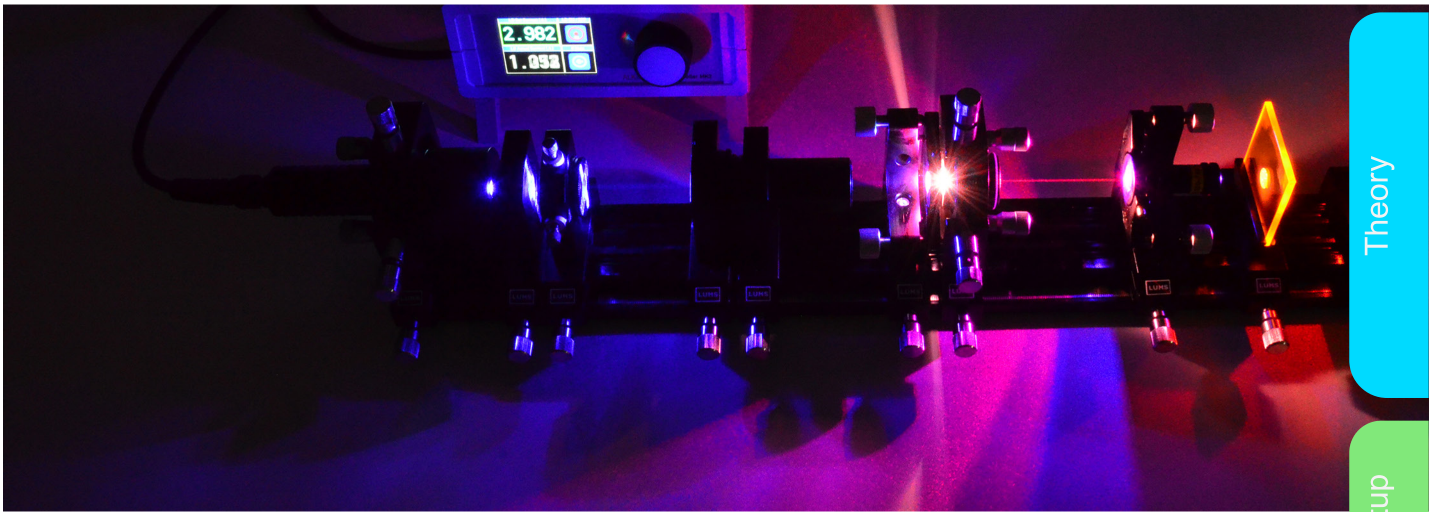
Photonik
Ingenieurbüro
Dr. Walter Luhs

Manual UM-LE10

Blue Diode Pumped Pr:YLF Laser



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1.0 Introduction

^{1}H																	^{2}He
^{3}Li	^{4}Be											^{5}B	^{6}C	^{7}N	^{8}O	^{9}F	^{10}Ne
^{11}Na	^{12}Mg											^{13}Al	^{14}Si	^{15}P	^{16}S	^{17}Cl	^{18}Ar
^{19}K	^{20}Ca	^{21}Sc	^{22}Ti	^{23}V	^{24}Cr	^{25}Mn	^{26}Fe	^{27}Co	^{28}Ni	^{29}Cu	^{30}Zn	^{31}Ga	^{32}Ge	^{33}As	^{34}Se	^{35}Br	^{36}Kr
^{37}Rb	^{38}Sr	^{39}Y	^{40}Zr	^{41}Nb	^{42}Mo	^{43}Tc	^{44}Ru	^{45}Rh	^{46}Pd	^{47}Ag	^{48}Cd	^{49}In	^{50}Sn	^{51}Sb	^{52}Te	^{53}I	^{54}Xe
^{55}Cs	^{56}Ba	57..71	^{72}Hf	^{73}Ta	^{74}W	^{75}Re	^{76}Os	^{77}Ir	^{78}Pt	^{79}Au	^{80}Hg	^{81}Tl	^{82}Pb	^{83}Bi	^{84}Po	^{85}At	^{86}Rn
^{87}Fr	^{88}Ra	89..103	^{104}Rf	^{105}Db	^{106}Sg	^{107}Bh	^{108}Hs	^{109}Mt	^{110}Ds	^{111}Rg	^{112}Cn	^{113}Uut	^{114}Fl	^{115}Uup	^{116}Lv	^{117}Uus	^{119}Uuo
		↓															
		^{57}La	^{58}Ce	^{59}Pr	^{60}Nd	^{61}Pm	^{62}Sm	^{63}Eu	^{64}Gd	^{65}Tb	^{66}Dy	^{67}Ho	^{68}Er	^{69}Tm	^{70}Yb	^{71}Lu	
		^{89}Ac	^{90}Th	^{91}Pa	^{92}U	^{93}Np	^{94}Pu	^{95}Am	^{96}Cm	^{97}Bk	^{98}Cf	^{99}Es	^{100}Fm	^{101}Md	^{102}No	^{103}Lr	

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.

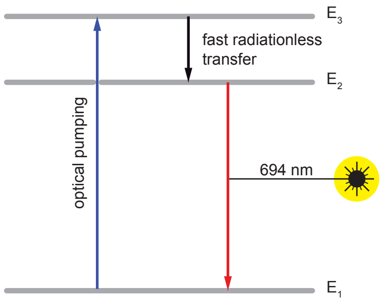


Fig. 1: Simplified three level system of the ruby laser

The ruby laser boosted tremendous research and initiated a hunt for 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 laser level 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.

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 milliseconds in the E_2 state (which is fairly long for optical transitions) before they reach the ground state again.

$$\left(N_2 - N_1\right) = \frac{\omega_0^2 \cdot \tau_{21} \cdot \Delta\omega_0}{2 \cdot c^3 \cdot \pi \cdot \tau_p} \qquad (1)$$

We learned, that a laser process can only start, if the so called Schawlow-Townes oscillation condition [2] is fulfilled. The equation (1) shows a simplified version of it. In this equation n stands for the index of refraction, ω_0 for the laser frequency and c for the speed of light, τ_{21} is the lifetime of the excited state, τ_p the lifetime of the photons in the cavity, N_2 is the population density of energy level E_2 and N_1 accordingly. If N_2-N_1 is greater than zero the population density of state E_2 is greater than that of state E_1. This situation is also termed as population inversion. Such an inversion can hardly be reached since N_1 is the population of the ground state, which is always populated. There are 5 milliseconds time to almost empty the ground state before the delayed transfer from E_2 starts to populate the ground state. 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 1964 [3]. 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 (Nd3+).

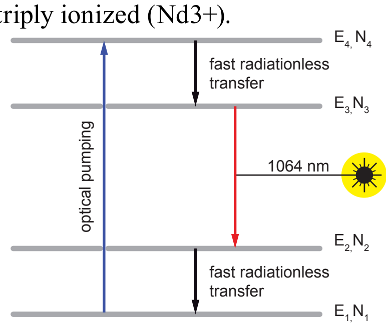


Fig. 2: Four level laser system

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 From the Fig. 2 we can conclude that the laser oscillation condition (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 thus 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.

Due to the steadily increasing demand of the multimedia applications powerful RGB (red green blue) light sources came into the focus of industrial research. Along this road the Praseodymium laser has been reinvented again since this material has the potential to emit directly visible laser radiation on many interesting wavelength. Whereas in the past this material has been of more scientific interest [6] it is nowadays considered as a noteworthy candidate for RGB applications. The recent new developments of compact Pr:YLF laser have been enabled due to the presence of powerful blue emitting laser diodes. Such blue laser diodes actually have been developed for the powerful RGB data projectors.

The aim of the experimental laser diode pumped Praseodymium YLF laser is to demonstrate this great potential as well as the exciting effect to study a four level laser system with visible radiation.

1.1 Praseodymium YLF Laser

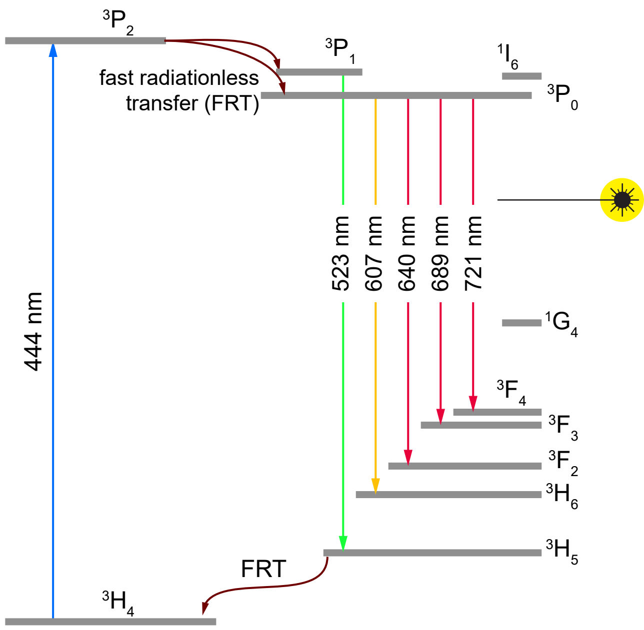


Fig. 3: Energy level system

Whereas the Neodymium material uses an Yttrium Aluminium Garnet as host crystal, the Praseodymium is doped into an Yttrium Lithium Fluoride crystal. The first optically pumped Praseodymium laser has been reported [6] in 1977. However it used a pulsed dye laser with an emission wavelength of 444 nm as pump source. This way of optically pumping could only be done in a scientific laboratory equipped with high power laser systems. Due to the availability of powerful GaN (Gallium Nitride) laser diodes [7] in 2007 with up to 0.5 W and nowadays (2019) up to 6 W boosted the development of Pr:YLF laser -the only solid state laser emitting in the visible part of the spectrum -.

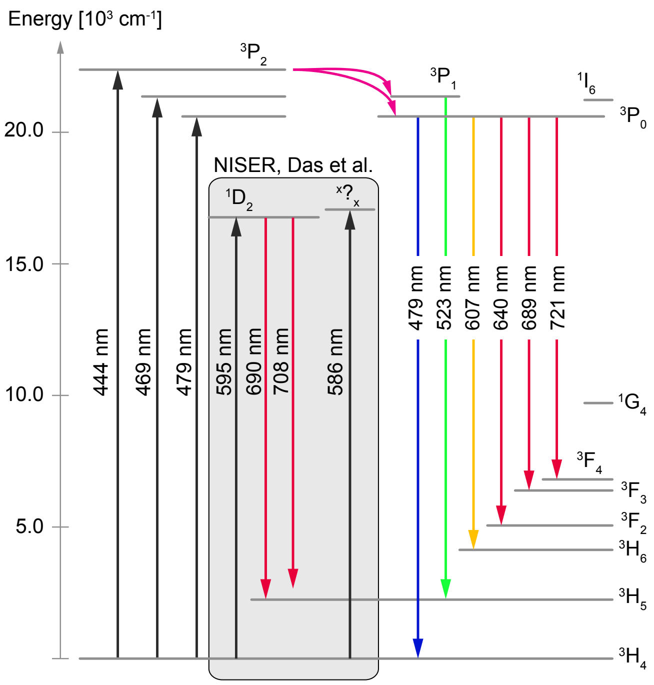


Fig. 4: Four level system of Pr:YLF laser

The [Fig. 3] shows an overview of the excitation spectrum of Pr:YLF when pumped with 444 nm. The pump process starts from the ground state $^3H_4$ and populates the $^3P_2$ state. From here the very fast radiationless transfer populates the initial laser levels. Depending on the wavelength (energy) the transition terminates in a variety of final states. From here the transition back to the ground state $^3H_4$ takes place as fast radiationless transfers. The given laser transitions are just a few among the most important strongest ones. A variety of much more lines are possible due to the strong Stark splitting of the involved energy levels. Some more spectroscopic assignments of laser lines can be found in [8].

Here, in this experiment, we stay with the practical realisation of the Pr:YLF laser system.

1.2 Principle of operation

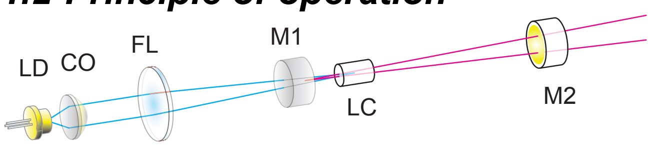


Fig. 5: Principle of operation

The radiation of the blue emitting laser diode (LD) is collimated by the collimator (CO) which commonly 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 blue pump laser radiation into the Praseodymium doped YLF crystal (LC). The Pr:YLF crystal is coated only with a broadband anti reflection coating on both sides, so called ARB coating. The wavelength ranges for lowest reflection covers the entire emission range of the Pr:YLF material including the pump radiation at 445 nm. The optical cavity is formed by a flat mirror on the left (M1) and a curved mirror at the right side (M2) as shown in Fig. 5.

In principle the laser mirror M1 could also be directly coated onto the left side of the laser crystal (LC). However, this will reduce the flexibility for the operation at different wavelength since for each particular wavelength an extra laser crystal would be required.

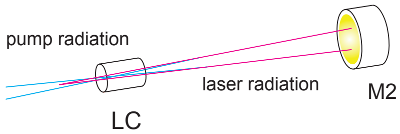


Fig. 6: Mode and pump volume

We consider as pump volume the space the pump beam occupies within the laser crystal (LC). In the same way we consider as mode volume the space the laser radiation occupies within the laser crystal. The mode volume is defined by the structure of the cavity. In our example we are using a flat (M1) and a curved mirror (M2) resulting in a hemispherical cavity. In such a cavity the smallest beam waist always lies on the surface of the flat mirror. The laser radiation is fed by an population inversion inside the crystal. However such an inversion can only exist, when this spot inside the crystal is covered by the pump radiation.

It is easy to understand that laser radiation is only or efficiently created when the pump volume is slightly larger than the mode volume. Within a practical setup one has to choose a proper focusing lens and a proper curvature of the spherical cavity mirror. The things are a bit more complicated than just mentioned, however we will keep in mind that the pump and mode volume overlap can be optimised by moving the focusing lens, laser crystal as well as the mirror M2.

2.0 Experimental Set-up

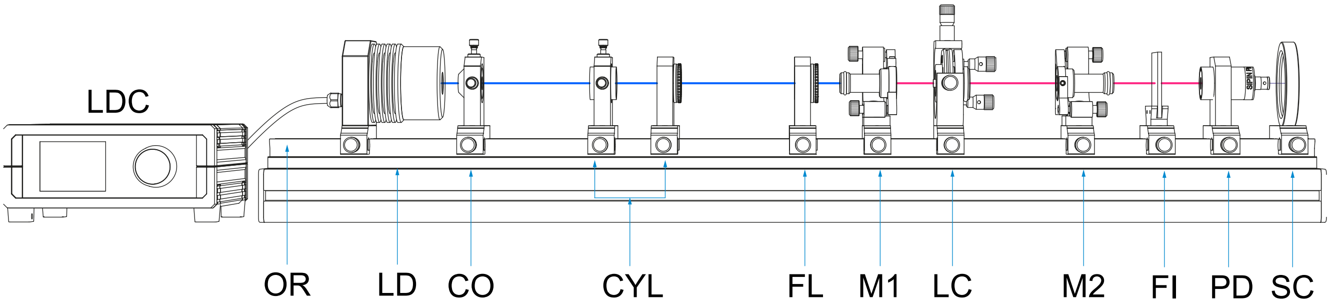


Fig. 7: Diode laser pumped Pr:YLF Basic Experimental Laser Setup

The Fig. 7 above shows the set-up of the Praseodymium YLF 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 is controlled by the diode laser controller LDC. Furthermore, it contains the photodetector display unit.

The collimator (CO) is used to collimate the divergent blue radiation of the pump laser diode (LD). The collimated beam passes the cylindrical lens telescope (CYL), the focusing lens (FL), the flat mirror of (M1) and focuses the beam into the Praseodymium doped YLF laser crystal (LC). The second mirror of the laser cavity M2 is followed by a filter (FI) which suppresses the pump radiation and transmits wavelength greater than 495 nm.

The optical signals like pump radiation, fluorescence as well as created laser radiation is detected by the photodiode (PD) which is connected to the LDC. From here the signal is transferred via a BNC cable to an optional oscilloscope to display time dependant signal. In the same way the modulator reference of the diode laser controller is connected to the oscilloscope. Components which are shown, but not described her, will be treated within the experiment section.

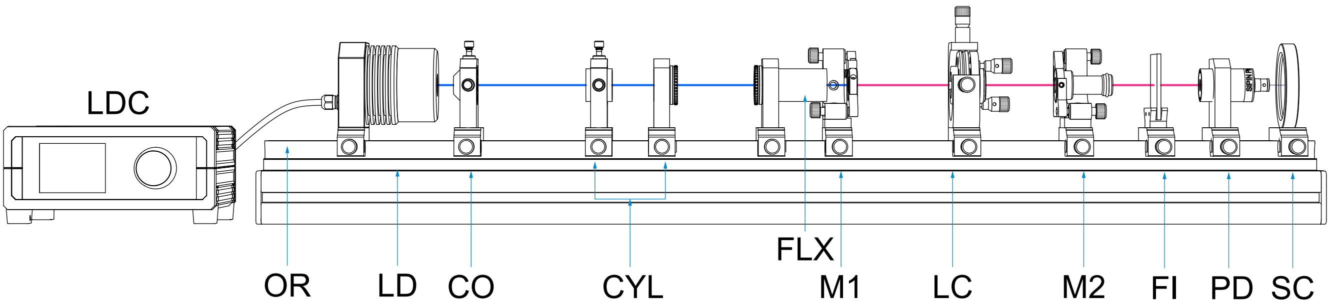


Fig. 8: Spherical Laser Cavity

In this setup the mirror M1 is a spherical mirror. For mechanical reasons, the mirror as well as focusing lens mount (FLX) require different shapes.

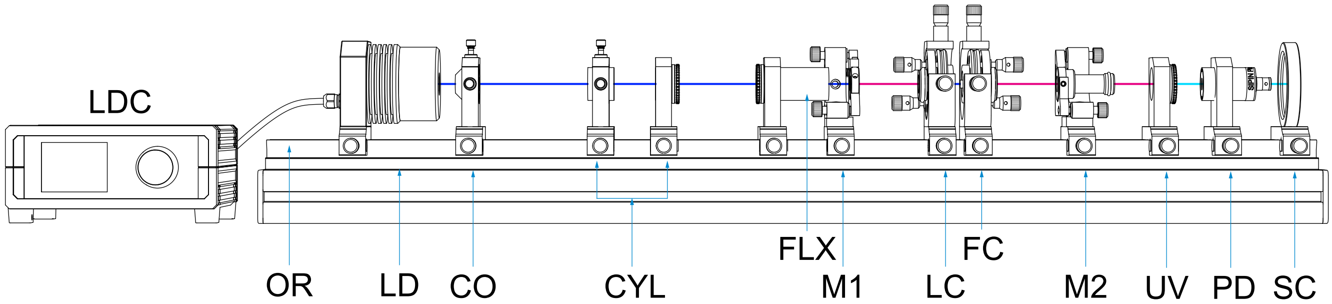


Fig. 9: Frequency Doubling 648 nm to 324 nm

The efficiency of frequency doubling is higher at higher intensities of the fundamental wave. Thus the SHG crystal must be position close to the laser crystal.

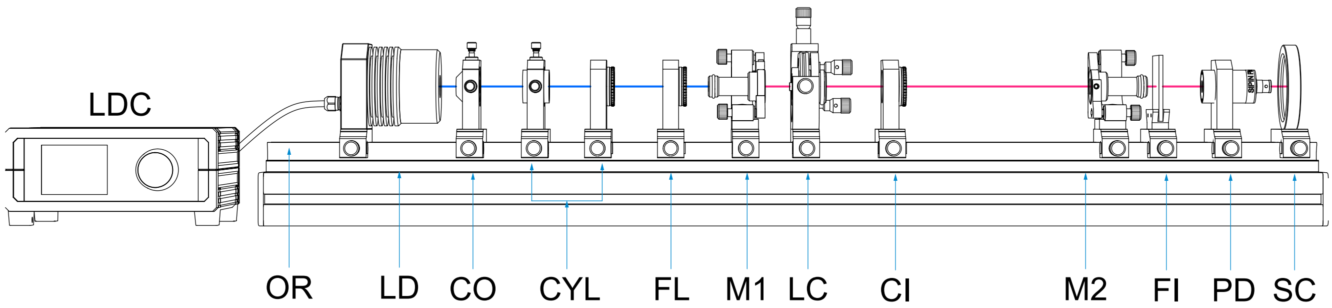


Fig. 10: Plane-plane cavity with cavity internal lens (CI)

For a few experiment plane waves inside the cavity are required. To avoid the difficulties of pure plane / plane cavities here a hemispheric cavity is realized, whereby the curved mirror is substituted by a lens (CI) and a flat mirror M2. Between the lens the flat mirror plane wave can exist.

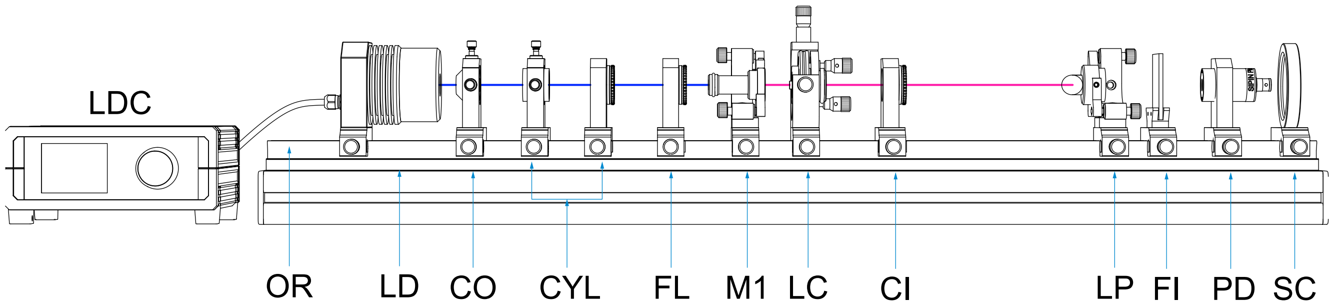


Fig. 11: Plane-plane cavity with Littro prism tuner (LP)

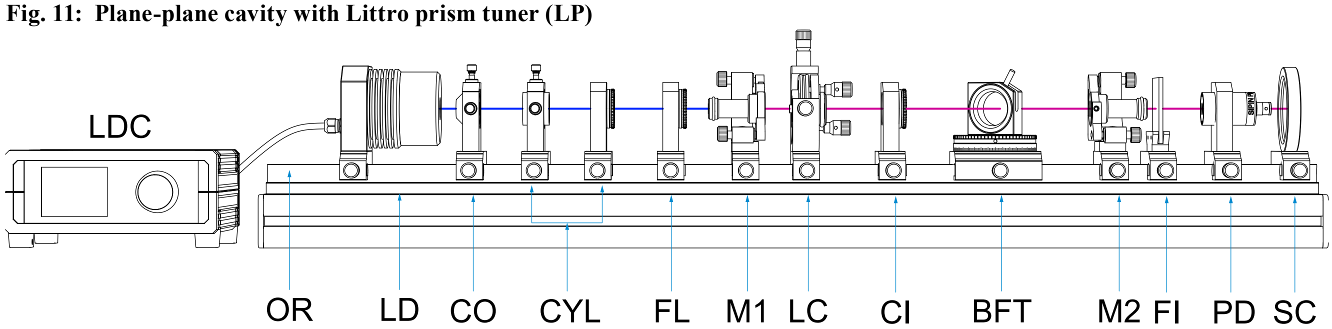


Fig. 12: Plane-plane cavity with BFT tuner

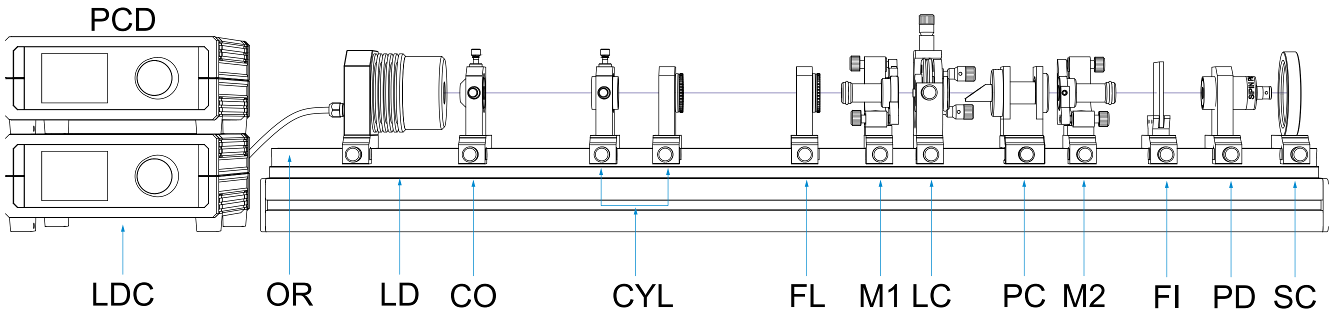


Fig. 13: Hemispheric cavity with Pockel's cell (PC) for short pulse generation

2.1 Description of the components

2.1.1 Optical rail

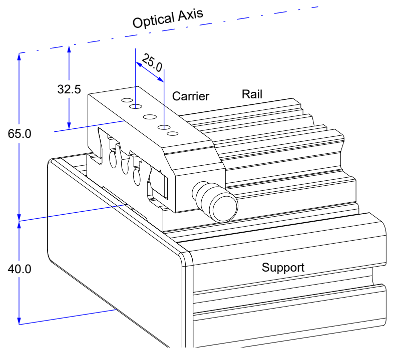
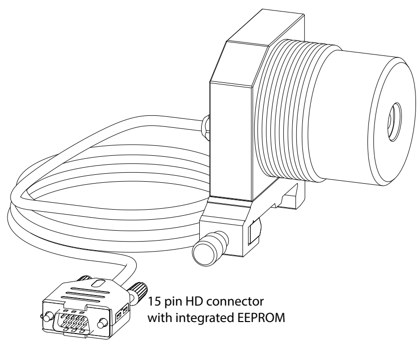


Fig. 14: Rail and carrier system

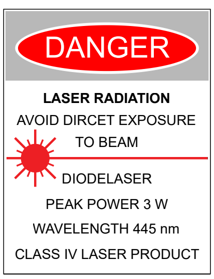
The rail and carrier system provides a high degree of integral structural stiffness and accuracy. Due to this structure, it is a further development optimized for daily laboratory use. The optical height of the optical axis is chosen to be 65/105 mm above the table surface. The optical height of 32.5 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.

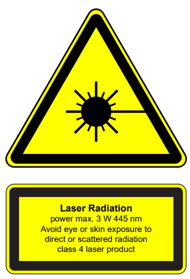
2.1.2 The diode laser module LD



For the efficient optical excitation of the Praseodymium doped YLF crystal a pump wavelength of 444 nm at its full power 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 3 Watt at a wavelength of 444 nm. A particularity of the blue diode lasers is that its wavelength strongly depends beside the temperature with 0.05 nm/°C also strongly on the injection current with 3.3 nm/A.

The diode laser is connected via a 15 pin SubD HD connector to the controller LDC. 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.

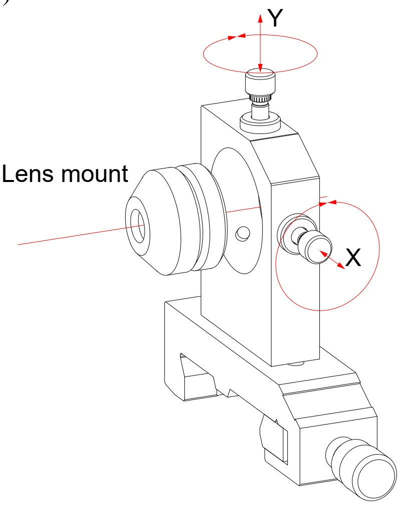




This device can emit highly concentrated visible light which can be hazardous to the human eye. The operators of the diode laser module have to follow the safety precautions found in IEC 60825-1 “Safety of laser products Part 1: Equipment classification, requirements and user’s guide” when connected to the controller [11].

2.1.3 Collimator (CO)

A high precision aspheric glass lens is mounted into a click holder (A,B)



Focal length 4.6 mm
Numerical aperture: 0.53
Clear opening: 4,9 mm
AR coating: 300 .. 700 nm, < 0.5 % reflection

The lens mount is centered 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.

2.1.4 Galilean cylinder lens telescope

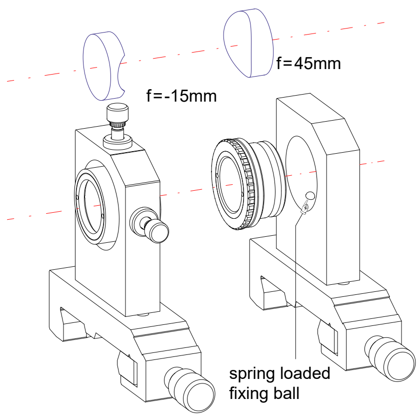


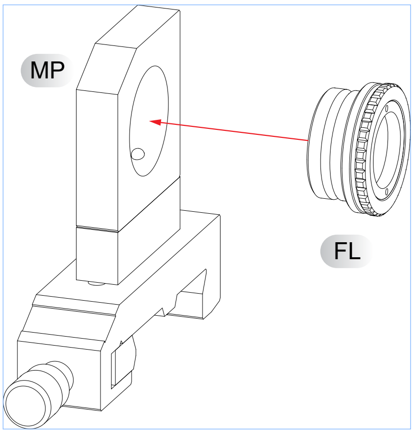
Fig. 15: Beam expander with cylindrical lenses

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.

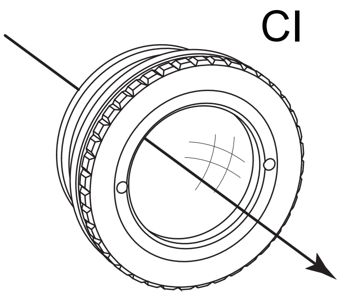
Such a telescope is made up from two cylindrical lenses and acts a beam expander, however, it effects only on one direction of the passing beam. It allows to convert an elliptical beam into an almost round one. The expansion ratio is 3 x. The first lens f1 is a concave and the second one f2 a convex cylindrical lens. The lens f1 is mounted into an XY adjustment holder to position the processed beam into the desired direction. The second lens is mounted into a C25 click holder which is kept in position by three spring loaded balls (SB) snapping into the groove CG of the C25 mount.

2.1.5 Focusing lens (FL)

To obtain a very high intensity of the pump light the collimated blue 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 keeping the lens precisely in position.



2.1.6 De-focusing lens (CI)



The optional mounted lens L2 is used to setup a plane-plane cavity in combination with the Littrow prism module as intra cavity element. It has a focal length of 50 mm and a high quality anti-reflection coating R<0.3% in a range of 425 .. 700 nm. The lens is mounted into a 25 mm click mount which can be inserted in any 25 mm mounting plate. It is used to form a parallel laser beam inside the cavity.

2.1.7 Laser mirror adjustment holder M1

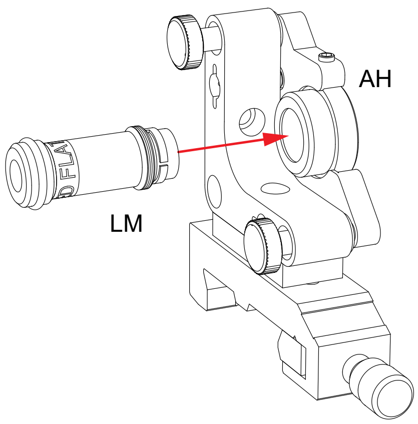


Fig. 16: Adjustment holder with M16 mirror adapter (LM)

The adjustment holder (AH) comprises of 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 1 inch mount into which the laser mirror mount (MM) is inserted and fixed by the grub screw (GS).
The adjustment holder is mounted to the carrier such that a "left" operating mode is achieved and thus forming the left mirror holder of the laser cavity. Due to the symmetry of the adjustment holder (AH) it can also be changed to the "right" mode if required.

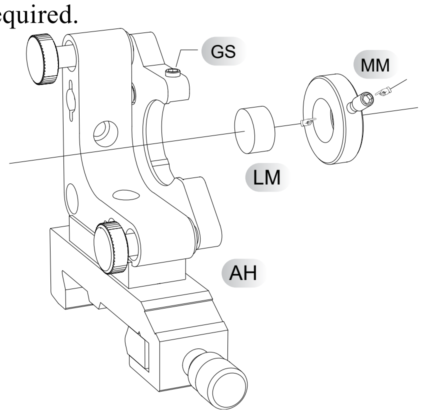


Fig. 17: Adjustment holder with 1 inch mirror adapter (MM)

2.1.8 Laser mirror adjustment holder M2

The adjustment holder (AH) comprises of 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 such 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.

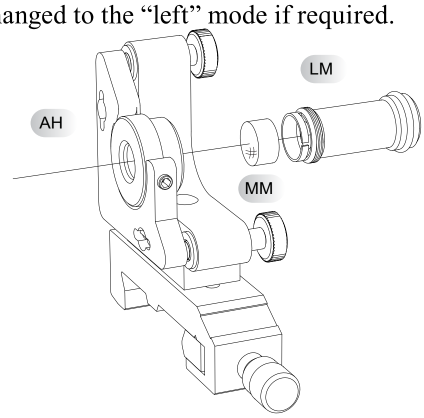


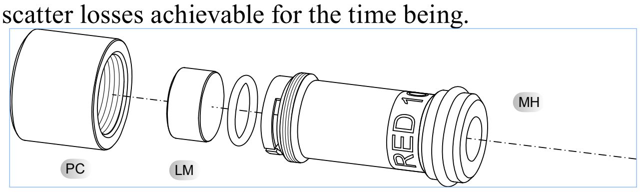
Fig. 18: Adjustment holder with M16 mirror adapter

2.1.9 Set of laser mirror

The set-up comprises two sets of mirrors each mounted separately as shown in Fig. 3.10. Each mirror has the standard diameter of 12.7 mm (½ inch) and a thickness of 6.35 mm (¼ inch).
The laser mirror (MM) is mounted into the holder LM and kept in position by two spring loaded flaps. A soft O-ring provides a soft seat of the mirror inside the holder (LM) especially when screwed into the adjustment holder. The mir-

Experimental Setup

rors are of supreme quality, coated by ion beam sputtering (IBS) yielding the highest degree of reflectivity and lowest scatter losses achievable for the time being.



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 right column.

Mounted laser mirror

Mark	Coating
RED	HT 445 / HR 580..720 nm
GREEN	HT 445 / HR 500..570 nm
ORANGE	HR 604 nm
	HR R > 99.98%
	HT T > 80%
ROC	Radius of Curvature

Label	Geometry
RED FLAT	fflat mirror
RED 100	ROC 100 mm
RED 150	ROC 150 mm
GREEN FLAT	flat mirror
GREEN 100	ROC 100 mm
ORANGE FLAT	flat mirror

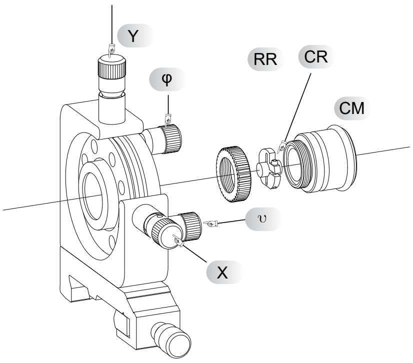
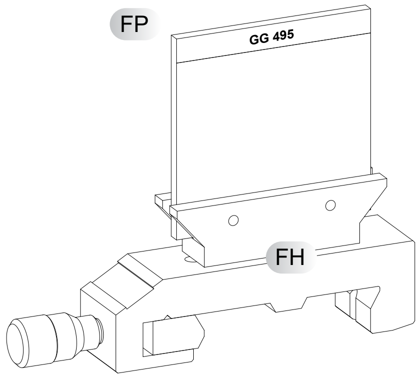


Fig. 19: Pr:YLF crystal 5 axes adjustment holder (LC)

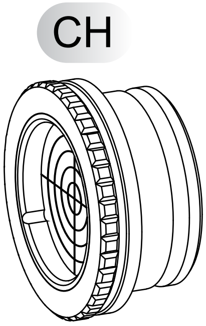
A Praseodymium doped Yttrium Lithium Fluoride crystal (CR) with a diameter of 5 mm and a length of 6 mm is mounted into a disk with 3 mm thickness and gently clamped. The disk holding the crystal is set into the mount (CM) where it is fixed by using the ring (RR). The crystal mount (CM) is inserted into 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 allowing the translative (X,Y) and azimuthal (υ,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 pump laser radiation.
The Pr dopant level is 0.7% and the crystal is cut along its c axis termed also as c-cut orientation.
The end faces of the crystal are polished better λ/10 and are coated with a high bandwidth anti reflection coating of 440 .. 740 nm with a residual reflectivity R of <0,1%.

2.1.10 The GG495 filter module (FI)



The coloured glass filter (FP) GG495 has a thickness of 3 mm and is used to suppress the pump radiation which is not absorbed by the Pr:YLF crystal. It is for important for the measurement of the lifetime of the excited state or to measure the fluorescence spectrum.

2.1.11 Crossed hair target (CH)



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 MG65

2.1.12 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 MK1 diode laser controller. The photodetector module is placed into the mounting plate (MP) where it is kept in position by three spring loaded steel balls.

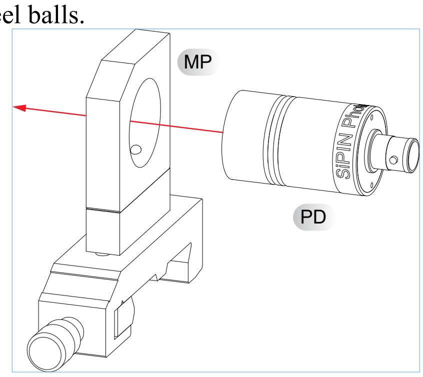


Fig. 20: Photodetector module

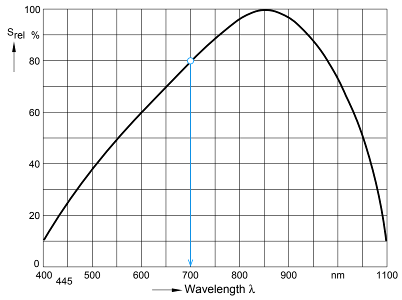


Fig. 21: Sensitivity curve of the BPX61 photodiode

Parameter	symbol	value
Rise and fall time of the photo current at: *RL*=50 Ω, *VR*=5V, *λ*=850 nm and *Ip*=800 µA	t_r, t_f	20 ns
Forward voltage IF = 100 mA, E = 0	*VF*	1.3 V
Capacitance at *VR* = 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, VR = 10 V	*IR*	≤30 nA
Spectral sensitivity, λ = 850nm	*S(λ)*	0.62 A/W

Table 1: Basic parameters of Si PIN photodiode BPX61

The Mk2 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. 22. 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 photo current 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. 21. From the Table 1 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. 21 (23% or 0.23).
The detected optical power P_{opt} in W is given as:

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

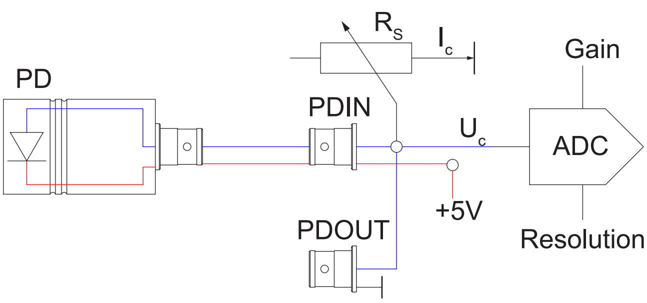
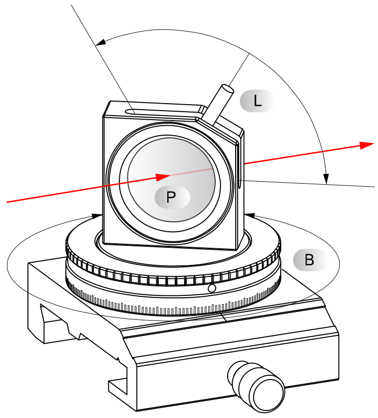


Fig. 22: Photodiode schematic

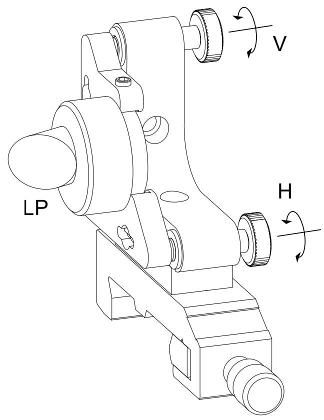
The photo voltage U_c is internally connected to a high precision ADC from which the microprocessor reads the value of the of U_c and the value of the load resistor R_S and displays their values on the touch screen of the MK2 controller.
It must be noted that the measured power is correct only if the 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.

2.1.13 Birefringent Tuner (BFT)



A detailed description of the property and function of a double refractive tuning element can be found in [12] or [13].
The double refractive or birefringent plate (P) is mounted in a dual rotational stage. For the intra-cavity operation the birefringent plate (P) needs to be aligned in such a way that the laser beam hits the plate under the Brewster angle to minimize the reflection losses. This can be accomplished by turning the rotary plate (B).
In addition the birefringent plate can be rotated around its optical axis by tilting the lever (L).
By rotating the plate (P) its optical retardation δ is changed. If the retardation of two passes is a multiple integer of the wavelength λ.

2.1.14 Littrow prism tuner (LP)



Another way to select different lines of a laser is to use a Littrow prism. A detailed description of tuning a HeNe Laser with a Littrow prism is given by Luhs [13].
Within this experiment we are using such a module to tune a Pr:YLF solid state laser. The Littrow prism is made from fused silica which is the required substrate for IBS coating. The spectral range of the IBS coating covers 580..720 nm with a reflectivity >99.98 %. The prism is mounted into a precise adjustment holder where it can be smoothly tilted in vertical (V) or horizontal (H) direction.

2.1.15 Active q-switch with Pockels Cell (PC)

Fig. 23: 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 [4]. 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

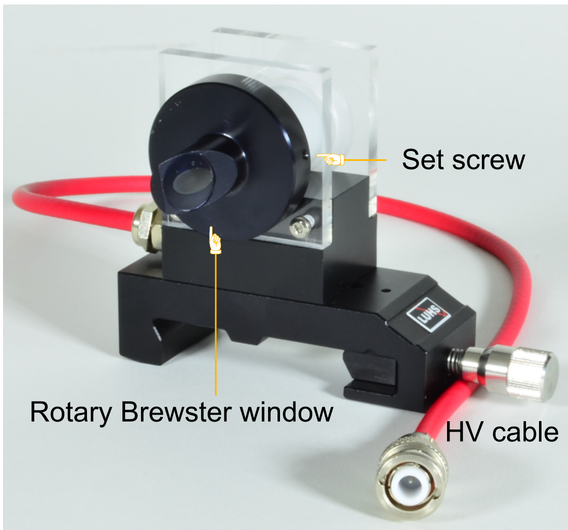


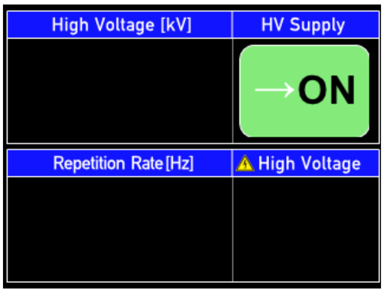
Fig. 24: Pockels cell with rotary Brewster window and high volt coaxial cable and BNC connector

2.1.16 Pockels cell controller

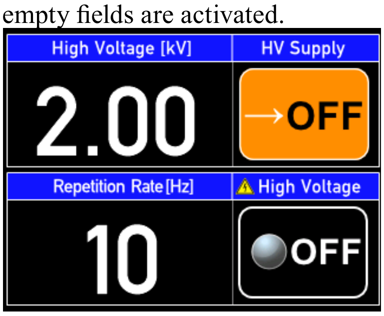
The Pockels cell controller is operated by a microprocessor touch panel and a rotary knob to set numerical set values. Pressing the knob pushes an emergency stop.

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.

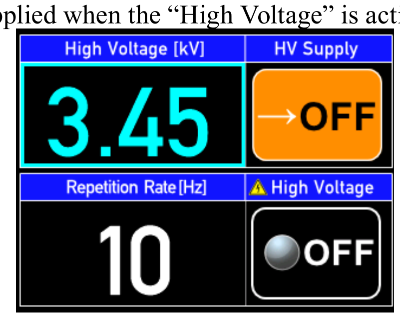
Right after switching on the controller, the start screen appears. To continue to the next screen a touch to it is required.



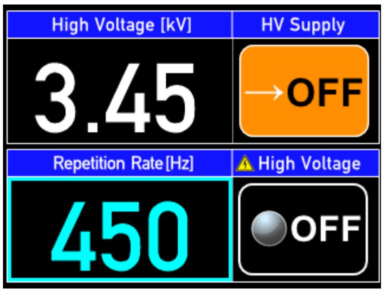
The high voltage module located inside the controller, has its own supply which is switched on by tapping the "ON" button. The empty fields are activated.



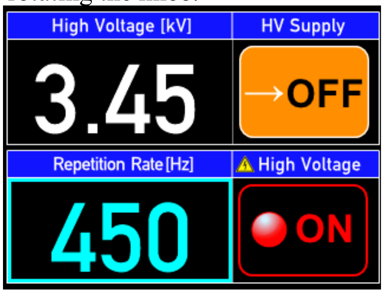
The additional elements on the screen allow the setting of the high voltage amplitude and repetition rate. The values are only applied when the "High Voltage" is activated.



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.

2.1.17 Digital Diode Laser Controller MK1

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.

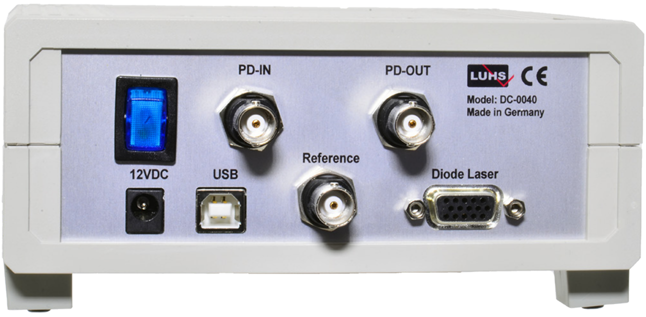


Fig. 25: Digital Diode Laser Controller MK1

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 synchronization 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. Further detailed specifications are given in the following section of the operation software.

2.1.18 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

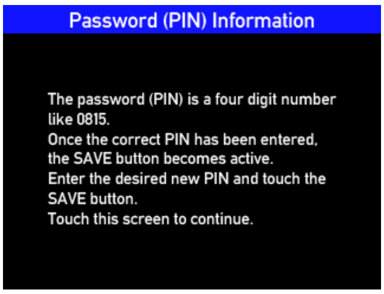
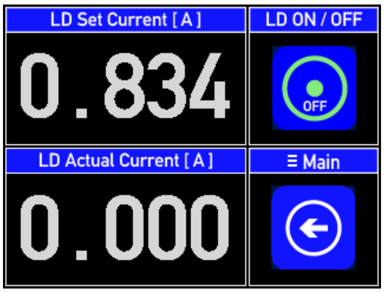
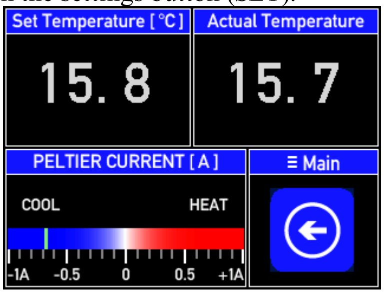


Fig. 28: Information for the password

Main Screen

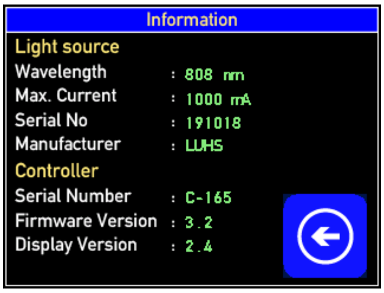


For immediate "Laser OFF" just tap the yellow button. To set the injection current simply tap the injection current display and turn the settings button (SET).



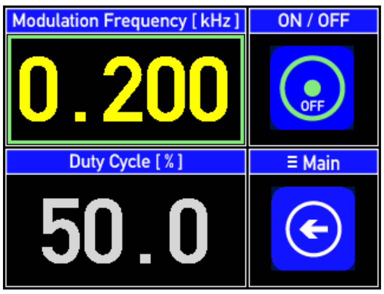
The same is true also for the "Set Temperature" section. When in operation and connected to the laser diode the actual temperature is shown in the "Actual Temperature °C section. Furthermore the actual current of the Peltier element is shown in such a way, that cooling or heating of the element can be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

Information screen



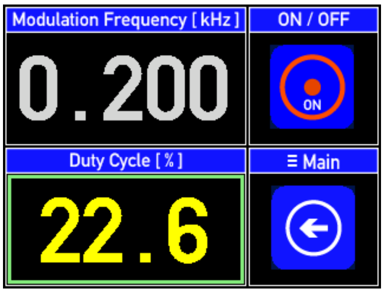
When tapping the Device Info button of the main screen this screen comes up. It again reads and displays the information stored in the EEPROM of the attached diode laser. If an entry exceeds the maximum or minimum limit value retrieved from the EEPROM of the attached diode laser the entry is reversed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

Modulation settings



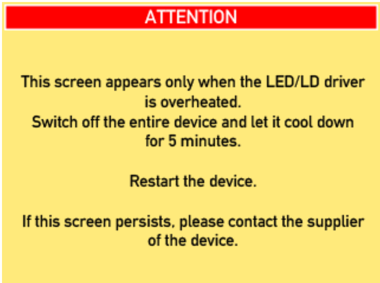
The diode laser can be switched periodically on and off. This is for a couple of experiments of interest. By tapping the display of the modulation frequency, the entry is activated. Turning the settings knob will set the desired frequency value. The modulation becomes active, when the Modulator ON/OFF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

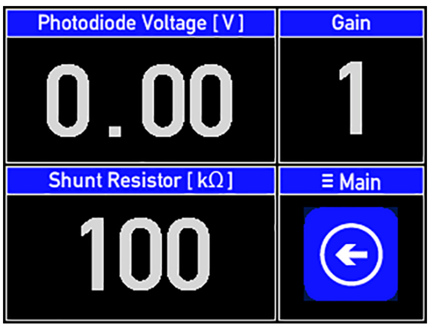
Overheating warning



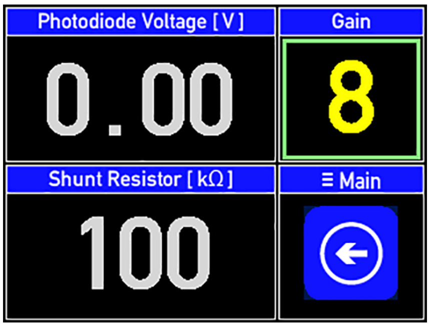
This screen you should never see. It appears only when the chip of the injection current controller is over heated. Switch of the device, wait a couple of minutes and try again. If the error persists, please contact your nearest dealer.

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

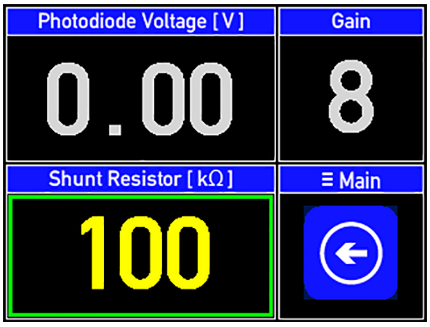
Photodetector Screens



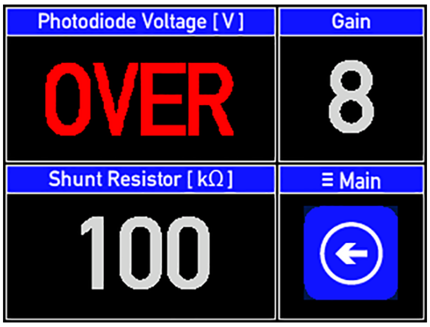
The photodiode page displays the measured photo voltage, the selected shunt resistor and the chosen gain.



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.

Important Note:
The controller reads at the start-up the EEPROM of the connected diode laser. In case it is a diode with 455 nm (as it is the case here), the HiMode is activated. That means that if the injection current is set higher than 0.710 the automatic modulation with 50% duty cycle is forced. This has two reasons:
1. keep the thermal load of the laser diode low in interest of a long life time.
2. Due to the optical pumping process the Pr:YLF crystal heats up and the efficiency goes down. The modulation reduced the thermal load of the crystal.

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 the to be expected values or curves.

3.1 Characterization of the diode laser

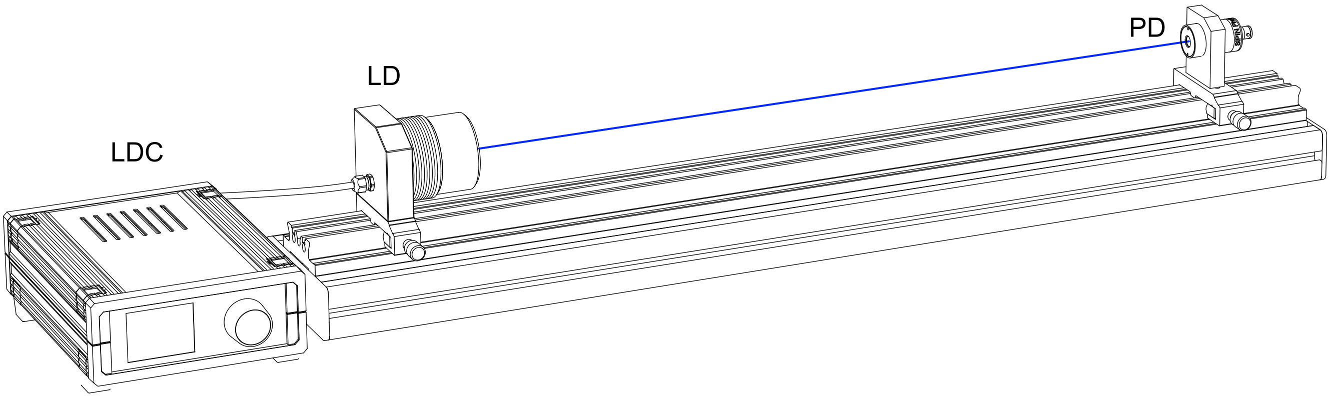
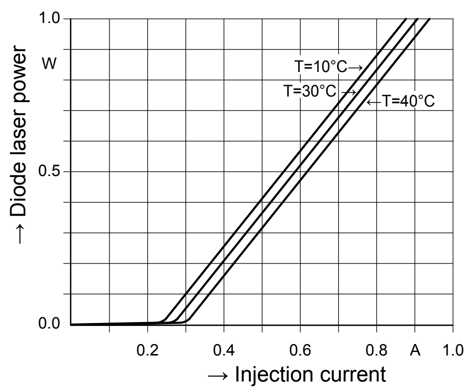


Fig. 29: Characterization of the blue diode laser

The task of this experiment is to measure the optical power versus the injection current for a set of fixed temperatures.

Wavelength	444	nm	
Temperature	30	°C	
S(λ)rel	0.23		Fig. 21
S(λ)	S(λ)rel · 0.23	A/W	
Injection current [mA]	Voltage Um [V]	RL[Ω]	Popt [mW]
0			
..			
1000			



Set the distance of the photodetector (PD) to the diode laser (DL) 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. The photodetector is connected with the provided BNC cable to the MK1 controller, where the detected intensity is displayed.

Experimental Setup

3.2 Collimating the blue diode laser beam

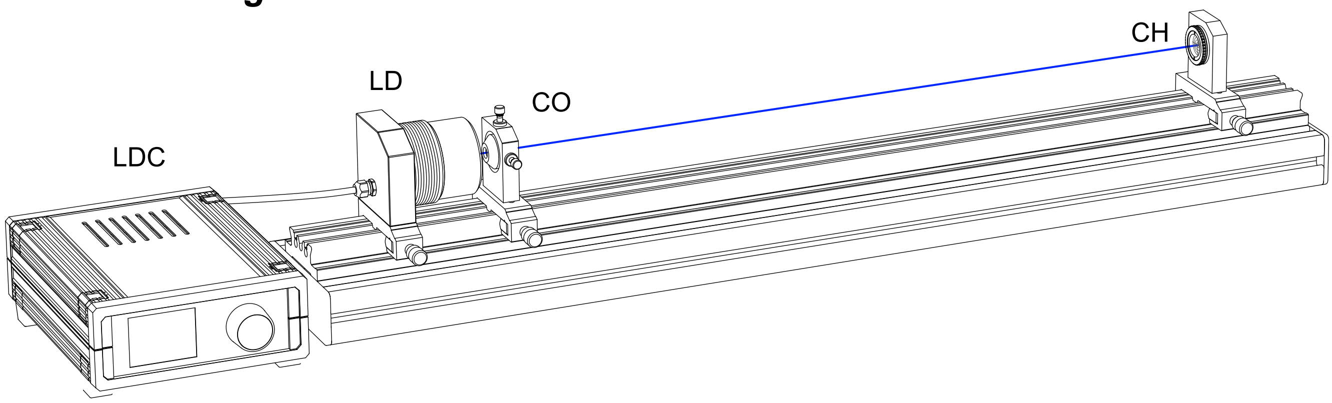
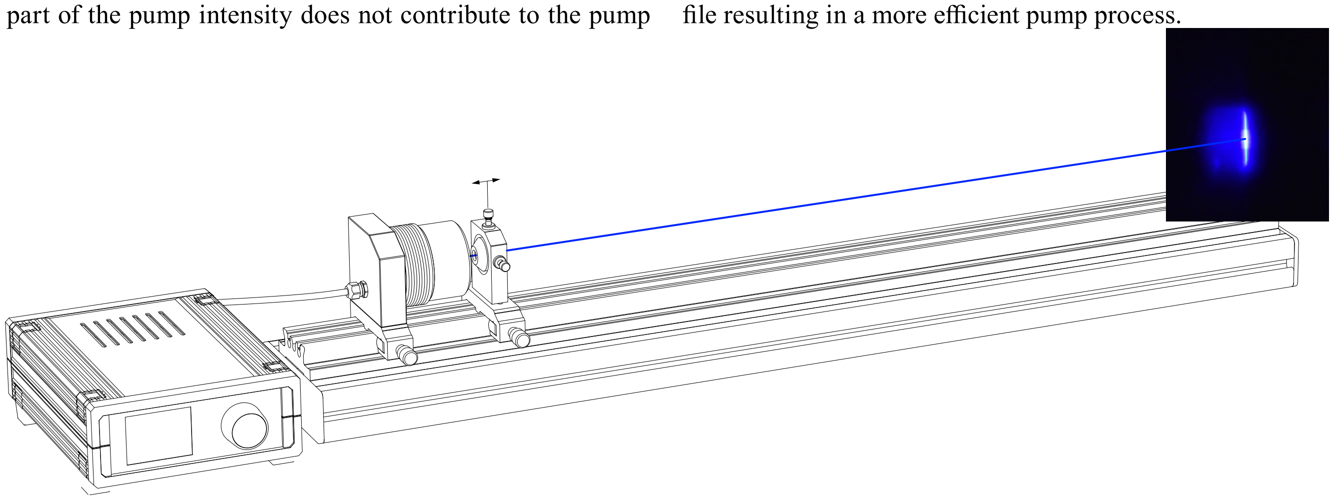


Fig. 30: Collimating and centring the diode laser beam

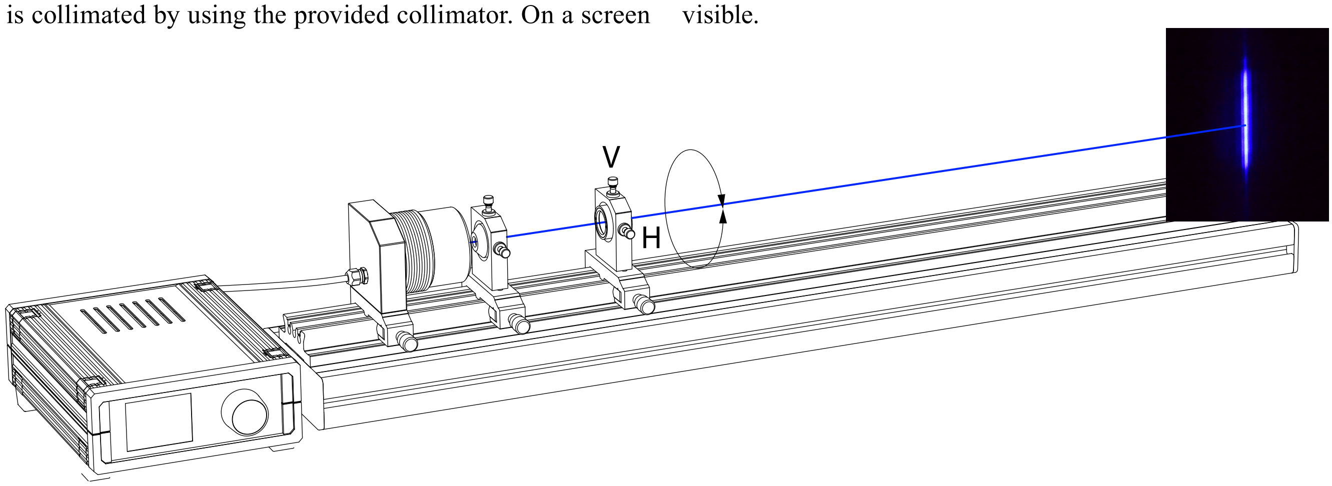
Place the collimator module (CO) in front of the diode laser with a free space of 10 mm between both. Switch on the diode laser and select not more than 250 mA injection current or such a value that the diode laser just start emitting laser radiation in addition to the blue LED radiation. Move the collimator 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 such 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 blue laser beam to the centre of the target screen.

3.3 Operation with cylindrical lens telescope

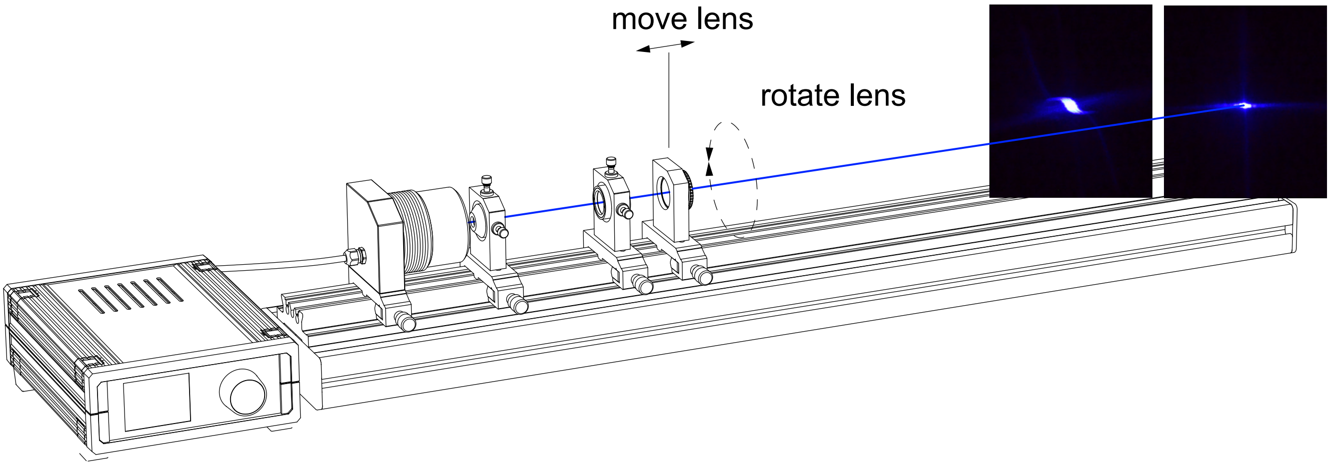
The emission of the diode laser has an elliptical beam profile which is disadvantageous for an optimum overlap of the pump and the mode volume of the cavity. A significant part of the pump intensity does not contribute to the pump process, resulting in higher thresholds and the generation of higher transverse mode. Using a cylindrical beam telescope, the pump beam is formed towards a more circular beam profile resulting in a more efficient pump process.



To align the provided cylindrical lens telescope, the beam is collimated by using the provided collimator. On a screen in a distance of 2 m or more, a sharp vertical structure is visible.



The first cylindrical lens with a focal length of 15 mm is placed in the front of the collimator. The lens is turned such that a vertical line appears on the screen. Actually only the vertical fine pitch screw (V) allows the vertical movement of the image on the screen.



Now the second cylindrical lens is inserted and moved along the optical axis until a sharp spot is imaged (right image of the figure above). If a spot like the left image appears, the lens is turned to achieve an almost round spot.

3.4 Preparing the pump laser focus

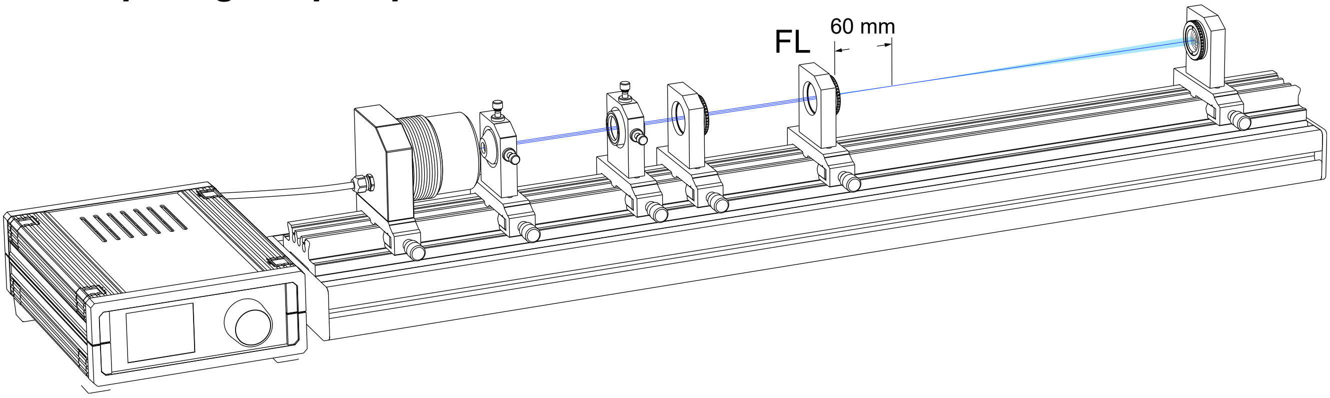


Fig. 31: Inserting the focusing module (FL) and creating the pump laser focus

Within the next step we will create a focus of the blue laser beam as shown in Fig. 22 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 Praseodymium doped YLF crystal rod will be placed. Before this will be done, switch off the blue laser.

3.5 Insert the Praseodymium YLF Crystal

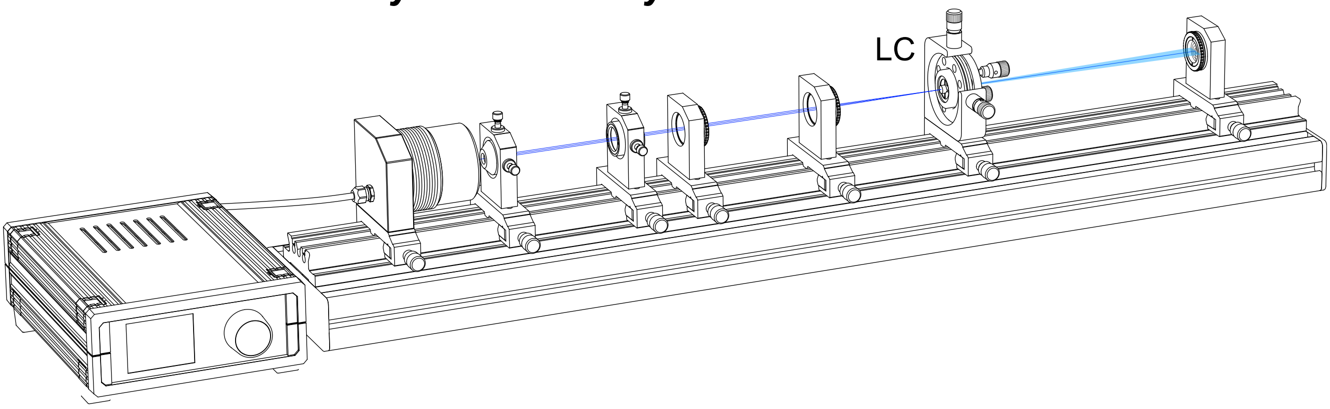


Fig. 32: Inserting the Praseodymium doped YLF crystal

The Praseodymium YLF crystal (LC) is placed onto the optical rail (OR) in such a way that the focus of the blue laser radiation lies inside the laser crystal. The crossed hair target (CH) is exchanged against the photodetector (PD).

A series of experiment will be performed to characterise the laser crystal.

Measurements

4.0 Measurements

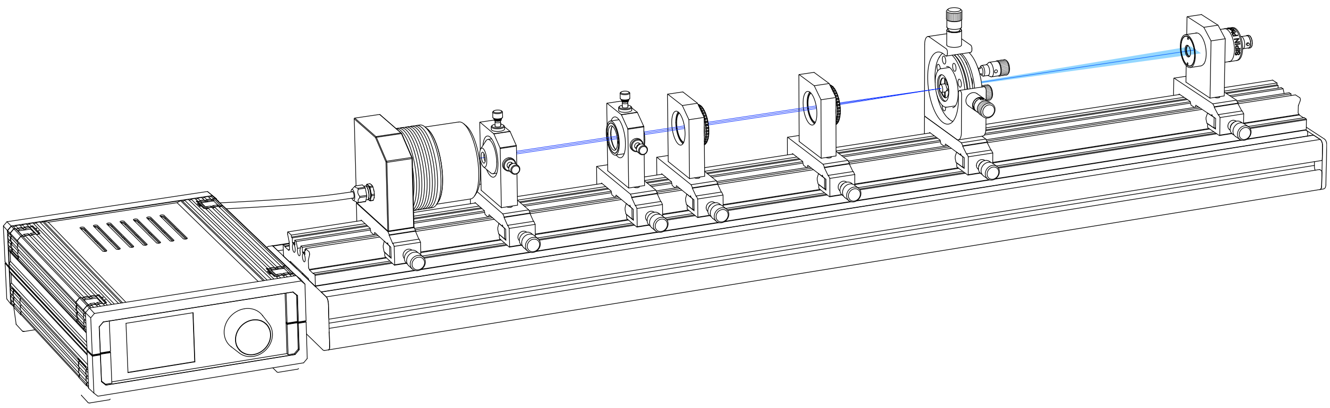


Fig. 33: Setup with photodetector PD

4.1 Measurement of absorbed pump laser power

To measure the output power in relative units the photodetector module (PD) is placed onto the rail as shown in Fig. 33. The detector is connected with the supplied BNC cable to the MK1 controller. For a set of different temperatures such as 10, 30 or 40°C the photo voltage Um of the photodetector signal box is recorded. The measurements will be taken with laser crystal out and in to determine the absorbed power.

Wavelength	444	nm	
Temperature	30	°C	
$S(\lambda)_{rel}$	0.23		Fig. 21
$S(\lambda)$	$S(\lambda)_{rel} \cdot 0.23$	A/W	

Injection current [mA]	Voltage U_m [V]		R_L [Ω]	Popt [mW]		$P_{absorbed}$
Laser crystal:	out	in		out	in	
0						
..				12	8	4
1000						

Table 2: Measurement data table

4.2 Absorption spectrum

A very elegant way to measure a global absorption spectrum is to make use of an optical spectrum analyser which are available even with a USB bus. Such a spectrum analyser displays a spectrum from 400 .. 1000 nm in almost real time.

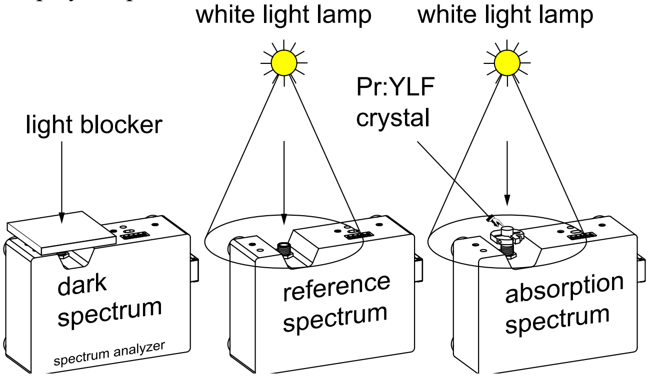


Fig. 34: Measuring the absorption spectrum of the Pr:YLF crystal with a white light lamp and a spectrum analyser

To create an absorption spectrum firstly the dark spectrum is measured and stored. Secondly a white lamp is used to provide a continuous white spectrum. The lamp is fixed with respect to the spectrometer in such a way that the spectrometer is illuminated, however not saturated. The white light spectrum is stored as reference spectrum. After that we carefully place the Pr:YLF crystal mounted in its disk on top of the spectrometer opening. The crystal completely covers the spectrometer entrance. Again the spectrum is recorded and stored.

The provided software allows the processing of all three spectra yielding the pure absorption spectrum.

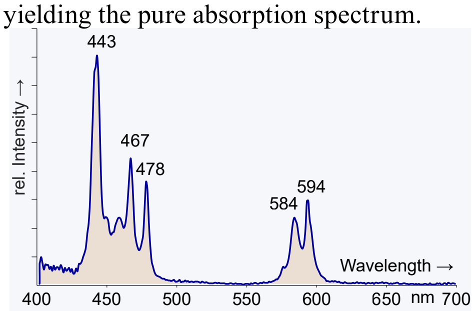


Fig. 35: Measured absorption spectrum of the Pr:YLF crystal

4.3 Excitation spectrum

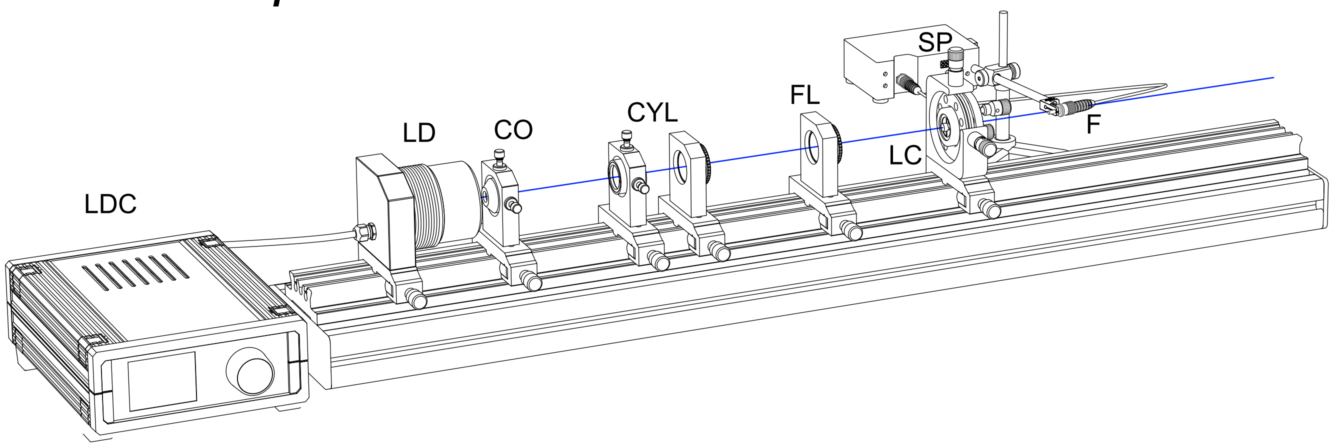


Fig. 36: Set-up to measure and record the excitation spectrum for pumping with 445 nm

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. 37.
The resolution of the spectrum analyser is just 2 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. 4.
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.

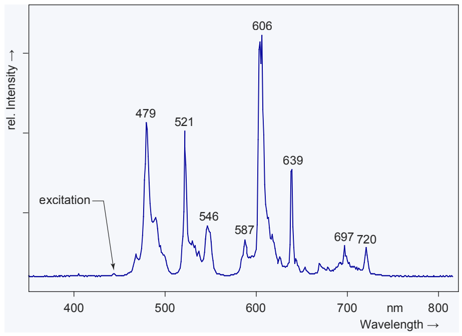


Fig. 37: Excitation spectrum

4.4 Measuring the lifetime of the excited states

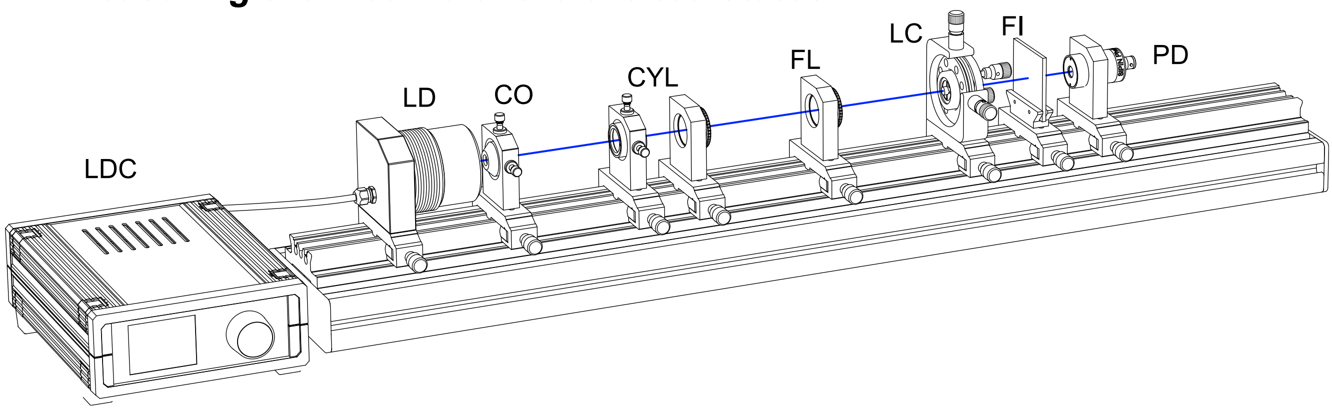


Fig. 38: Setup to measure the lifetime of the excited state

In this experiment we are interested in the temporal behaviour of the fluorescence light. 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 LDC controller and the output of it to the oscilloscope to channel 1. Channel 2 is connected via the provided BNC cable with the modulation reference of the diode laser controller LDC (Fig. 25). The oscilloscope triggers on channel 2 (modulation reference) at falling edge. The life time τ_s of the excited state is defined as the time, when the fluorescence intensity IF drops to I_0/e. This time can be taken from the oscilloscope display as shown in Fig. 39. In [9] the value of the lifetime is mentioned to be 50 µs.

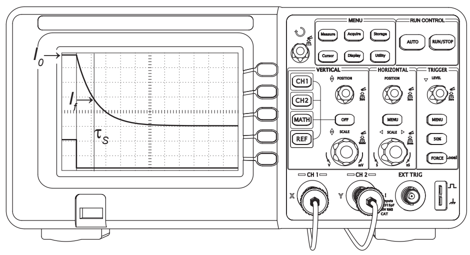


Fig. 39: Fluorescence decay curve

4.5 Completion of the set-up for laser operation

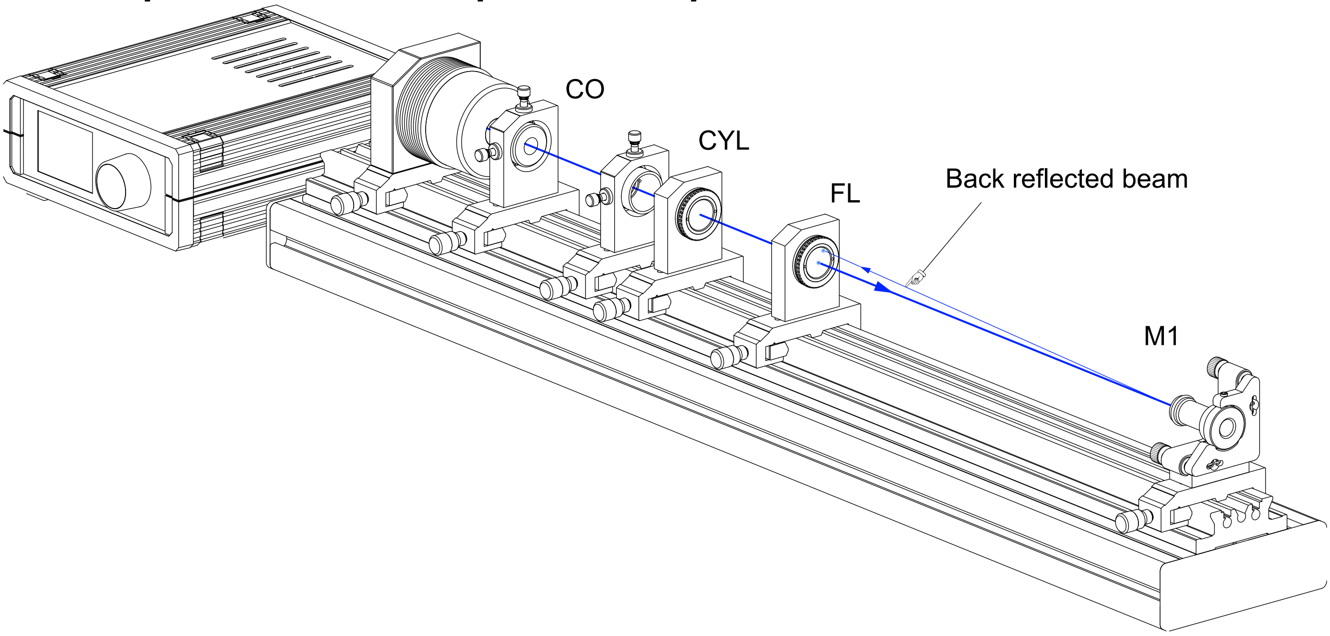


Fig. 40: Basic alignment of laser mirror M1

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 blue pump radiation. For this purpose we observe the scatter spots on lens (FL).
By turning the fine pitch screws for vertical (V) as well horizontal (H) tilt the back reflected beam is centred to the spot of the incident beam. The laser mirror mount (M1) is moved towards the focusing lens in such a way that the focus lies well behind the laser mirror. Depending on the desired setup, the mirror M1 can be a flat one, commonly in a M16 mount, or a curved one (ROC 100), commonly in an 1" adaptor mount.

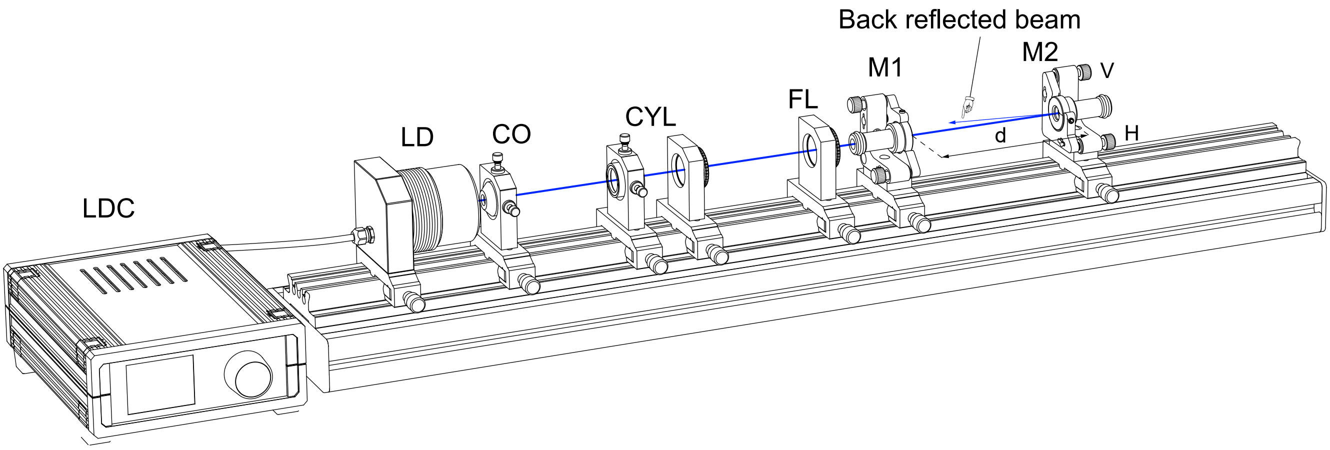


Fig. 41: Inserting laser mirror M2

The laser mirror module M2 is placed onto the rail. The distance d should be chosen that it is less than the radius of curvature (RM2) of the mirror M2. If d exceeds the distance RM2, the cavity is optically unstable and no laser radiation can 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.

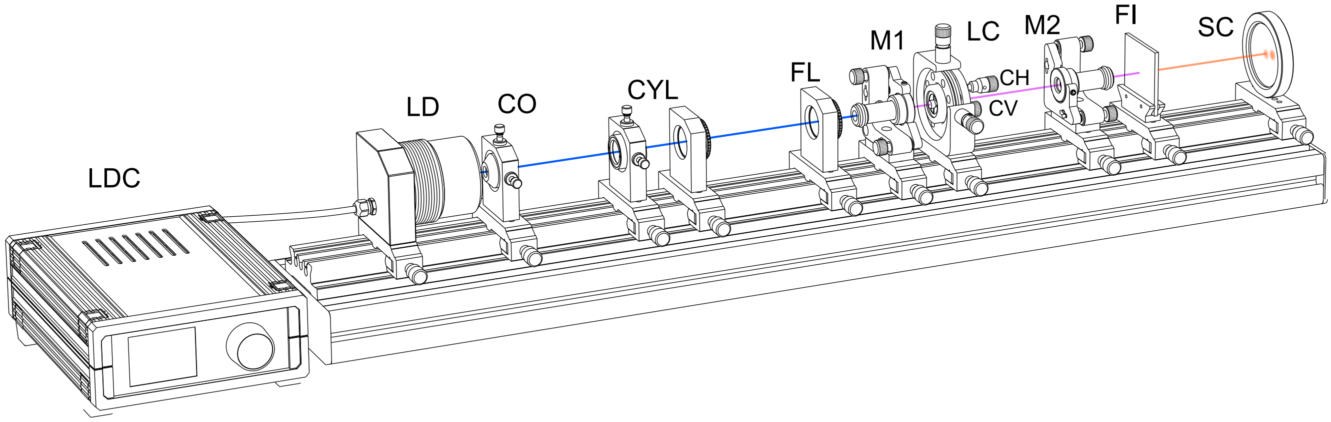


Fig. 42: Setting the Pr:YLF laser crystal into the cavity

After aligning M1 and M2 we place the mounted Praseodymium doped YLF crystal (LC) into the cavity as close as possible to the mirror M1. After powering the pump laser we will notice again a very bright white fluorescence. Behind the mirror M2 we will notice a mixture of unabsorbed blue diode laser light as well greenish fluorescence which however we will notice only if we are placing the GG495 onto the rail. By means of a small sheet of white paper we will notice a greenish spot in the centre. The greenish colour results from the coating of the laser mirror M2 which reflects the red radiation of the strong white fluorescence light. If we are turning the adjustment screws (H,V) of the mirror M2 we will notice another green spot moving accordingly. If we now adjust this spot to the centre of the fixed ones red laser oscillation occurs suddenly. If not, turn the Pr:YLF with its holder (see also Fig. 19) in such a way that the transmitted blue light becomes minimum.

Once the red laser light occurs the entire set-up will be aligned for best performance. The distance δ and the position of the focusing lens is optimised. Furthermore the Pr:YLF crystal is aligned perpendicular to the laser axis by turning the adjustment screws CV for vertical as well as CH for horizontal tilt.

The better the alignments are the lower the laser threshold will be. Good values are below 300 mA for the injection current of the diode laser.

4.6 Stability criteria and laser power

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 Rm of the second mirror. A nice description and derivation of the stability criteria of an optical cavity is given in [4], [13] or [14].

The output power is measured versus the position of the mirror M2. The experiment comes with two different radius of curvature (ROC) 100 and 150 mm. For each ROC the measurement is recorded like Fig. 32 below.

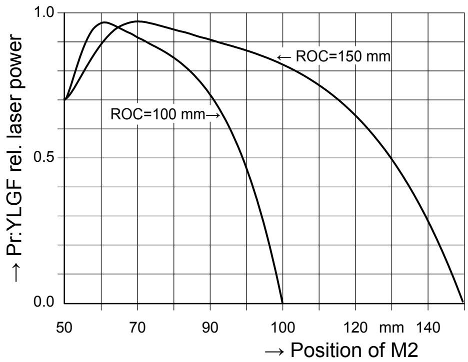
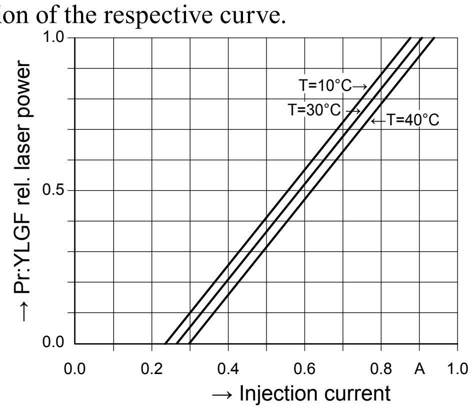


Fig. 43: Pr:YLF laser power vs cavity mirror position M2

4.7 Measuring 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. 47) the threshold and the slope efficiency is obtained from the linear regression of the respective curve.



4.8 Measurement of laser parameter

4.8.1 Measuring dynamic laser behaviour, spiking

To measure the temporal behaviour of the Pr:YLF laser we 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 GG495 Filter (FI) and connecting the photodetector to the controller. The output PDOUT 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 tor 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.

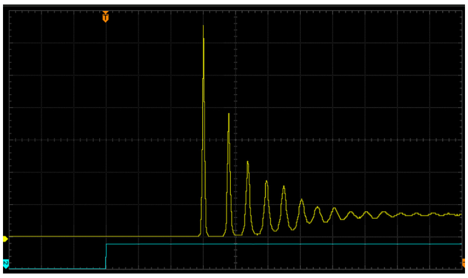


Fig. 44: Display of laser spiking

4.9 Wavelength selection and tuning

Wavelength selection by selective laser mirror

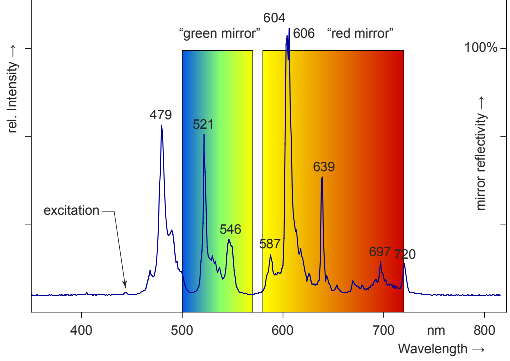


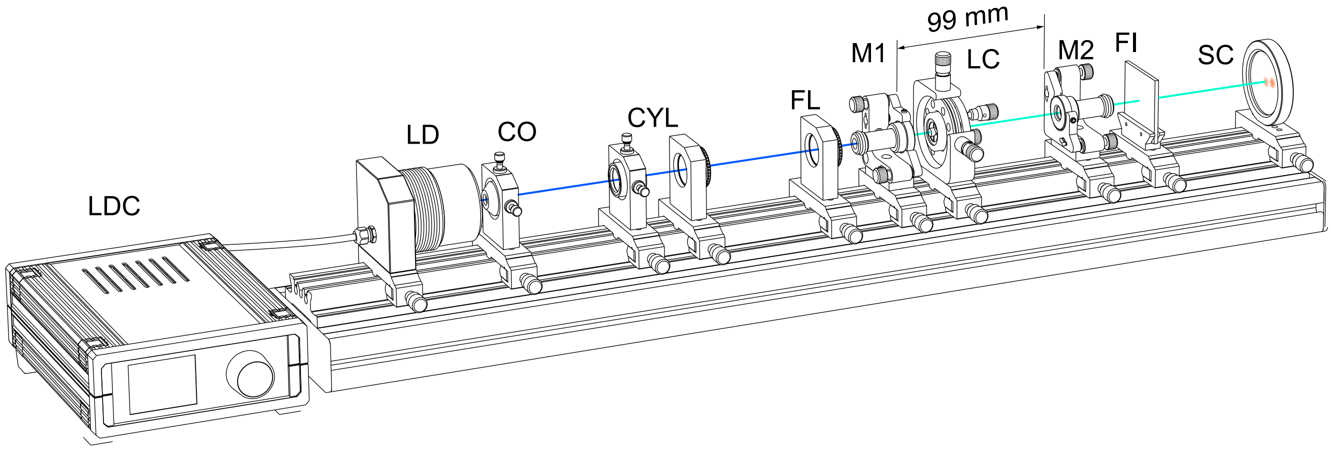
Fig. 45: Selective Mirror coating

The experiment comes with three types of laser mirror coatings. One type is the „green mirror", an „orange mirror" and the other one the "red mirror". In Fig. 35 all three types are shown with respect to the fluorescence lines of the Pr:YLF crystal.

Wavelength (nm)	*Transition*	*Effective Cross section 10^{-19} cm²*
479	$^3P_0 \rightarrow {}^3H_4$	1.9
523	$^3P_1 \rightarrow {}^3H_5$	0.3
607	$^3P_0 \rightarrow {}^3H_6$	1.4
639	$^3P_0 \rightarrow {}^3F_2$	2.2
698	$^3P_0 \rightarrow {}^3F_2$	0.5
721	$^3P_0 \rightarrow {}^3F_4$	0.9

Table 3: Cross section of the main lines and their transitions taken from reference [10]

A strong fluorescence line does not necessarily result also in a strong laser transition. The gain of a transition increases beside other parameter linear with so called effective cross section which are given in Table 3. It confirms what we already noticed with our laser experiments using the "red mirror" that the 639 nm is the strongest one. Also here it is valid that the winner takes it all. To force the laser to oscillate on another line we need to introduce losses for the unwanted line. Within the next chapter we will demonstrate how this can be accomplished. A simple, however expensive method is to use cavity mirrors which have a high reflectivity for the wanted line. As an example for this method we are going to use special coated mirrors to operate the "green line" at 523 nm and the orange line at 607 nm. The effective cross section for the 523 transition is only 0.3 and is the weakest among all other lines. Low cross section means high threshold and careful cavity alignment.



Before we start to use to operate the weak green line we first optimise the set-up with the red mirror. The cavity is set close to its optical stability limit of 100 mm. By means of a good ruler or vernier the distance from face to face of the mirror adjustment holder a distance of 99 mm is set. The Pr:YLF crystal is 2 mm apart from the Mirror M1. Checking by eye is sufficient. The focusing lens is slightly moved to find the position for best laser performance. Switch of the pump laser and without changing the positions of the components replace mirror M1 and M2 are against the "green mirror". Switch on the blue diode laser and set the injection current to its highest value. You might not see any green emission for the moment. Try to scan with the screws of M2 and if you are lucky the green line comes up. If not, go for the detailed instruction as follows:.

1. Darken the room as much as possible
2. Take the yellow GG filter and look through it into the cavity to see the right laser mirror mount.
3. Turn the knob for the horizontal adjustment until you will see a small green spot on the rim of the laser mirror mount
4. Align this spot while still visible on the rim vertically to the centre of the mirror
5. Move back the green spot horizontal to the centre of the mirror.
6. You should see now two spots on the mirror (weak) while aligning the moving accordingly, bring both together and the green line should appear.

Fig. 46: Aligning the green spot viewing through the GG495 filter

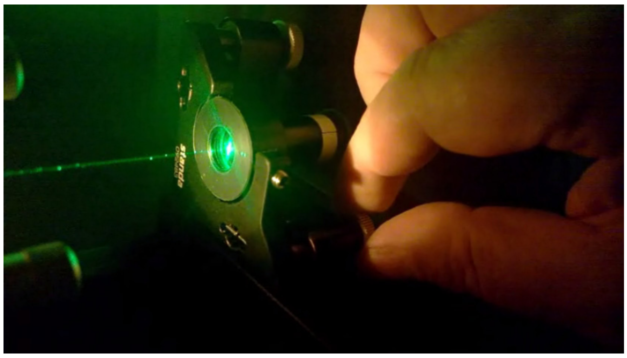
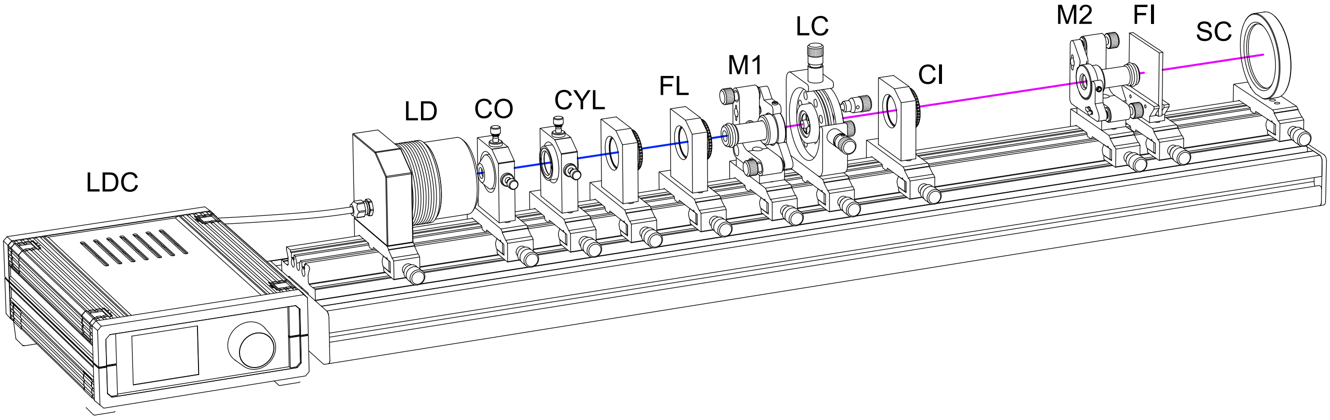


Fig. 47: Finally the green line lases!

4.10 Setup for operating the Pr:YLF laser at different wavelengths



We arrange the setup as shown in Fig. 42. We leave all components up to LC (from left) as the are already aligned. We exchange the spherical mirror of M2 against the „RED FLAT" mirror and move the adjustment holder more than 250 mm apart from the Pr:YLF crystal (LC). The f=50 mm lens (CI) is set onto the rail in such a way, that the distance is 50 mm apart from the flat mirror surface of M1. Behind the internal lens CI a parallel beam is created which is reflected back by the flat mirror of M2. Thus the distance of M2 to the mirror of M1 is arbitrary. On the screen two fluorescence spots are visible which needs to be aligned on top of each other. The red line starts to operate and the position of the lens CI is changed for best performance. Instead of the „RED FLAT" of M2 also the orange and green mirror will be used.

4.11 Wavelength selection with birefringent tuner

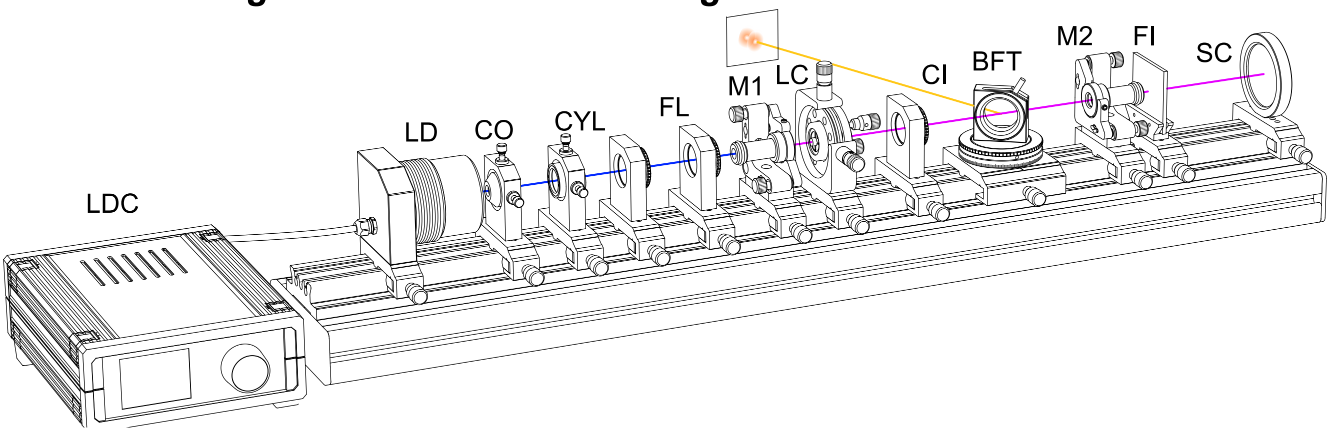


Fig. 48: Setup with birefringent tuner

As already mentioned the Praseodymium laser has the potential to oscillate on different visible wavelengths. The goal of this experiment is to tune to as much as possible of these wavelength. In principle a laser oscillates on a wavelength for which the gain is the highest and losses are the lowest. The gain is determined basically by the laser material, the losses however, mainly by the laser cavity. Basically for each wavelength a set of mirrors with appropriate coating can be created, however this is a quite cumbersome way to select a specific wavelength. It would be much better, just to turn a knob to tune to a different wavelength. Such devices exist, one of it is the so called Littrow Prism and another one is the birefringent tuner. In the set-up of Fig. 48 we using a birefringent tuner (BFT) which is simply placed into the cavity. To minimize insertion losses, the birefringent or double refractive plate is turned to the Brewster's angle. Instead of

Measurements

observing the fluorescence spot at the output of M2 we are using now the reflections caused by the BFT and align the mirror M2 in such a way that the spots of the fluorescence light are fully overlap. When rotating the birefringent plate by tilting the lever laser emission should occur. Gently tune to the maximum of performance and optimise the alignment of the mirror M2. By tilting the lever some other wavelength should show up. It is important that the birefringent plate is cleaned and no dust particles are visible. It should be noted that the different fluorescence lines are differently polarised to each other. Due to the alignment under the Brewster angle the BFT forces a defined polarisation direction which might cause losses to other lines. To obtain laser oscillation though for this lines the Pr:YLF must be rotated with respect to the optical axis.

4.12 Wavelength selection with Littrow prism

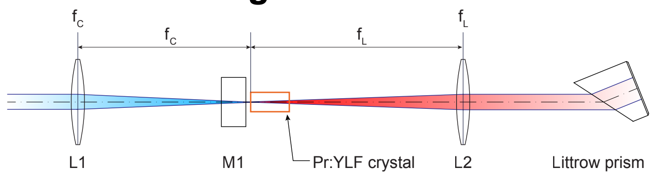


Fig. 49: Cavity design for Littrow prism tuning

Using a Littrow prism for laser line tuning requires a modification of the laser cavity since the reflecting surface of the prism is flat resulting in a cavity with two flat mirror. It is well known that such a cavity will be optically stable, however is extremely hard to align and to maintain laser oscillation. In order to have again a hemispherical arrangement we need to place a lens (L2) in front of the littrow prism creating a parallel beam, now even the position of the Littrow prism is not critical at all.

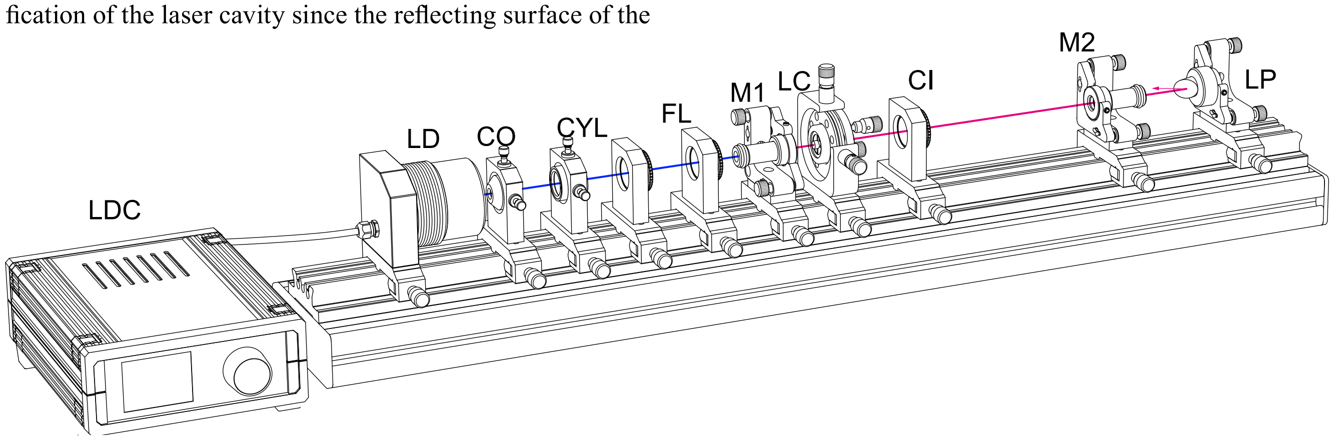


Fig. 50: Setup with Littrow Prism

From the previous setup we remove the birefringent tuner (BFT) and align the cavity accordingly. We are using the „RED FLAT" for M2. The beam leaving the cavity behind M2 we will use later as pilot beam for the alignment of the Littrow prism. We set the Littrow prism (LP) onto the rail in a convenient position. The red laser beam is reflected back from the prism and by aligning with the Littrow prism adjustment screws the beam is reflected back into the cavity, Close to the perfect alignment position multi reflections occur. That is the moment when we remove the mirror M2 as well the filter (FI).

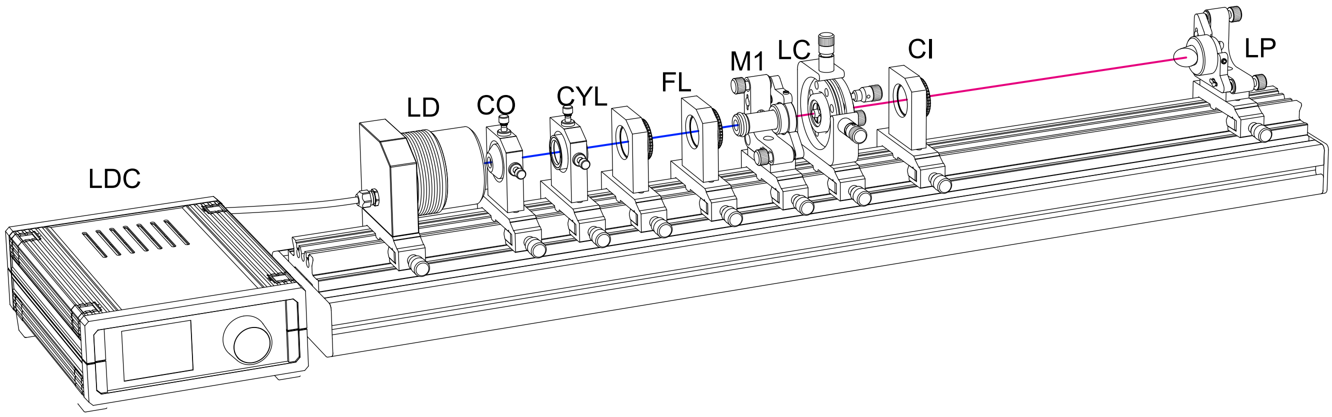


Fig. 51: Final setup with the Littrow prism

Now the Pr:YLF laser operates with the Littrow prism (LP). After aligning for best operation of all adjustable components we tilt the LP around its horizontal axis. We will note, that the gain of the red line is so high, that instead of ceasing and to give space for other wavelength, higher transverse modes occur. By rotating the Pr:YLF crystal around its axis, the polarisation conditions can be changed to favour the orange line and also the lines at 689 nm and 721 nm.

4.13 UV Second Harmonic Generation

Second harmonic generation is a process with a relatively low efficiency. Thus highest possible intensities of the fundamental wave are required, which can be achieved inside the laser cavity and the beam waist of the fundamental wave. To obtain an accessible beam waist the hemispherical cavity of the Pr:YLF laser is converted into a concentric one. Such a cavity consists out of a spherical mirror (M1) with a radius of curvature of 100 mm and another spherical one (M2,

R=150 mm).
The focal length of (L1) is 60 mm and with the plan-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 ≤ g1·g2 ≤1 must be fulfilled, which means:

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

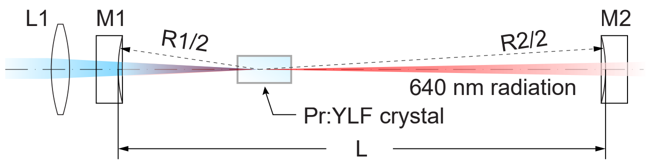


Fig. 52: Nearly concentric resonator

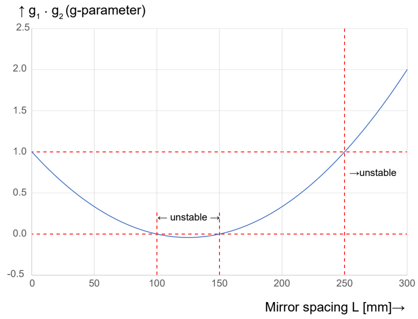


Fig. 53: g-Parameter versus mirror spacing

For a rapid check of the stability range for our cavity parameter with R1= 100 mm and R2 = 150 mm. we put the formula into a calculation sheet like Excel or other and create the graph of g1·g2 versus the mirror spacing L. The result is shown in Fig. 53. We notice a peculiarity in the range for the mirror spacing of 100 to 150 mm: the cavity is not stable. In principle two ranges show the desired stability, however, below 100 mm the space is not sufficient to add the Pr:YLF as well as the frequency doubler crystal to the cavity. It remains in the range above 150 mm up to 250 mm.

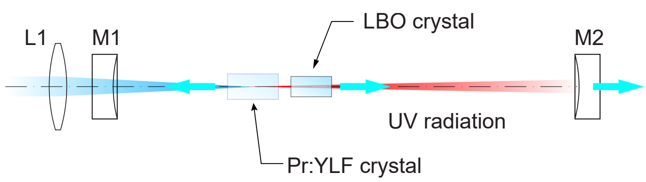


Fig. 54: LBO Frequency doubler inserted into the cavity

In the first step of the UV experiment we align and optimise the setup for the fundamental wave at 640 nm. We remove the M16 laser mirror mount and replace it with the 1/2 inch to 1 inch adapter which already contains the 100 mm mirror. The mirror M2 will be replaced by the 640/320 nm SHG mirror having a radius of curvature of 150 mm. This mirror has besides the high reflectivity for the fundamental wave of 640 nm a high transmission for the second harmonic at 320 nm.

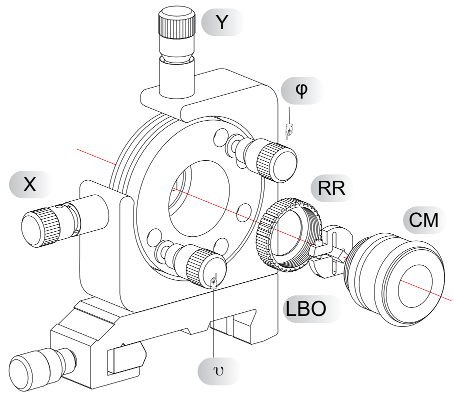


Fig. 55: Frequency doubler module

A Lithium Triborate (LiB_3O_5 or LBO) crystal (LBO) with a cross section of 3x3 mm and a length of 8 mm 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 translative (X,Y) and azimuthal (υ,φ) adjustment.
The crystal mount (CM) can be rotated free of play around its axis. It is important to rotate the crystal with respect to the polarisation of the fundamental laser radiation to achieve the best phase matching.
The LBO crystal is cut for type I phase matching for 640 (e) → 320 nm (o). The end faces of the crystal are polished better λ/10 and are coated with a high bandwidth anti reflection coating of 440 .. 740 nm with a residual reflectivity R of <0,1%.

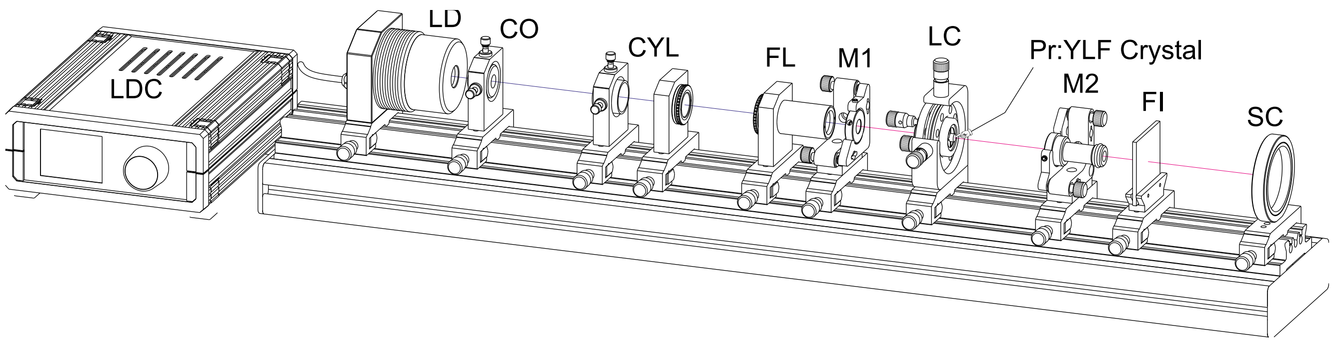


Fig. 56: Pr:YLF laser operating in a nearly concentric arrangement

Once the fundamental wave is operating, the fine adjustment takes place. The mirrors are aligned, the Pr:YLF crystal aligned perpendicular and rotated for maximum absorption. Furthermore the position of the focusing lens L1 is optimised as well as the position of the Pr:YLF crystal inside the cavity.
If this all has been done the next exciting step will be the UV generation

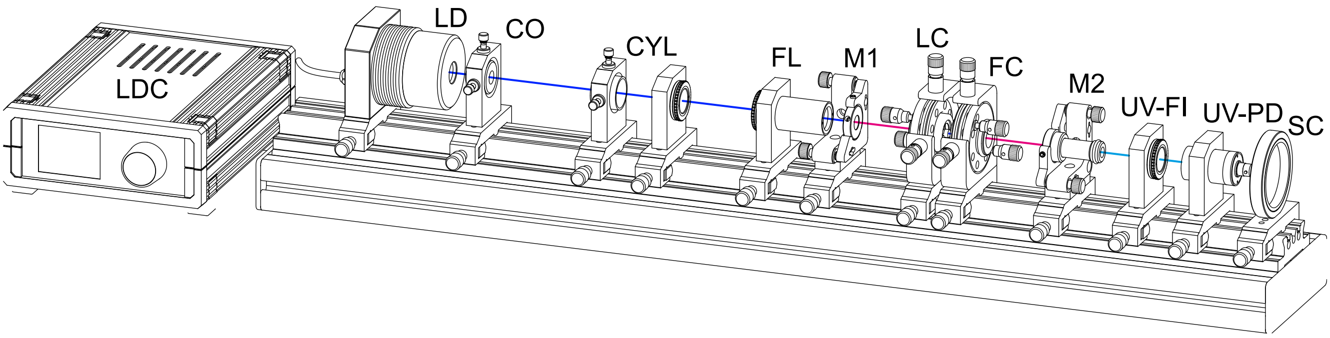


Fig. 57: LBO Frequency doubler inserted into the cavity

The created UF radiation can be verified either by the spectrometer or the UV photodetector or simply by using a white sheet of paper. When using a suitable power meter, a UV output of several mW can be detected. It will be noticed that the SHG efficiency strongly depends on the LBO's orientation which can be aligned by using the five axes adjustment holder. It should be observed that also the Pr:YLF crystal should be aligned since the LBO crystal forces a polarisation direction.

4.14 Generation of short pulses

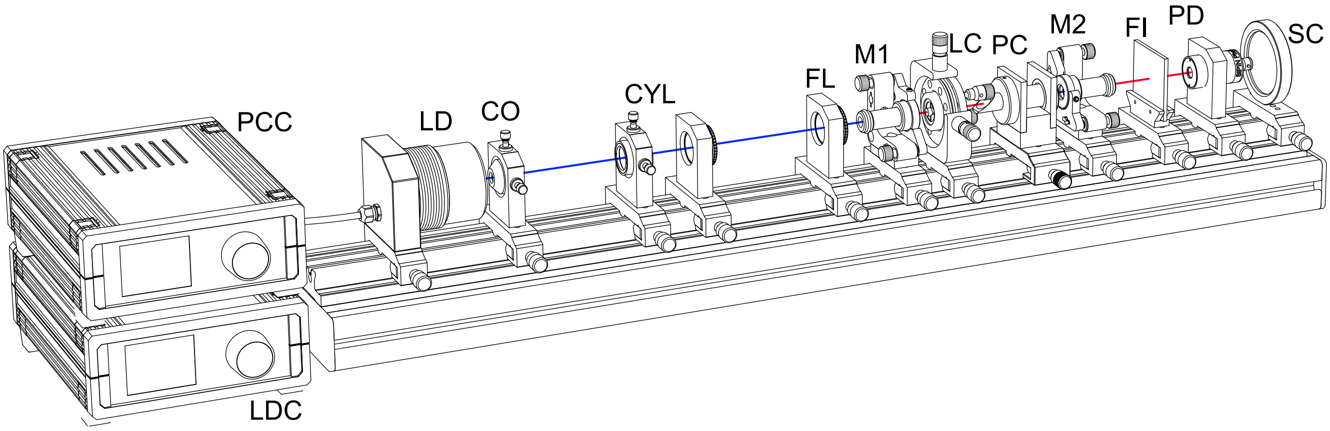


Fig. 58: Set-up with Pockels cell as active q-switch

The Pockels cell is inserted into the cavity and its HV cable is connected to the HV Pockels driver (Fig. 23). The Pockels cell driver is switched on and the voltage set to the lowest value. The Pr:YLF laser should work properly. Now increase the voltage to such a value, that the Pr:YLF laser stops oscillating. Set the repetition rate around 60 Hz for the beginning. The photodetector (PD) is connected to the MK1 controller box. The output PDOUT is connected to the first channel of an oscilloscope. The second channel is connected to the buffered modulation reference signal of the frequency generator.

The scope is set tor trigger on the falling edge of the trigger signal. On the scope we will observe a single peak of the Pr:YLF laser. Since the rise time of the laser pulse takes place in a couple of nanoseconds the load resister RL of the photodetector amplifier should be set to low values until the shape of the oscilloscope track of the laser pulse does not change any more.

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