stability ranges of the laser cavity
3. Power absorption in Ti:sapphire crystal
4. Polarization of the laser beam. A beam polarization quality.
5. Why the laser beam in mode-locked regime is brighter than that in cw?
6. What is the central wavelength of the cw regime in Ti:Sa oscillator? Why?
7. What is the relation between the gain and losses in the laser?
8. Negative dispersion regime.
9. How long the pulse you measured in the experiment? How it looks like in space?
10. What is the coherence length of the pulse?
11. How many (longitudinal) modes you generate in cw and ML? What is the frequency separation between them?
12. Why metal mirrors are not used in Ti:sapphire laser oscillator?
13. Calculate the cavity dispersion to be compensated by chirped mirrors. How many such mirrors do you need if, in average, one chirped mirror provides -40 fs^2 at 800 nm?

11. Books and papers to read

1. A. E Siegman. Lasers. Oxford University Press, 1986.
2. J.-C. Diels, W.Rudolph. . Ultrashort laser pulse phenomena. Academic Press, 1995.
3. W. Koechner. Solid-state laser engineering. Springer, 1999
4. W. T. Silfvast. Laser fundamentals. Cambridge University press, 2004
5. O. Svelto. Principles of lasers. Plenum Press, 1998
6. F. X. Kärtner. Few-cycle laser pulse generation and its applications. Springer, 2004
7. C. Rulliere. Femtosecond laser pulses. Springer, 2005.
8. J. Eichler, H. J. Eichler. Laser. Springer, 2003.
9. F. Krausz et al. Femtosecond solid-state lasers. IEEE J.Quant.Electron., **28** 2097 (1992).
10. Ch. Spielmann et al. Ultrabroad femtosecond lasers. IEEE J. Quant. Electron. **30** 1100 (1994).
11. http://www.rp-photonics.com/passive_mode_locking.html

Appendix I

Safety rules

The pump laser and the Ti:sapphire oscillator belong to IV safety class. Prior to the Exercise, safety rules of operation with lasers must be carefully read. They must be strictly obeyed during the Exercise.

The most important safety rules in brief

1. Direct laser beams from both the Ti:Sa laser (the central wavelength around 800 nm) and the pump Ar-ion laser (operating at a mixture of lines in a range of 476-515 nm) are extremely dangerous for your eye. You have to place yourself so that to be able to watch the laser beam only from aside. Never place your eye against the beam even it is blocked! The shield can fall down or lasing can appear during the cavity adjustment.
2. Reflections from the mirrors are of the same danger for your eye as the direct laser beam. Accidental reflections from metal/glass surfaces are of comparable danger. You have also to avoid contact of the beam with your skin. **For most of the operations (except the laser start, see item 3) with the laser, you must wear special goggles.**
3. To adjust the laser cavity and start lasing, you may avoid goggles because they suppress the fundamental @800 nm and prevent a proper and convenient adjustment of the laser cavity. Be sure during the starting procedure that the appearing laser beam will not be reflected into your eye by no means.
4. First, place and fix the power meter head so that the fluorescent beam from the laser falls onto the center of it. Then use the *matt* white paper screen behind the OC and between the power meter during the starting procedure. You have to inform the people around that you start the laser and possible danger occurs.
5. When you adjust the laser or equipment near the laser, avoid placing your eye at the height of the laser beam.
6. Shield all the unused reflected beams so that there are no direct laser beams escaping the optical table.

Laser safety in details

(From Wikipedia, the free encyclopedia http://en.wikipedia.org/wiki/Laser_safety).

A laser is a light source that can be dangerous to people exposed to it. Even low power lasers can be hazardous to a person's eyesight. The coherence and low divergence of laser light means that it can be focused by the eye into an extremely small spot on the retina, resulting in localised burning and permanent damage in seconds. Certain wavelengths of laser light can cause cataracts or even boiling of the vitreous humor, the fluid in the eyeball. Infrared and ultraviolet lasers are particularly dangerous, since the body's "blink reflex", which can protect an eye from excessively bright light, works only if the light is visible.

Classification

The lasers which are involved into the Exercise, belong to class 4: highly dangerous; even indirect scattering of light from the beam can lead to eye or skin damage. This generally applies to laser powers of more than 500 mW, or lasers that produce intense pulses of light. Although the intensity of the beam may be only a few times that of bright sunlight, when it enters the eye the beam can be focused on a very small spot near its diffraction limit.

The laser powers mentioned above are typical values; the classification is also dependent on the wavelength and on whether the laser is pulsed or continuous. Also, even a high power laser may be assigned to a low safety class if it is enclosed so that no laser radiation can leave the case and injure a person.

Guidelines

The use of eye protection when operating lasers of class 4 is strongly recommended and required in the workplace by U.S. Occupational Safety and Hazard Administration (OSHA). However, it is common practice in scientific research that operators do not use eye protection even while working with class-IV lasers. The problem is that the use of safety glasses over longer times is often uncomfortable, and in many types of optical experiments it is also somewhat inconvenient. For example in spectroscopy, the experimental arrangement is constantly being modified and fine-tuned, during which it often is necessary to see where the beam is going. This is often most simply achieved with the naked eye, rather than e.g. with a camera. In this situation, many scientists assign a higher priority to convenience and comfort than to safety, and routinely breach the laser safety regulations.

Although not everybody agrees on these practices, most scientists involved with lasers agree about the following guidelines.

- Everyone who touches a laser should be aware of the risks. This awareness is not just a matter of time spent with lasers; to the contrary, long-term dealing with invisible risks (e.g. from infrared laser beams) tends to reduce risk awareness, rather than to sharpen it.

- Many experimentalists feel quite secure when dealing with an experiment carried out on an optical table, where all laser beams travel in the horizontal plane only, and all beams are stopped at the edges of the table. Experimentalists just make sure never to put their eyes at the level of the horizontal plane where the beams are travelling, in case that a reflected beam accidentally leaves the table. This guideline significantly reduces the risk, but a lot of hazards still remain when no protecting glasses are used:
    - In a non-trivial optical setup, it is very hard to ensure that all mirrors, filters, and lenses are strictly kept in a vertical position at all times, particularly when the setup is constantly modified.

  - Accidental upward reflections can be caused by watches and jewelry. Even if those are banned, operators often use metallic tools (e.g. screwdrivers) which can get into a beam path. Note that reflections normally stay unnoticed until an accident occurs.
  - When picking up something from the floor, closing the eye may not give sufficient protection against multi-watt laser beams, as the eye's lid is partially transparent, particularly for infrared light.
  - Nobody can guarantee that all these hazards can be safely avoided without wearing protecting glasses, when infrared laser beams with non-negligible powers are used in the experiment. Working without glasses under these circumstances means trading safety for convenience. This is commonplace, but not safe, and for this reason not allowed by any official safety regulations.

- Adequate eye protection is required by anyone in the room, not just the one who tweaks an experiment.

- High-intensity beam paths (say, above 200 mW) that are not frequently modified should be guided through black tubes. For ultraviolet beams, this is necessary even for much lower power levels due to the risk of skin cancer.

- Particular care is to be taken when optical elements such as mirrors are inserted or removed. Alignment can also be dangereous because it can e.g. make a laser beam hit some metallic post, from where it can be reflected.

Appendix II

Pump Laser Verdi V10