Part 2: Laser in pulsed operation

1 Theoretical principles

1.1 Generation of short laser pulses

The output power of existing continuous wave laser systems is between a few milliwatts (He-Ne lasers) and a few hundred watts (Nd or CO_2 lasers). However, there is a possibility to increase the output power of the laser for a small period of time by pulsed laser operation. Solid-state lasers are particularly suitable for this purpose, as they can achieve pulse peak output powers of up to 10^{12} W. This value corresponds approximately to the average electrical energy generation of the entire world. The difference, however, lies in the period in which this performance is achieved. While all the power plants together reach this value continuously, a single laser produces this high output power only for a duration of 10^{-13} s.

In this case, the extremely short pulse duration appears to be disadvantageous, but there are also applications which exactly require this. One example is laser ablation, which is a method in material processing. Here, a small volume of material at the surface of a work piece can be evaporated if it is heated high enough in a very short amount of time. On the other hand, supplying the energy gradually would allow the heat to be absorbed into the bulk of the piece, never attaining a sufficiently high temperature above the evaporation point of the material.

Other applications rely on the very high peak pulse power to obtain strong non-linear optical effects, like it is necessary for efficient second-harmonic generation or for optical parametric oscillators (OPO) which converts an input laser wave into two output waves of lower frequencies.

Finally, ultra-fast laser spectroscopy techniques use laser pulses for the study of dynamics on extremely short time scales (attoseconds to nanoseconds). Different methods are used to examine dynamics of e.g. charge carriers, spin polarizations, or the motions of atoms and molecules. Many different procedures have been developed spanning different time scales and photon energy ranges. One example is the so-called pump-probe experiment, where a first laser pulse creates some kind of imbalance in the investigated sample (e.g. photo-excited charge carriers or a spin polarization) and a second laser pulse, which has a variable time delay to the first one, probes the time evolution of this imbalance.

In principal, there are three possibilities for generating short laser pulses:

1. Using a pulsed pump source,
2. temporarily changing the quality factor of the optical resonator (Q-switching),
3. and the so-called mode coupling.

1.2 Short revision

To better understand the methods of pulsed pump sources and the quality modulation of a laser system, it is advisable to once again look at the processes in a four-level laser system (see Fig. 1(a), the following is a short revision of the far more detailed explanations in the first part of the introduction - equations and definitions of the physical quantities can be found there).

By optical pumping, electrons are excited from level N_0 to level N_3. The latter state has a very short lifetime, so that it remains almost unoccupied even under heavy pump powers. Because of non-radiative transitions, electrons go from level N_3 to the metastable level N_2. The transition of an electron from level N_2 to level N_1 creates a photon of the laser frequency $\nu = \frac{E_2 - E_1}{h}$. Since the level N_1 also has a very short lifetime, like N_3, the electron now quickly returns to the ground level N_0. Since the respective lifetimes of the levels N_3 and N_1 are very short, these states remain almost unoccupied. Once optically pumped, inversion occurs between levels N_2 and N_1.

When the laser starts up, the active medium spontaneously emits photons in all directions. However, a small part of the emission occurs along the axis of the resonator. These spontaneous photons can travel back and forth through the resonator and hence the active medium. As the laser medium posses a finite size and the probability for the induced

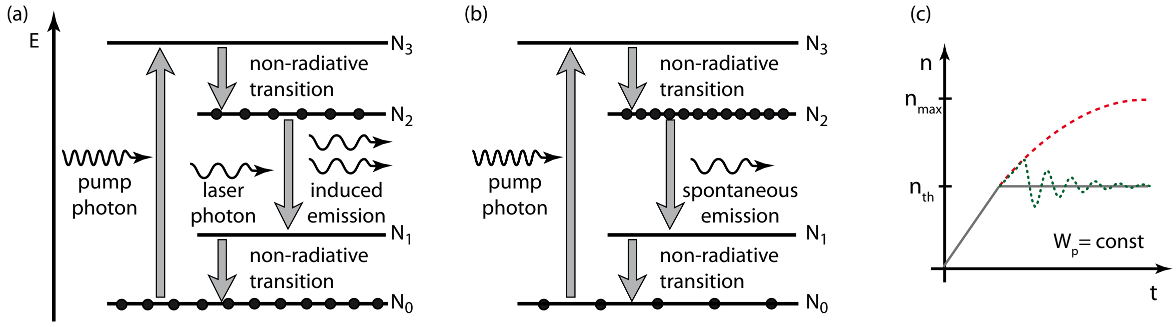


Figure 1: Schematic diagram of a four-level laser system with (a) and without (b) optical resonator. (c) Population inversion with an optical resonator under ideal conditions (gray solid line), with an optical resonator with transient effects (green dotted line) and without an optical resonator (red dashed line) as a function of time at a constant pumping power.

emission is also finite, this optical feedback is a necessary requirement for a photon to create several replicas before it is coupled out of the resonator (as the actual laser beam) or is lost due to absorption or diffraction processes. The increase in the photon field ρ over times then triggers more and more induced emission events from laser level N_2 to laser level N_1.

Finally, a steady case condition with a positive photon density ($\rho > 0$) is reached. In this case no inversion beyond the threshold inversion value can be generated even with the strongest pumping mechanisms. Instead of the population inversion, the photon density increases with increasing pumping power (see Fig. 1(c)), which thus limits the inversion at the threshold value because of an increased probability of induced emission. If this equilibrium has been established, the number of electrons at the excited level N_2 can be considered constant. The light inside the resonator is now amplified by the amplification factor G as much as it is attenuated by the losses L (scattering, reflection and transmission) during a passage through the laser medium. Thus, for stationary operation follows: $G \cdot L = 1$.

1.3 Pulsed pumping and spiking

So far only the steady state solution of the rate equations was discussed. However, in practice, conditions of perturbed equilibrium occur (amongst other things, due to slight mechanical disturbances of the laser resonator or fluctuations in the pump light intensity). Small deviations of the population inversion or of the photon density from the equilibrium lead to damped harmonic oscillations of n and ρ, respectively. However, larger deviations from the equilibrium may also lead to undamped, non-harmonic oscillations of the output power, which make the occurrence of large power spikes possible. In this case, the first power peak ("initial spike") can exceed the steady-state value of the output power by magnitudes. A deviation from the steady state condition undoubtedly occurs when the pump-light source is switched on. In this case the rate equations are only solvable numerically and hence only a qualitative view of the so-called spiking will be discussed in the following.

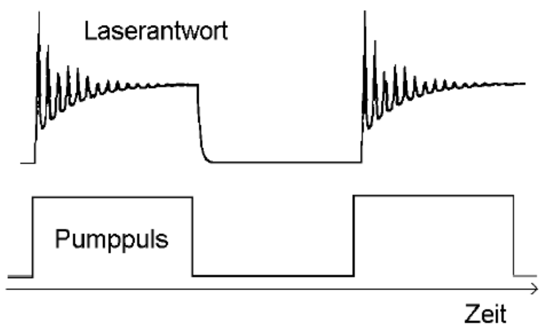


Figure 2: Spiking

Until the threshold pump power P_{th} is reached, there are practically no photons present in the resonator. When the population inversion reaches the threshold, a photon field is formed. However, due to the resonator propagation time, it takes a while until the photon density reaches the steady state value. During this period the inversion, which rises linearly with time, increases above the value of the threshold inversion (see green dotted line in Fig. 1(c)).

This in turn means a more rapid increase in the photon density and hence a temporarily higher output power compared to the steady state condition (see Fig. 2). Due to induced emissions, the population inversion is then reduced so quickly that it drops to a value below the threshold and the laser oscillation stops. In this way, the radiation field collapses, the laser intensity decreases. The laser goes off until enough atoms have been excited by the pumping process and the intensity can rise again. The process starts again, but this time the laser is only slightly below the threshold and the expected inversion overshoot is not so large as before. In this manner the system approaches the steady state condition.

This kind of pulsed laser pumping can yield laser pulse lengths down to 10^{-6} s.

1.4 Q-switching

In case of the pulsed pumping method, there is still a functional optical resonator present all the time. For the Q-switch method this is not the case anymore. Rather, the optical resonator is temporarily "switched off" by an optical element, which covers one mirror (see Fig. 3).

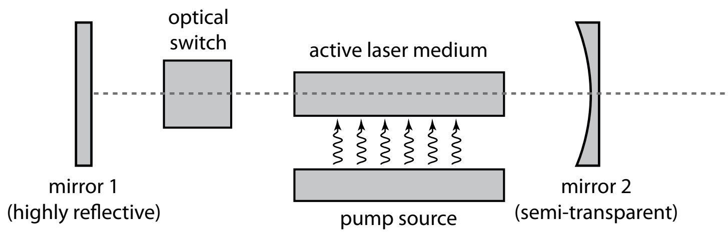


Figure 3: Schematic of a laser system with an optical switch for pulse generation.

A Q-switch is achieved by putting some type of variable and controllable attenuator inside the optical resonator. When the attenuator is switched off, the laser beam can pass it without significant loss. Therefore, the photons inside the optical resonator can travel forth and back between the two mirrors and laser operation is possible. But when the attenuator is switched on, light which leaves the active medium along the optical axis cannot experience the feedback effect but is rather coupled out of the system at mirror 2 or reflected/absorbed at the optical switch. This attenuation inside the cavity corresponds to a decrease in the quality factor (Q-factor) of the optical resonator.

Now the active laser medium is pumped while the Q-switch is set to prevent the feedback of light. Hence, there is no significant photon field ρ inside the resonator and accordingly no induced emission processes (see Fig. 1(b)). As a result the population of level N_2 and therefore the population inversion can now grow above its steady state laser threshold n_{th} (see Fig. 1(c)). With increasing population of level N_2, also the spontaneous emission increases. As a result a new equilibrium value n_{max} is reached, but with much higher value of inversion (much more electrons are at the level N_2 than in case of a non-covered mirror). Thus, excitation energy has been stored in the Nd-YAG crystal. The gain G for a passage through such a medium is now substantially greater than in the steady case condition: $G \cdot V > 1$.

At this point, the Q-switch is now quickly changed from low to high Q, allowing feedback and the process of optical amplification by stimulated emission. Because of the large amount of energy already stored in the active laser medium, the intensity of light in the laser resonator builds up very quickly ("light avalanche"). This also causes the energy stored in the medium to be depleted almost as quickly. The net result is a short pulse of light output from the laser.

Example: If $G \cdot V = 2$, the light intensity is thus doubled, the initially spontaneous emission is increased by a factor of $2^{40} \approx 10^{12}$ after 40 cycles. The light output of the spontaneously emitted photons is about 10^{-9} W and increases by the amplification to 10^3 W. If one assumes a resonator length of 50 cm, the light takes a time of approx. $7 \cdot 10^{-8}$ s for these 40 revolutions.

With an ideal optical switch, the transmission increases from zero to one in no time. This means that the switch, which first is completely impermeable to laser radiation, becomes completely transparent at the moment of opening. Real switches, however, always require a finite period of time to change the transmission from the initial value $T_1 > 0$ to the final value $T_2 < 1$. The switch is thus neither completely impermeable at the beginning, nor completely transparent after opening. Therefore, real switches always cause losses.

In principle, there are two main types of Q-switches:

1. Active Q-switches are externally controlled, variable attenuators. This may be a mechanical device such as a shutter or a spinning mirror/prism placed inside the cavity, or (more commonly) it may be some form an electro-optic device such as a Pockels cell (which is also used in this experiment). The reduction of losses (increase of Q) is triggered by an external event, typically an electrical signal. Therefore, the pulse repetition rate can be externally controlled.

2. Passive Q-switches are saturable absorbers, a material whose transmission increases when the intensity of light exceeds some threshold. The material may be an ion-doped crystal, a bleachable dye, or a passive semiconductor device. Initially, the loss of the absorber is high, but still low enough to permit some laser operation once enough energy is stored in the active laser medium. As the laser power increases, it saturates the absorber, i.e., rapidly reduces the resonator loss, so that the power can increase even faster. Ideally, this brings the absorber into a state with low losses to allow efficient extraction of the stored energy by the laser pulse. After the pulse, the absorber recovers to its high-loss state and the population inversion can recover. The next pulse is delayed until the energy in the active medium is fully replenished.

Compared to mode locking, which will be discussed in the following section, Q-switching leads to much lower pulse repetition rates, much higher pulse energies, and much longer pulse durations in the order of 10^{-9} s.

Active Q-switch: The electro-optical switch

The electro-optic switch in this experiment consists of a combination of a polarizer and an electro-optic element named Pockels cell (see Fig. 4). The Pockels cell consists of a crystal, which gets birefringent when a voltage is applied to it. For light with a wavelength λ that travels through a medium of length L with an index of refraction n the incurred phase in the medium is given by:

$$\varphi = 2\pi n L/\lambda \tag{1}$$

A birefringent crystal now has both an ordinary and an extraordinary axis with different index of refraction (n_o and n_e, respectively). The electric field vector of a light beam that is traveling through a birefringent crystal can now be separated into two components along these two axes. Thus, the two components experience a phase retardation equal to:

$$\Delta\varphi = \frac{2\pi}{\lambda}\left(n_\mathrm{o} - n_\mathrm{e}\right) L. \tag{2}$$

The so-called Pockels effect now states that the occurrence of birefringence scales with an applied electric field E:

$$\Delta n = n_0^3 \cdot r_\mathrm{eff} \cdot E, \tag{3}$$

where n_0 is the refractive index without any applied field, r_eff is a material constant, and E is the applied electric field strength. Here, the crystal is placed between two capacitor plates and hence the electric field E is in first order given by the applied voltage V and the thickness of the crystal. Therefore, at a certain voltage the phase retardation equals to $\pi/2$ and the crystal acts as a $\lambda/4$ wave plate.

After passing through the polarizer, the laser beam is linearly polarized. The polarizer is now adjusted in such a way that the plane of polarization hits the optical axis of the birefringent crystal under 45°. If the crystal acts as a $\lambda/4$ plate, the light which passes through the crystal will then be circularly polarized. At the mirror the light is reflected and experiences a phase jump of 180°. If the light passes through the birefringent crystal once again, the circularly polarized light becomes linearly polarized again. The polarization plane, however, is perpendicular to that of the original beam. And thus this light cannot pass the polarizer. Therefore, the quality of the resonator is reduced and laser operation is not possible.

If the voltage at the Pockels cell is switched off, the polarized light can pass through the crystal without changing the polarization direction. The polarizer is no longer an obstacle for the reflected light wave. Hence, the quality of the resonator increases. In the experiment, instead of a polarizer, a Brewster window is used which fulfills the same purpose.

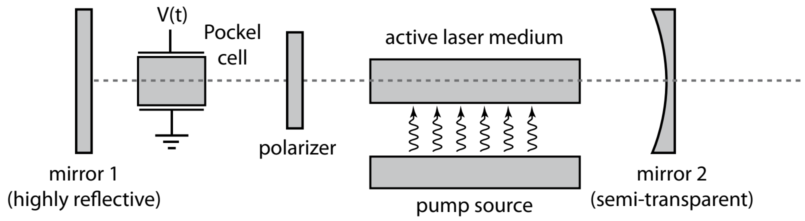


Figure 4: Schematic of a laser system with a Pockels cell as an optical switch for pulse generation.

Brewster window

The Brewster window used in the experiment is a glass slide. If unpolarized light is incident on this glass plate, the E-vector can be divided into two components: One component parallel to the plane of incidence and one perpendicular to the plane (see Fig.12). The parallel component is called π (or p) component, the perpendicular σ (or s) component. In the case of completely unpolarized light, the two components have on average the same amplitude. If the light falls on the glass plate (or another dielectric) at a certain angle, the so-called Brewster angle θ_P, the reflection coefficient for the π-component is equal to zero (see Fig. 5(a) and Fresnel equations). Accordingly, the reflected beam is linearly polarized and its plane of oscillation is perpendicular to the plane of incidence. However, the intensity of the reflected beam is small (about 10% of the incoming beam).

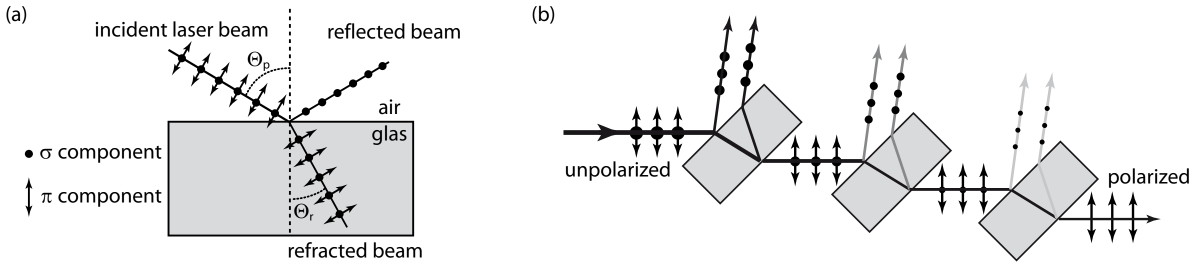


Figure 5: (a) Illustration of the polarization of a light beam which hits the surface of a glass slide at the Brewster angle. (b) Polarization of a light beam by subsequent transmission through a glass slide.

The π-component of the incident beam is completely refracted at the angle θ_P, but the σ-component only partially. The transmitted beam is thus only partially polarized. If the beam successively crosses more Brewster windows, the transmitted beam will more and more π-polarized (Fig. 5(b)). The reflected beam and the refracted beam are perpendicular to each other, so that:

$$\theta_p + \theta_r = 90^\circ \quad (4)$$

The law of refraction for this case states:

$$n_1 \sin\theta_p = n_2 \sin\theta_r \quad (5)$$

Substituting equation 4 into 5 yields:

$$\tan\theta_p = \frac{n_2}{n_1}. \quad (6)$$

This law was derived by Sir David Brewster in 1812 and therefore equation 6 is called Brewster's law. Brewster found this equation empirically, but it can also be derived from Fresnel's formulas.

If π-polarized light is incident on the glass slide under the Brewster angle, there is no reflected beam as the light is transmitted completely. If, on the other hand, σ-polarized light falls on the plate at the same angle, the losses on the Brewster plate are high (about 10% are reflected). In the resonator, these losses are sufficient to prevent the laser from oscillating as the photons pass through the Brewster window several times and therefore the losses add up.

1.5 Mode-locking

In the mode-locking technique, the laser pulses are generated by interference of standing waves (longitudinal resonator modes). This is the most effective method for generating short laser pulses and thus achieves pulse durations in the femtosecond range (10^{-15} s).

The first step in understanding the mode-locking is, that all lasers produce light over some natural bandwidth or range of frequencies. So far only an ideal four-level laser system was discussed, where all laser active atoms inside the medium are absolutely equal and without external disturbances. But even in this case induced emission and therefore amplification of light does not occur only for photons with the sharp energy ΔE_{12}, but also for photons in a narrow energy range $\Delta E_{12} \pm \delta E$.

The reason for this are the finite upper- and lower-level lifetimes, which lead to an energy-broadening δE of the transition energy caused by the energy uncertainty principle. Therefore, even this ideal laser system exhibits a so-called finite gain bandwidth, over which amplification of light can occur (Fig. 6(a)). Of course, for laser operation the product of the gain G times the losses L of the whole laser system has to be larger than 1.

In real crystals much larger gain bandwidth exists caused by different broadening mechanism. E.g. the disorder in the laser active crystal allows different laser-active ions to occupy sites with different electric fields, so that the narrow-bandwidth contributions from different ions are averaged out, resulting in a broad overall gain spectrum. Another broadening mechanism is the interaction of the electronic states with lattice vibrations, i.e. with phonons. For example, a typical helium-neon laser has a gain bandwidth of about 1.5 GHz (a wavelength range of about 0.002 nm at a central wavelength of 633 nm), whereas a titanium-doped sapphire (Ti:sapphire) solid-state laser has a bandwidth of about 128 THz (a 300 nm wavelength range centered at 800 nm).

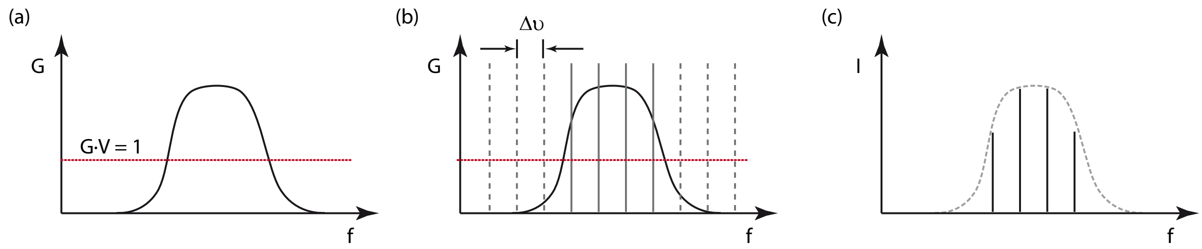


Figure 6: (a) Schematic laser bandwidth spectrum with the amplification threshold $G \cdot V = 1$. (b) as in (a) but with the longitudinal modes of the optical resonator. (c) Resulting laser output spectrum.

The second factor which determines a laser emission frequencies is the optical resonator. As it was derived in the first part of the introduction, the mode spacing between the longitudinal modes within the optical resonator with a length L is given by:

$$\delta \nu = \frac{c}{2L}. \tag{7}$$

These modes are depicted together with the gain bandwidth in Fig. 6(b). The active laser medium thus only amplifies the modes that fulfill both the resonator condition and the amplification condition $G \cdot V = 1$. The resulting laser output spectrum is shown in Fig. 6(c).

According to equation 7, a laser with a mirror separation of 30 cm has a frequency separation between longitudinal modes of 0.5 GHz. Thus for the two lasers referenced above, the 1.5 GHz bandwidth of the HeNe laser would support up to three longitudinal modes, whereas the 128 THz bandwidth of the Ti:sapphire laser could support approximately 250,000 modes.

In a simple laser, each of these modes oscillates independently, with no fixed phase relation between each other. The individual phase of each mode may vary randomly due to such things as thermal changes in the material of the laser. In lasers with only a few oscillating modes, interference between these modes can cause beating effects in the laser output, leading to fluctuations in intensity. In lasers with many thousands of modes, these interference effects tend to average to a near-constant output intensity.

But as soon as all modes have a fixed phase between each other, the laser output behaves quite differently. Instead of a random or constant output intensity, the modes of the laser will periodically constructively interfere with one another, producing an intense burst or pulse of light. Such a laser is said to be “mode-locked”.

The duration of the pulse is determined by the number of modes which are oscillating in phase. If there are N modes locked with a frequency separation $\Delta \nu$, the so-called mode-locked bandwidth is $N\Delta \nu$. The wider this bandwidth, the shorter the pulse duration from the laser. A mathematical analog to this effect is e.g. the Fourier series of a rectangular pulse function, where the actual form of the rectangular pulse is approximated by a series of sine and cosine terms. The more frequencies are included in the Fourier series, the better the shape of the rectangular pulse is approximated.

One can show that for a pulse with a Gaussian shape, the minimal possible pulse duration Δt is given by:

$$\Delta t \approx \frac{0.441}{N\Delta\nu}. \tag{8}$$

According to equation 8, the shortest Gaussian pulse for the HeNe laser with a 1.5 GHz spectral width is around 300 ps. Whereas for the 128 THz bandwidth of the Ti:sapphire laser, the pulse duration is only 3.4 fs. These values represent the shortest possible Gaussian pulses consistent with the laser linewidth. In a real mode-locked laser, the actual pulse duration depends on many other factors, such as the actual pulse shape, and the overall dispersion of the resonator.

1.6 Active and passive mode-locking

There are both "active" and "passive" methods for producing mode-locking. Active methods typically use an external signal to induce a modulation of the light inside the resonator. Passive methods do not use an external signal, but rely on placing some element into the laser resonator which causes self-modulation of the light.

A common active mode-locking technique is to put a so-called acousto-optic modulator into the resonator. The key element of an acousto-optic modulator is a transparent crystal through which the light propagates. A piezoelectric transducer attached to the crystal will vibrate according to an oscillating electric signal, which then creates sound waves in the material. These can be thought of as moving periodic planes of expansion and compression that change the index of refraction. Light can then experience Bragg diffraction at the traveling periodic refractive index grating generated by the sound wave. The optical frequency of the scattered beam is Doppler-shifted by an amount equal to the frequency of the sound wave (depending on the propagation direction of the acoustic wave relative to the beam). If the modulator is now driven at the same frequency as the cavity-mode spacing $\delta\nu$, then the diffracted light correspond to the two cavity modes adjacent to the original mode. Since the diffracted light is in-phase, the central mode and the adjacent modes will eventually be phase-locked.

Passive mode-locking can e.g. be accomplished with a saturable absorber, which exhibits an intensity-dependent transmission. Ideally a saturable absorber will selectively absorb low-intensity light, and transmit light which is of sufficiently high intensity. When placed in the resonator, a saturable absorber will attenuate low-intensity constant wave light. However, because of the somewhat random intensity fluctuations experienced by an un-locked laser system, any random, intense spike will be transmitted preferentially by the saturable absorber. As the light in the cavity oscillates, this process repeats, leading to the selective amplification of the high-intensity spikes, and the absorption of the low-intensity light. After many round trips, this leads to the mode-locking effect of the laser.

Another method for passive mode-locking utilizes the fact that short laser pulses have high intensities and therefore strong electric field strengths. Hence, non-linear optical effects become important (see first part of the introduction). E.g. a lens can be build from a highly non-linear material in such a way that high-intensity light is being focused differently from low-intensity light. If an aperture is carefully arranged in the lens focus point of the high-intensity light, one can significantly increase the losses for the low-intensity light, so that laser oscillation almost exclusive is present for the high-intensity laser pulses.

Questions and tasks for self-check

1. What are the advantages of a pulsed laser?
2. Which methods are available for generating short laser pulses?
3. How does quality modulation work?
4. How does a $\lambda/4$ wave plate works?
5. Why can the peak pulse power of a pulsed laser system surpass the average power of a cw-laser?
6. How does an electro-optical switch works?

2 Experimental procedure

Both the diode laser which is used for optical pumping and the Nd-YAG-laser which will be assembled in this experiment can lead to irreparable damage of your eyes! The emitted radiation lies within the not visible infrared range (805 nm or 1064 nm, respectively) which increases the danger. Therefore, the continuous use of laser safety glasses throughout the whole experiment is mandatory! An unattended operation of the laser system is not allowed! Reflections of the laser beam into the room (e.g. caused by watches, rings, etc.) should be prevented at all cost. Both the diode laser and the Nd-YAG-laser are Class 3B laser systems, i.e. that a focused beam can burn your skin and ignite materials.

ATTENTION: Before positioning/removing any kind of optical element, always decrease the injection current to the minimal value and turn the safety key to the "Off" position.

IMPORTANT: Only touch the optical components at the black powder coated surfaces! A fingerprint on an optical component will be considered as a MAJOR ERROR in the execution of the experiment and will be considered as such in the final mark scheme.

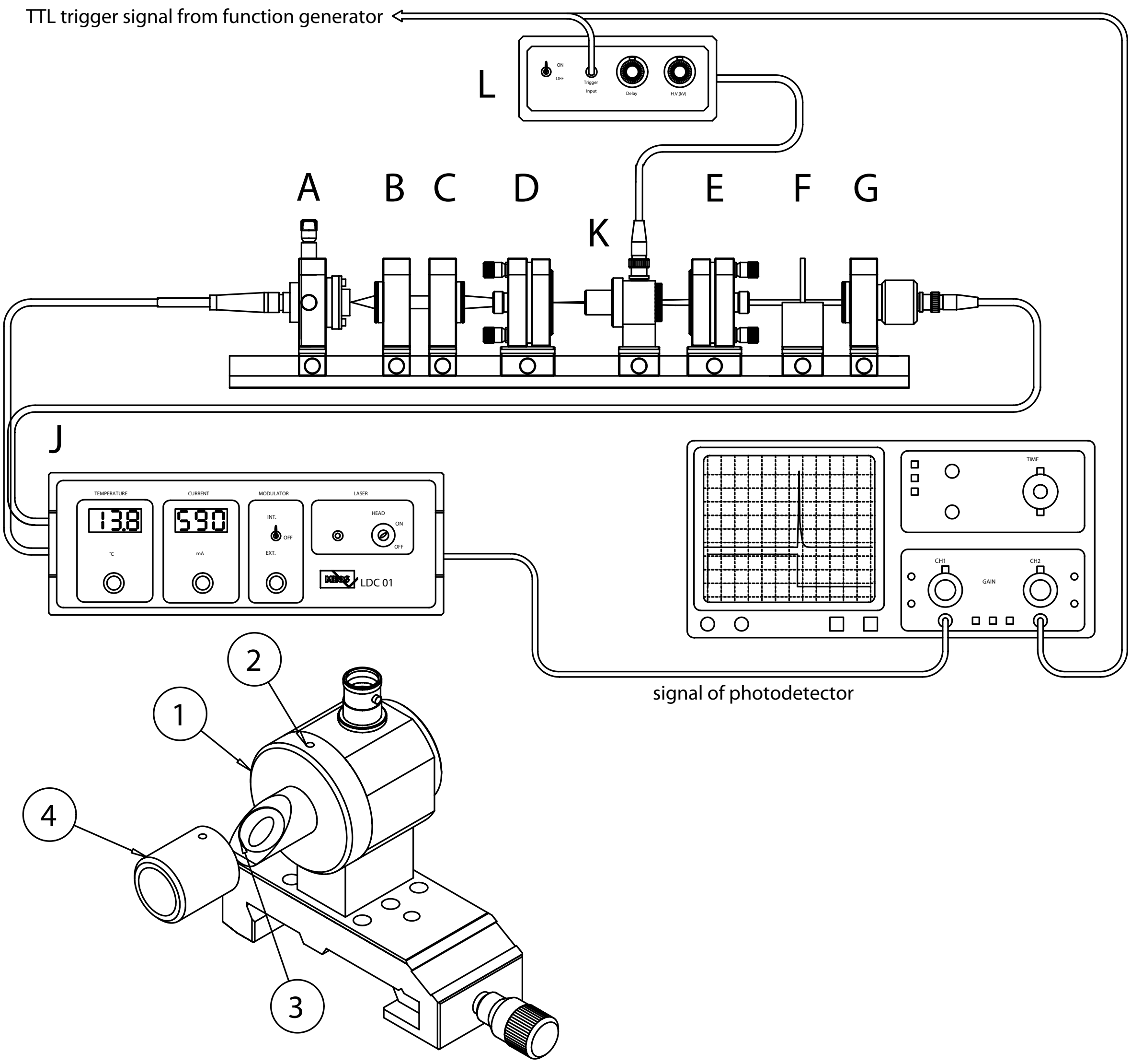
And because it cannot be mentioned often enough: ALWAYS WEAR LASER PROTECTION GLASSES!

2.1 Additional components of the Nd-YAG-laser system

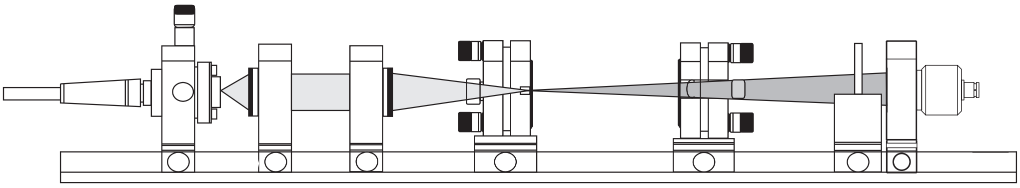
K Pockels cell and Brewster window: The Pockels cell is provided with an rotatable Brewster window (1) made from a glass plate ($n = 1,5$). By loosening the screw (2) the cap containing the window can be rotated. If a maximum of output power is reached, the screw is fastened again. The Brewster window (3) is covered by an additional cap (4) which prevents the damage of the window as well as shielding laser stray light coming from the window.

L Pockels cell driver: The Pockels cell is connected to the high-voltage power supply with a special high voltage cable (MHV cable, do not use a BNC cable!). The trigger input of the driver is connected to a function generator.

M A function generator will deliver a rectangular trigger signal for the Pockels cell driver. The Pockels cell driver will only work properly, if the amplitude of the trigger signal is high enough.


TTL trigger signal from function generator
L
A
B
C
D
K
E
F
G
J
TEMPERATURE
CURRENT
MODULATOR
LASER
13.8
590
°C
mA
INT.
OFF
EXT.
HEAD
ON
OFF
LDC 01
TIME
CH1
GAIN
CH2
signal of photodetector
1
2
3
4

2.2 Spiking



It is assumed that the laser system is left in the condition of the last experiment ("Frequency doubler") from the day before.

Remove the KPT crystal, remove the power sensor, and change the filter plate back to the RG1000 type. If available, also remount the R100-2 type mirror.

The spiking curve becomes more regular when fewer transversal modes oscillate. Therefore, adjust the resonator in such a way, that the emitted laser radiation is more or less a point (use an IR converter card for monitoring). If available, you can also place an aperture with variable diameter (a so-called iris diaphragm) into the resonator to suppress most of the transversal modes.

Now use the internal modulator of the injection current to periodically pump the Nd-YAG laser. If the photo diode signal is displayed on the oscilloscope, you can record the resulting spiking curve.

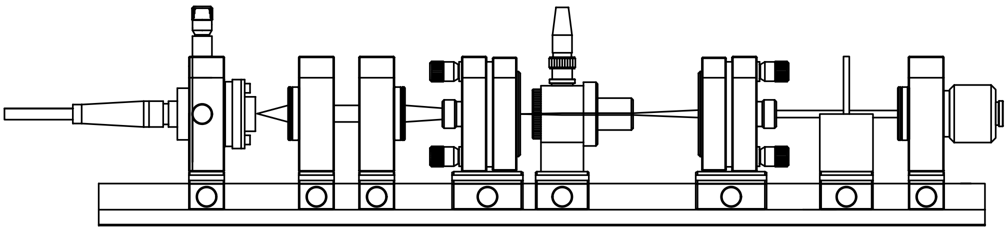
Spiking can be most impressively demonstrated if the laser is operated just above its threshold.

2.3 Active Q-switch

Switch off the internal modulator and set the injection current to 600 mA. Once again adjust the laser system to the highest possible output power (Guiding values are: 20 – 40 mW in case of the "SHG" mirror and 100 – 200 mW in case of the "R 100-2" mirror).

Important: Note the highest possible output power at 600 mA for this step and for every further adjustment step (i.e. after putting the Pockels cell and then the Brewster window into the resonator). You will need these values to compare the maximum peak power to the power in cw-operation. Furthermore, you can quantify the optical losses caused by the additional optical elements.

Now remove the Brewster window from the Pockels cell by loosening the screw with a hex key. Then put the Pockels cell near module D inside the optical resonator. As the thick crystal can cause quite a huge beam displacement, a new adjustment of the resonator is necessary. Because of large optical losses, the achieved output power will be reduced by approximately a factor of 20.



In the next step, put the Brewster window on the Pockels cell, but do not tighten the screw yet. Then connect the Pockels cell to its driver and the driver to the function generator. Set the frequency of the function generator to 1 kHz.

Before switching on the high voltage driver, its setting should be at the minimum. Also make sure that the laser beam hits the middle of the photo diode module G.

Now switch on the laser. Slowly increase the high voltage setting of the Pockel cell driver and simultaneously rotate the Brewster window. At some point you should observe the pulses on the oscilloscope.

Increase the amplitude of the pulses by adjusting the mirrors of the resonator, the angle of the Brewster window and the high voltage. **Important:** If the Brewster angle is not set correctly, there is an additional continuous wave contribution next to the pulses. By rotating the Brewster window a full turn, you will see the appearance and disappearance of the pulses and a change in the dc-voltage value. A certain minimal dc voltage reading at the oscilloscope is unavoidable and is caused by the current-to-voltage converter and the voltage amplifier. Nevertheless, an unwanted cw-contribution is discernible with the help of the oscilloscope. The pulse will depopulate the upper laser level and hence the cw-contribution will temporarily vanish. As a result the voltage signal right before the appearance of the pulse is slightly higher than $100 - 200\ \mu$s after the pulse. Eventually, the inversion will be grown strong enough that the cw-contribution starts again. This will be seen as a small increase in the oscilloscope signal between to successive pulses.

2.4 Averaged power vs frequency

If the laser system is optimized for maximal peak amplitudes, put the power sensor (module I) into the system and measure the average beam power $\bar{P}$ as a function of frequency (at an injection current of 600 mW, temperature setting corresponding to the equations in the first part of the instructions).

There will be three different regimes: First the power will linearly increase with frequency, then there is an unstable plateau, and finally the power will vanish for high frequencies. Measure enough data points to illustrate all three regimes.

Guiding values are: In case of the “SHG” mirror, the maximal power is several hundred μW to 1 mW at the end of the linear regime, and in case of the “R 100-2” mirror it is several mW.

2.5 Pulse shape vs frequency

Now remove the power sensor (module I) and look at the shape of the pulses as a function of applied frequency. Record some pulse shapes for the first two regimes.

Try to explain the change in pulse shape with frequency and how this is connected with the measurement of the averaged power versus frequency.

2.6 Determination of the peak power

To determine the peak power of the laser pulses, both the measurements with the oscilloscope and the one with the power sensor have to be combined. The sensor can measure a power signal, but it is time-averaged over many, many pulses. On the other hand the oscilloscope can record the time-resolved pulse shape.

Make a plausible assumption concerning the relationship between the measured voltage at the oscilloscope and the power of the pulse. With this derive a formula with which you can calculate the maximum peak power.