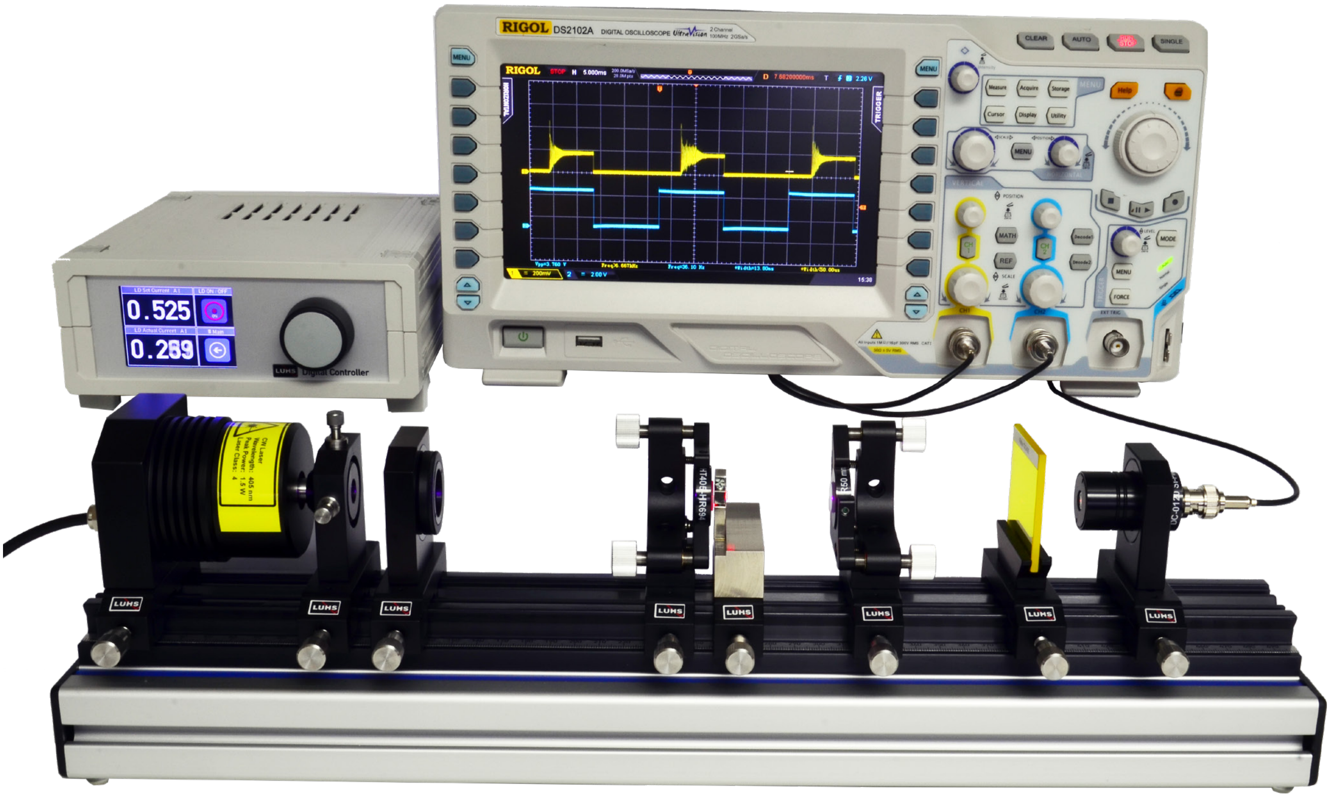
Photonik
Ingenieurbüro
Dr. Walter Luhs

UM-LE02 Manual for Ruby Laser



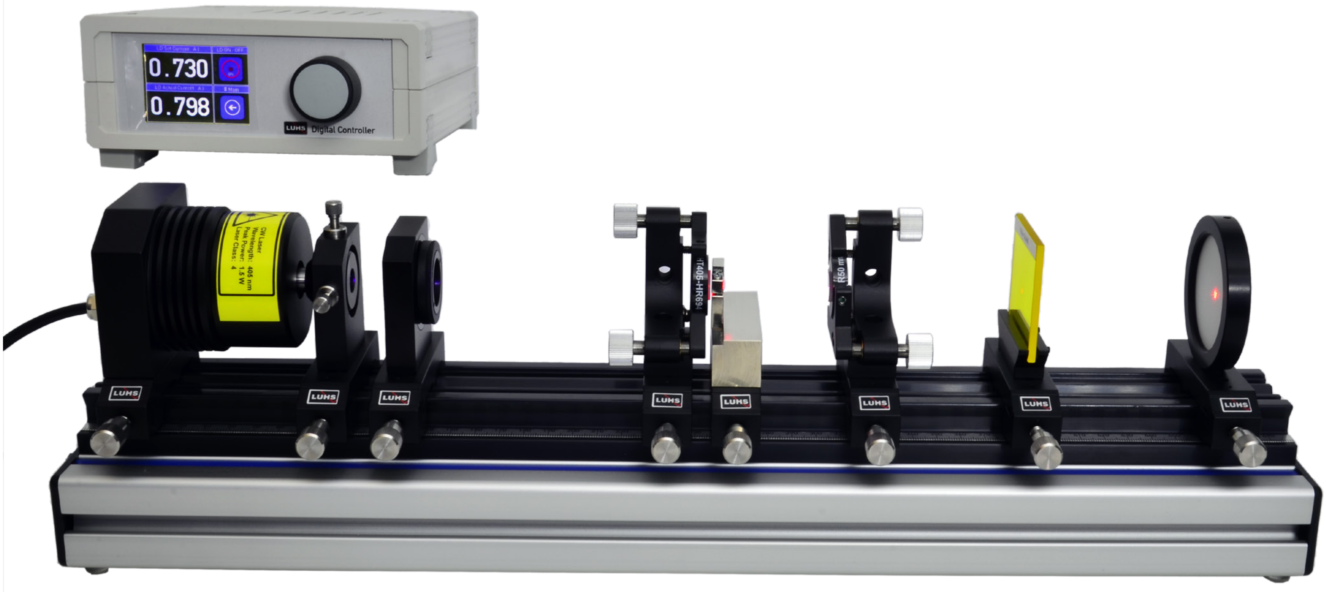


Table of Contents
Introduction
Theory
Experimental Setup
Measurements

Table of Contents

1.0 Introduction

The invention of the laser in 1960 by Theodore Maiman revolutionized the society in many regards. Townes and Schalow predicted the laser and Maiman was the first demonstrating the operation of a laser using a ruby crystal. The spectroscopic data of the possible pumping and lasing transition as a useless three level system have been known quite well and despite the contrary opinion of other researcher Maiman continued and succeeded in his work. This was only possible due to the long lifetime of the excited state around 3 milliseconds.

Each lecture in Photonics or laser physics starts with this great invention. With this experiment we want to track some of the great measurements at a ruby crystal. By using the provided spectrometer and the help of daylight we measure the absorption spectrum of the ruby crystal.

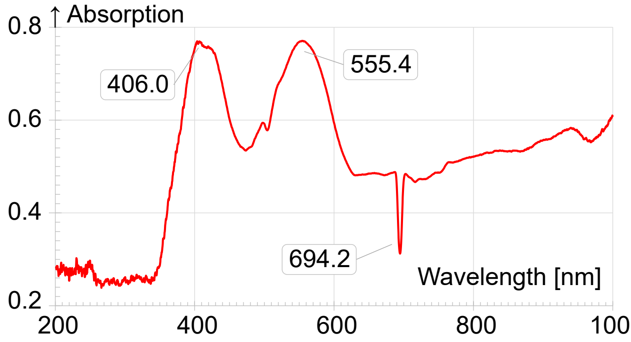


Fig. 1: Measured absorption spectrum

We clearly notice two broad absorption bands peaking at 405 and 560 nm respectively. So, it makes sense instead of using a flash lamp as Maiman did, to use a blue LED or diode laser. Exposing the ruby crystal with the blue radiation a bright dark red fluorescence appears which we analyse with spectrometer and will find the strong line at 694 nm. The same line which Maiman observed as laser emission. The controller of the light source allows us to switch it periodically on and off. By means of a photodetector and an oscilloscope we can measure the timely decay of the red fluorescence. From this curve we clearly estimate the lifetime to same values as the scientists obtained in the beginning of the laser era.

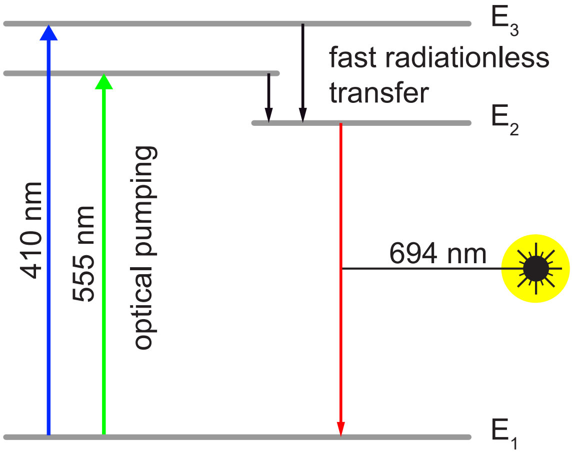


Fig. 2: Simplified energy level diagram of ruby

When Theodore Maiman laid out his first project proposal for funding, he received quite a lot of criticism. Although no laser has been brought to operation to that time, it was known based on the calculation of Schawlow and Townes, that the laser process requires a population inversion. That means, that the number of excited Ruby atoms with energy E_2 must be greater than that of E_1. Because the laser end level is the same as the start level a population inversion should not be possible. However, it turned out, that the level E_2 is a so-called metastable state and the probability of optical transition from here down to the ground state are is quite low. That means further, that the lifetime of the level E_2 is that high, that for a short moment a population inversion can be maintained. The starting lasing process significantly depletes the population of level E_2 by stimulated emission and consequently ceases the population inversion. However, if the pump source is able to compensate the depletion, real cw operation of the ruby laser can be achieved [1].

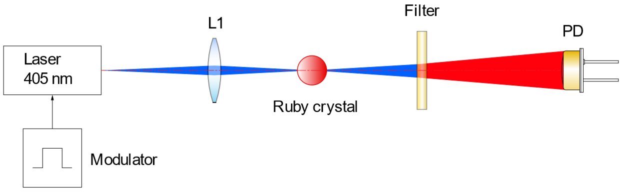


Fig. 3: Measuring the lifetime of the state E_2

Since the lifetime of the excited state is about 3.5 ms, it can be measured with simple equipment. As light source a commonly available laser diode emitting a wavelength of 405 nm as used in blue ray DVD player. The radiation is collimated and focused by the lens L_1into the ruby crystal. The filter blocks the pump radiation and transmits the fluorescence emission centred around 694 nm.

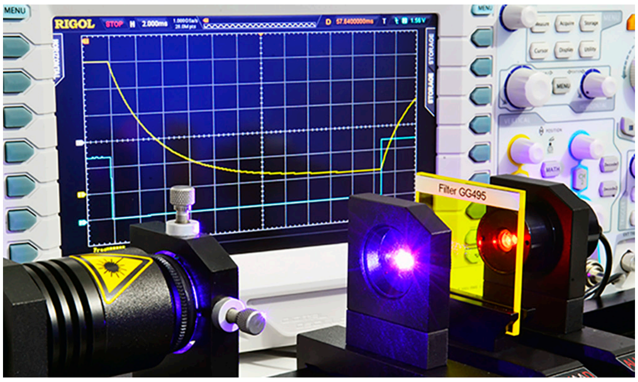


Fig. 4: Setup to measure the fluorescence decay

The fluorescence light hits the photodetector (PD) and is displayed on an oscilloscope. In addition, the modulation signal of the laser diode is used as trigger signal. From the decay curve of the fluorescence light, the lifetime of the excited state is determined.

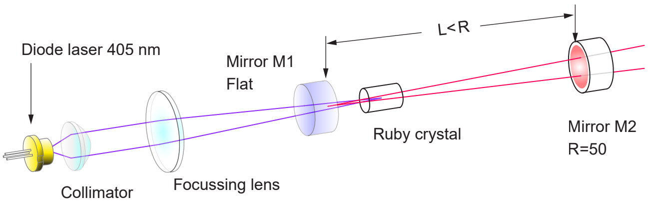


Fig. 5: Laser operation with a hemispheric cavity

Within this experiments a cw Ruby laser is demonstrated as shown above. The Ruby laser is excited with a diode laser emitting 405 nm, which coincides with the maximum wavelength of one of the absorption bands.

2.0 Experimental Setup

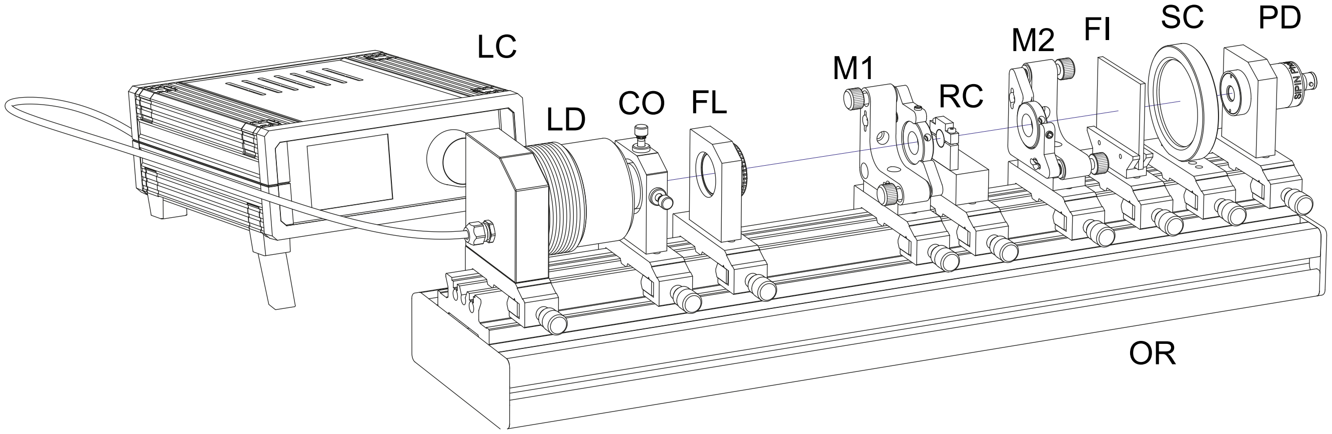
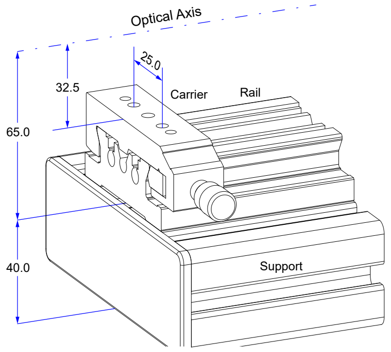


Fig. 6: Setup overview

2.1 The rail and carrier system (OR)



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 optical height of the optical axis is chosen to be 65/105 mm above the table surface. The optical height of 32.5 mm above the carrier surface is compatible with all other systems like from MEOS, LUHS, MICOS, OWIS and LD Didactic. Consequently, a high degree of system compatibility is achieved. The attached support elevates the working height above the table and significantly improves the handling of the components.

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 output power is 1 Watt at a wavelength of 405 nm.

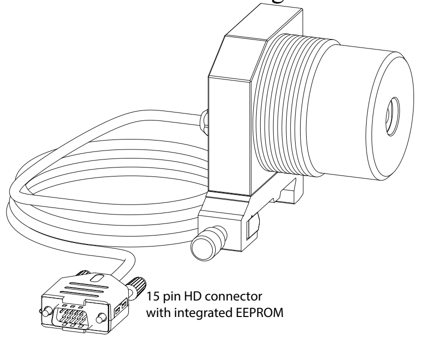


Fig. 7: Diode laser module (DL)

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.

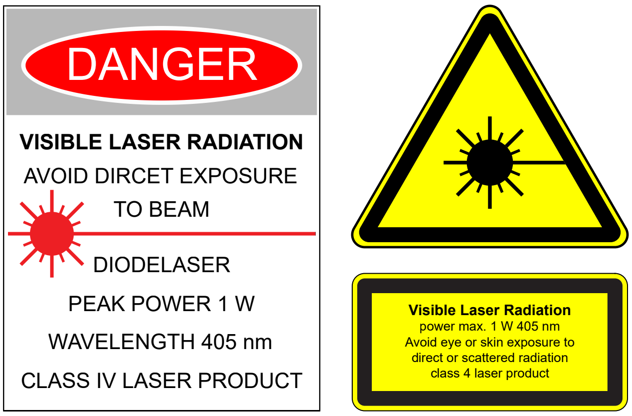
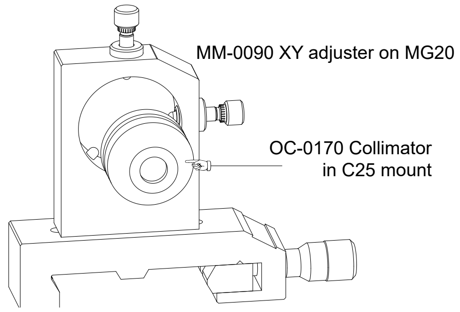


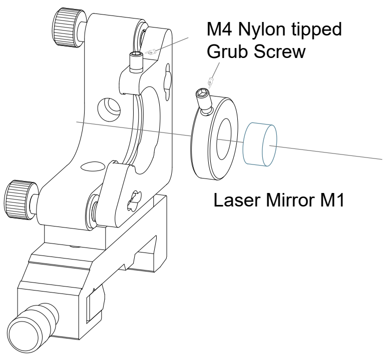
Fig. 8: Laser warning labels

2.3 XY adjuster (CO) and Collimator



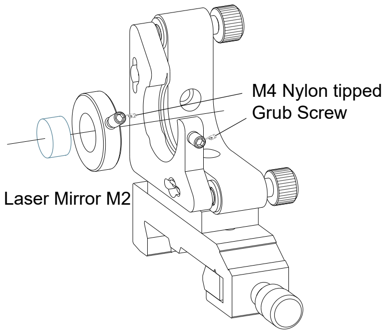
A high precision aspheric glass lens is mounted into a click holder (A) which is inserted into the XY adjuster. With the fine pitch screws the collimator (OC-0170) can be adjusted accordingly. The glass lens has a focal length of 4.6 mm, the numerical aperture is 0.53 and the clear opening is 4,9 mm. In addition, the lens has an anti-reflex coating in a spectral range of 350 - 700 nm with a residual reflection of < 0.5 %.

2.4 Laser Mirror M1



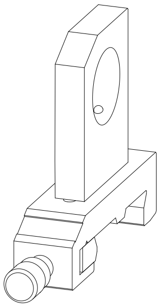
The laser mirror M1 has a diameter of 1/2 inch and is mounted with the adapter into the 1 inch adjustment holder. The flat M1 mirror has a hight transmission (HT) for 405 nm and a high reflection for 694 nm (HR > 99.9%.

2.5 Laser Mirror M2



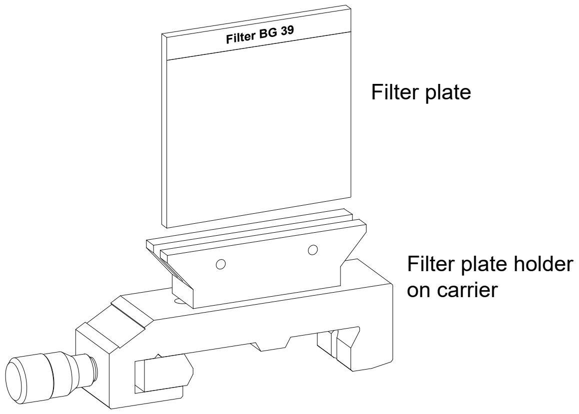
The laser mirror M2 has a diameter of 1/2 inch and is mounted with the adapter into the 1 inch adjustment holder. The curved mirror (ROC 50 mm) M2 mirror has a hight reflectivity (HR) for 405 nm and a transmission of 1% for 694 nm (HR = 99.0%).

2.6 Mounting plate C25 on carrier (MP)



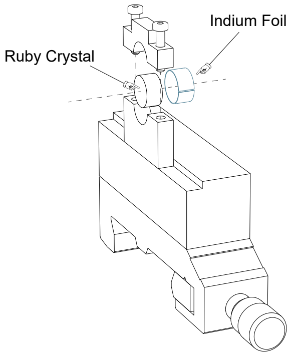
This frequently used component is ideal to accommodate parts with a diameter of 25 mm where it is kept in position by three spring loaded steel balls. Especially C25 mounts having a click groove are firmly pulled into the mounting plate due to the smart chosen geometry. The mounting plate is mounted onto a 20 mm wide carrier.

2.7 Filter Plate holder (FI) and GG495



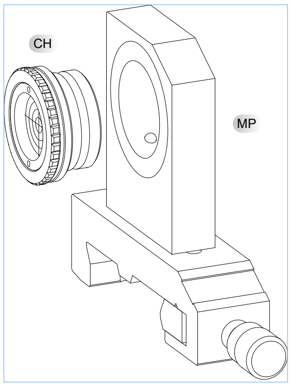
This filter plate holder is designed to accommodate standard optical filter plates with a thickness of 3 mm, a width of 50 mm and a height of 50 mm. The plate is held in position by two grub screws which have spring loaded balls at their tips. This coloured glass filter has a size of 50x50 mm and a thickness of 3 mm and is used to block the blue radiation below 495 nm and transmit the red radiation.

2.8 Mounted Ruby Crystal



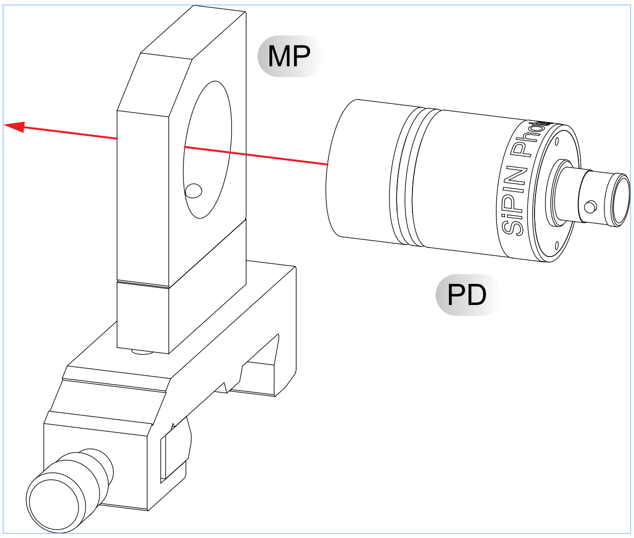
The ruby rod is surrounded by a thin Indium foil to improve the heat transfer from the crystal to its holder. The crystal has a thickness of 5 mm and a diameter of 9 mm. Both faces are coated with anti reflex layer for 405 nm and 694 nm.

2.9 Target screen



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.

2.10 DC-0120 Si-PIN Photodetector (PD)



A Si PIN photodiode is integrated into a 25 mm housing with two click grooves (PD). A BNC 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.

Parameter	symbol	value
Rise and fall time of the photo current at: R_l=50 Ω, Vr=5V, λ=850 nm and Ip=800 µA	τ_r, τ_f	20 ns
Forward voltage I_f = 100 mA, E = 0	Vf	1.3 V
Capacitance at Vr = 0, f = 1 MHz	C_0	72 pF
Wavelength [nm] of max. sensitivity	λ_{Smax}	850
Spectral sensitivity S~10% of Smax	λ	1100
Dimensions of radiant sensitive area [mm^2]	L x W	7
Dark current [nA], Vr = 10 V	Ir	≤30
Spectral sensitivity [A/W], λ = 850nm	S(λ)	0.62

Table 1: Basic parameters of Si PIN photodiode BPX61

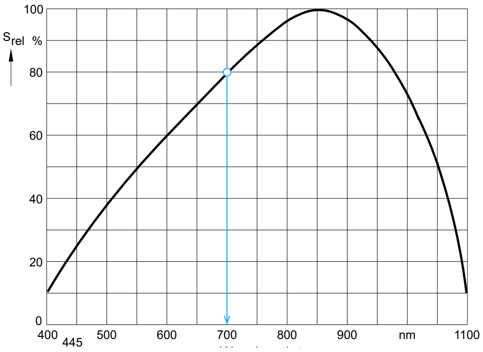
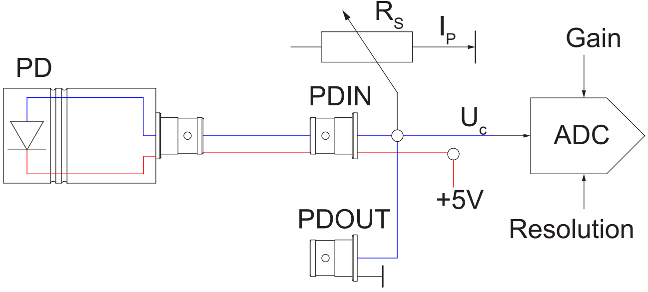


Fig. 9: Sensitivity curve of the BPX61 photodiode

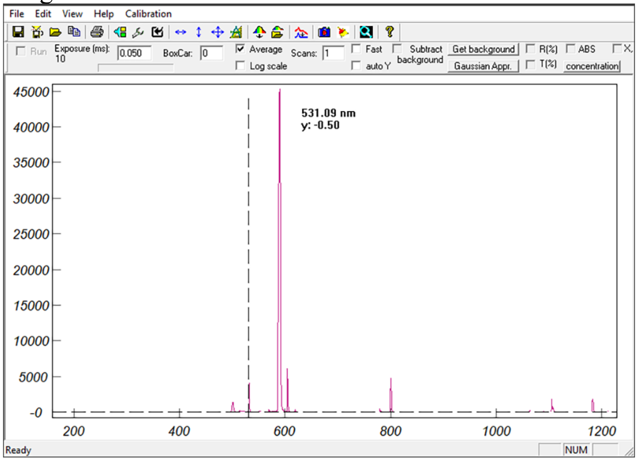
The photodetector is connected via a BNC cable to the laser diode controller to BNC jack PDIN. Via the BNC shield the photodiode bias voltage is provided.



Inside the controller the anode of the photodiode is connected via the digital controlled shunt resistor (R_S) to ground. The voltage across the shunt resistor is linear to the photo current I_P. This voltage Uc is present at the BNC jack PDOUT and can be connected to an oscilloscope. The ADC converts the voltage into a digital signal which is displayed on the touch screen of the controller. The gain as well as resolution is controlled by the MK1 controller.

Fig. 10: Fibre coupled spectrometer 200 - 1200 nm, USB (optional)

As an option a spectrometer (LR2) is provided. It covers a range from 100 to 1200 nm. The resolution is 2 nm.



☐ Run Exposure (ms): 10 0.050 BoxCar: 0 ☑ Average ☐ Log scale Scans: 1 ☐ Fast ☐ auto Y ☐ Subtract background ☐ R(%) ☐ T(%) ☐ ABS ☐ X,

531.09 nm
y: -0.50

Fig. 11: Spectrometer software

The software does not need an installation and can be run even from an USB pen drive.
The spectrometer comes with a 50 µm fiber with SMA905 connectors.

Fig. 12: F-SMA Fiber jacket in C25 mount (optional)

This adapter allows to position the fiber entrance in the center of the optical axis.

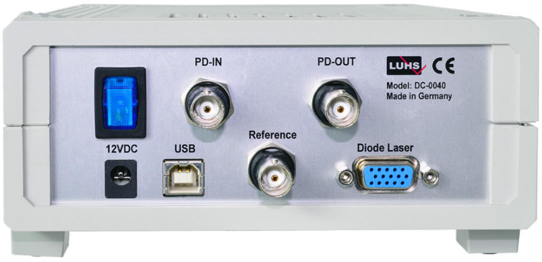
1.1 Laser Diode Controller (LDC)

The controller is operated by a touch screen and a digital potentiometer with a knob.

The laser diode module is connected via the 15 pin HD SubD 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 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. Further detailed specifications are given in the following section of the operation software.



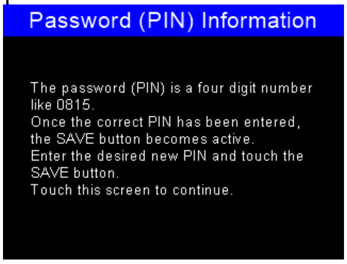
The back side of the controller contains the connector for power (12V 1A, a power supply is provided), the Reference modulation signal, the 15 pin HD SubD connector for the laser diode and the In and Out BNC for the photodetector.

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

Digital Controller DC-0048
Touch screen to continue.

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 PIN, the next screen is displayed, and the system is ready for operation. Touching the “HOW TO?” brings up the next screen.

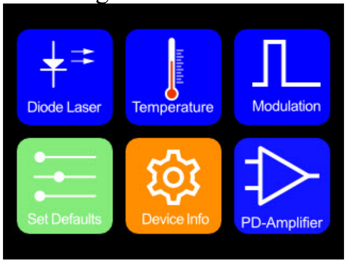


Password (PIN) Information

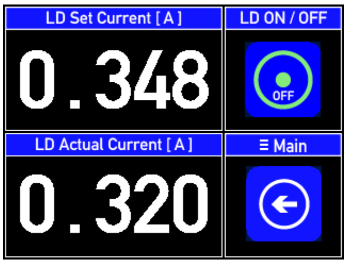
The password (PIN) is a four digit number like 0815.
Once the correct PIN has been entered, the SAVE button becomes active.
Enter the desired new PIN and touch the SAVE button.
Touch this screen to continue.

The appearing text explains how to change the default password.

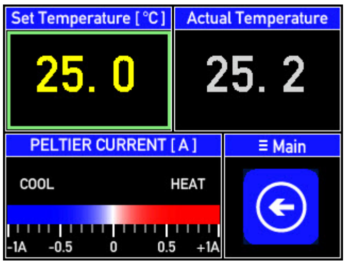
After the correct password has been entered, the main screen is activated. It shows the buttons for the current settings of the attached diode laser, its temperature and modulation. Furthermore, the photodiode amplifier, the device info, and a Set to Defaults” button. The individual functions are explained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



The current settings screen shows the set current as well as the actual current.

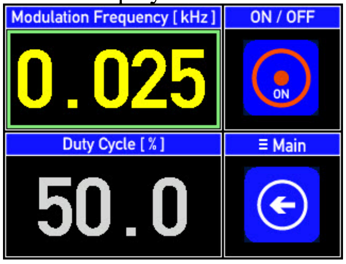


With the LD ON/OFF touch button the laser is switched on or off. The ≡Main touch button switches back to the main page. By turning the knob, the value of the injection current can be set and is immediately applied, provided the LED ON/OFF touch button is activated. Touching the LED ON/OFF button switches the LED ON or OFF. When switched ON, the actual current is displayed in addition.



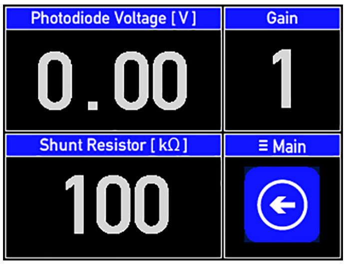
Set Temperature [°C]: 25. 0
Actual Temperature: 25. 2
PELTIER CURRENT [A]

“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. By touching the “Set Temperature display field it is highlighted. By turning the knob now, the value of the temperature can be set and is immediately applied. However, it may take some minutes before the stable value is reached. The diode laser module used here has no Peltier element and only the actual temperature is displayed.



Modulation Frequency [kHz]: 0.025
Duty Cycle [%]: 50.0

The LED or 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. For some experiments it is important to keep the thermal load on the optically pumped object 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.



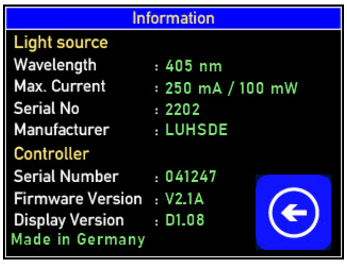
Photodiode Voltage [V]: 0.00
Gain: 1
Shunt Resistor [kΩ]: 100

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.

Missing Laser Diode or LED

We could not detect a
LIGHT SOURCE.
Please switch of the controller
connect one and restart.

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



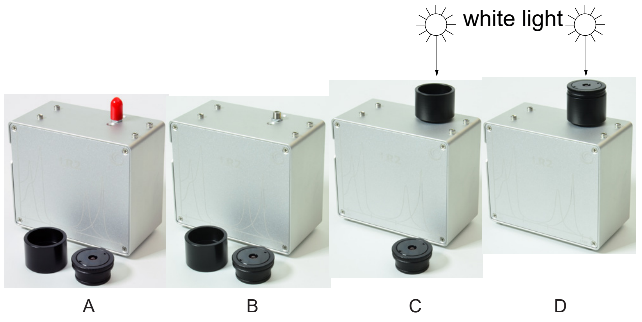
Information

Light source
Wavelength : 405 nm
Max. Current : 250 mA / 100 mW
Serial No : 2202
Manufacturer : LUHSDE
Controller
Serial Number : 041247
Firmware Version : V2.1A
Display Version : D1.08
Made in Germany

The diode laser module is connected via the 15 pin HD SubD jacket at the rear of the controller. The controller reads the EEPROM of the laser diode and sets the required parameter accordingly. This information and some more information about the controller are shown on the info screen.

3.0 Measurements

3.1 Absorption



The spectrometer allows to record the absorption spectrum of the Ruby crystal. By using the light of a simple light bulb, a sequence, the dark (A), reference (C, with adapter) and transmission (D with crystal) spectra are recorded and stored.

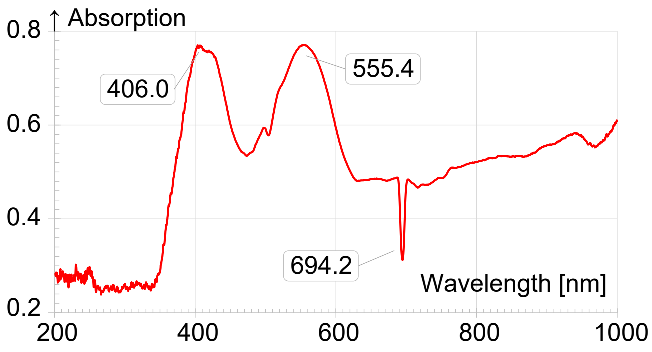


Fig. 13: Measured absorption spectrum

The provided software calculates T=(C-B)/(A-B) and 1-T yields the absorption spectrum (Fig. 4.70). Two main absorptions appear around 406 and 555 nm. At 694 nm a narrow dip appears, which is caused by the fluorescence already generated by the white probe light.

3.2 Laser beam Alignment

Prior to the following experiments, the divergent beam of the laser diode needs to be collimated and aligned with respect to the optical axis of the mechanical set-up.

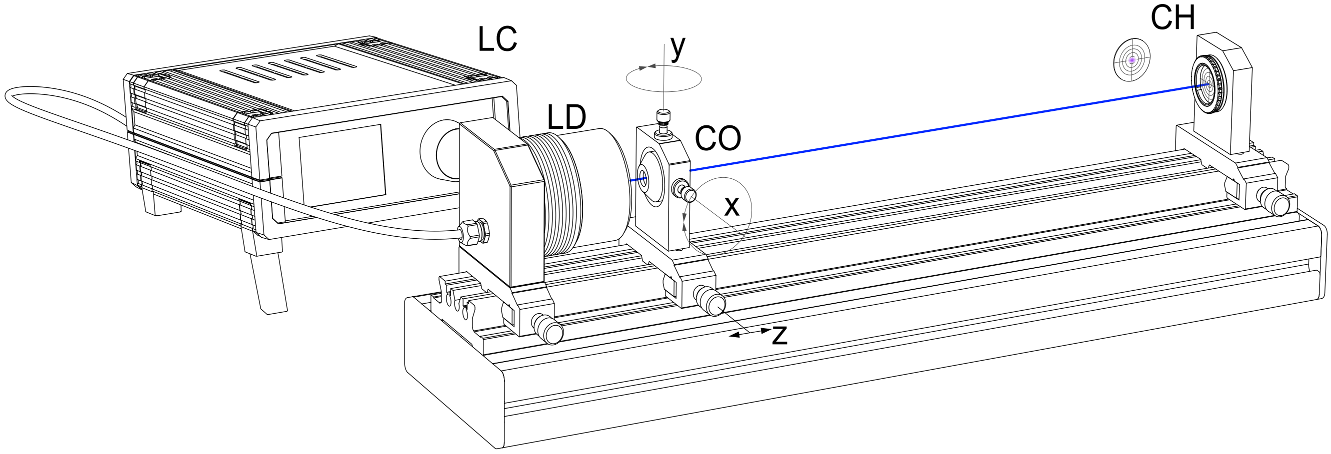


Fig. 14: Aligning the diode laser beam

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.

Move the collimator towards the diode laser and observe the image on the crossed hair target (CH). Align if necessary, the X and Y fine pitch screws of the collimator module (CO) in such a way that the image is centred to the crossed hair target (CH). 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 start to grow again. If you reached this point, stop the movement and check with a piece of paper 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.

3.3 Excitation Spectrum, Fluorescence

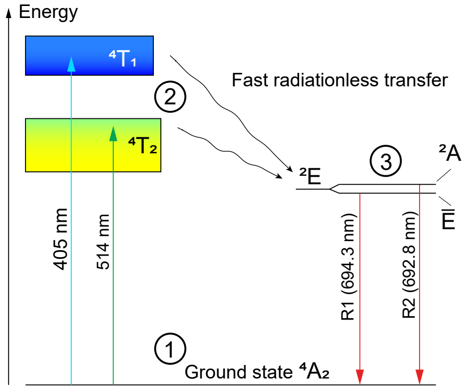


Fig. 15: A more detailed energy level diagram

When pumping with a 405 nm laser diode the pump process populates the $^4T_1$ energy band. By a fast radiationless transfer, the energy or population is directed to the ^2E level. This level is split into the ^2A and levels from where the R1 and R2 lines start to the ground level $^4A_2$.

3.4 Excitation Spectrum

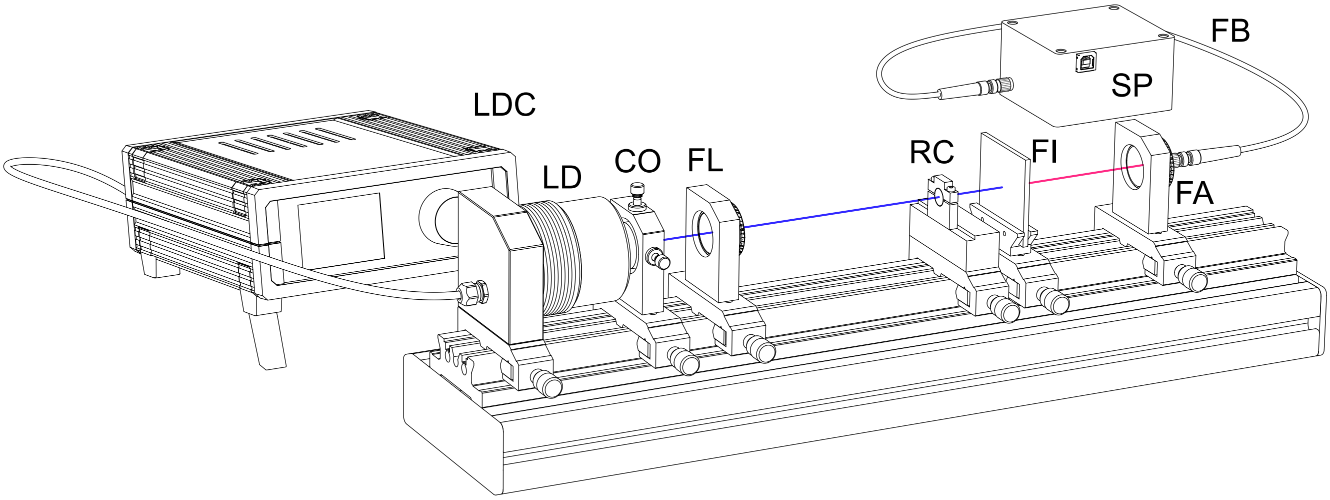


Fig. 16: Set-up to measure the excitation spectrum

The ruby ball is positioned in such a way, that the focus of the diode laser radiation lies within it. The GG495 filter is placed direct behind the ruby crystal to block residual pump radiation which might saturate the spectrometer. The fiber of the spectrometer is attached to a mounting plate and placed behind the filter (FI). Depending on the fluorescence intensity and spectrometer sensitivity settings, the distance to the filter is optimized.

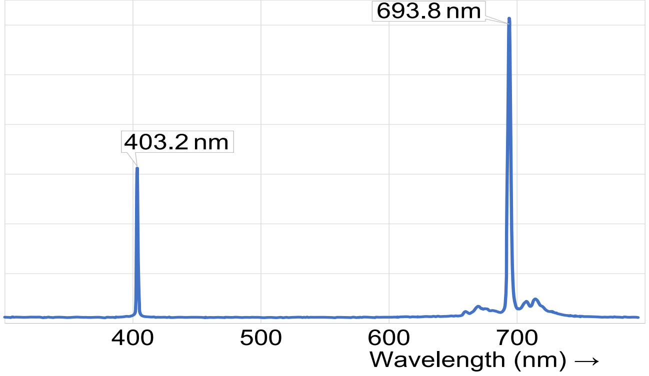


Fig. 17: Fluorescence spectrum taken with LR2 spectrometer, resolution <2 nm

Due to the high sensitivity of the spectrometer no focussing lens is required. The spectrum (Fig. 17) shows beside the pump laser line the famous 694 nm Ruby laser line.
The resolution of the spectrometer does not resolve the closely spaced (1.5 nm) R1 and R2 lines.

3.5 Lifetime of the excited state

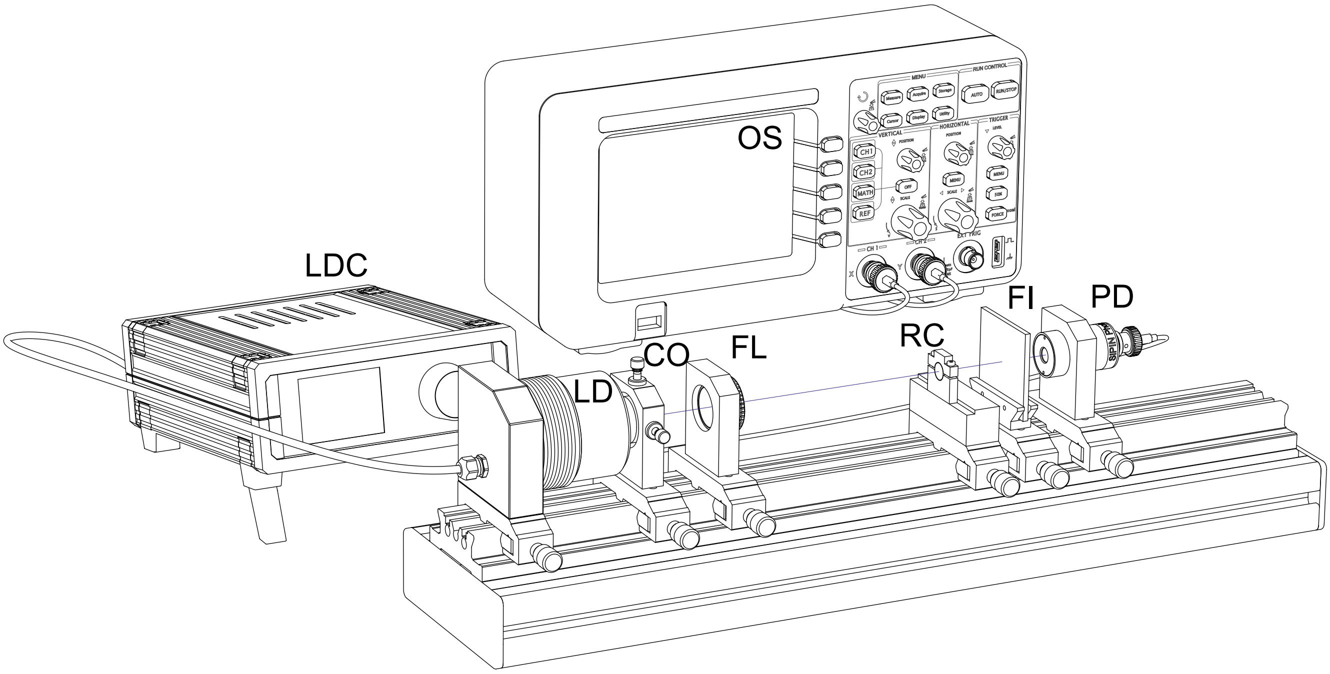


Fig. 18: Set-up to measure the lifetime of the excited state

For this measurement, an oscilloscope is needed. From the previous set-up Fig. 18 the fiber adapter (FA) is removed from the mounting plate (MP). The photodetector (PD)is placed into that mounting plate instead. The photodetector (PD) is connected to the PDIN input of the controller. The PDOUT is connected to the channel 1 of the oscilloscope while the REFERENCE is connected to channel 2 of the oscilloscope.

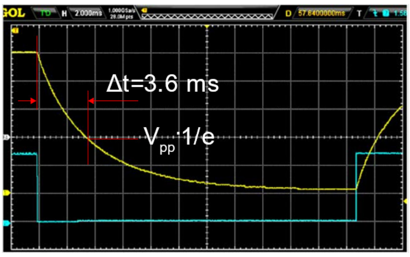


Fig. 19: Oscilloscope image of fluorescence decay

The blue diode laser is periodically switched on and off shown by the blue track of the oscillogram. The yellow track shows the fluorescence signal of the Ruby crystal. To determine the lifetime of the excited state the fluorescence signal after switching off the excitation is important. The time when the signal decreases to 1/e of its initial intensity is defined as lifetime Δt. The inverse value of it is the Einstein coefficient for spontaneous emission. The Fig. 19 shows such an example in which the value of the lifetime Δt has been measured to be 3.6 ms.

3.6 Laser Operation

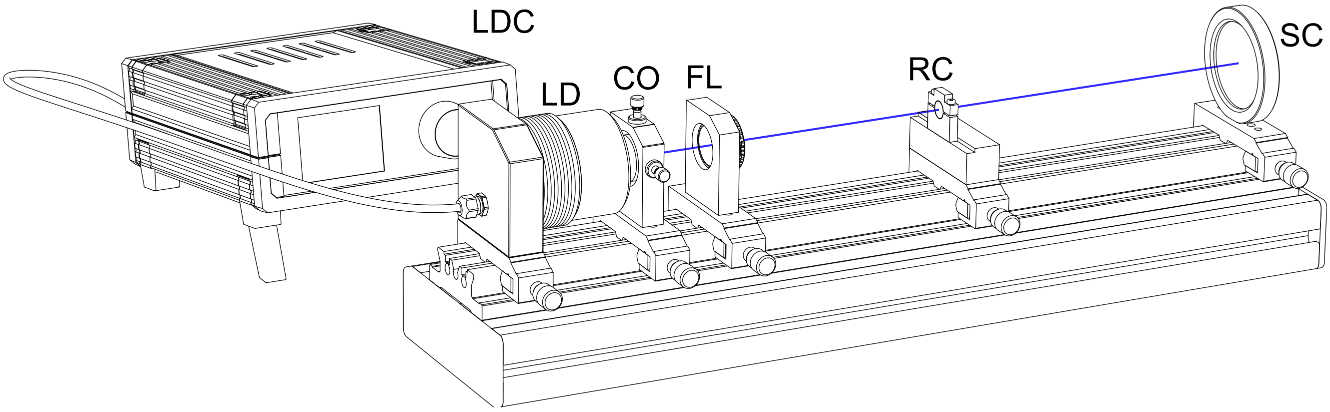


Fig. 20: Alignment of Ruby Crystal (RC)

The focusing lens FL has a focal length of 150 mm. The ruby crystal ()RC is placed such that the focus lies well within the crystal. This can be visually checked when the pump laser is switched on. The power should be set near to the lasing threshold. A reddish fluorescence track becomes visible inside the crystal and red fluorescence occurs. Move the crystal forth and back while noticing the fluorescence intensity. If the intensity drops, the position for best performance is achieved.

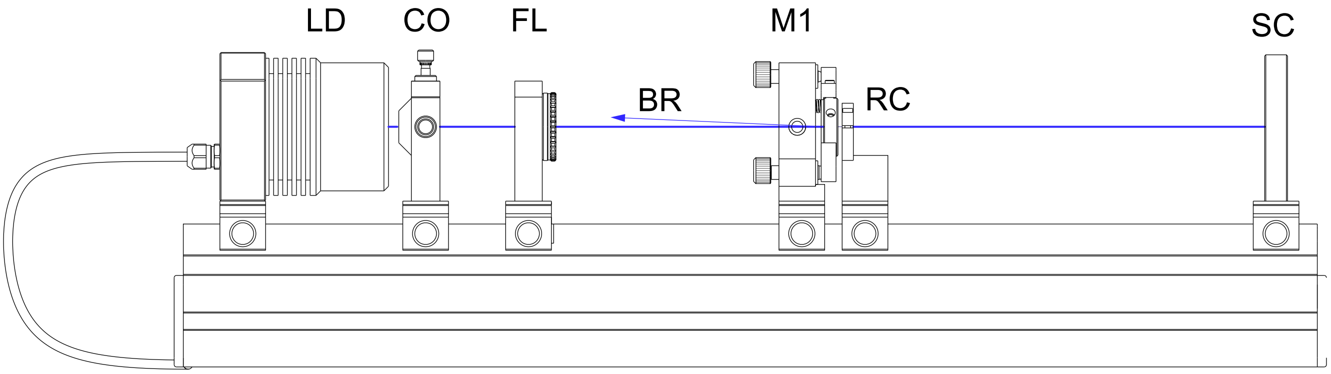


Fig. 21: Placing Mirror M1

The flat mirror M1 is placed close to the ruby crystal. The spacing between the mirror and the ruby crystal is about 1mm. The mirror M1 has a residual reflectivity for the 405 nm pump radiation. The back reflected beam (BR) is used to align the mirror M1. On the surface of the focussing lens a small spot of the passing pump light is visible. BR is aligned such that both beams are coaxial.

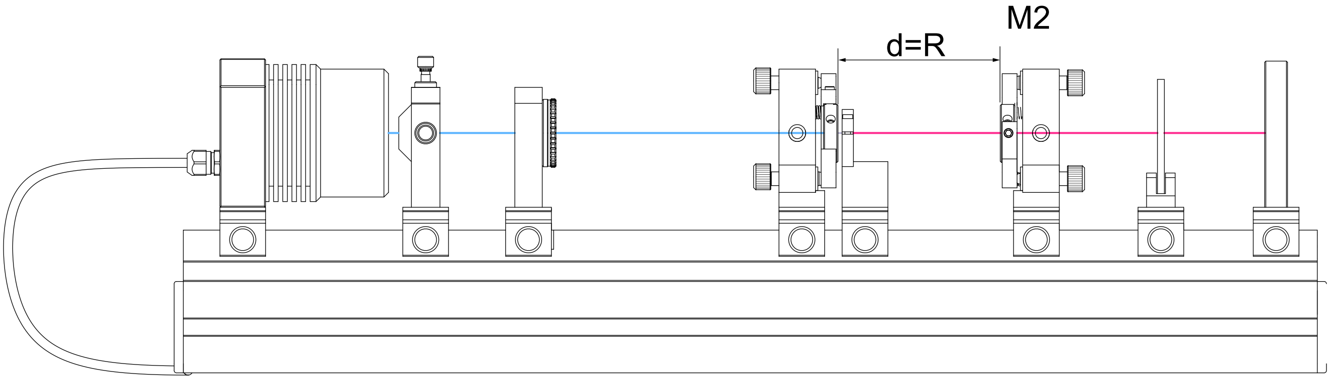


Fig. 22: Placing Mirror M2

The curved mirror M2 is placed onto the rail. The distance d to M1 must be chosen that it is slightly less 50 mm, which is the radius of curvature (ROC = 50 mm) from M2.

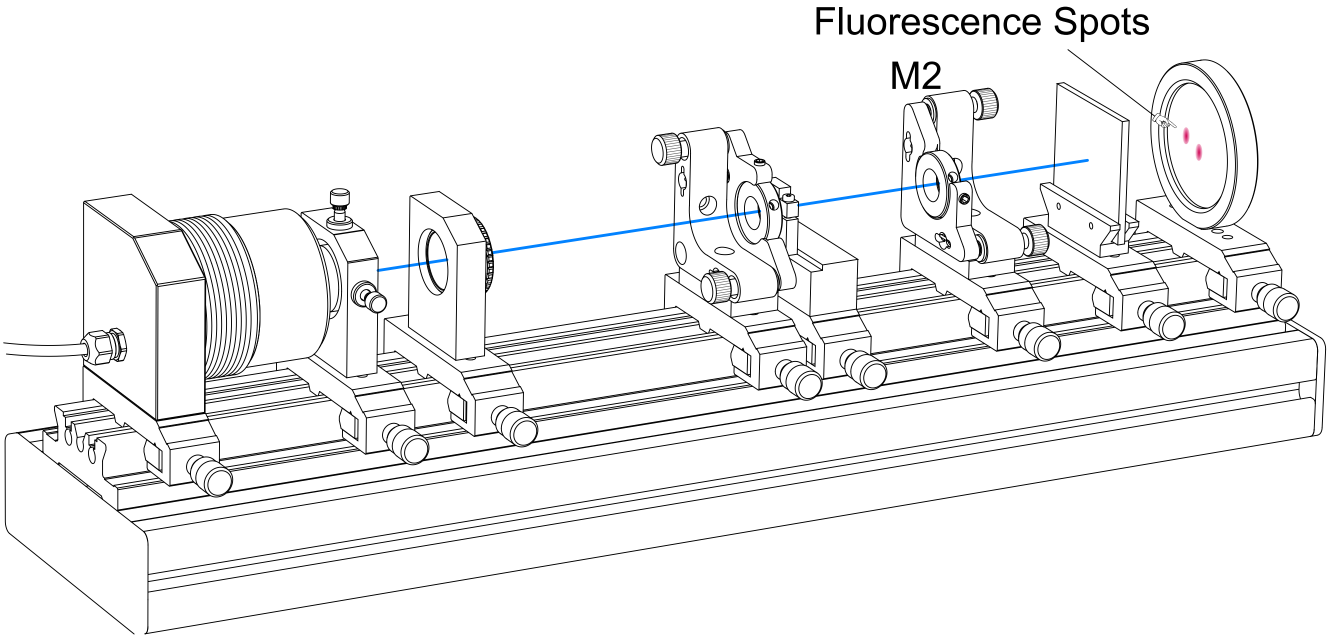


Fig. 23: Final adjustment

In a darkened room and full pump power two weak fluorescence spots are visible. One is fixed while the other follows the alignment of mirror M2. If no spots are visible, the distance d is too large and outside the optical stability range. Reducing the distance d by moving the mirror M2 (only) they become visible again. As soon as both spots sufficiently overlap, laser oscillation occurs!

3.7 Static and Dynamic Measurements

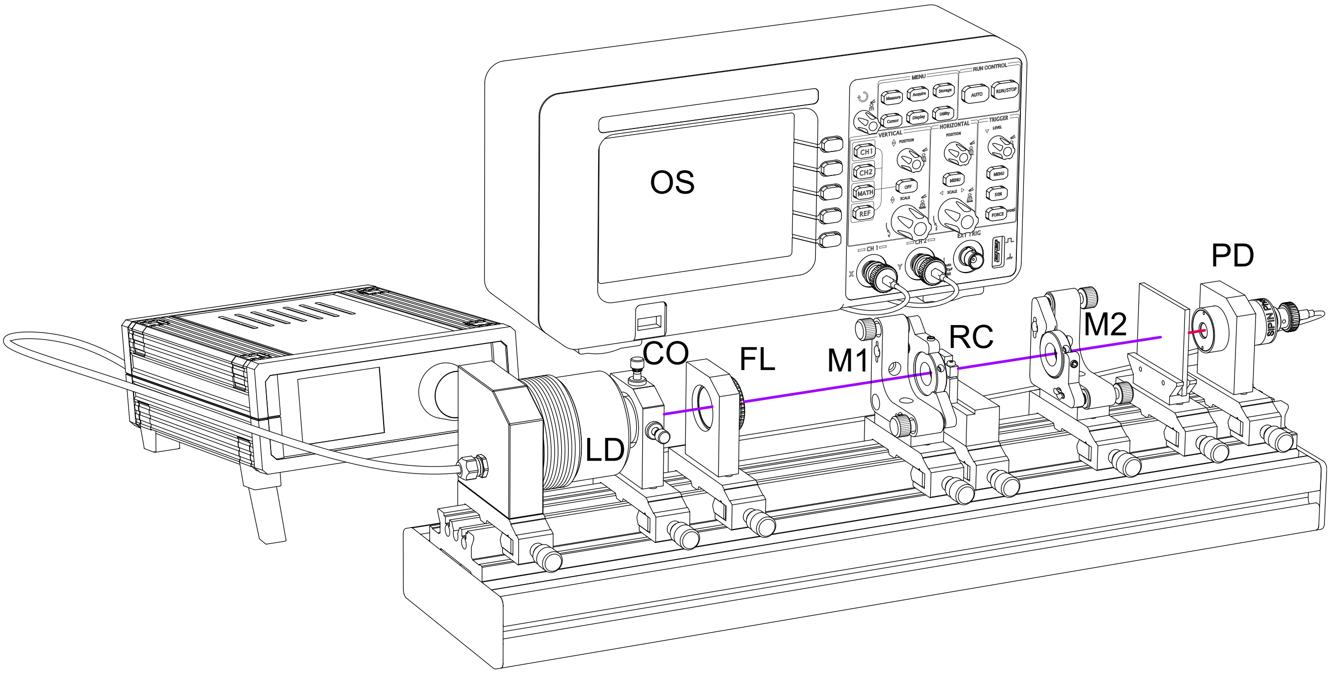


Fig. 24: Setup for static and dynamic measurements

3.7.1 Ruby laser output power, threshold and slope efficiency

The translucent screen is replaced by the photodetector (PD) which is connected to the controller (LD). The photo voltage (output signal) is connected to an oscilloscope. For dynamic measurements the modulation signal is connected to the second channel of the oscilloscope and is used as trigger.

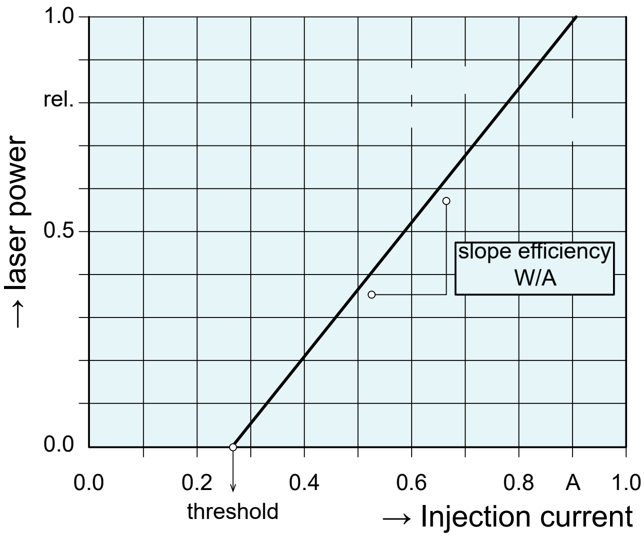


Fig. 25: Static measurement example: Ruby laser power vs pump power (injection current)

The user sets the injection current and reads the photo voltage from the display of the controller.

3.8 Dynamic Measurements

For this class of experiments the injection current of the pump laser is periodically switched on and off. The frequency as well as duty cycle can be set by the controller (LD).

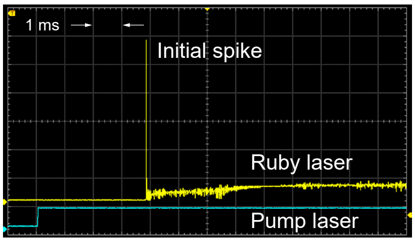


Fig. 26: Initial spike of the ruby laser

The yellow track is the response taken with the photodetector and the blue one is the modulation signal used as trigger.

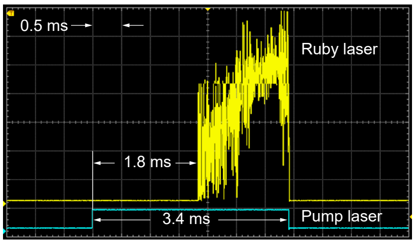


Fig. 27: Simulation of a flash lamp pulse

In this example the timing of the pump laser is set to be a flash lamp, the same way as Maiman operated the first laser.

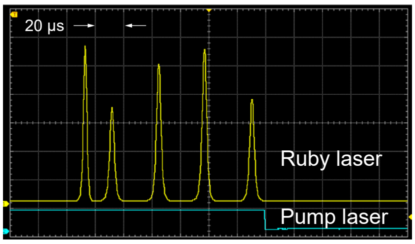


Fig. 28: Spiking of the ruby laser

Near the threshold single spiking pulses occur.

4.0 Bibliography

1. W. Luhs and B. . Wellegehausen, “Diode pumped cw ruby laser,” , 2019. [Online]. Available: https://osapublishing.org/osac/abstract.cfm?uri=osac-2-1-184. [Accessed 13 6 2020].