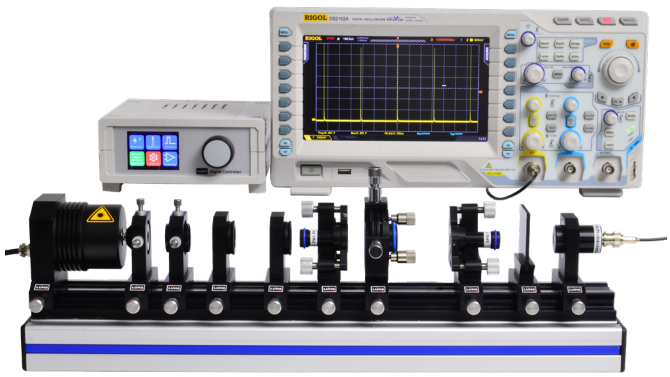
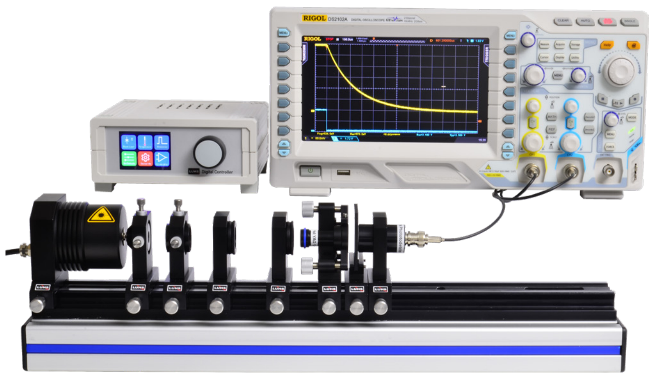
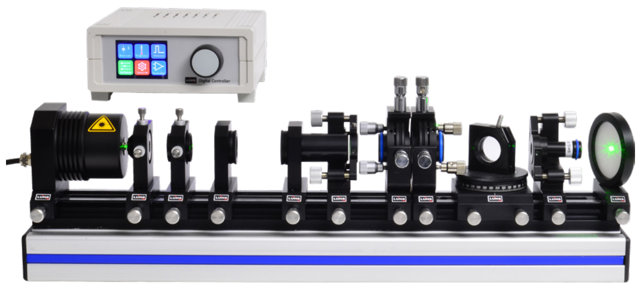
UM-LE06 Manual for:

LE-0600 Diode pumped Nd:YAG Laser
LE-0700 “Green” SHG with Diode pumped Nd:YAG Laser
LE-0800 Generation of Q-Switch Laser Pulses







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1.0 Introduction

The first ever operated laser was an optically pumped solid state laser. This laser has been discovered by Theodore Maiman in 1960 [1]. The active material was the element 24, the Chromium, which was embedded into a transparent host crystal. The host crystal is a transparent corundum crystal also known as Aluminium oxide (Al_2O_3). The Chromium dopant replaces some Aluminium atoms thus changing the optical properties of the crystal. The so doped crystal shows a red colour and is also known as ruby.

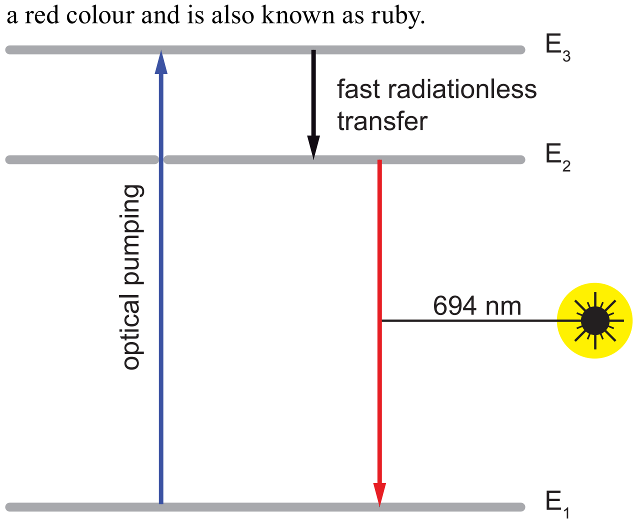


Fig. 1: Simplified three level system of the ruby laser

The ruby laser boosted a tremendous research effort and initiated a hunt for other more promising laser materials. One of the major drawbacks of the ruby laser was the fact that it could only operate in pulsed mode. This is due to its three level laser system as shown in Fig. 1. By excitation with suitable light Chromium ions of the ground state E_1 are excited and consequently populate the excited state E_3.

From here the only way back to the ground state is via the E_2 energy level. In a first step the excited Cr ions are transferring a fraction of their energy to the lattice of the host crystal and are assembling in the energy level E_2. The transfer from $E_3 \rightarrow E_2$ is very fast and takes place in a few picoseconds.

Note:
Population inversion is hard to achieve in a three level energy system like the ruby laser.

However, the energy level E_2 is a so called metastable state. That means that the Cr ions are trapped in this state, since an optical transition to the ground state is forbidden due to the rules of quantum mechanics. Nature is not strictly merciless, and a forbidden transition still has a certain probability and can be considered as a weak optical transition. Nevertheless, the Cr ions will remain approximately 5 micro seconds in the E_2 state (which is fairly long for optical transitions) before they reach the ground state again.

$$N_2 - N_1 = \frac{2\pi n^2 \nu^2}{c^2} \qquad \text{eq. 1}$$

We learned that a laser process can only start, if the so called Schawlow-Townes [2] oscillation condition of eq. 1 is fulfilled. The equation shows a simplified version of it. In this equation n stands for the index of refraction, ν for the laser frequency and c for the speed of light, N_2 is the population density of energy level E_2 and N_1 accordingly. Only if N_2-N_1 is greater zero, the equation yields useful results. In other words, the population density of state E_2 must be greater than that of state E_1. This situation is also termed as population inversion.

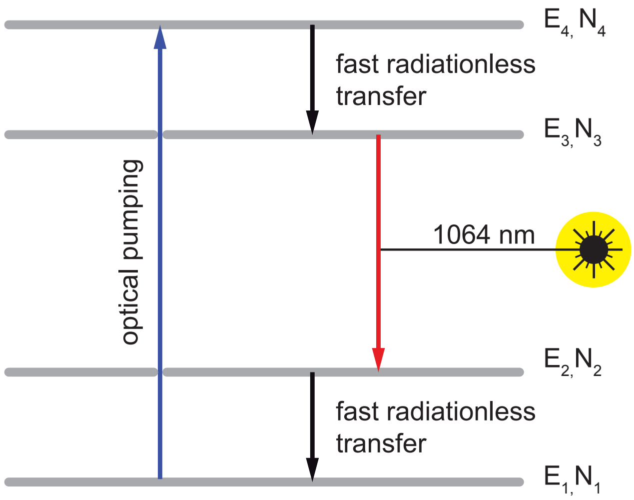


Fig. 2: Four level laser system

Such an inversion can hardly be reached since N_1 is the population of the ground state, which is always populated. Only under "hard pumping" most Cr ions will be transferred to E_2. We have just 5 microseconds time to almost empty the ground state before the delayed transfer from E_2 starts to populate the ground state.
This is one of the reasons that a ruby laser in general emits pulsed laser radiation. On the search for a more suitable laser material the element 60 (Neodymium) turned out to be a good candidate. Laser operation of Neodymium was first demonstrated by J. E. Geusic et al. at Bell Laboratories in [4]. In the same way as for Chromium atoms of the ruby laser the Neodymium atoms are embedded in a host crystal which in this case is a composition of Yttrium, Aluminium and Oxygen $Y_3Al_5O_{12}$ forming a clear crystal of the structure of a garnet. The Neodymium is replacing a small fraction of the Yttrium atoms and due to the integration inside the lattice it is triply ionized Nd^{3+}.
The outstanding property of such a Nd:YAG laser lies in the fact that the laser process takes place inside a 4 level energy system (Fig. 2). This and the possibility of creating more than 10.000 W output power made this laser to an indispensable tool for a great variety of applications.
Furthermore, this laser system is an integral part of the lectures in photonics since it exhibits the important 4 level laser system [7]. From the Fig. 2 we can conclude that the laser oscillation condition of eq. 1 is already fulfilled once the optical pumping takes place. In this system the population inversion is created between the energy levels E_3 and E_2 and since E_2 is far above the ground state, its population is zero. So even a single excited Neodymium ion provides an population inversion. The Nd:YAG laser began their triumphant success as workhorse in medicine and industry.
Based on the energy levels of the Neodymium only invisible laser radiation could be created. However the technology of optically second harmonic generation (SHG) or also termed as frequency doubling could bring visible laser radiation. The most important one has been the green 532 nm

radiation created by SHG of the strong 1064 nm radiation of the Nd:YAG laser. Even by third and fourth harmonic generation deep UV radiation could be created based on the non-linear optical effects.

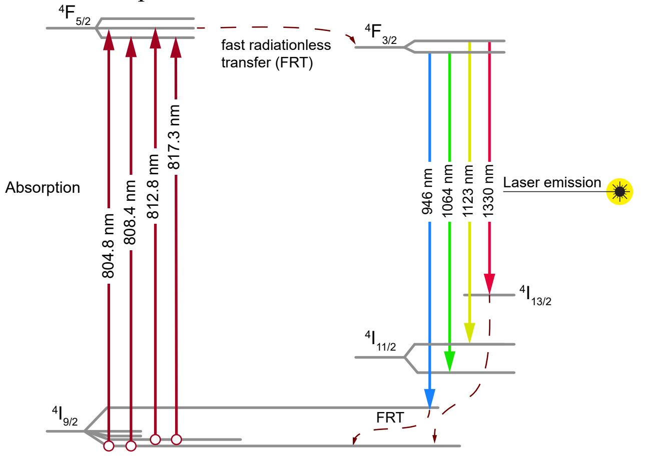


Fig. 3: Energy level system of Nd:YAG laser

The Fig. 3 shows an overview of the excitation spectrum of the Nd:YAG material when it is pumped with 808 nm. The pump process starts from the ground state $^4I_{9/2}$ and populates the $^4F_{5/2}$ state. Due to the so called Stark splitting the energy level shows further sub levels. The ground state $^4I_{9/2}$ consists for instance out of 5 sub levels allowing 4 pump transitions to the excited sub levels of the $^4F_{5/2}$ state. From here the very fast radiationless transfer (FRT) populates the initial laser levels of $^4F_{3/2}$. Depending on the wavelength (energy) the transition terminates in a variety of final states. From here the transition back to the ground state $^4I_{9/2}$ takes place also as fast radiationless transfers. The given laser transitions are just a few among the most important strongest ones.

Now it is time to talk about the practical realisation of a Nd:YAG laser system.

1.1 Principle of operation

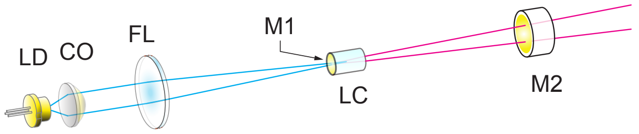


Fig. 4: Principle of operation of the Nd:YAG laser

The radiation of the diode (LD) is collimated by the collimator (CO) which is a high precision aspheric lens with a short focal length and a high numerical aperture. The resulting beam is parallel in one axis showing a more or less rectangular to elliptical intensity cross section. The focusing lens FL is used to focus the pump diode laser radiation into the Neodymium doped YAG crystal (LC). The Nd:YAG crystal is coated on one side with a high reflective coating (M1) for 1064 nm and 532 nm and a high transmission of the pump radiation of 808 nm. The other side of the Nd:YAG rod is coated with an anti-reflex coating to minimize the reflection losses inside the cavity. The optical cavity is formed by the flat mirror on the left (M1) and a curved mirror at the right side (M2) as shown in Fig. 4.

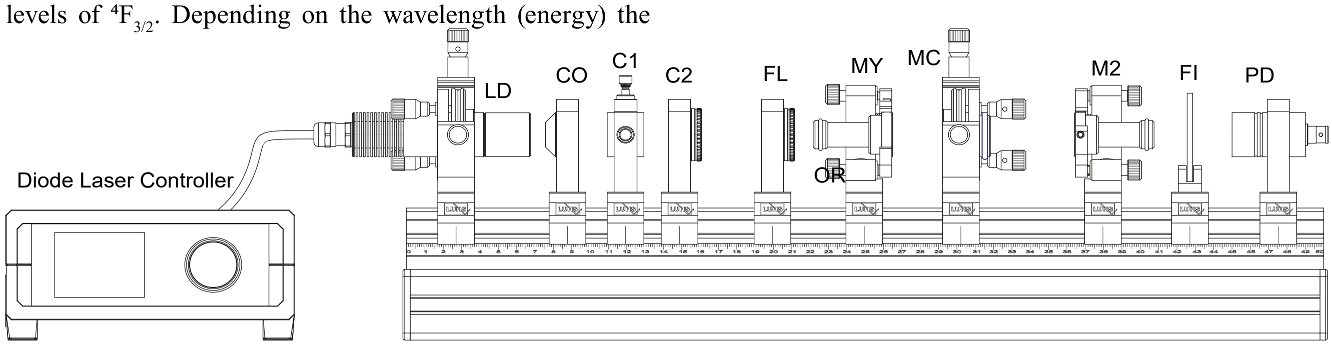


Fig. 5: Diode laser pumped Nd:YAG Experimental Laser Setup

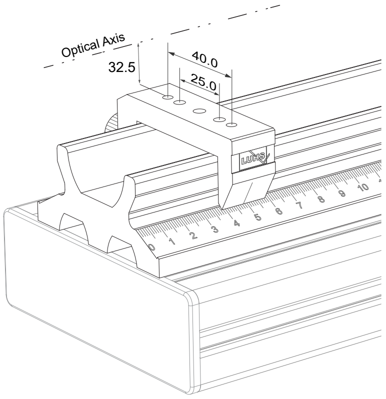
The Fig. 5 shows the set-up of the Neodymium YAG experimental laser. All optical components are placed onto an optical rail (OR) with "optics click" mechanisms which allows a convenient but very precise positioning of carrier as well as optics mounted in "click holder".

The laser diode's injection current, temperature and modulation are controlled by the diode laser controller MK1. The collimator (CO) is used to collimate the divergent radiation of the pump laser diode (LD). The collimated beam passes the cylindrical lens telescope formed by C1 and C2 to obtain an almost round beam profile. The focusing lens (FL) focuses the beam into the Neodymium doped YAG laser crystal (MY). The second mirror of the laser cavity M2 is followed by a filter (FI) which suppresses the pump radiation and transmits wavelength greater than 1000 nm. For the second harmonic generation or frequency doubling 1064 nm → 532 nm or 1330 → 660 nm a KTP crystal is used. It is mounted into a precise five axes adjustment holder (MC) for efficient phase matching.

The optical signals like pump radiation, fluorescence as well as created laser radiation are detected by the photodiode (PD) which is connected to the photodetector signal box. From here the signal is transferred via a BNC cable to an optional oscilloscope to display time dependant signal (CH1). The modulator reference from the diode laser controller is also connected to the oscilloscope (Ch2).

2.0 Description of the components

2.1 Optical rail



The rail and carrier system provides a high degree of integral structural stiffness and accuracy. Due to this structure it is a further development optimized for daily laboratory use. The position of the carrier on the optical rail can be precisely adjusted thanks to the attached ruler and the markings on the carrier. The optical height of 32.5 mm above the carrier surface and the mounting holes are compatible with all other systems like from MEOS, LUHS, MICOS, OWIS and LD Didactic. Consequently, a high degree of system compatibility is achieved.

2.2 The diode laser module LD

For the efficient optical excitation of the Neodymium doped YAG crystal a pump wavelength of 808 nm is required. The pump laser diode is mounted onto a Peltier element to control the operating temperature in a range of 10-50°C. The output power is 1 Watt at a wavelength of 808 nm. The emitted wavelength depends beside the temperature with 0.25 nm/°C also on the injection current.

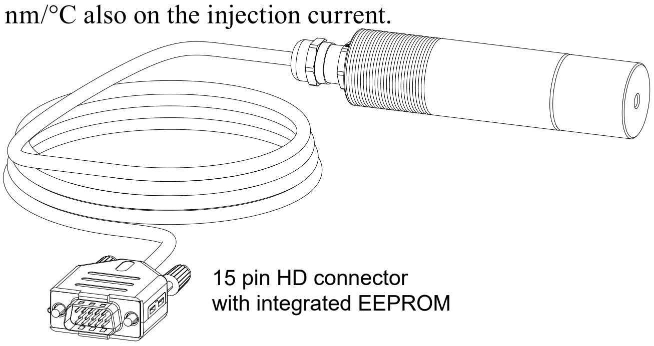


Fig. 6: Diode laser module (DL)

This device can emit highly concentrated invisible light which can be hazardous to the human eye. The operators of the diode laser module must follow the safety precautions found in IEC 60825-1 **"Safety of laser products Part 1: Equipment classification, requirements and user's guide"** when connected to the controller and powered up. The diode laser is connected via a 15 pin SubD HD connector (CN) to the controller MK1. Inside the connector an EPROM contains the data of the laser diode and when connected to the controller, these data are read and displayed by the controller.

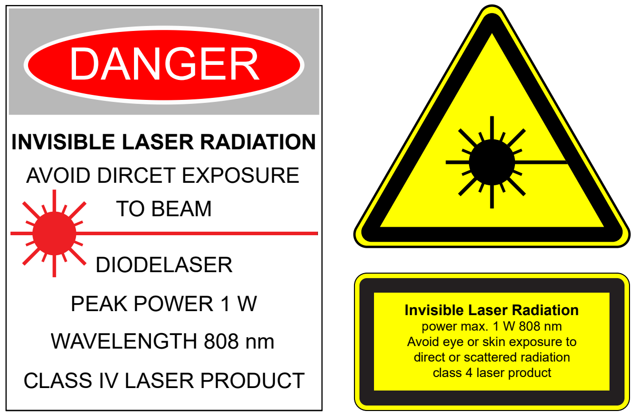


Fig. 7: Laser warning labels

2.3 Collimator (CO)

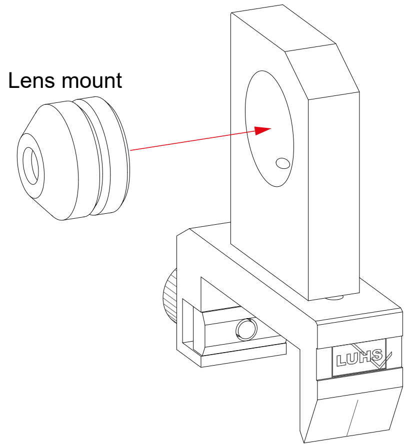


Fig. 8: Collimator module with XY adjuster

A high precision aspheric glass lens is mounted into a lens mount having a circumferential groove. The glass lens has a focal length of 4.6 mm, the numerical aperture is 0.53 and the clear opening is 4,9 mm. In addition the lens has an anti-reflex coating in a spectral range of 700 .. 900 nm with a residual reflection of < 0.5 %. The lens mount is centred by means of three ball tipped pins. One of the pins is spring loaded whereas the other two are adjustable in X and Y direction.

2.4 Galilean cylinder lens telescope

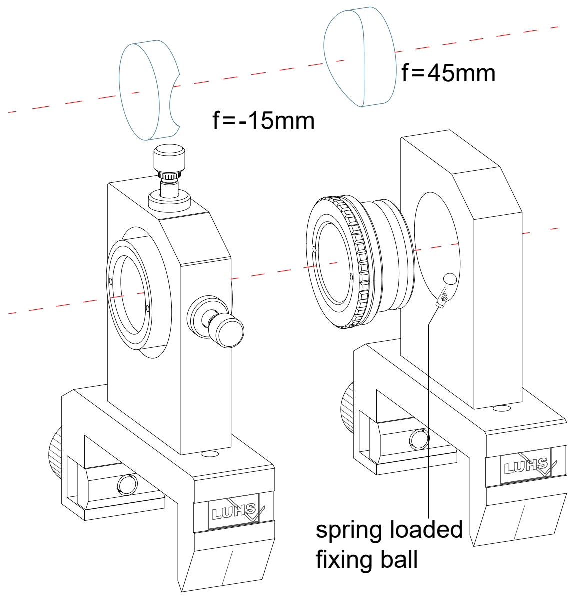


Fig. 9: Beam expander with cylindrical lenses

For best efficiency of optical pumping, it makes sense to form the laser beam of the diode laser such, that a circular beam results. This is accomplished by a beam expander with cylindrical lenses which affects only one direction of the laser diode's beam. To maintain the direction, the first lens is made adjustable. Both lenses can be rotated in their holders to adjust the roundest spot size.

2.5 Focusing lens (FL)

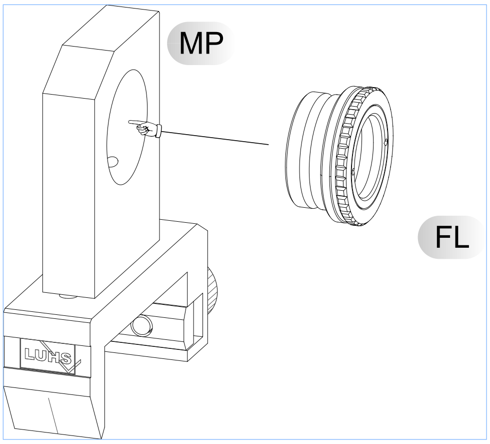


Fig. 10: Focusing module with 60 mm lens (FL)

To obtain a very high intensity of the pump light the collimated laser beam is focused by using a biconvex lens with a focal length of 60 mm. The lens is mounted into a so called click mount (FL) with a mounting diameter of 25 mm. The mount is clicked into the mounting plate (MP) where three spring loaded steel balls keep the lens precisely in position.

2.6 Laser mirror adjustment holder M1

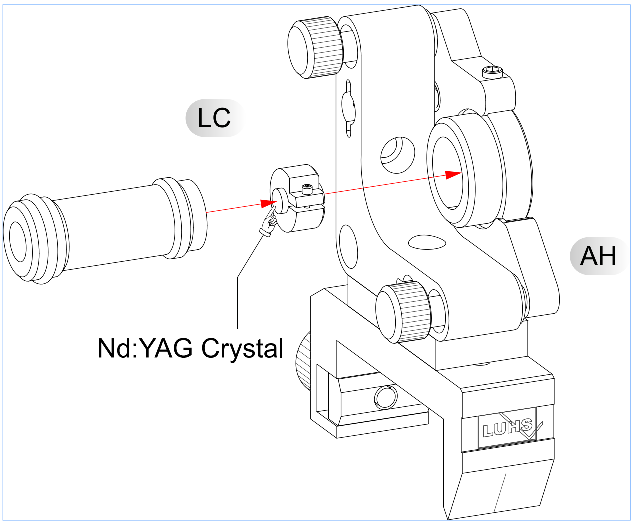


Fig. 11: Laser mirror adjustment holder "left" with Nd:YAG rod (LC)

The adjustment holder (AH) comprises two high precision fine pitch screws. The upper screw is used to tilt the moveable plate vertically and the lower one to tilt it horizontally. The mounting plate provides a M16 mount into which the laser mirror holders are screwed. The mirror is pressed against a mechanical reference plane inside the M16 mount in such a way that the mirror is always aligned perfectly when removed and screwed in again.
The adjustment holder is mounted to the carrier that a "left" operating mode is achieved and thus forming the left mirror holder of the laser cavity including the Nd:YAG rod as active material.
Because the adjustment holder (AH) is symmetrical, it can also be switched to the 'right' mode if needed.
The Nd:YAG rod is coated so that it can be used with different wavelengths and mirrors.:

	HT	HR	SHG
	808 nm	1330 nm	red
	808 nm	1123 nm	yellow
	808 nm	1064 nm	green

The opposite side of the Nd:YAG rod is always anti-reflex coated for the fundamental as well as the second harmonic wave.

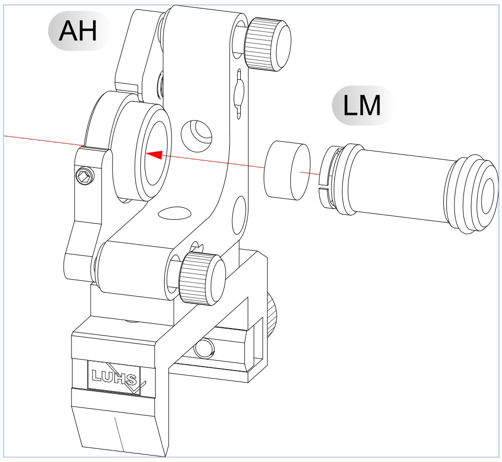


Fig. 12: Mirror adjustment holder "right" with mirror M2

The adjustment holder (AH) comprises two high precision fine pitch screws. The upper screws is used to tilt the moveable plate vertically and the lower one to tilt it horizontally. The mounting plate provides a M16 mount into which the laser mirrors (LM) are screwed. The mirror is pressed against a mechanical reference plane inside the M16 mount in such a way that the mirror is always aligned perfectly when removed and screwed in again. The adjustment holder is mounted to the carrier that a "right" operating mode is achieved and thus forming the right mirror holder of the laser cavity. Due to the symmetry of the adjustment holder (AH) it can also be changed to the "left" mode if required.

2.7 Set of laser mirror

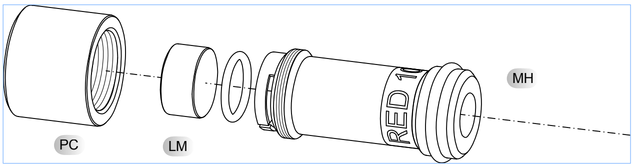


Fig. 13: Laser mirror mount

The mirrors are mounted separately as shown in Fig. 13. Each mirror has the standard diameter of 12.7 mm (1/2 inch) and a thickness of 6.35 mm (1/4 inch).
The laser mirror (LM) is mounted into the holder MH and kept in position by two spring loaded flaps. A soft O-ring provides a soft seat of the mirror inside the holder (MH) especially when screwed into the adjustment holder.

Label	Coating	Geometry
SHG RED	HT 808 / HR 1330 nm	ROC 100 mm
SHG RED 1%	HT 808 / T1% 1330 nm	ROC 100 mm
SHG YEL	HT 808 / HR 1123 nm	ROC 100 mm
SHG 100	HT 808 / HR 1064 nm	ROC 100 mm
SHG 100 2%	HT 808 / T2% 1064 nm	ROC 100 mm

Table 1: Marking and labelling of the mirrors

The mirrors are of supreme quality, coated by ion beam sputtering (IBS) yielding the highest degree of reflectivity and lowest scatter losses achievable till date. A cap (PC) protects the sensitive mirrors when not in use. Each mirror is labelled and the meaning of the marks is given in the left column of Table 1.

2.8 The RG 1000 filter module (FI)

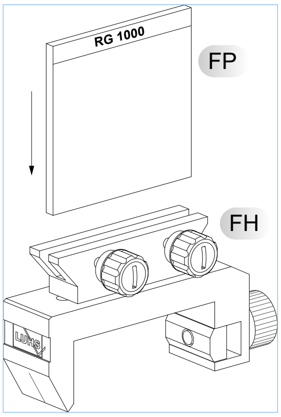


Fig. 14: Filter module (FI) with plate holder

The coloured glass filter (FP) RG1000 has a thickness of 3 mm and is used to suppress the pump radiation which is not absorbed by the Nd:YAG crystal. It is for instance important for the measurement of the lifetime of the excited state to measure the fluorescence spectrum and the laser power of the Nd:YAG laser without pump radiation.

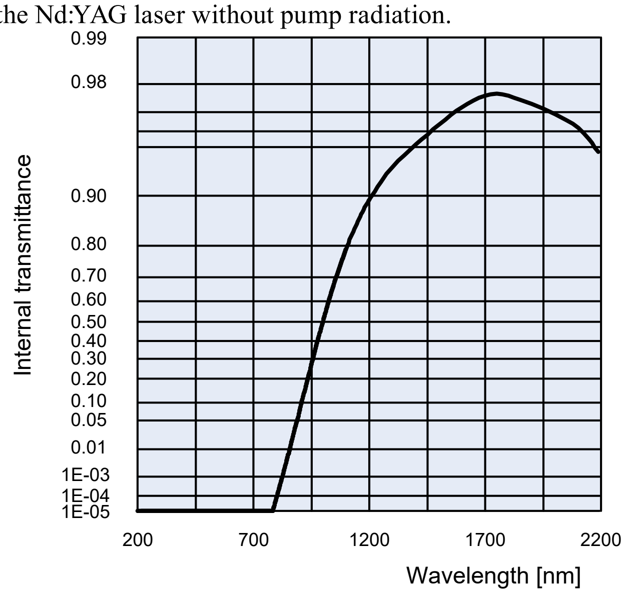


Fig. 15: Transmission curve of the RG1000 filter, 3 mm thick

2.9 Crossed hair target (CH)

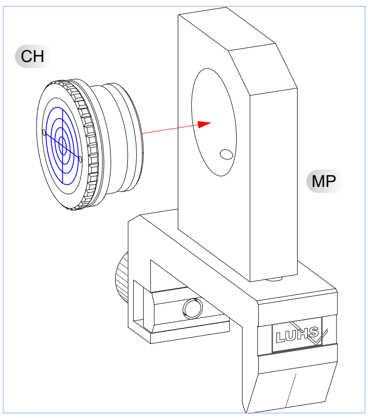


Fig. 16: Crossed hair target

A crossed hair target screen is part of a 25 mm click holder (CH) which can be inserted into the mounting plate (MP). By means of three precision spring loaded steel balls the screen is kept in position. It is used to visibly align a light beam with respect to the optical axis of the rail and carrier system MG75.

2.10 Si PIN photodetector module (PD)

A Si PIN photodiode is integrated into a 25 mm housing with two click grooves (PD). A BNC cable and connector is attached to connect the module to the photodetector signal box ZB1. The photodetector module is placed into the mounting plate (MP) where it is kept in position by three spring loaded steel balls.

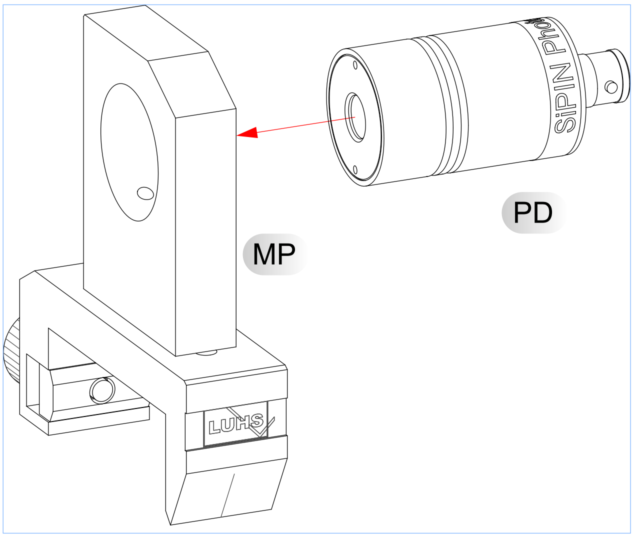


Fig. 17: Photodetector module

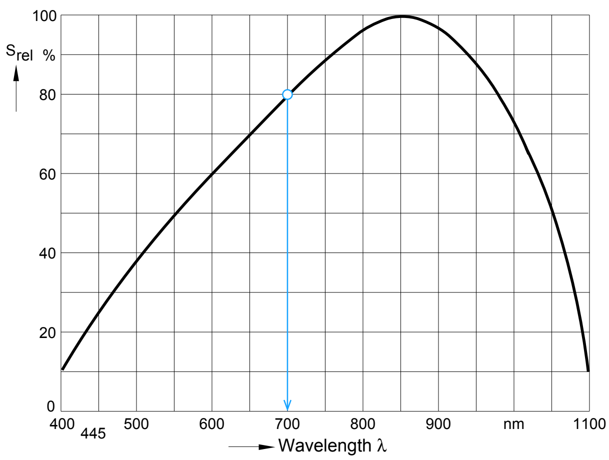


Fig. 18: Sensitivity curve of the BPX61 photodiode

Parameter	symbol	value
Rise and fall time of the photo current at: R_L=50 Ω, V_R=5V, λ=850 nm and I_p=800 µA	t_r, t_f	20 ns
Forward voltage I_F = 100 mA, E = 0	V_F	1.3 V
Capacitance at V_R = 0, f = 1 MHz	C_0	72 pF
Wavelength of max. sensitivity	λ_{Smax}	850 nm
Spectral sensitivity S~10% of S_{max}	λ	1100
Dimensions of radiant sensitive area	L x W	7 mm²
Dark current, V_R = 10 V	I_R	≤30 nA
Spectral sensitivity, λ = 850nm	$S(\lambda)$	0.62 A/W

Table 2: Basic parameters of Si PIN photodiode BPX61

The controller contains a digital resistor and provides +12 VDC for the reverse voltage of the photodiode. They are connected to the BNC input (PDIN) as shown in the schematic of Fig. 19. At the output PDOUT of the signal box a signal is present which is given by the following equation:

$$I_c = \frac{U_c}{R_S} = \frac{U_{display}}{R_S \cdot Gain}$$

I_c is the photocurrent created by illuminating the photodiode with light. U_c is the voltage drop across the selected load resistor R_S. $U_{display}$ is the value of U_c displayed on the controller's touch screen multiplied by the selected gain (GAIN). To convert the measured voltage U_c into a respective optical power we use of the spectral sensitivity S(λ) [A/W], which depends on the wavelength of the incident light according to Fig. 18. From the Table 2 we take the value for S(850nm) as 0.62 A/W. To obtain the value for another wavelength, 445 nm for instance, we have to multiply this value with the S_{rel}(445 nm) from Fig. 18 (23% or 0.23).
The detected optical power P_{opt} in W is given as:

$$P_{opt} = \frac{I_c}{S(\lambda)}$$

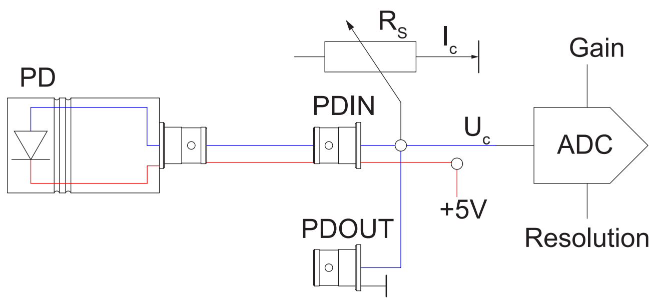


Fig. 19: Photodiode schematic

The photo voltage U_c is internally connected to a high precision ADC from which the microprocessor reads the value of the of U_c and the value of the load resistor R_S and displays their values on the touch screen of the MK2 controller.
It must be noted that the measured power is correct only if the entire light beam hits the detector. Based on the selected load resistor the sensitivity will be high for higher resistors but the rise and fall time will be longer. For fast signals, a low resistor should be used, however the sensitivity will be lower.

2.11 Frequency Doubler Module KTP

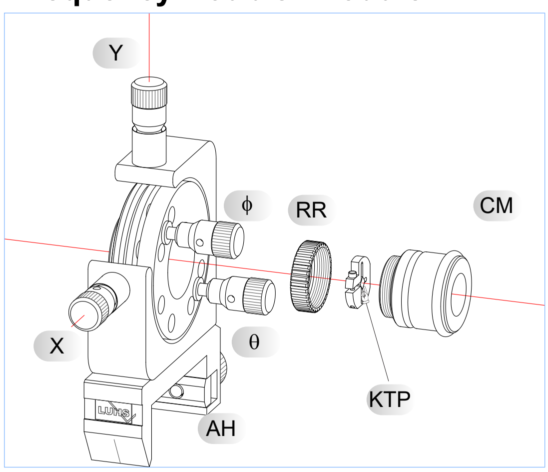


Fig. 20: Frequency Doubler Module KTP

For the frequency doubling or second harmonic generation a KTP crystal will be used. The KTP (Potassium titanyl phosphate $KTiOPO_4$ has a size of 3x3x6 mm and is mounted into a disk with 3 mm thickness and gently clamped. The disk holding the crystal is set into the mount (CM) where it is fixed by using the ring (RR). The crystal mount (CM) is inserted into the five axes adjustment holder. It is kept in position by a spring loaded steel ball in the same way as for the lens click mounts.
Four precise fine pitch screws of repetitious accuracy allow the translational (X,Y) and azimuthal (Θ,φ) adjustment.
The crystal mount (CM) can be rotated free of play around its axis. This is important to rotate the crystal with respect to the polarisation of the fundamental laser radiation.
The end faces of the crystal are polished better λ/10 and are coated with a high bandwidth anti reflection coating with a residual reflectivity R of <0,1%. The standard operation is the frequency doubling 1064nm → 532 nm. In addition the Nd:YAG laser can be operated also on 1330 nm as well as 1123 nm (see Fig. 3). Within this experiment we will not operate the 946 nm line since the available pump power is not sufficient to reach the threshold for this transition. KTP crystals are available for:

1330 nm → 665 nm		red
1123 nm → 561.5 nm		greenish yellow
1064 nm → 532 nm		green

2.12 Passive q-switch with Cr^{4+}:YAG

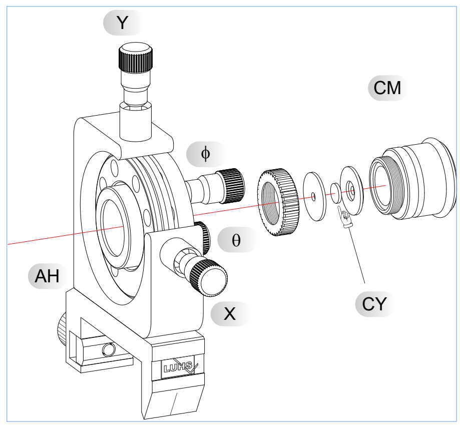


Fig. 21: Passive q-switch module with Cr^{4+}:YAG crystal (CY)

The Chromium YAG crystal has a diameter of 7 mm and a thickness of 1 mm. It is mounted between two disks into the crystal mount (CM) a threaded retaining ring (R) keeps the crystal and the two disks in position. The crystal mount (CM) is inserted into the five axes adjustment holder (AH). It is kept in position by a spring-loaded steel ball in the same way as for the lens click mounts. Four precise fine pitch screws of repetitious accuracy allow the translational *(X,Y)* and azimuthal *(θ, φ)* adjustment. From time to time the crystal needs to be cleaned for proper operation.

2.12.1 Active q-switch with Pockels Cell

Fig. 22: Active q-switch with Pockels cell

The active q-switch consists of a DKDP crystal (potassium di-deuterium phosphate (KD*P = DKDP)). Applying a high voltage to it, a phase retardation results which value depends on the applied voltage. Further details and a more comprehensive description of the fundamentals are given by Luhs [6]. The properties of the crystal (PC) are as follows:

Material: DKDP, diameter 8 mm
Quarter wave voltage: 3300 V
Contrast ratio: 1000:1
Clear aperture: 8 mm

The crystal is operated with the controller (PCD) which has the following properties:

Output voltage: 2000..4000 V
Switching time: 10 ns @ 4000 V
Repetition rate: 0 .. 2kHz

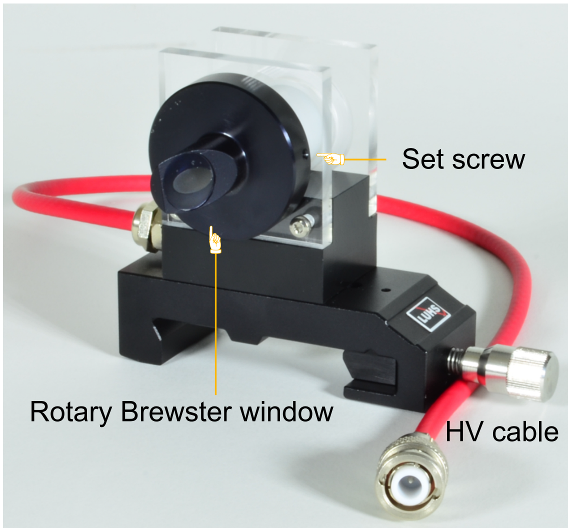


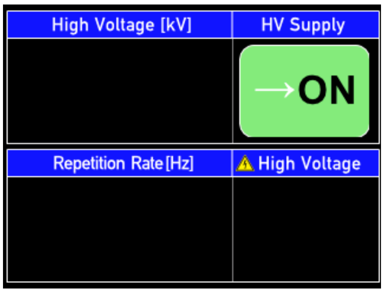
Fig. 23: Pockels cell with rotary Brewster window and high volt coaxial cable and BNC connector

2.13 Pockels cell controller

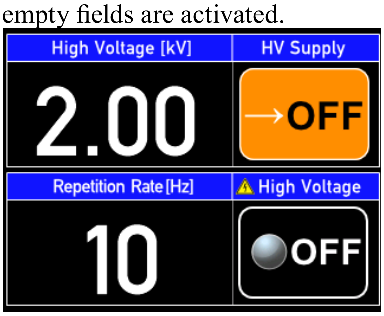
The Pockels cell controller is operated by a microprocessor touch panel and a rotary knob to set numerical set values. Pressing the knob pushes an emergency stop.

The controller is operated by a wall plug power supply proving 12 VDC at 1A. The high voltage is available at a special high voltage BNC connector.

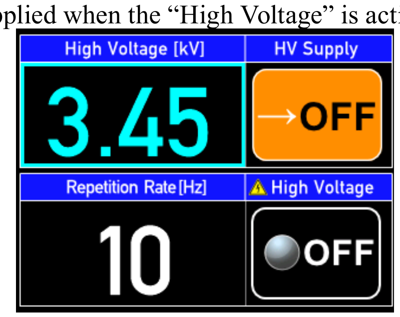
Right after switching on the controller, the start screen appears. To continue to the next screen a touch to it is required.



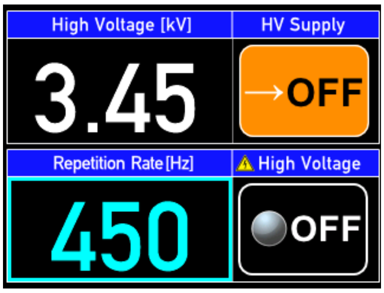
The high voltage module located inside the controller, has its own supply which is switched on by tapping the "ON" button. The empty fields are activated.



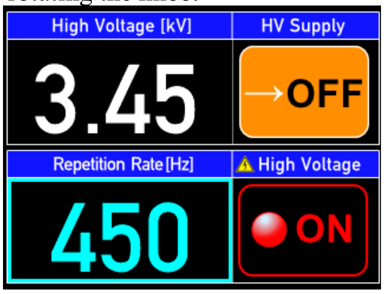
The additional elements on the screen allow the setting of the high voltage amplitude and repetition rate. The values are only applied when the "High Voltage" is activated.



By tapping the hight voltage display it will be activated and by turning the knob the set value is modified accordingly.



Activating the “Repetition Rate” display allows the setting the value by rotating the knob.



The set values are instantly applied when the “High Voltage” button is activated.

2.14 Digital Diode Laser Controller

This microprocessor operated device contains a laser diode controller and a photodiode amplifier. A touch panel display allows in conjunction with the digital knob the selection and setting of the parameters for the attached laser or photodiode.

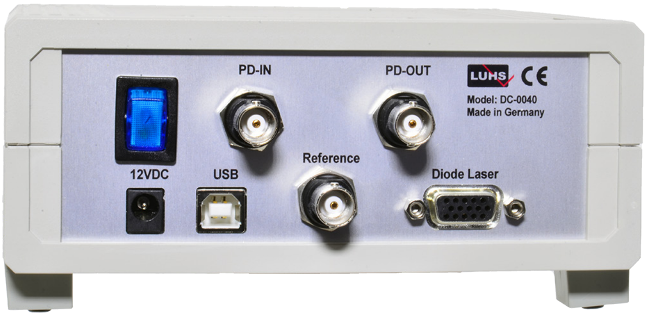


Fig. 24: Digital Diode Laser Controller MK1

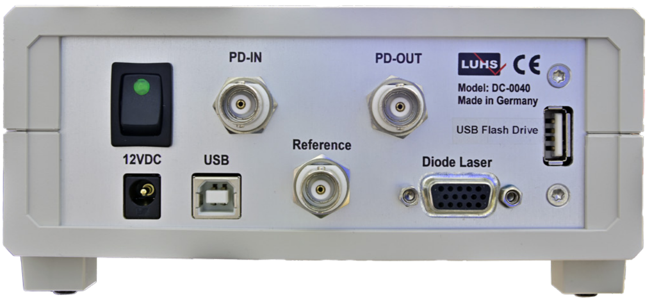


Fig. 25: Digital Diode Laser Controller with Data Recorder Option (USB Flash Drive)

The laser diode module is connected via the 15 pin HD SubD panel jacket (LD). The controller reads the EEPROM of the laser diode and sets the required parameter accordingly. The MK1 is powered by an external 12V/ 1.5 A wall plug supply. A USB bus allows the connection to a computer for remote control. Furthermore, firmware updates can be applied simply by using the same USB bus.
The MK1 provides an internal modulator which allows the periodic switch on and off of the diode laser. A buffered synchronisation signal is available via the BNC jacket (MOD). Furthermore, the duty cycle of the modulation signal can be varied in a range of 1...100 % to enable the measurement of thermal sensitivity of the optically pumped laser crystal.
The controller is equipped with industrial highly integrated circuits for the bipolar Peltier cooler (Maxim, MAX 1978) as well as for the injection current and modulation control (iC Haus, iC-HG) of the attached laser diode.
The photodetector is connected via the provided BNC cable to the PD-IN BNC panel jack. The analogue photo voltage is available at the PD-OUT panel jack.
When the LED or laser is operated in modulated mode, the reference modulator signal is available at the “REFERENCE” BNC connector.
If the controller is equipped with the data recorder function, there is an additional USB port on the rear panel for a USB flash drive.
Further detailed specifications are given in the following section of the operation software.

2.15 Diode laser controller screens

When the external 12 V is applied, the controller starts displaying the screen as shown in the figure below.

Fig. 26: Start screen

Laser Safety

The first interactive screen requires the log in to the device since due to laser safety regulations unauthorized operation must be prevented. In general, this is accomplished by using a mechanical key switch. However, this microprocessor operated device provides a better protection by requesting the entry of a PIN.
After entering the proper key, the next screen is displayed and the system is ready for operation.

Fig. 27: Authentication screen

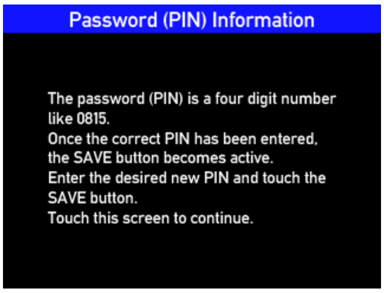
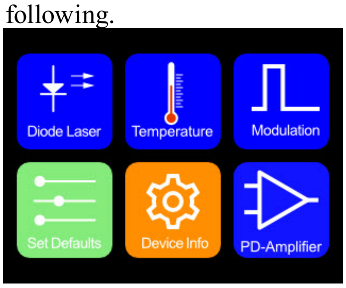


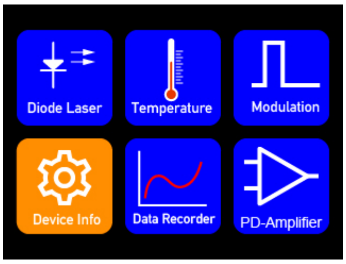
Fig. 28: Information for the password

Main Screen

After the correct password has been entered, the main screen is activated. It shows the buttons for the current settings of the attached diode laser, its temperature and modulation. Furthermore, the photodiode amplifier, the device info, and a Set to Defaults" button. The individual functions are explained in the following.

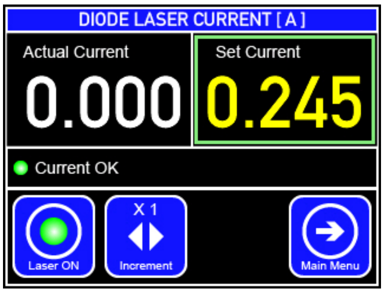


Data Recorder

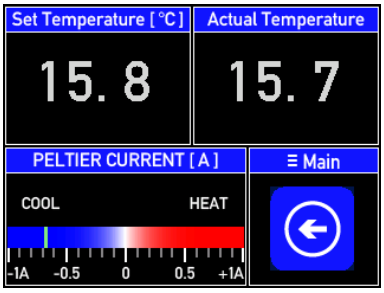


If the controller is equipped with the data recorder function, an additional button labelled ‘Data Recorder’ appears.

Diode Laser or LED Settings

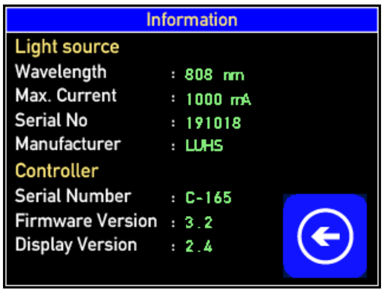


To change the set current of the diode laser, touch the “Set Current” window. Once activated it is framed with a green border. By turning the settings knob (SET) the desired value is selected. For faster settings of the current in 10 mA instead of 1 mA the increment button is touched. Touch the “LASER ON” to switch the laser on. The PID controller is activated and drives the laser slowly to the desired value. This may take a few seconds to reach the set value. For immediate “Laser OFF” just touch Laser ON button.



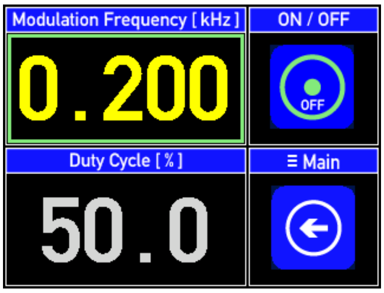
The same is true also for the “Set Temperature” section. When in operation and connected to the laser diode the actual temperature is shown in the “Actual Temperature °C section. Furthermore the actual current of the Peltier element is shown in such a way, that cooling or heating of the element can be observed.

Information screen



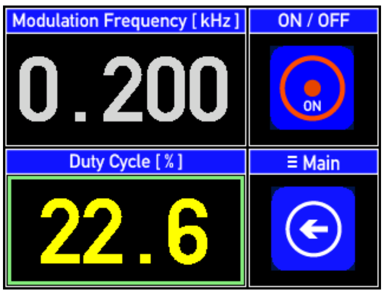
When tapping the Device Info button of the main screen this screen comes up. It again reads and displays the information stored in the EEPROM of the attached diode laser. If an entry exceeds the maximum or minimum limit value retrieved from the EEPROM of the attached diode laser the entry is reversed to the respective minimum or maximum value.

Modulation settings



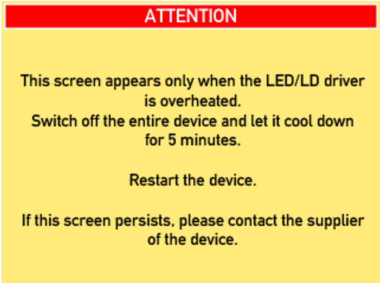
The diode laser can be switched periodically on and off. This is for a couple of experiments of interest. By tapping the display of the modulation frequency, the entry is activated. Turning the settings knob will set the desired frequency value. The modulation becomes active, when the Modulator ON/OFF button is tapped.

Duty Cycle settings



For some experiments it is important to keep the thermal load on the optically pumped laser crystal as low as possible or to simulate a flash lamp like pumping. For this reason, the duty cycle of the injection current modulation can be changed in a range of 1...100 %. A duty cycle of 50% means that the OFF and ON period has the same length. The set duty cycle is applied instantly to the injection current controller.

Overheating warning

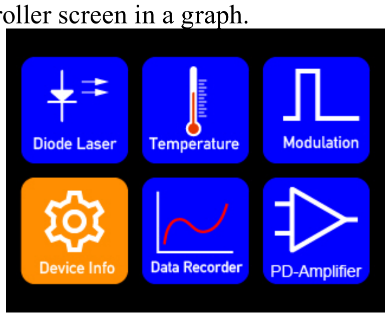


This screen you should never see. It appears only when the chip of the injection current controller is over heated.
Switch of the device, wait a couple of minutes and try again.
If the error persists, please contact your nearest dealer.

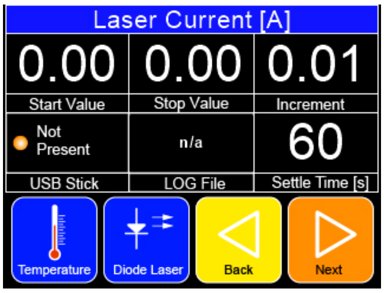
This screen is self-explanatory and appears either when no laser diode is connected or the data reading from the EEPROM is erroneous.

Data Recorder Option

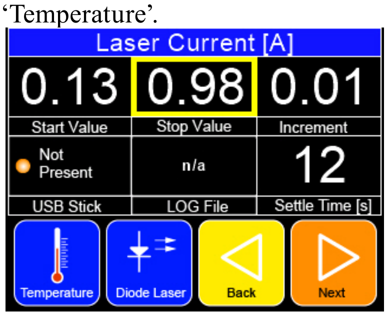
If the controller is equipped with the data recorder function, automatic measurements can be performed. Either the injection current or the diode laser temperature can be changed incrementally. The values measured with the photodiode are read out and the respective function is displayed in real time on the controller screen in a graph.



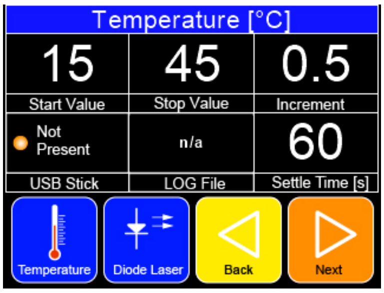
This allows various dependencies to be measured. The Y value is always the signal from the photodiode, while the X value can be the temperature or injection current of the laser diode.
A USB flash drive must be connected before starting the measurements. For convenience, a USB extension cable is supplied, which is plugged into the back of the controller. The USB flash drive can now be conveniently plugged in.
The controller recognises the USB flash drive and searches the root directory for files with the structure MK-XXX.cvs. If none are found, the first file is given the name MK-001.cvs. If such a file is found, the number XXX is incremented by 1.
After touching the button labelled 'Data Recorder', the screen for entering the desired parameters appears.



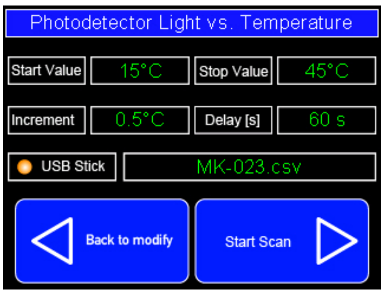
Here, you can now select which measurements are to be performed by touching the corresponding button. Either 'Laser Current' or 'Temperature'.



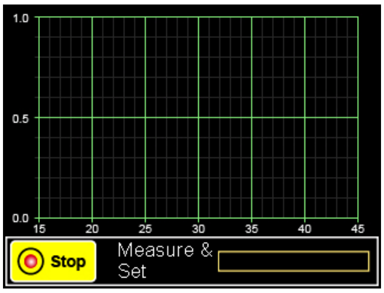
After touching the respective input field, it is activated and highlighted with a yellow frame. Turn the controller's control knob to set the desired value. For both measurement types, a start value, an end value and the increment are entered. The value of the 'Settle Time' is the time in seconds between setting the value and reading the photodiode voltage.



The same applies to setting the temperature. Since it takes longer to reach the selected temperature here than with the injection current, the waiting time should be set accordingly. It is advisable to first set the starting temperature value manually and wait until this value is stable. To access the temperature input, touch the 'Back' button.
Before performing the measurements, the free parameter must be set to either temperature or injection current. The values for the shunt resistance and amplification must also be set in the photodiode menu. The photovoltage should not exceed 2 volts, otherwise the preamplifier will saturate.
After pressing the 'Next' button, an overview of the set values is displayed.

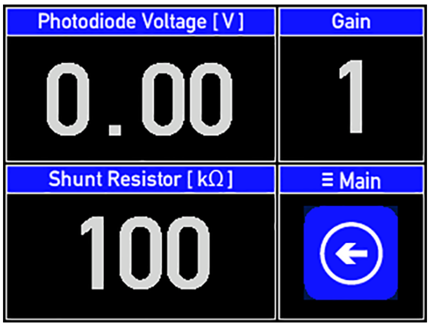


Once all values have been set correctly, the scan can begin. To do this, tap the 'Start Scan' button. If you wish to make any changes, tap the 'Back to modify' button.

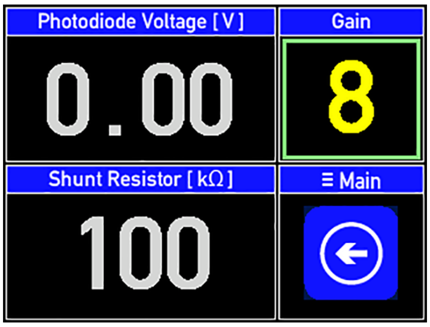


When you press the 'Start Scan' button, the plot screen appears. Depending on your selection, the X-axis is divided into units of °C or mA. The Y-axis shows the photovoltage values.
The progress bar shows the waiting time and the measurement time. Touching the 'Stop' button cancels the measurement and no data is saved. The data is temporarily stored in a matrix and written to the USB flash drive at the end of the measurement.
A few examples of measurements are given in chapter "3.17 Data Recording" on page 32.

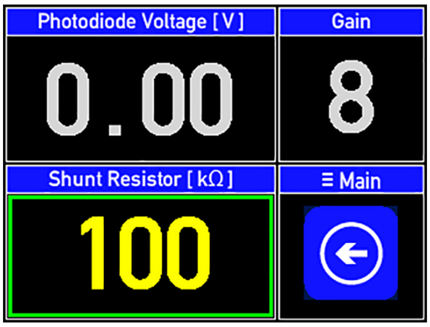
2.16 Photodetector Screens



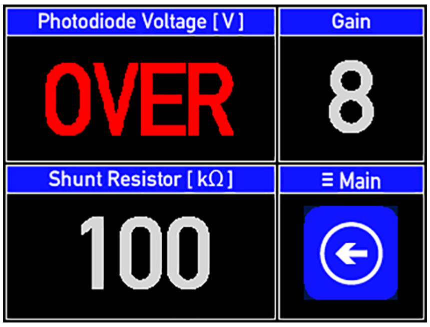
The photodiode page displays the measured photo voltage, the selected shunt resistor and the chosen gain.



Tapping the gain display field switches the gain from 1, 2, 4 and 8.



Activating the shunt resistor display field lets one set the shunt resistor by turning the digital knob. The value ranges from 1 kOhm to 200 kOhm.



If the photo voltage exceeds the inter reference voltage of 2.048 V the display shows the overload state. Reduce the gain or the shunt resistor. If the overload state remains although both values are set to minimum values, the injection current should be reduced as well.

Measurements

3.0 Experimental set-up and Measurements

In the following we will explain step by step the set-up for the different experiments and measurements. Please note that we will not publish measured results. However, we will give wherever possible qualitative information of the to be expected values or curves.

3.1 Characterisation of the diode laser

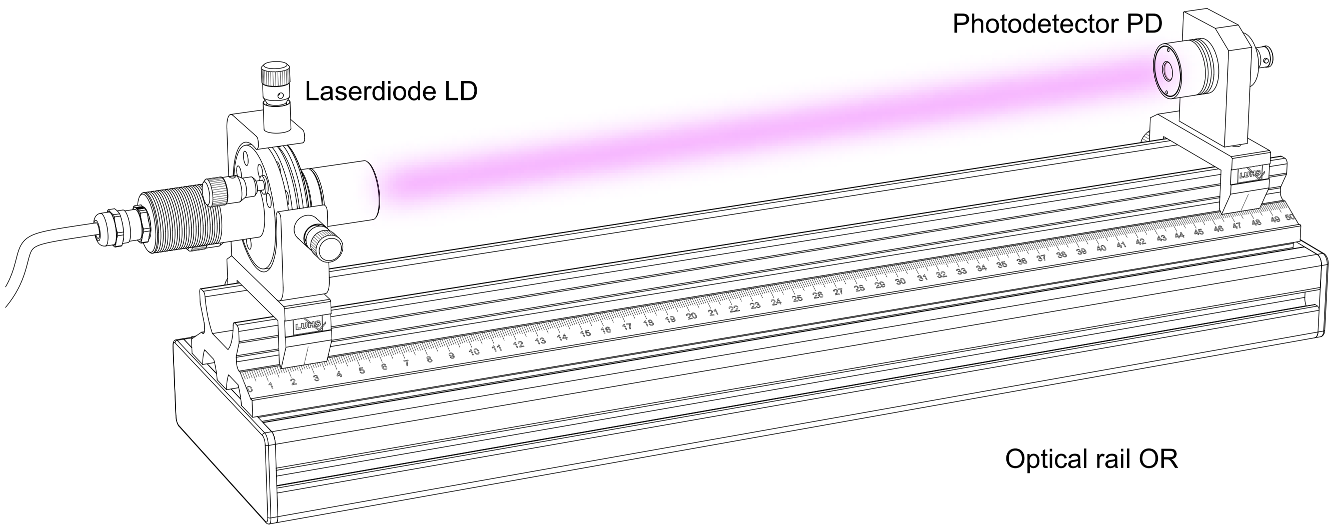


Fig. 29: Characterization of the diode laser

The task of this experiment is to measure the optical power versus the injection current for a set of fixed temperatures. To measure the output power in relative units the photodetector module (PD) is placed onto the rail as shown in Fig. 36. The photodetector (PD) is connected to the signal box (see also section "2.10 Si PIN photodetector module (PD)" on page 7 and "It must be noted that the measured power is correct only if the entire light beam hits the detector. Based on the selected load resistor the sensitivity will be high for higher resistors but the rise and fall time will be longer. For fast signals, a low resistor should be used, however the sensitivity will be lower." on page 8). The output of the box is connected either to an oscilloscope or to a digital multimeter which is set to voltage measurement. For a set of different temperatures such as 10, 30 or 40°C the voltage U_m of the signal box is recorded.

Wavelength	808	nm	
Temperature	30	°C	
$S(\lambda)_{rel}$	0.23		Fig. 18
$S(\lambda)$	$S(\lambda)_{rel} \cdot 0.23$	A/W	
Injection current [mA]	Voltage U_m	$R_L [\Omega]$	P_{opt} [mW]

Table 3: Suggestion for a measurement sheet

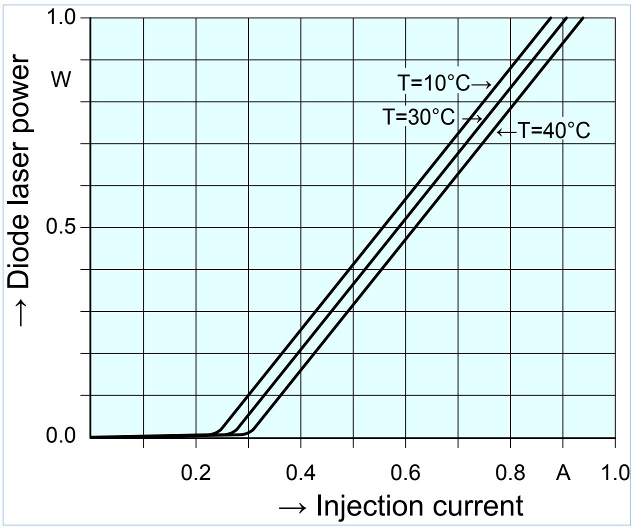


Fig. 30: Laser power versus injection current and temperature as parameter

Note:
Set the distance of the photodetector to the diode laser in such a way, that the detector is not saturated. The measured power is just a fraction of the actual power since only a fraction of it reaches the detector.

Measurements

3.1.1 Emission spectrum of the laser diode

It is important to know the wavelength of the laser diode because it depends on the temperature of the laser chip and the applied injection current. Furthermore, the wavelength depends also on the production process and therefore the given wavelength has a range of 808 ± 5nm. Within this experiment an optical spectrum analyser is used. The provided optical fibre is placed near to the emission of the laser diode and the spectrum is recorded. This is repeated for different temperatures of the diode laser. The resulting spectra are combined in one graph as shown in Fig. 32.

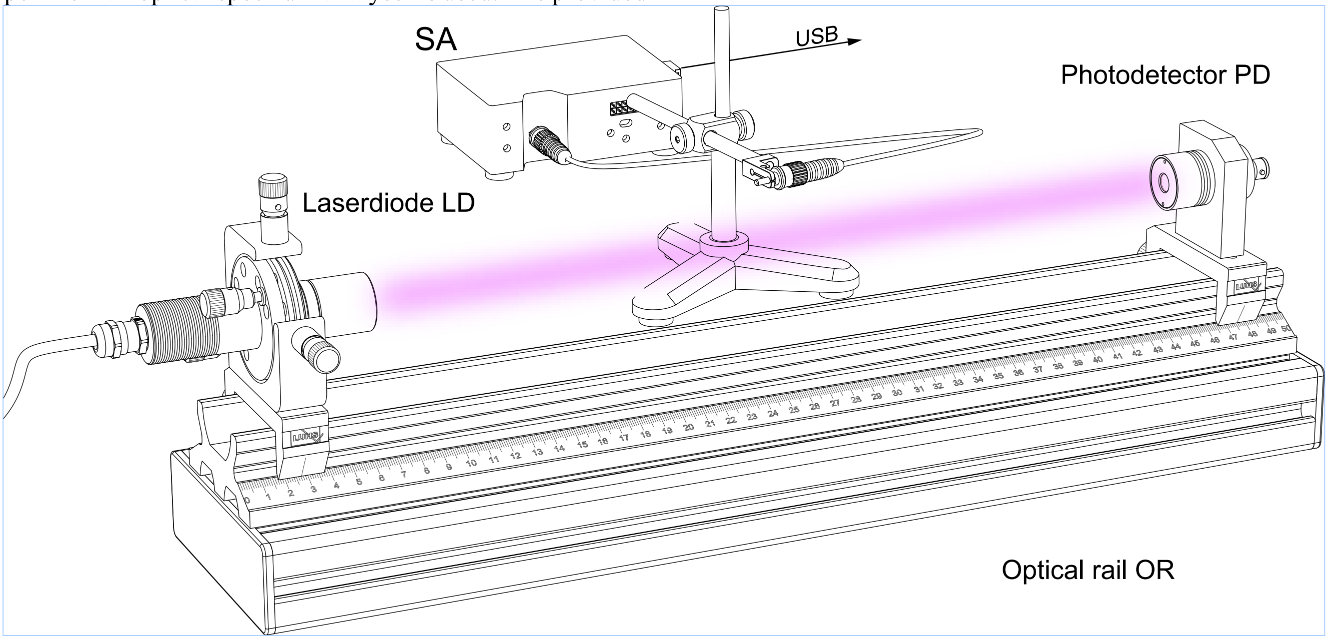


Fig. 31: Set-up to measure the emission spectrum of the laser diode

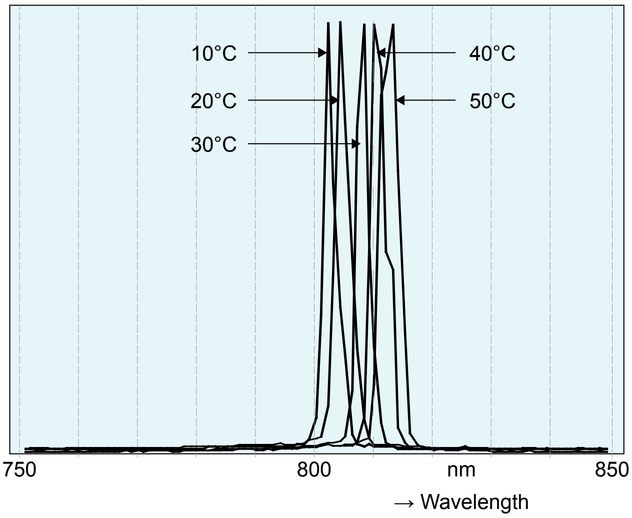


Fig. 32: Emission spectra of the laser diode for different temperatures

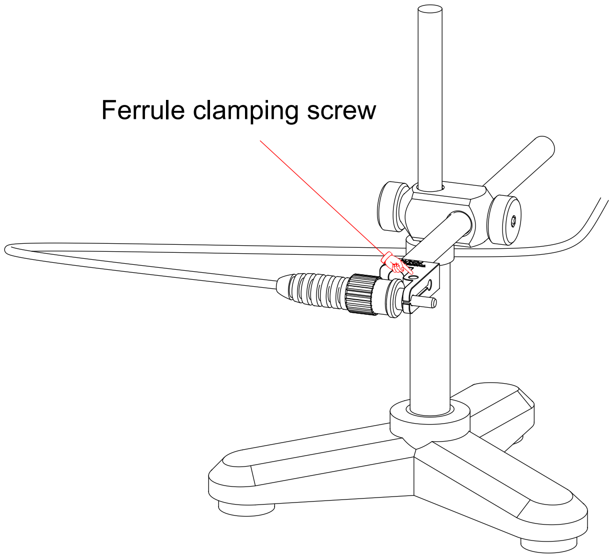


Fig. 33: Tripod and clamp for the spectrometer fibre

The spectrometer comes with a tripod with articulated arms and a fixture to clamp the ferrule of the fibre of the spectrometer.

Measurements

3.1.2 Collimating and centring the diode laser beam

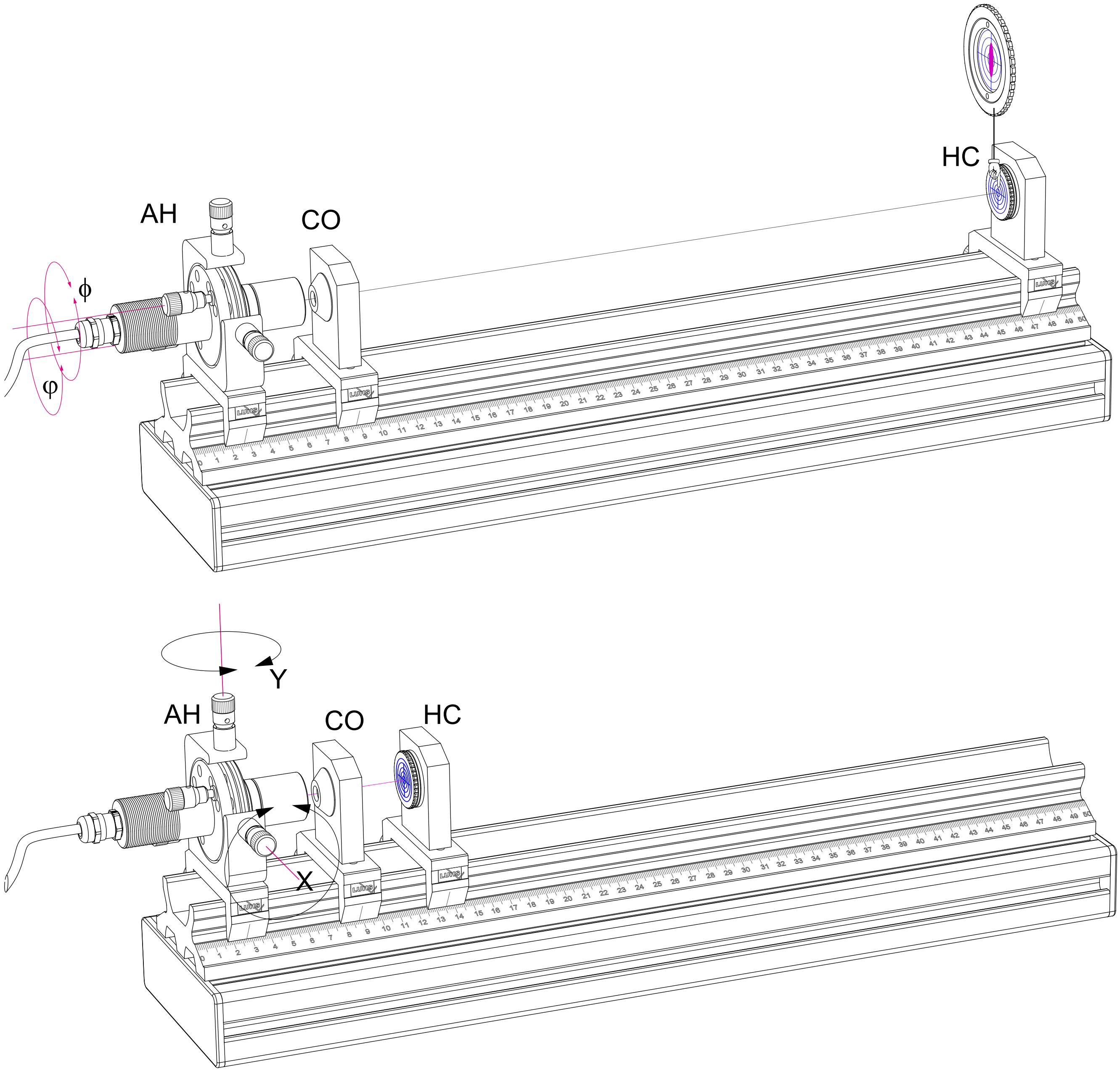


Fig. 34: Collimating and centring the diode laser beam

Place the collimator module (CO) in front of the diode laser with a free space of 10 mm between both. Switch on the diode laser and select not more than 250 mA injection current or such a value that the diode laser just starts emitting laser radiation. To visualize the beam, use the infrared converter screen.

Move the collimator towards the diode laser and observe the image on the crossed hair target (HC). Align if necessary, the X and Y fine pitch screws of the adjustment holder (AH) in such a way, that the image is centred to the crossed hair target (HH). Go closer with the collimator to the diode laser and you will notice that the beam cross section on the crossed hair target becomes smaller and smaller. If you continue to move the collimator against the diode laser the image of the beam on the crossed hair target starts to grow again. If you reached this point, stop the movement and check with a piece of paper or with the infrared converter screen if the beam is almost parallel along its way to the target. If not, fine tune the position of the collimator and fix its position by fastening the clamping screw. If required also realign the spot of the laser beam to the centre of the target screen.

Finally, a narrow elliptical spot as shown in Fig. 34 shall be achieved.

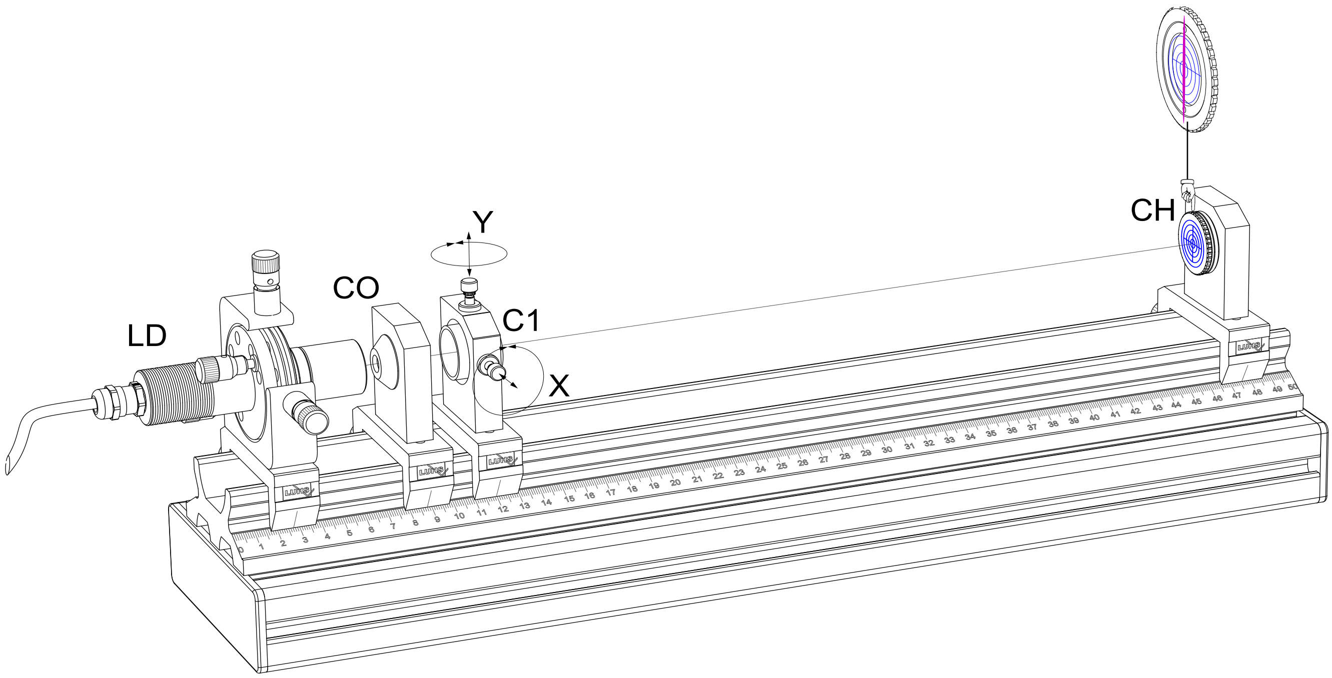


Fig. 35: Inserting the first cylindrical lens (C1).

The first cylindrical lens (C1) is mounted into an XY adjustment holder to recentre the now even more stretched beam in its vertical axis.

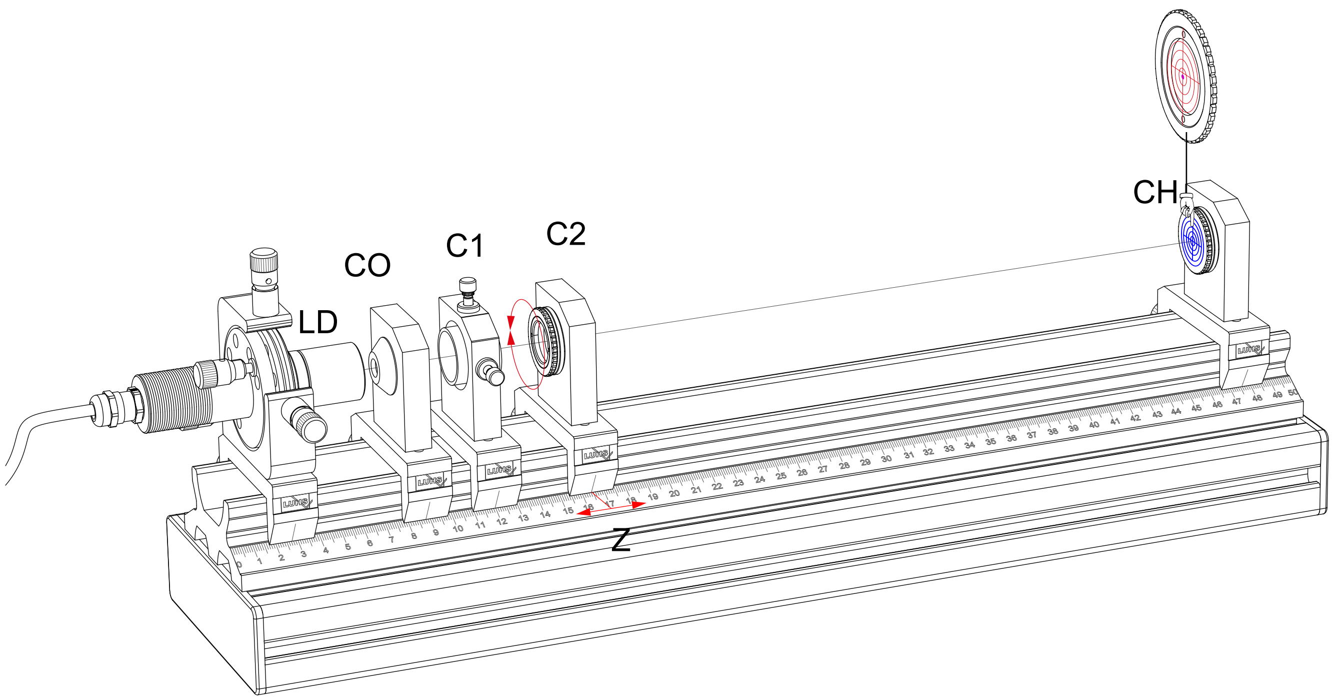


Fig. 36: Inserting the second cylindrical lens (C2)

The cylindrical lens C2 is moved forth and back to obtain the smallest spot on the crossed hair target. Furthermore, it may be rotated in its mounting plate for best round image.

3.2 Preparing the pump laser focus

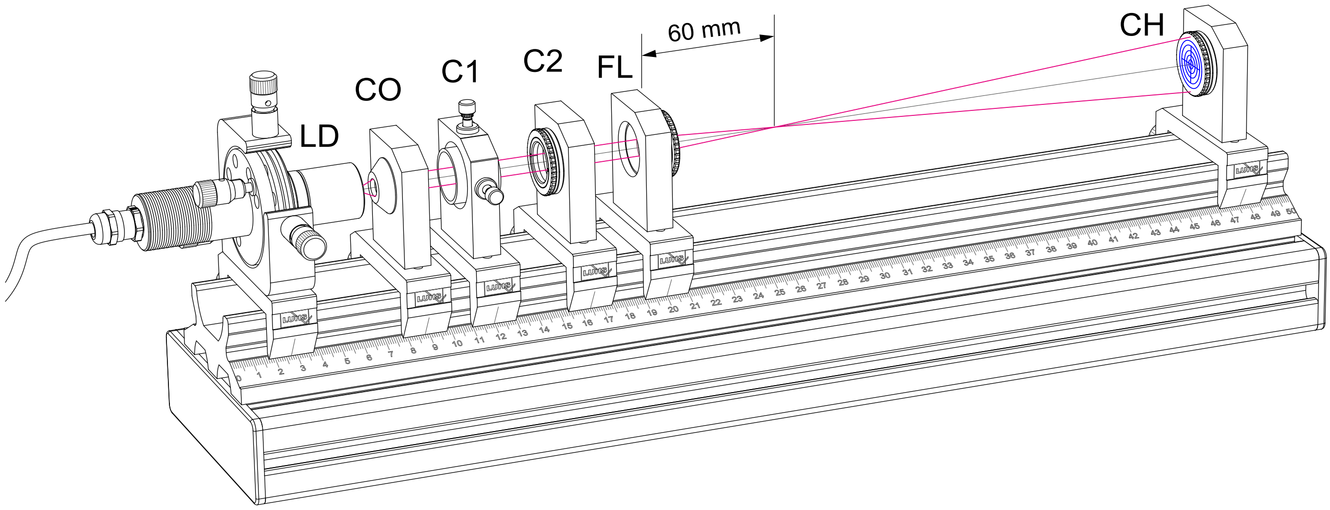


Fig. 37: Inserting the focusing module (FL) and creating the pump laser focus

Within the next step we will create a focus of the diode laser beam as shown in the figure above. The position of the focusing lens module (FL) is not critical, since the initial beam is always parallel. In a distance of 60 mm which corresponds to the focal length of the applied lens a focus is created and can be viewed on a piece of paper. This position is noted down by reading the position on the ruler since this is the position where in the next step the Neodymium doped YAG crystal rod will be placed. Before this is done, switch off the laser.

3.3 Inserting the Nd:YAG crystal

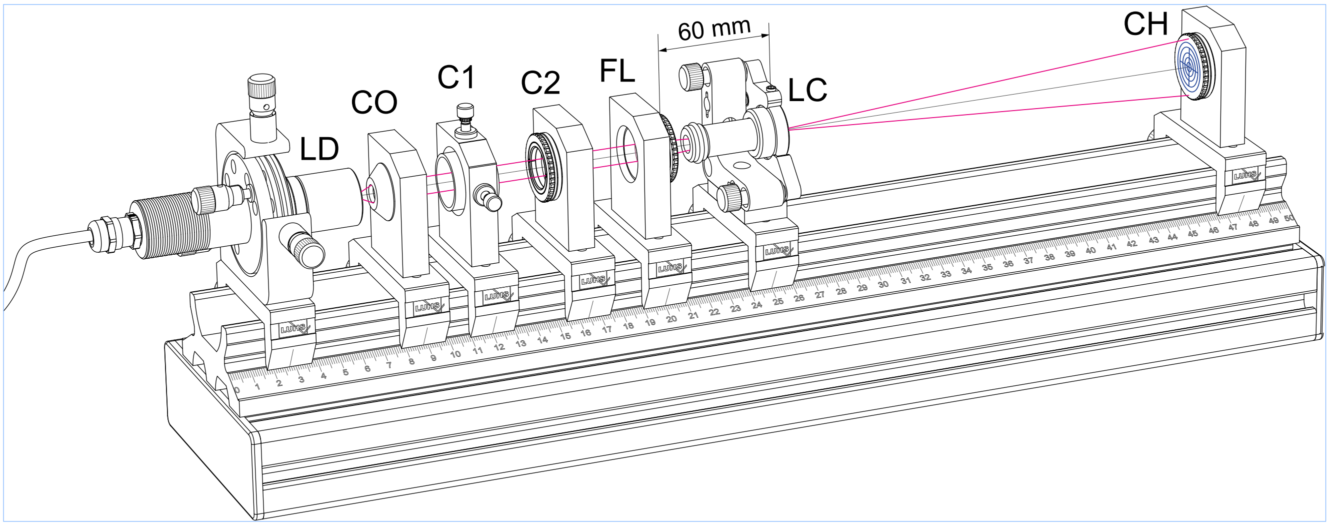
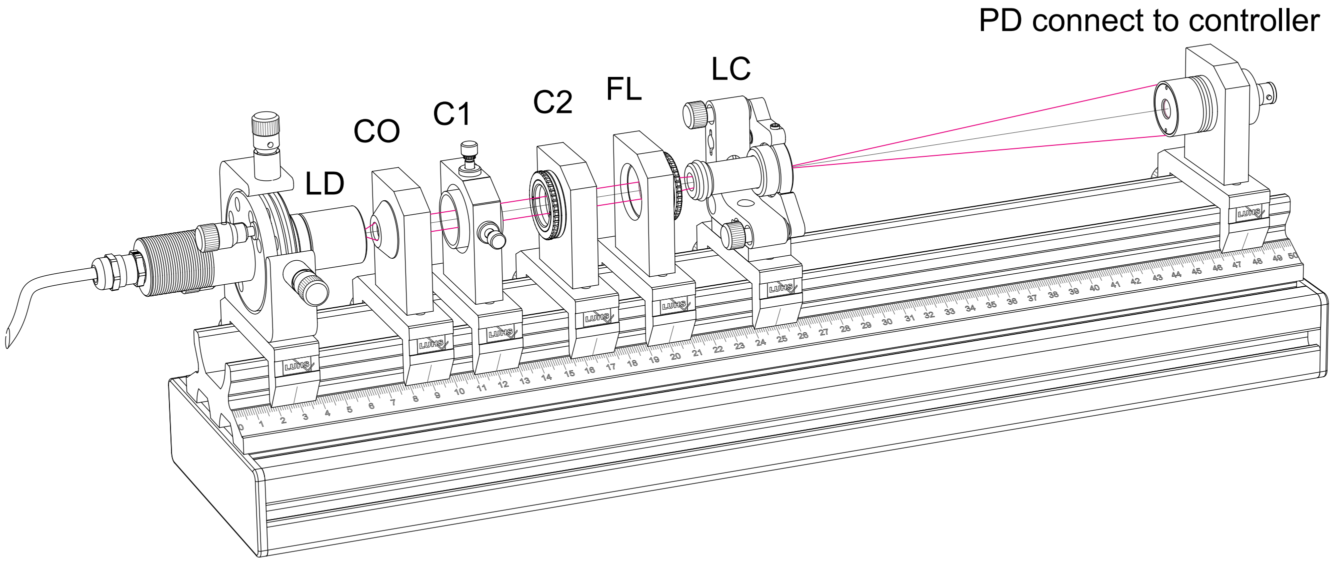


Fig. 38: Inserting the Nd:YAG crystal

The neodymium yttrium aluminium garnet (Nd:YAG) crystal (LC) is placed on the optical rail (OR) so that the focus of the diode laser radiation is well inside the laser crystal. The crossed hair target (CHT) is replaced with the photodetector (PD).

3.4 Characterising the Nd:YAG Crystal



A series of experiment will be performed to characterise the laser crystal. The first experiment deals with the property of the diode laser as well as the absorption of the Nd:YAG crystal. It is well known that the emitted wavelength of the diode laser depends on its temperature as well as injection current. More details can be found here [6].

In the following experiment the dependence of the wavelength of the diode laser beam on the diode temperature and the injection current is determined. Normally, these types of measurements are carried out with a high-resolution spectrometer. Another method is to use the well-known absorption lines of the Nd:YAG. The energy level diagram for Nd ions in the YAG crystal shows four main absorption transitions which can be pumped by the laser diode (Fig. 3). The centre of the absorption lines is located at: 804.4 nm 808.4 nm 812.9 nm and 817.3 nm

3.5 Absorption measurement of the Nd:YAG crystal

The adjustment holder with the Nd:YAG rod (see Fig. 11) is used in addition to the existing set-up for the previous measurement. The YAG rod should be positioned such, that the laser light illuminates the YAG rod centrally. The supplied photodetector is positioned behind the YAG rod. The distance should be chosen in such a way that the light intensity does not saturate the detector. Attention must be given in sensitive ranges to ensure that no extraneous light invalidates the measurement.

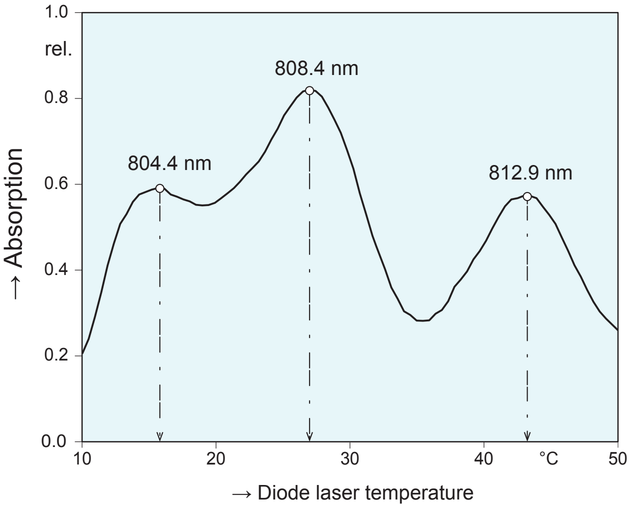


Fig. 39: Absorption of the Nd:YAG crystal as function of the pump wavelength

To measure the output power in relative units the photodetector module (PD) is placed onto the rail as shown in Fig. 30. The detector is connected to the controller. The output of the controller is connected either to an oscilloscope or to a digital multimeter which is switched to voltage measurement. For a set of temperatures such as 10...50°C in steps of 2°C or less the displayed photo voltage U_m of is recorded. The measurements will be taken with laser crystal out and in, to determine properly the absorbed power.
At the start of the measurement the diode laser module is switched on again. The residual pump light passing through the YAG rod can be observed with the converter screen. If the diode temperature is now changed, an increase or decrease in the intensity of the residual light can be observed which is caused by the wavelength dependence of the semiconductor laser.

Once set, the level of injection current must be constant when carrying out the following measurement, because it also affects the wavelength and the output power.
The measurement is taken, beginning with the lowest possible temperature. A period of a few minutes should expire before the laser diode has cooled down to a constant value. The measurements are then taken in suitable temperature steps up to the maximum temperature. The Table 4 may be used as template for the measurement.

Temperature °C	Voltage U_m (V)		R_L(Ω)	Popt (mW)		P_{abs}
Laser crystal	OUT	IN		OUT	IN	
10						
12						
14						
↓						
50						

Table 4: Template for recording absorption data

Measurements

3.5.1 Recording the excitation spectrum

We are using again a spectrum analyser however, now equipped with an optical fibre (F). The excitation fluorescence is so strong that holding the fibre in direction of the pumped laser crystal an almost noise free signal will be detected. Such a spectrum is shown in Fig. 41. The resolution of the spectrum analyser is just 1 nm and a better one will yield more resolved lines. However, with this simple spectrum analyser the fluorescence lines can be assigned to the transitions of the energy level diagram as shown in Fig. 3. This way of observing the fluorescence spectrum almost perpendicular to the excitation beam reduces its anyway strong intensity and favours the observation of the weaker fluorescence lines.

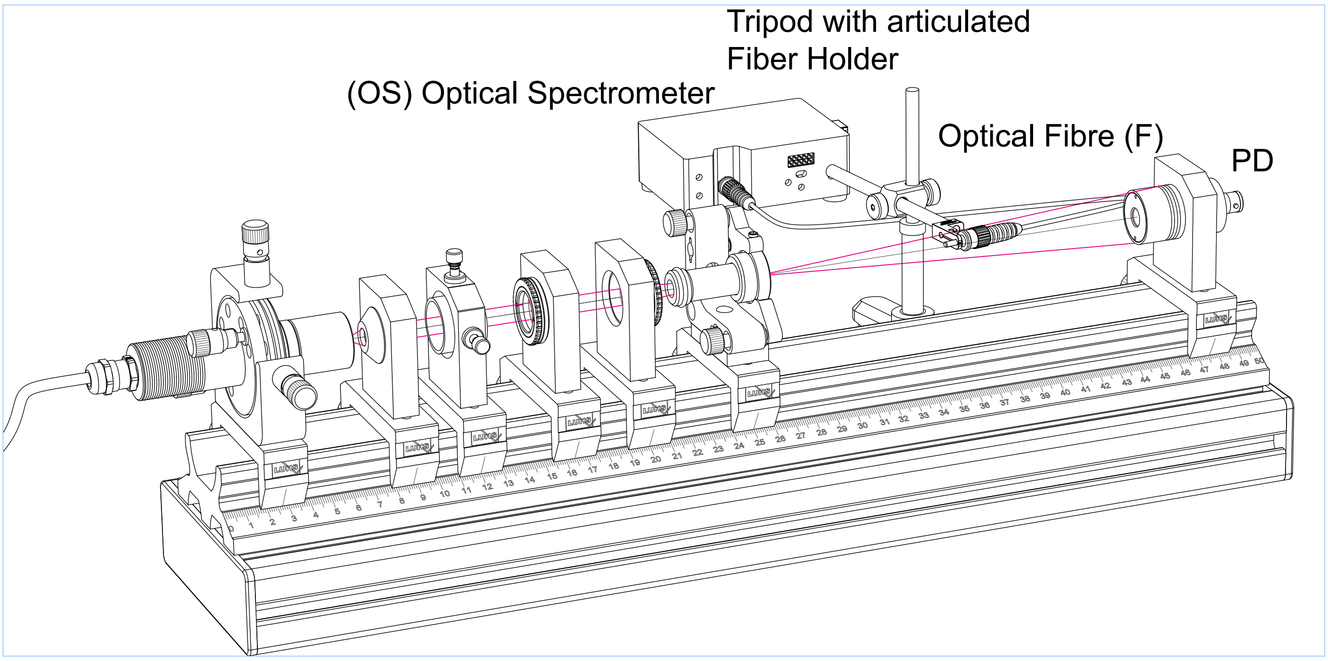


Fig. 40: Setup to measure the fluorescence spectrum

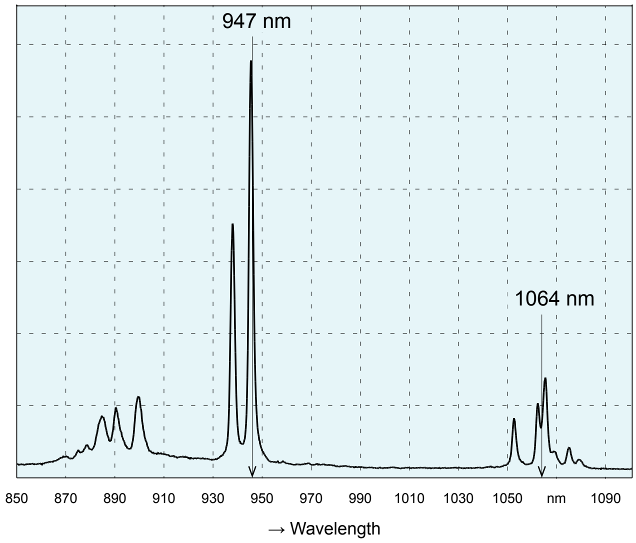


Fig. 41: NIR fluorescence spectrum of Nd:YAG rod excited with 808 nm

Depending on what spectrum analyser is selected the recorded range may differ. At this point it becomes clear that only the strength of a fluorescence line is important for the laser process but mainly the underlying emission process. In the spectrum of Fig. 41 the 947 nm fluorescence appears even much stronger than those of the 1064 nm radiation, however, this is due to the spectral sensitivity of the spectrometer's sensor.

Measurements

3.6 Measuring the lifetime of the excited states

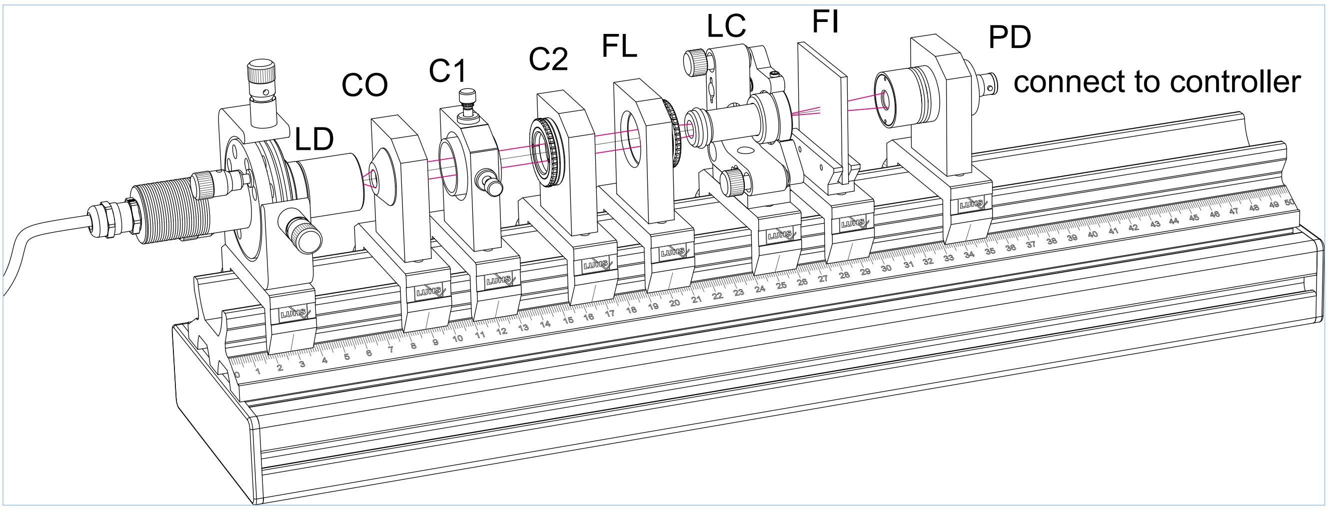


Fig. 42: Set-up to measure the lifetime of excited states

The lifetime of the excited state plays an important for an efficient laser process. The lifetime determines also the dynamic behaviour of the laser and its capability of q-switching. Therefore, we are interested in this experiment in the temporal behaviour of the fluorescence light. The laser diode is now operated in pulsed mode. To suppress the unwanted pump radiation, we are inserting the filter module (FI) in front of the photodetector (PD). The photodetector is connected to the controller and the output of it to the oscilloscope to channel 1 (CH1). Channel 2 (CH2) is connected via the provided BNC cable with the modulation reference output of the diode laser controller MK1 (Fig. 24).

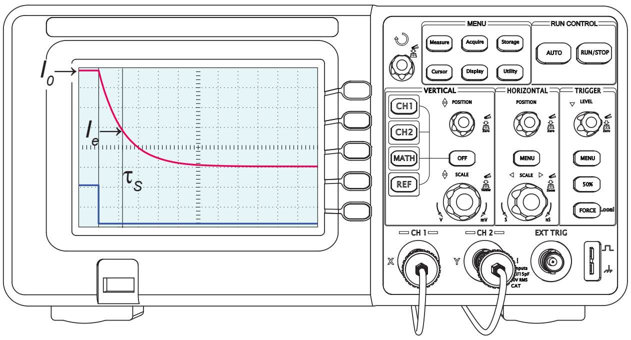


Fig. 43: Oscilloscope to measure the lifetime of the excited state

The oscilloscope is configured to trigger on channel 2 (CH2) (which is the modulation reference) at falling edge. The life time τ_S of the excited state is defined as the time, when the fluorescence intensity I_e drops to I_0/e. This time can be taken from the oscilloscope display as shown in (Fig. 43).

Note: Place the filter RG1000 and the photodetector as close as possible to the Nd;YAG rod to obtain the largest fluorescence signal

3.7 Complete the set-up for laser operation

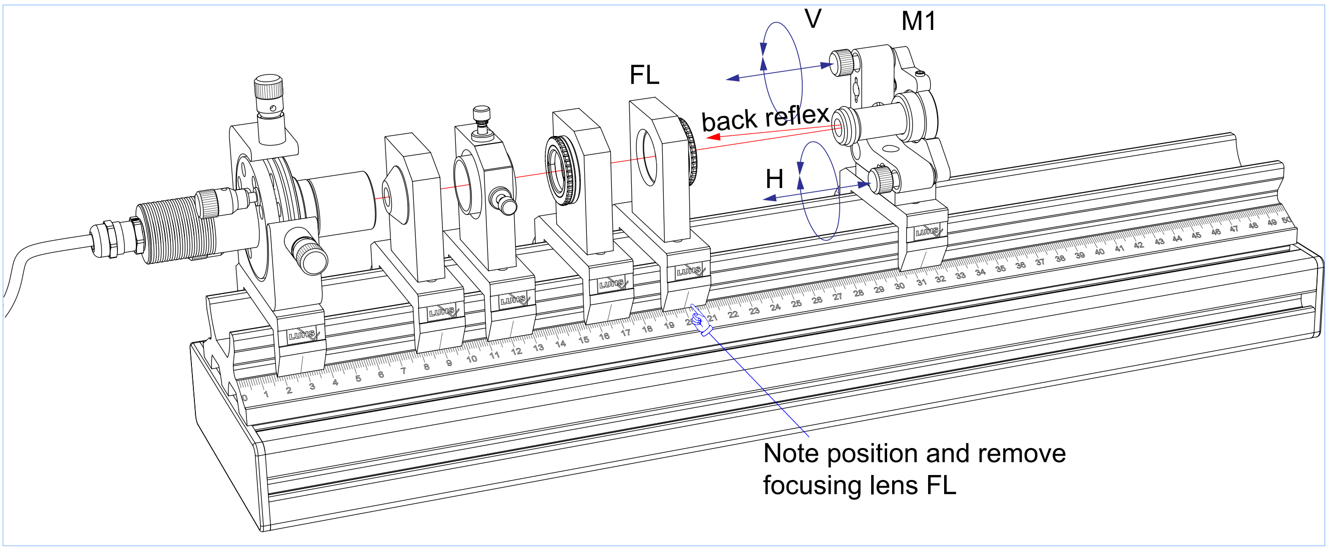


Fig. 44: Basic alignment of laser mirror M1

After completing the spectroscopy related measurement, we are going to prepare the set-up for laser operation. For the first step we need to align the mirror M1 perpendicular to the laser diode radiation. For this purpose, we remove the focusing lens (FL). We note down its position so that we can place it back when the laser mirror M1 will placed into its final position. After the removal we place the laser mirror module (M1) onto the optical rail as shown in Fig. 44.
By turning the fine pitch screws for vertical (V) as well horizontal (H) tilt the back reflected beam such that is centred to the incident beam. When this has been done the focusing lens is placed back into its position. The laser mirror mount (M1) is moved towards the focusing lens in such a way that the focus lies well behind the laser mirror. It is recommended to perform this step in a moderately darkened room since the visibility of laser diode radiation is quite low. Keep in mind that this alignment is not crucial at all.

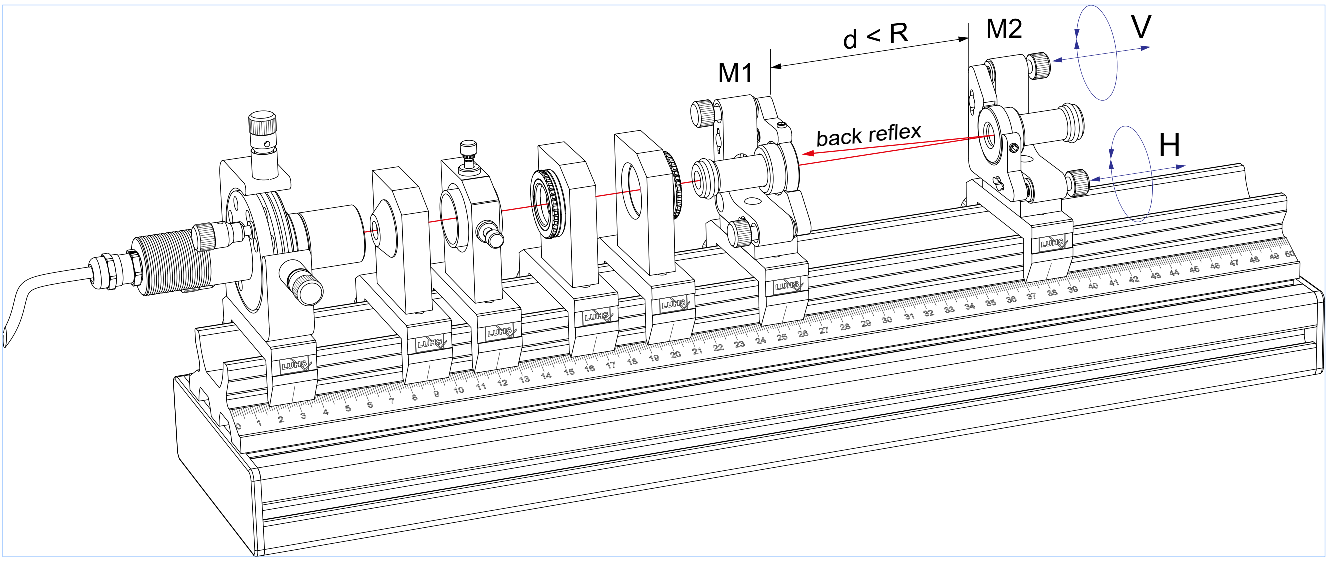


Fig. 45: Alignment of the second cavity mirror M2

The laser mirror module M2 is placed onto the rail. The distance d should be chosen such, that it is less than the radius of curvature (R_{M2}) of the mirror M2. If the distance d exceeds the value of R_{M2} the cavity is optically unstable, and no laser radiation will be obtained.
The back reflex of M2 is now centred to the spot on M1 by adjusting the fine pitch screws for horizontal (H) and vertical (V) movement. It should be mentioned that due the poor visibility of the pump laser beam of 808 nm it is recommended to do the alignment in a darkened room.

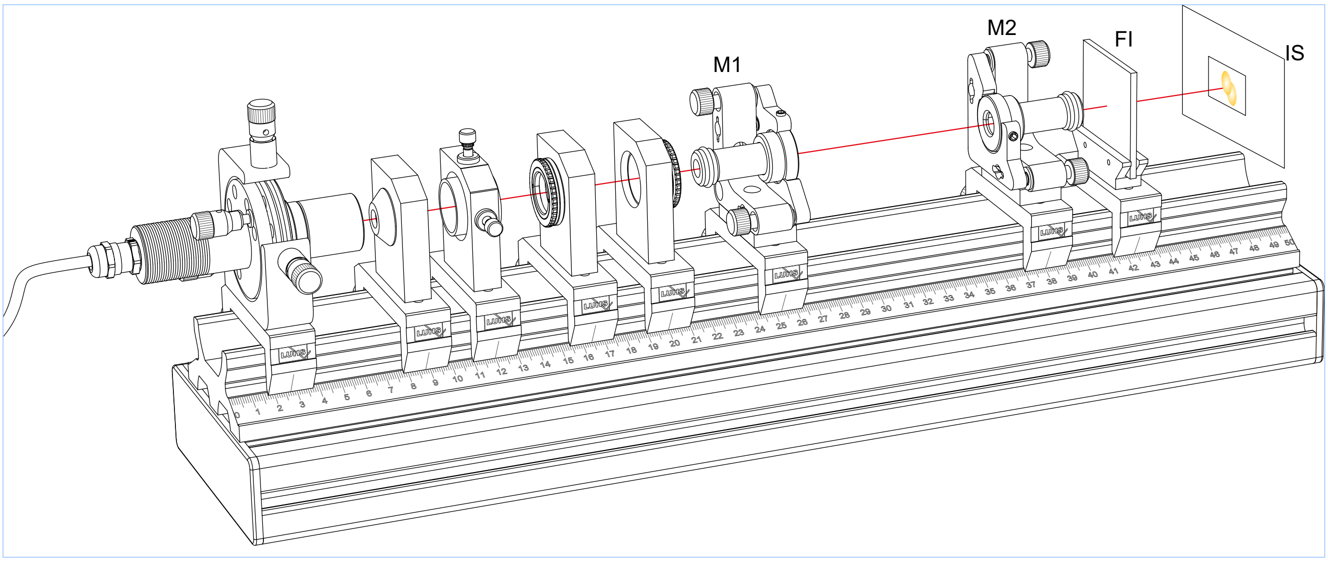


Fig. 46: Laser operation!

Place the filter module (FI) with the RG1000 filter on the rail. This filter blocks all radiation below a wavelength of 1000 nm. That means the pump radiation which has not been absorbed by the Nd:YAG crystal is efficiently blocked. Use the infrared converter screen (IS) and hold it behind the RG1000 filter. You will see a glowing orange spot on the sensitive area of the card. The Nd:YAG laser is operating! Once this orange spot can be seen the entire set-up will be aligned for best performance. Instead of using the converter screen the photodetector connected via the box ZB1 to a digital voltmeter or oscilloscope can be used as well. The position of the focusing lens may be optimised. Furthermore the Nd:YAG crystal and the mirror M2 aligned for maximum laser output. The better the alignments are, the less the laser threshold will be. Good values are below 300 mA for the injection current of the diode laser.

3.8 Stability criteria and laser power

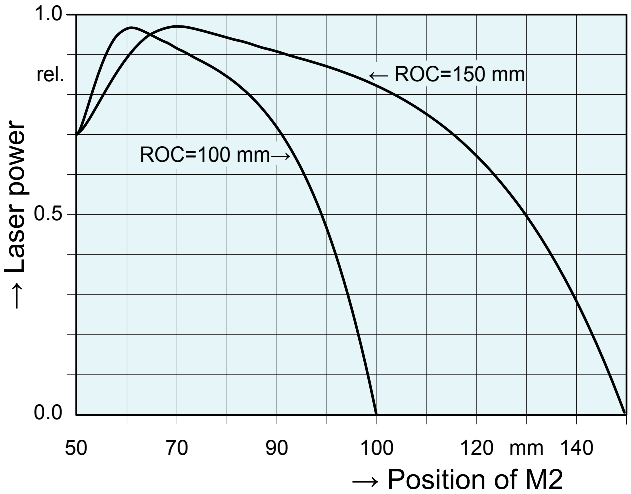


Fig. 47: Laser output power and stability range

Once the laser threshold has been optimised the stability criteria of the optical cavity is validated. Since the applied cavity type is a hemispherical one the mirror distance d must be less or equal than the radius of curvature of the second mirror. A nice description and derivation of the stability criteria of an optical cavity is given in [6] or [5].

The output power is measured versus the position of the mirror M2. The experiment may come with two different radius of curvature (ROC) 100 (standard) and 150 mm (optional). For each ROC the measurement is recorded like Fig. 47

3.9 Measuring the threshold and slope efficiency

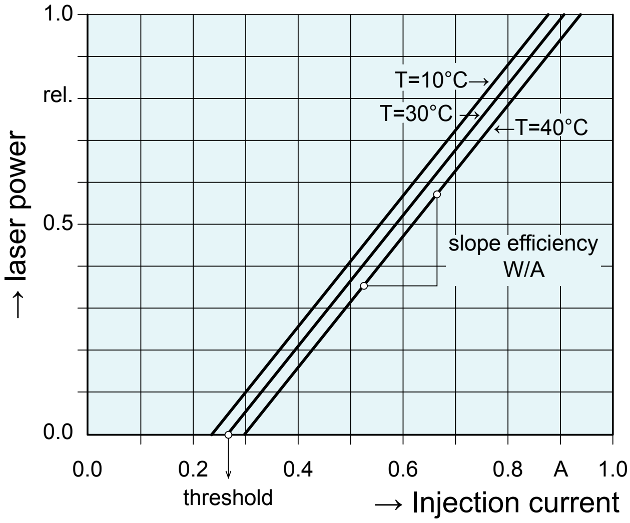


Fig. 48: Laser threshold and slope efficiency

For an optimised and well-adjusted set-up, the laser output power is measured for a set of different temperatures of the laser diode. From the resulting graph (like Fig. 48) the threshold and the slope efficiency is obtained from the linear regression of the respective curve.

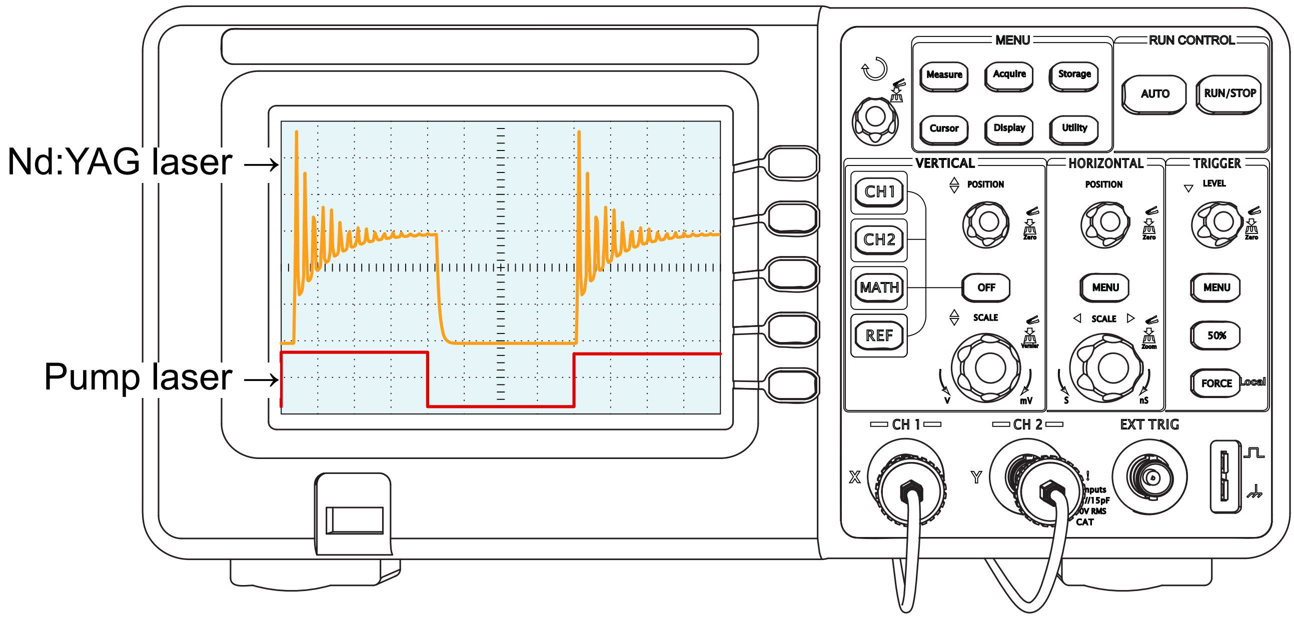


Fig. 49: Demonstration of spiking

To measure the temporal behaviour of the Nd:YAG laser we are going to modulate the injection current of the diode laser, that means we are periodically switching on and off the pump radiation. To monitor the response on an oscilloscope we are placing the photodetector (PD) behind the RG1000 Filter (FI) and connecting the photodetector to the controller (PD IN). The output of the controller (PD OUT) is connected to the first channel of an oscilloscope. The second channel is connected to the buffered modulation reference signal of the diode laser controller. The scope is set to trigger on the rising edge of the modulation signal. When powering on the diode laser we will observe the so-called spiking which results from the long lifetime of the excited state. The upper track shows the response of the Nd:YAG laser and the lower one the power of the pump laser. The spiking becomes clearer and more impressive when the injection current is reduced down to the threshold of the laser.

3.10 Passive q-switch with Cr:YAG crystal

In the previous experiment we already noticed that the Nd:YAG laser responded with a high initial spike when the pump suddenly was switched on. In this case the pump radiation was changed, another method to achieve pulsed radiation is to change the quality q of the cavity (Fig. 50).

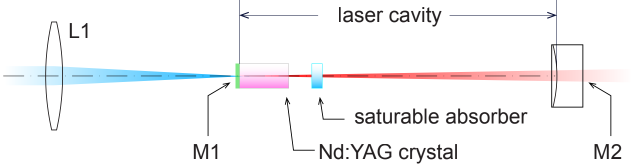


Fig. 50: Principle of passive q-switch operation

This is done by a saturable absorber which is placed into the cavity. The absorption of such a crystal is chosen such that the losses will prevent laser oscillation. However, due to the continuing pumping process the intensity of the created fluorescence increases and the initial absorption of the absorber bleaches out. If the reduced losses reach again the laser threshold the impounded population inversion releases a giant laser pulse. Herewith the population inversion is reduced to such an extent that the laser process ceases. Due to the reduced intensity the absorption of the absorber goes up again to its initial value which also means that the cavity is blocked again: it has a low-quality q. It takes a while until the excited state is reloaded again by the pump process and the next laser pulse is released.

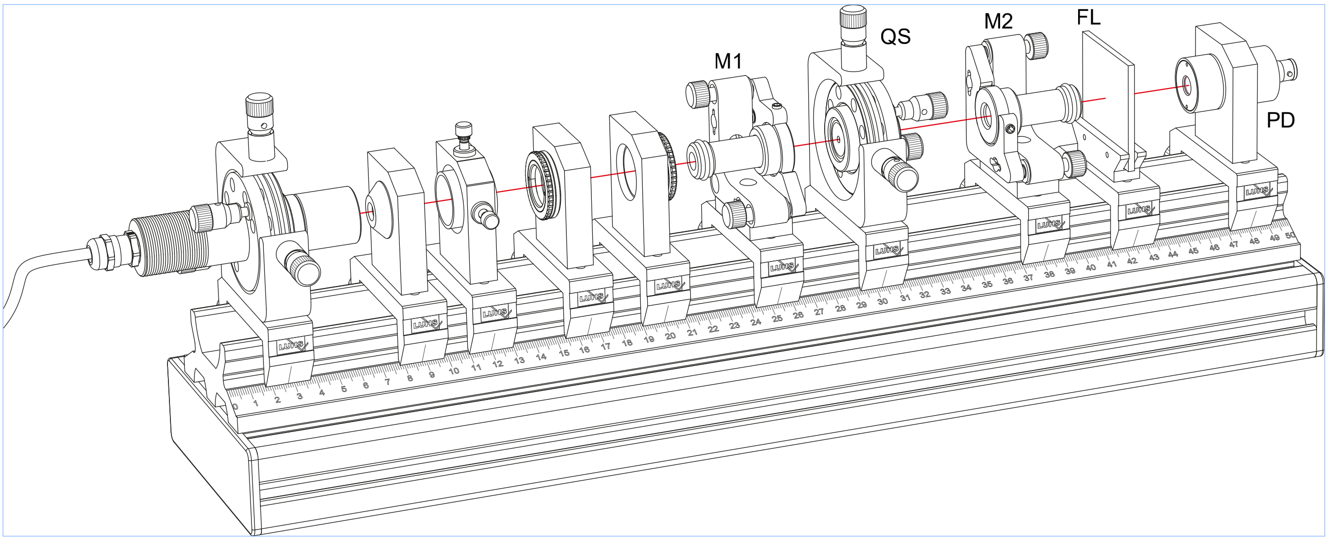


Fig. 51: Set-up for passive q-switch with Cr^{3+}:YAG as saturable absorber

As already shown in the principle of Fig. 50 the saturable absorber is placed inside the cavity. In the experimental set-up a Cr^{3+}:YAG crystal is used, which is mounted into a five axes adjustment holder (QS) as described in detail in section 2.12 on page 8. It is good practise to align the Nd:YAG laser for best performance before the passive q-switch is placed into the cavity.

Note: The best performance is obtained when the cavity is operated close to its stability limit.

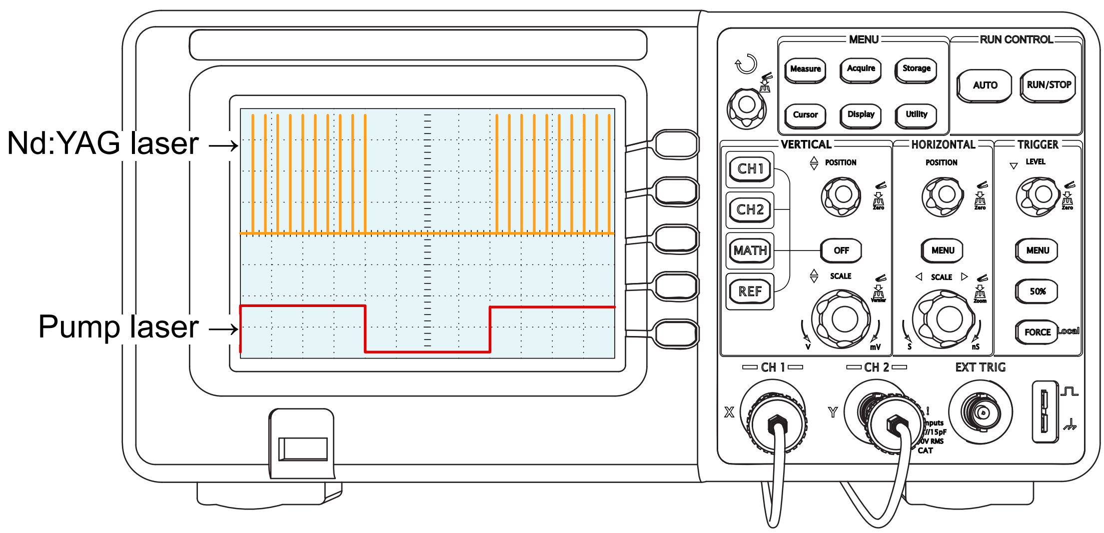


Fig. 52: Passive q-switch of Nd:YAG laser with intracity saturable absorber

To observe the appearance of q-switch pulses the photodetector connected to the diode laser controller MK1 is used. The output is connected to CH1 and the modulation reference output of the diode laser controller MK1 to CH2 of the oscilloscope. The oscilloscope is configured to trigger on the rising edge of the modulation signal. Actually, the passive q-switch does not require the modulation, however it makes it the interpretation of the signals on the oscilloscope easier.

3.11 Active q-switch with Pockels Cell

Another possibility to manipulate the quality factor q of an optically cavity is to use a Pockels cell. Details of the active q-switch module are given in section 2.12.1 on page 9. If you require more information about the how it works we recommend the source [6].

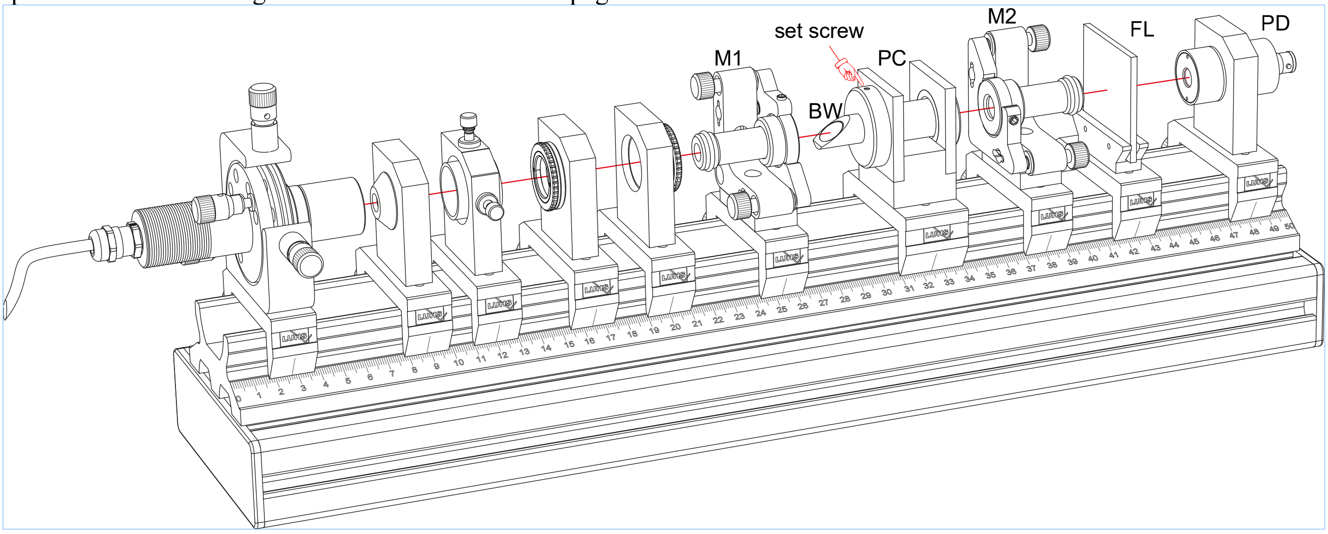


Fig. 53: Set-up with intra-cavity Pockels Cell

The blocking of the cavity is based on switching the polarisation instead of the absorption. In a first step we have to force the Nd:YAG laser to operate in a well-defined direction of polarisation. This is done by the Brewster window (BW) which is part of the Pockels cell (PC). Once the Pockels cell is inserted into the cavity the cavity is aligned again for best performance. In general the Nd:YAG crystal has a preferred polarisation based on stress or other introduced birefringence. Thus, the Brewster window shall be aligned in such a way that it supports this direction of polarisation. This can be achieved by rotating the Brewster window after loosening the set screw as indicated in Fig. 53 and the figure below.

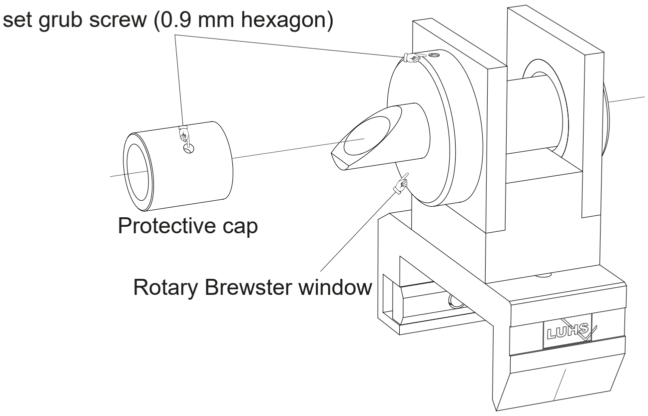


Fig. 54: Pockels cell's Brewster rotary window and protective cap.

Note:
It is important to place the protective cap to the Brewster window to block dangerous reflected laser light from the Brewster window surface.

Instead of continuously applying the high voltage to the Pockels cell, this driver version applies a short pulse. This requires, that the Brewster window is rotated such, that the Nd:YAG laser does not lase. Once this position has been found the set screw is tightened again.

The Pockels cell driver is switched on and on the oscilloscope the signal of the photodiode is monitored. It is important that the photodiode is operated with a 50 Ohm shunt. The trigger of the used channel is set to pulse detection. Since the pulses are very short (100 ns) it takes a while to find the signal. The high voltage applied to the Pockels cell is optimized for maximum amplitude.

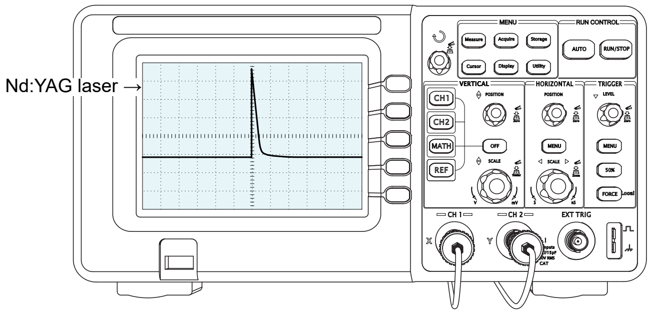


Fig. 55: Active q-switch pulses

To CH1 we connect as usually the output of the ZB1 box. Due to the short pulses in the nano second regime the 50 Ω resistor of the ZB1 should be selected. The photodiode's trace of the oscilloscope shows an asymmetric pulse shape, the rise is faster than the fall. The creation of the photons goes very fast and assuming we would have an ideal cavity with ideal mirrors the created photons would stay forever inside the cavity. Fortunately, some of them passing the real mirror to the detector, otherwise we will not be able to detect them. Depending on the quality q of the cavity the lifetime of the photons inside the cavity is determined showing the decay like course of the falling edge. This effect is also known as "cavity ring-down" and is exploited for the cavity ring-down spectroscopy (CRDS).
The pulse profile may also be affected by the saturation of the photodiode. To exclude this, the pump power of the Nd:YAG laser is reduced.

3.12 Frequency Doubling or Second Harmonic Generation (SHG)

Second harmonic generation was first demonstrated by Peter Franken et. al. in Ann Abor at the University of Michigan 1961 [3]. It happened shortly after the invention of the Ruby laser in 1960. Now powerful coherent light was available required for such a non-linear optical process. They focused the ruby laser with a wavelength of 694 nm into a quartz sample and analysed the light with a spectrometer on photographic paper. On that paper a small spot at the position of 347 nm became apparent, which indicated the production of light at 347 nm and paved the way for vast research in this area. Nowadays a rich variety of special optical crystals exist for the efficient generation of wavelength which are directly not available by the laser source.

$$P^{(2)}(2\omega) = \chi^{(2)} \cdot \vec{E}(\omega) \cdot \vec{E}(\omega)$$

χ is known as the non-linear susceptibility tensor and simply said it describes the strength of the non-linearity of the material which is in interaction with the electrical field $\vec{E}(\omega)$ of the fundamental wave. $P^{(2)}(2\omega)$ is the polarisation of the dipole inside the material. This forms the first condition for efficient SHG, the material should have a high nonlinear susceptibility. The second requirement, the phase matching condition demands that the fundamental and harmonic are travelling in phase in the same direction requiring $n(2\omega) = n(\omega)$. Due to the dispersion of optical materials this can only be achieved when the material is double refractive to satisfy the requirement:

$$n_e(2\omega) = n_o(\omega) \text{ or } n_o(2\omega) = n_e(\omega)$$

whereby n_o is the ordinary index of refraction and n_e the extraordinary.

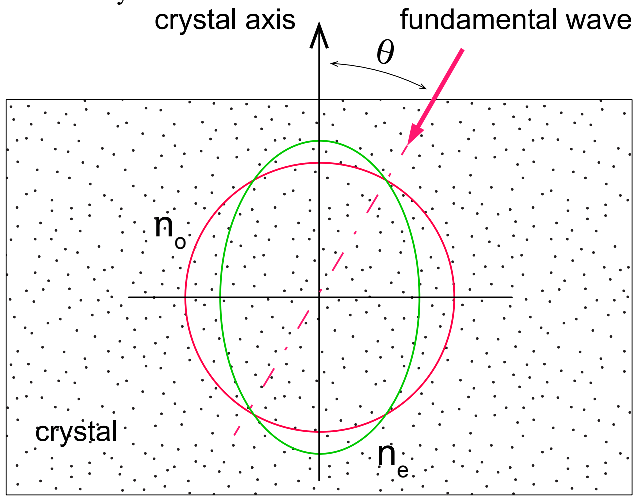


Fig. 56: Index ellipsoid of a double refractive material

The art of the optical engineering means to find a suitable crystal and to cut it in a practical way that the user can mount it into his equipment. The KTP crystal used in this equipment has a size or 2x3x5 mm and it is cut with respect to the optical axis for efficient generation of 532 nm or for the other fundamental waves for 665 and 562 nm.

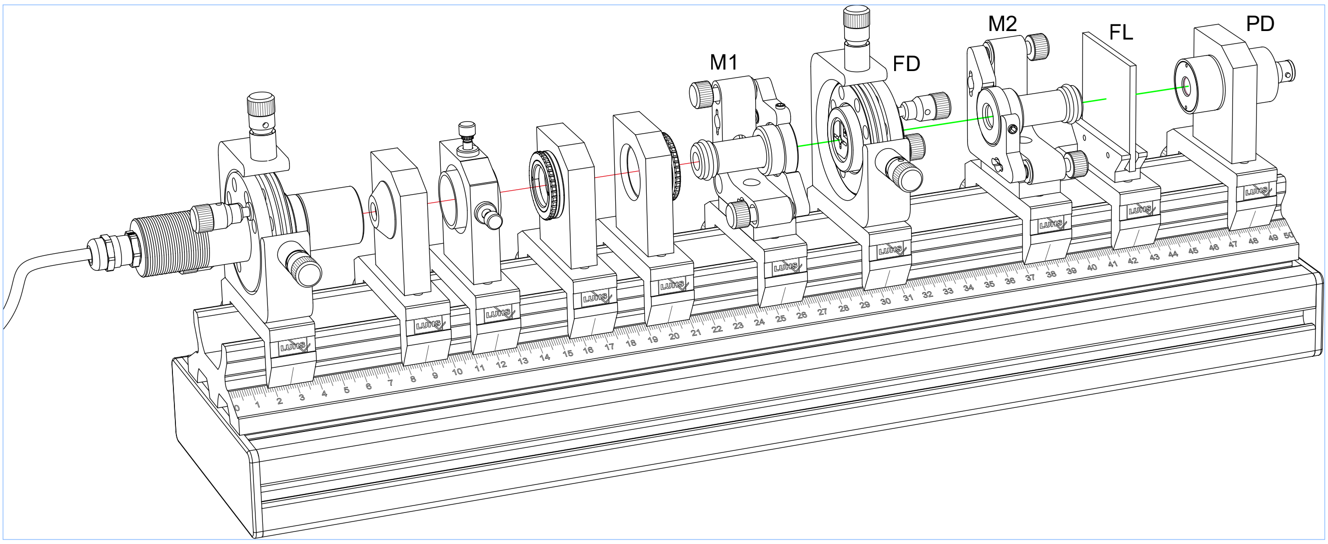


Fig. 57: Set-up for second harmonic generation with a KTP crystal

It is a good idea to mount the crystal into a five-axis holder to align the crystal for best phase matching condition. The SHG module (2.11 on page 8) is placed into the cavity in such a manner that it is as close as possible to the Nd:YAG rod. At this place the beam waist of the Nd:YAG radiation has its smallest diameter resulting in a high intensity which favours the conversion efficiency of the SHG process. Instead of the RG1000 the BG39 filter is used which only transmits the visible radiation. By means of the photodetector we can perform a variety of measurements related to the SHG process.

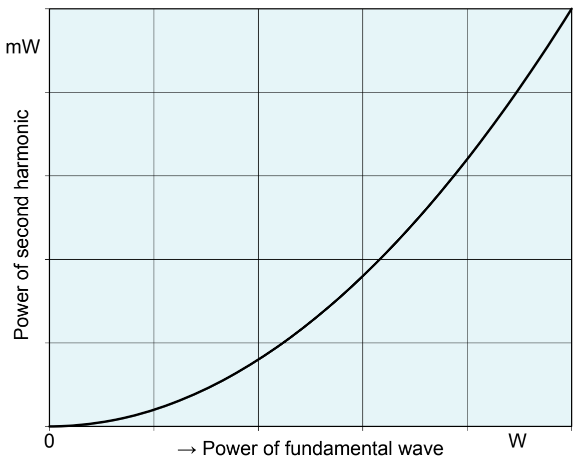


Fig. 58: Quadratic relation between the fundamental and second harmonic power

Such an example is shown in Fig. 58. Here the power of the green (SHG) radiation is drawn against the fundamental power. We can assume that the fundamental power (intracavity Nd:YAG radiation) is linear to the injection current. For those who require to be more precise, can measure the fundamental power using the RG1000 filter in front of the photodetector and calculating the power based on the parameter of the detector in W. Taken into consideration the reflectivity of the mirror M2 of 99.9 % the measure power is just 0.1 % of the power inside the cavity. A typical output power is 30 mW which is 0.1% of the intracavity power which yields 30 W of internal power! So far, we mainly focused on the well-known conversion 1064 nm→532 nm. However, all above said is of course valid for other available conversions like 1330 nm → 665 nm as well as 1123 nm → 561.5 nm.

3.13 Higher transverse modes

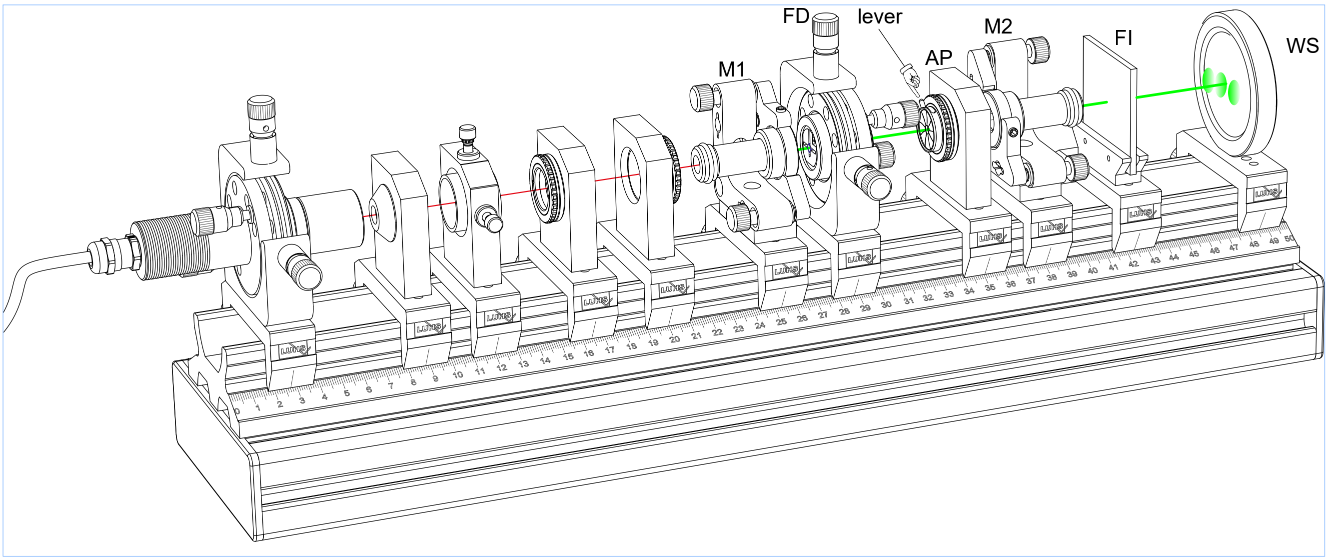


Fig. 59: Demonstration and control of transverse mode

Due to the high gain and cavity design a lot of transverse modes of the fundamental wave exist which become visible due to the SHG process. By means of an adjustable iris (AP), which is used inside the cavity close to the spherical mirror, the manifold of these modes can be controlled down to TEM_{00}.

3.14 Frequency Doubling with Active q-Switch

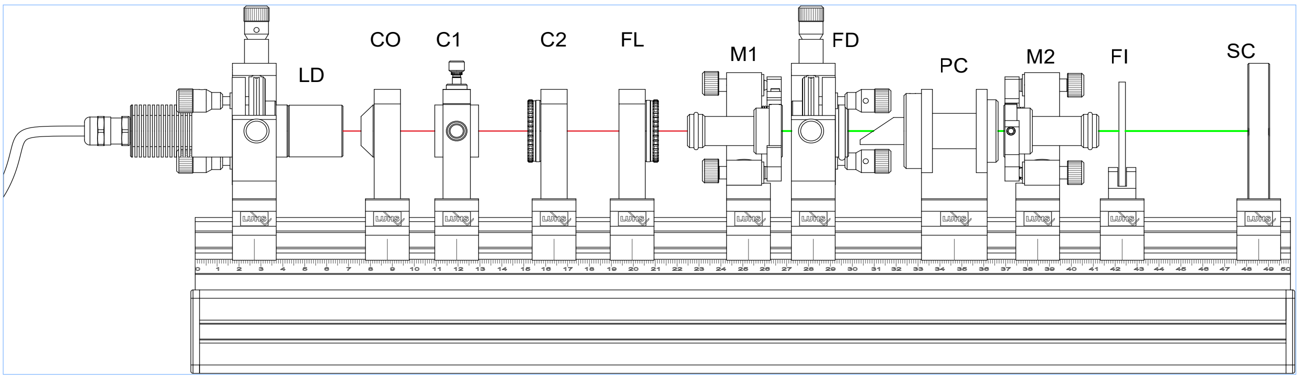


Fig. 60: Active q-switch and intra-cavity frequency doubling

From the previous chapter we learned that the SHG power depends quadratically on the power of the fundamental radiation. Thus, it is a good idea to combine the active q-switch and the second harmonic generation. Such a set-up is shown in Fig. 60. The average power will certainly below that one obtained of the continuous wave (cw) SHG. But the peak power will be much higher.

3.15 Extra-cavity Frequency Doubling

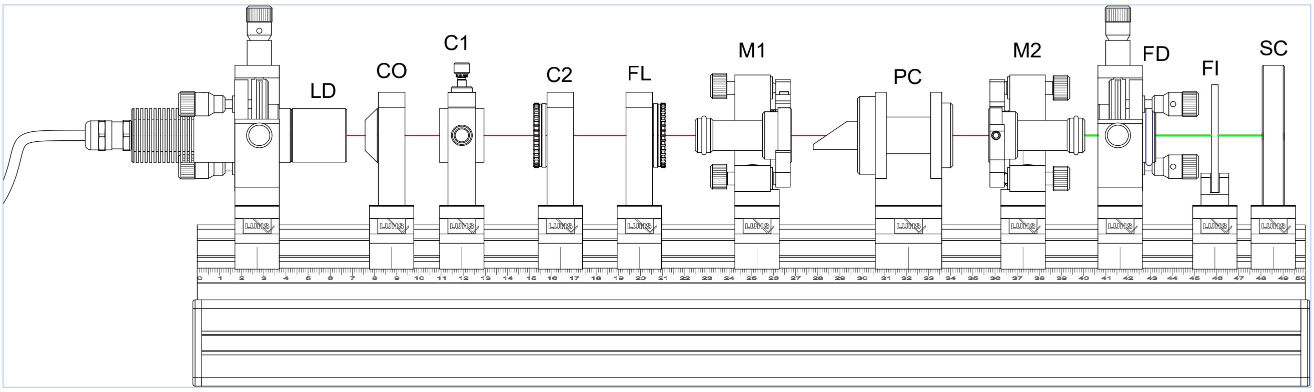


Fig. 61: Extra-cavity Frequency Doubling.

From the previous chapter we learned that for the efficiency of the SHG process the initial power of the fundamental radiation is of crucial importance. Although knowing that we want to perform in the last experiment extra-cavity frequency doubling. In order to achieve high peak power outside the cavity we are using in this experiment a mirror M_2 with a output coupling of 2 %. We expect to get in the cw mode about 150 mW radiation at 1064 nm. If we assume further that we will get 10 mW average power with a repetition rate of 1000 Hz (set by the HV controller of the Pockels cell) and a typical q-switch pulse width of 100 ns the peak power per pulse should reach:

$$P_{peak} = \frac{P_{average}}{f \cdot \delta t} = \frac{0.01W}{1000\,Hz \cdot 100 \cdot 10^{-9}\,s} = 100W!$$

Note: For the extra cavity we need an extra focusing lens module with a focal length of 60 mm to achieve a small spot for high intensity of the fundamental mode.

3.16 Frequency doubling with passive q-switch

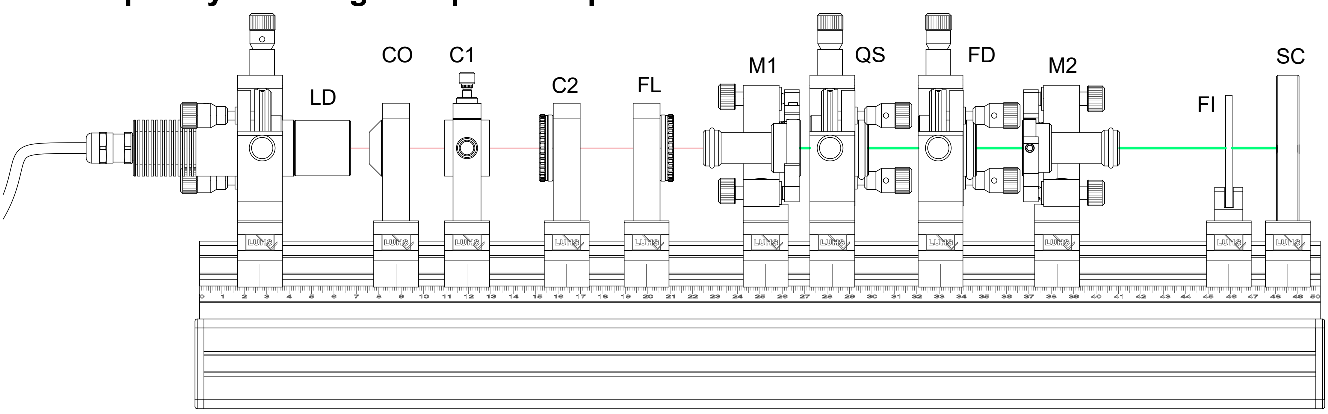


Fig. 62: Intra-cavity frequency doubling (FD) with passive q-switch (QS) with the OM-0050 Cylindrical Beam Expander

3.17 Concentric Cavity Extension

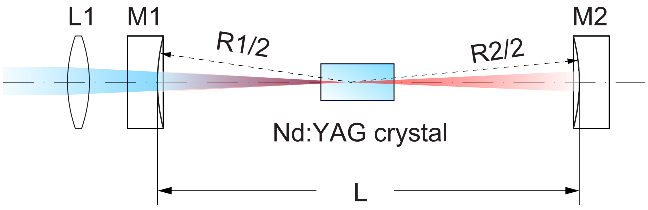


Fig. 63: Concentric Nd:YAG Laser Cavity

The cavity consists out of a spherical mirror (M1) with a radius of curvature R of 100 mm and another spherical one (M2) with R=100 mm). The focal length of (L1) is 60 mm and with the plane-concave imaging effect of M1 a longer focus than 60 mm depending on the distance between L1 and M1 can be achieved. Of course the stability criteria $0 \le g_1 \cdot g_2 \le 1$ must be fulfilled, which means:

$$0 \le \left(1 - \frac{L}{R_1}\right) \cdot \left(1 - \frac{L}{R_2}\right) \le 1$$

$$R_1 = R_2$$

$$0 \le \left(1 - \frac{L}{R_1}\right)^2 \cdot \le 1$$

For a rapid check of the stability range for our cavity parameter with R_1= 100 mm and R_2 = 100 mm, we put the formula into a calculation sheet like Excel or other and create the graph of g_1g_2 versus the mirror spacing L. The result is shown in Fig. 64.

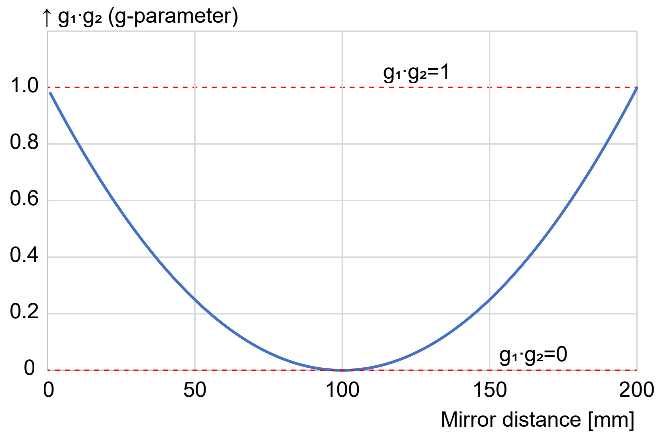


Fig. 64: Stability diagram for R=100 mm mirror

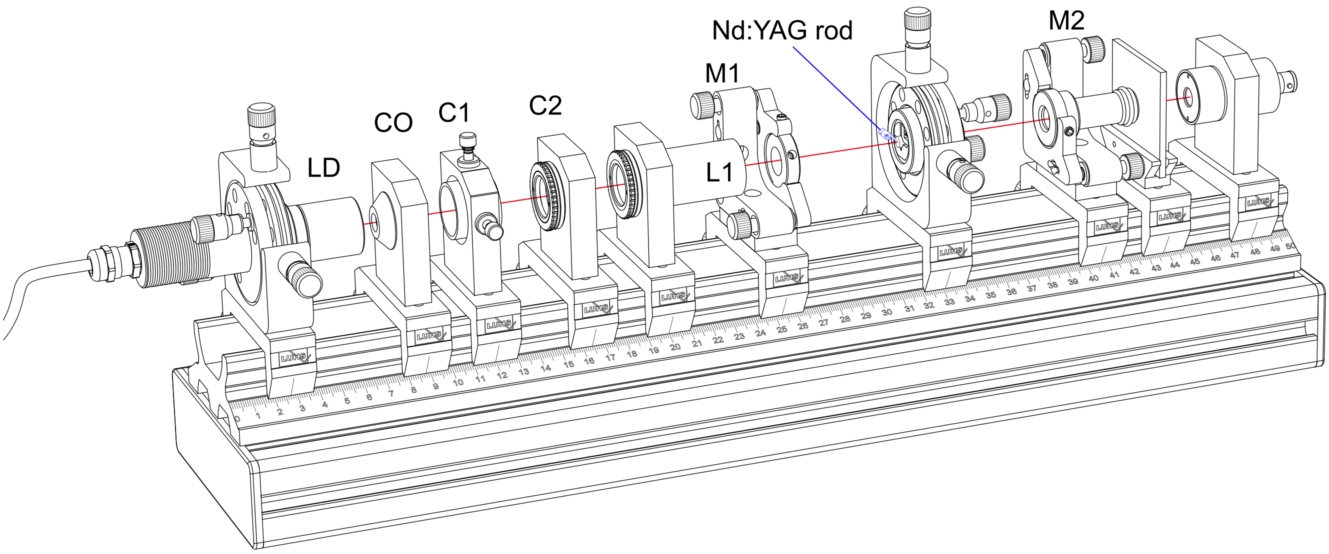
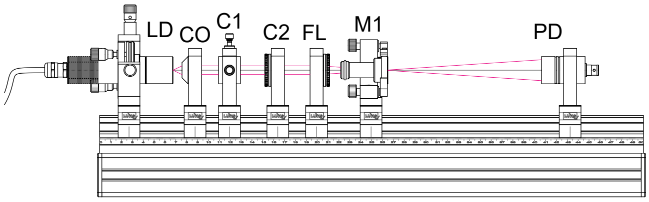


Fig. 65: Nd:YAG laser with concentric cavity

Measurements

3.18 Data Recording

3.18.1Transmission versus Laser diode's Temperature



The temperature of the laser diode (LD) is scanned and the transmitted light through the Nd:YAG rod (M1) is recorded.

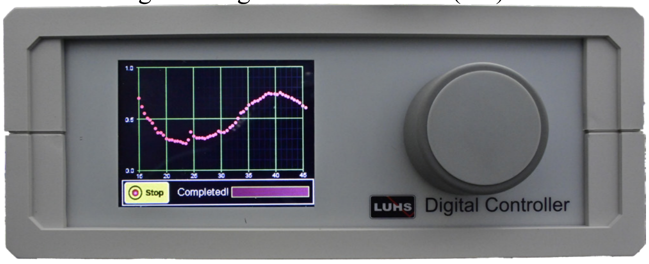


Fig. 66: Live plot shown on the controller

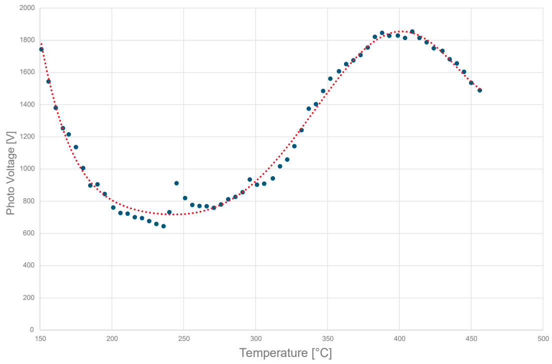
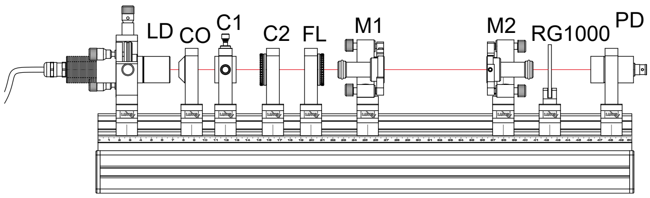


Fig. 67: Photodiode voltage versus Temperature

The measured data is processed and plotted using Microsoft Excel, for example. The data file contains the values of the free parameters such as current or temperature and the set values of the photodiode in the header. For the above case:

PD Shunt: 1.0 kOhms
PD Gain: 1
Scan Mode: Temperature vs. PD
Current: 504mA

3.18.2 Output Power versus Pump Power



The RG1000 filter is placed in front of the photodetector PD to block the pump radiation and ensure that the detector only measures the laser wavelength of 1064 nm.

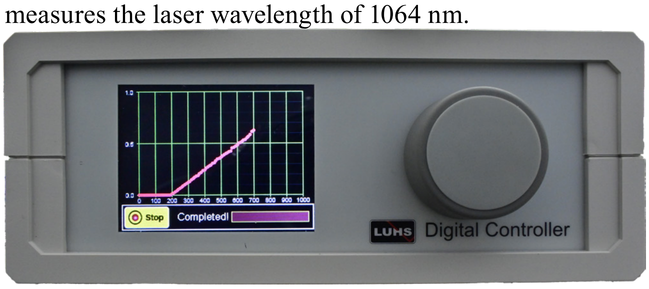


Fig. 68: Live plot laser versus pump power shown on the controller

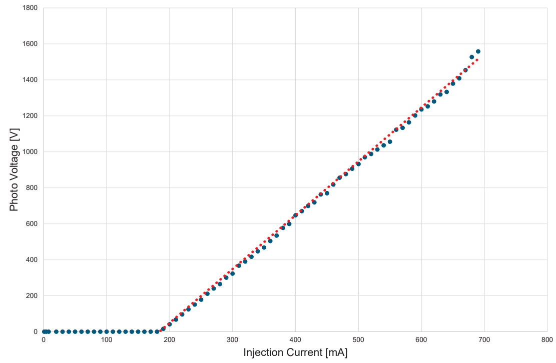
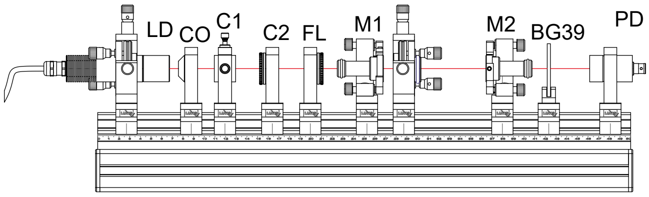


Fig. 69: Laser output power versus pump power

PD Shunt: 8.0 kOhms
PD Gain: 1
Scan Mode: Current vs. PD
Temperature: 25.1°C

3.18.3 SHG Power versus Pump Power



The BG39 filter is placed in front of the photodetector PD to block the pump and laser radiation and ensure that the detector only measures the power of the wavelength of 532 nm.

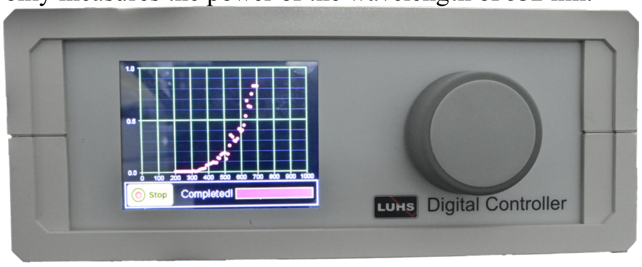


Fig. 70: Live plot SHG Power versus Pump Power shown on the controller

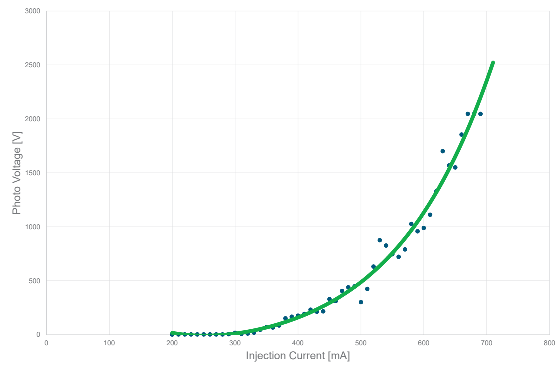


Fig. 71: Non-linear SHG Power Curve

PD Shunt: 10.0 kOhms
PD Gain: 1
Scan Mode: Current vs. PD
Temperature: 25.2°C

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