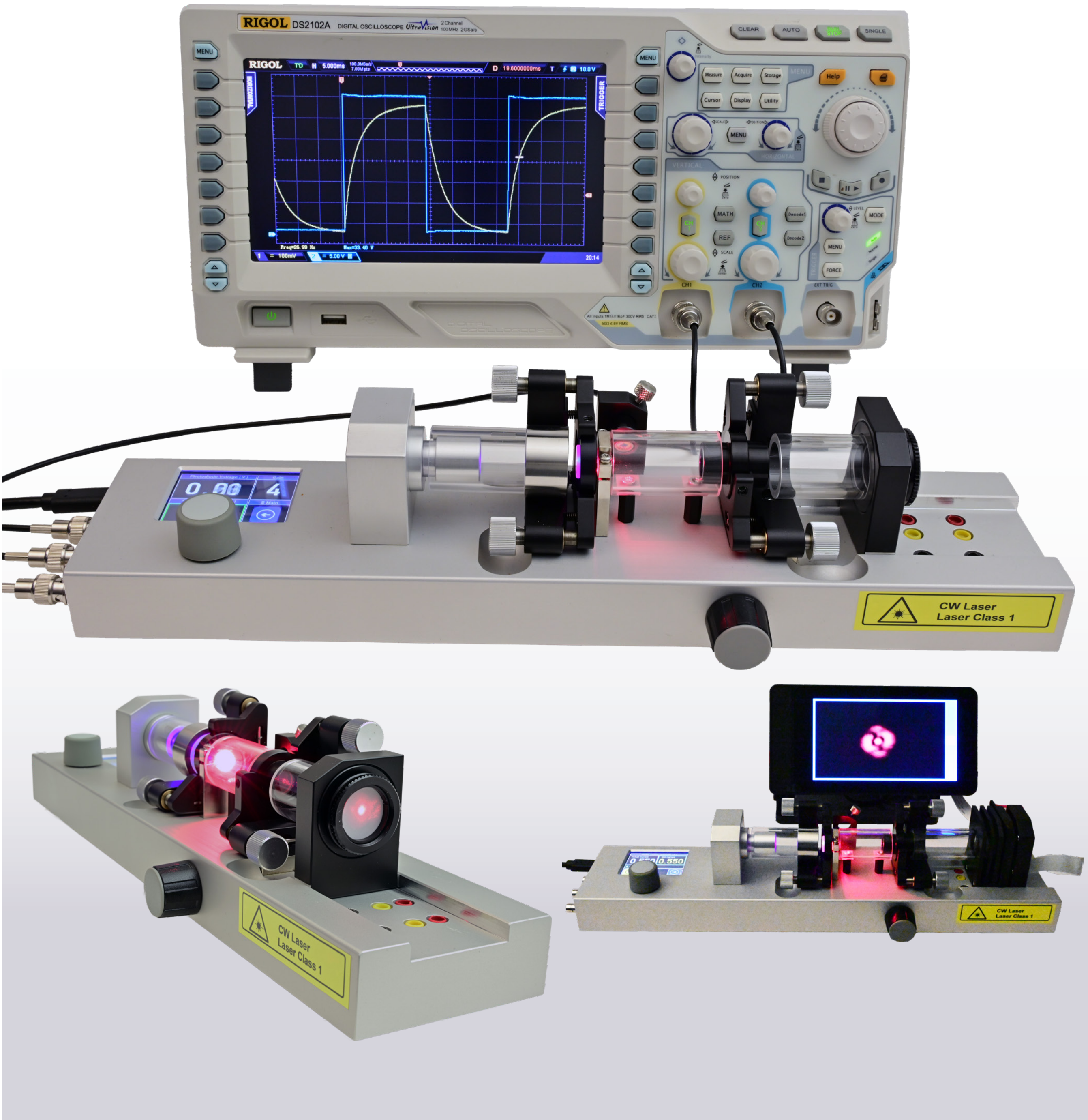
Ingenieurbüro
Dr. Walter Luhs

UM-16 Manual for the Ruby Laser RL4000



Inhalt

Table of Contents

1 Introduction

1.1 *Theory part – compendium of important basics*

To start with, a bit of history

Einstein's 1917 work on the absorption and emission of light laid the theoretical foundation for the later development of MASER and LASER, as the possibility of stimulated emission was described in addition to spontaneous emission. This is how the ammonia maser oscillator (Townes, Gordon, Zeiger) was created in 1954. The theory for optical frequencies that they developed in 1958 showed the possibility of producing coherent light by means of stimulated emission in an optical resonator. Theodore Maiman presented the first-ever laser oscillator in 1960 with a flashlamp-pumped ruby crystal. The gas laser (He-Ne laser) developed by Javan and Bennet followed in the same year. Basov built the first semiconductor injection laser (diode laser) back in 1962.

Three requirements for laser oscillation

To generate laser radiation, several things are needed:

1. An active material in which light amplification through stimulated emission is possible. To do this, a population inversion must be able to be generated there. This requires a third, metastable electronic level with a long lifespan, which can be filled effectively - i.e. very quickly or at a high rate - when the active material is excited. Therefore only certain materials are suitable.

2. A pumping process with which the active medium is stimulated. This can be done optically (solid-state laser, dye laser), electrically (injection laser) or, for example, through a chemical process.

3. A laser resonator that feeds the light emitted in a certain direction back into the active and excited amplifier medium so that it passes through it again and again and is further amplified by stimulated emission. As with acoustic feedback between the speaker and microphone in an amplifier, the system then begins to oscillate with its natural frequencies. The laser resonator consists of two dielectric mirrors with very high reflectance (99.9% and 98%) for the frequency of the laser light.

1.1.1 The ruby laser

Suitable active materials for solid-state lasers are, for example, chromium (ruby laser) or rare earths such as neodymium, praseodymium (e.g. Nd:YAG or Nd:Glass laser). These atoms or ions are incorporated into transparent crystal lattices in such a low concentration (approx. 0.05% by weight) that they are present there almost isolated and an interaction between them is only possible through light. Ruby is a chromium-doped sapphire crystal Cr^{3+}:Al_2O_3 . The energy level scheme of chromium in the sapphire crystal is shown in Fig. 1 in simplified form. In addition to the two broad absorption bands E2 at 405 nm and at 530 nm, both of which are suitable for pumping, there is a metastable level E3 - double on closer inspection - with a long lifetime, depending on the strength of the doping, between 3 and 3.5 ms amounts. A very rapid process, much faster than the electron lifetime of approximately 10 ns in the E2 pump levels, ensures that they are immediately emptied into the metastable level E3. The population inversion between E3 and the ground state E1 is thus established as a prerequisite for the laser transition E3 → E1 with a wavelength of 694 nm. A population inversion $N_3 > N_1$ is achieved when more than half of the chromium ions are in the metastable state, i.e. when $N_3 > \frac{N}{2}$ where $N = N_1 + N_3$ is.

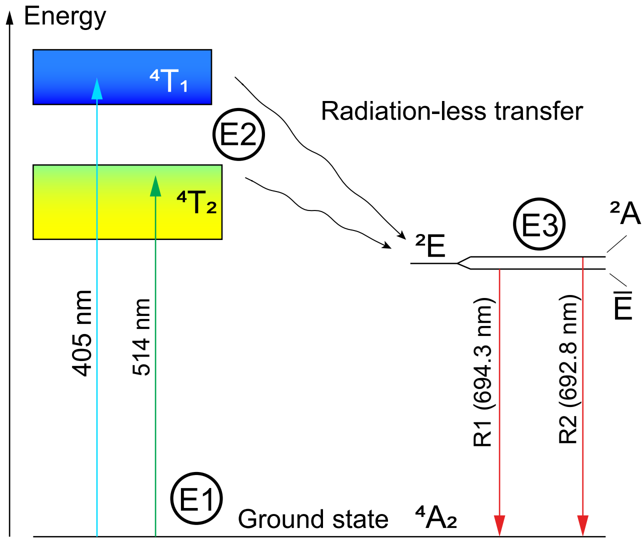


Fig. 1: Three-level scheme of the ruby laser

Since the ground state and lower laser level of the ruby laser are identical, enormous pumping must be carried out to generate the population inversion. For this reason, until a few years ago it was believed that the ruby laser could only be operated with a pulsed pump source (flash lamp). W. Luhs and B. Wellegehausen [1,2] were able to show for the first time in 2019 that cw operation can be achieved with the ruby laser even at room temperature. This is thanks to the new light sources available today in the form of diode lasers, since, in contrast to flash lamps, their entire light energy can now be used for pumping when it is irradiated resonantly into an absorption band of the ruby.

With the four-level laser, population inversion is easier to achieve because the fourth level, i.e. the lower laser level, is always quickly emptied.

The ruby crystal is a uniaxial crystal and is cut so that the resulting laser radiation is linearly polarized.

1.1.2 Quantum transitions,

From Bohr to Einstein – absorption, spontaneous and stimulated emission – Einstein coefficients

Electrons have quantized energies, i.e. only discrete permitted energy states, which are referred to as energy levels. In the classic Bohr atomic model, these energy states correspond to circular orbits with different radii. Orbits with a larger radius represent - in accordance with the equation of radial force and Coulomb force - a higher energy state. The electronic transition between two orbits, for example between the ground state n and an excited state m , happens suddenly. This requires a photon with the difference energy $h\nu = E_m - E_n$ be absorbed. The photon disappears and the electron goes into the excited state m above. After its lifetime of about 10 ns (10^{-8} s) in the excited state, the electron returns to the ground state and emits a photon with exactly this energy difference. This is called spontaneous emission of a photon. The spontaneous transition probability A_{mn} (transitions per unit of time) is the reciprocal of the lifetime.

If there are many atoms with electrons in the excited state, one can stimulate the excited electrons in the active medium to immediate transition to the ground state by irradiating photons of the same frequency. This is called stimulated emission. Its can be triggered by a spontaneously emitted photon. The stimulated emission is proportional to the radiation density $u(\nu)$ of the irradiated field causing them. The total transition probability to the ground state is then:

$$P_{mn} = A_{mn} + u(\nu) B_{mn}$$

The phase of the stimulated radiation is equal to the phase of the field stimulating it, so this radiation is coherent.
The probability of absorption P_{nm} of the external field is proportional to a material-typical coefficient B_{nm} and to the radiation field $u(\nu)$. The coefficients A_{mn}, $B_{mn,}$ B_{nm} are called Einstein coefficients.

1.1.3 Population numbers, spontaneous and stimulated emission

In thermal equilibrium, the Boltzmann relation applies to a system with the energy levels E_1 (ground state) and E_2 (excited state) with the population numbers N_1 and N_2

$$N_2 = N_1 \cdot e^{-(E_2 - E_1)/kT} = N_1 \cdot e^{-h\nu/kT}.$$

The occupation numbers mean the electron density in the respective states.
Since the absorption, which is proportional to N_1, and (spontaneous plus stimulated) emission, which are proportional to N_2, are in balance in thermal equilibrium

$$B_{12} N_1 u(\nu) = A_{21} N_2 + B_{21} u(\nu).$$

If you solve the equation for the radiation density $u(\nu)$ and sets N_2 according to the Boltzmann relation, on one hand this results from the coefficient comparison with Planck's radiation formula, which was first carried out by Einstein $B_{21} = B_{12} = B$ and on the other hand the relationship

$$\frac{A_{21}}{B} = \frac{8\pi h \nu^2}{c^2}.$$

This then results in the ratio of spontaneous emission (incoherent radiation) and stimulated emission (coherent radiation) to

$$\frac{A_{21}}{B \cdot u(\nu)} = e^{h\nu/kT} - 1.$$

For optical frequencies at room temperature, the spontaneous emission is about 10^{38} times more intense. At longer wavelengths the ratio for stimulated emission becomes much more favorable and becomes approximately unity at 70 µm. That's why it's easy to understand that MASER (Microwave Amplification...) was developed first and LASER later.
In order to operate a laser, the population in the upper laser level must be larger than in the lower level. This requires a non-equilibrium state called population inversion, which can only be achieved with an additional metastable level as the upper laser level. A population inversion can be generated with less pumping effort with the four-level laser, since there is another level as the lower laser level that is always quickly emptied.

1.1.4 Optical resonator and axial modes

The active medium in the non-equilibrium state acts as an optical amplifier, which uses the spontaneously emitted photons to stimulate further excited atoms to emit coherently - albeit in random directions. The amplifier alone is not enough to generate laser emission. A feedback mechanism with a filter is needed to obtain an oscillator for the desired frequency. The necessary feedback is realized by the optical resonator - also called cavity. The resonator consists of two mirrors that repeatedly send the stimulated radiation back and forth through the active medium in a selected direction, further amplifying it. A certain proportion (approx. 2%) is emitted as a usable laser beam at the output mirror.
Between the two mirrors at a fixed distance L to each other - also called Fabry-Perot interferometer - only standing waves can exist whose nodes are on the mirrors. The mirror distance L must therefore correspond to half a wavelength or an integer multiple of half a wavelength: $L = n\,\lambda/2$. This then applies to the possible resonance (or natural) frequencies, which are called axial or longitudinal resonator modes

$$\nu_n = \frac{c}{n^*} \cdot \frac{n}{2L}$$

with n^* as the refractive index of the medium between the mirrors.
Since the wavelength of light is very small compared to the resonator length L, n is a very large number. Of interest here is the **Frequency spacing** neighboring axial modes

$$\Delta\nu = \nu_{n+1} - \nu_n = \frac{c}{2Ln^*}.$$

For our ruby laser ($L \approx 5$cm, $n^* \approx 1$) results in an axial mode spacing of 3 GHz. This can be measured, for example, with a fast photodiode and frequency analyzer or with a Fabry-Perot etalon.

theory

1.1.5 Line widths, gain profile and modes, how monochromatic is a laser?

Despite quantum transitions, the spectral lines are not sharp. The so-called homogeneous or natural line width (half-width of the line) follows from the uncertainty principle

$$\Delta E \cdot \Delta t = \frac{\Delta E}{\Delta \nu} \approx h,$$

where $\Delta\nu$ the frequency uncertainty means.
From the lifetime of excited states follows

$$\frac{\Delta\nu}{\nu} \approx 10^{-8}.$$

The ruby laser's wavelength of 694 nm corresponds to a light frequency of 432.3 THz. This results in a frequency uncertainty of 4.3 MHz.
Other processes such as the residence time of the photons in the resonator (resonator decay time), number of modes in the gain profile of the active medium and output power influence the actual spectral laser line width.

The amplification profile of solid-state lasers is in the range of 300 to 500 GHz, which corresponds to a half-width of the line of 0.5 to 1 nm. Therefore, a number of natural frequencies of the resonator (axial modes) can be amplified with their frequency separation of 3 GHz from the active medium. In addition, there are the non-axial modes, which will be discussed in more detail later, and which are located at a short distance from the axial modes in terms of high energy. This means that the laser beam contains a number of different frequencies. If exactly only one axial mode is amplified, the radiation is monochromatic. To do this, the frequency spacing of the axial modes must be greater than the width of the gain profile.

1.1.6 Resonator quality and its resolution power

The quality factor Q of a resonator depends on its losses, i.e. on how much energy per oscillation period of the resonator frequency ν_R leaves the resonator. The main loss comes from transmission T of the decoupling mirror. From the quality Q

$$Q = \frac{2\pi\nu_R L}{cT} = \frac{\nu_R}{\Delta\nu_R}$$

the resolving power of the resonator $\Delta\nu_R$ can be calculated. For our ruby laser with 2% mirror transmission, wavelength 694 nm and a resonator length of approx. 0.05m this results $\Delta\nu_R$ =19MHz. This means that the axial mode spacing of 3 GHz can be observed very well.

1.1.7 Resonators, stability, Gaussian modes

There are different types of resonators with correspondingly different stability ranges [3]. The following are mentioned here:

1. Resonator with two plane-parallel mirrors (very difficult to adjust),
2. Confocal resonator with two concave mirrors with identical mirror radii R and the focal points accordingly $R/2$ and a stable resonator length of $L < R$.
3. Symmetrical concentric resonator as a special case of the confocal resonator, in which both mirror surfaces lie on a spherical surface and a diffraction-limited point is created in the middle (stable for $L \leq 2R$).
4. Unsymmetrical concentric resonator consisting of a concave and a plane mirror, stable for L . Here half of the concentric resonator is replaced by its mirror image, which is created on the flat mirror.

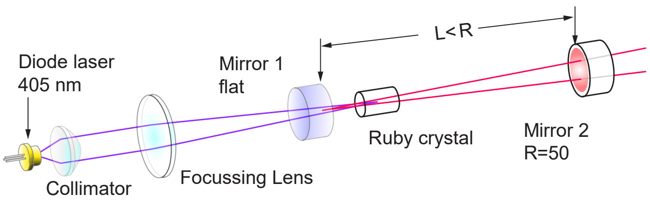


Fig. 2: Asymmetrical concentric resonator

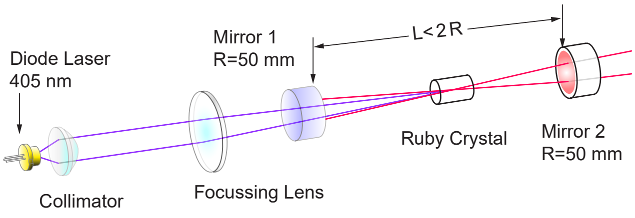


Fig. 3: Symmetrical concentric resonator

W. Luhs and B. Wellegehausen were the first to demonstrate room temperature cw operation for the ruby laser with both a concentric and an asymmetrical concentric (semi-concentric) resonator [1, 2].

The cw-Ruby Experimental (Class 1) laser uses the semi-concentric resonator. This can be seen from the outside because the ruby crystal is arranged right next to the flat coupling mirror. Both mirrors are dielectric mirrors, each consisting of several dielectric layers applied to the mirror glass. The layer thicknesses and their refractive indices are calculated in such a way that the desired spectral transmission and reflection properties are created through multiple interference effects. For example, the coupling mirror is transparent for the 405 nm pump radiation of the diode laser, but is for the red ruby emission $R > 99.9\%$ highly reflective. The output mirror reflects both wavelengths $R > 98\%$. Behind the output mirror there is an additional filter that absorbs any residual pump radiation.

The laser beam geometry is determined by the curvature and distance of the mirrors. The axial modes have a Gaussian beam cross section

$$I(r) = I_0 \exp\left(-\frac{2r}{w^2}\right),$$

where r the distance from the axis and w is the beam cross section. The minimum beam cross section, the beam waist, is located in the middle of the concentric resonator and here, in the semi-concentric resonator, at the coupling mirror (Fig. 2).

In the experiment, the Gaussian form of the axial mode (also TEM_{00} called) can be checked, recorded and adjusted using special software using a camera and Raspberry PI.

1.1.8 TEM modes (non-axial or transverse electro-magnetic modes)

Since the laser beam generated in the resonator also has a lateral extent, non-axial modes appear, which are referred to as TEM modes, particularly with increasing power and when the resonator is not adjusted optimally. The reason is that the phase of the light wave is no longer constant over the entire mirror surface. The phase changes in different areas of the mirror surfaces so that there are several bundles of rays in the laser beam. The resonance frequencies of these modes apply to round mirrors (radius r_S)

$$f_{n,m,l} = c\sqrt{\left(\frac{n}{2L}\right)^2 + \left(\frac{X_{m,l}}{2\pi r_S}\right)^2} .$$

$X_{m,l}$ is that lth zero point of the Bessel function of mth $order$. The TEM modes are therefore high-energy with a small frequency spacing, which depends on m and l and increases $m+l$ grows, in each case next to the axial modes. Since their

atomic numbers n are very large, these are not included in the denotation of TEM modes.
Depending on the geometry of the laser beam (round, rectangular, cylindrical, elliptical), which results, among other things, from the shape of the mirrors, the excitation spot and other elements, such as Brewster windows in gas lasers, a distinction is made between different forms of TEM modes. In the experiment you can influence the beam geometry and thus the number of beam bundles by adjusting the resonator and, with a little sensitivity, a wide variety of TEM mode images realize. This can be observed particularly well near the laser threshold and with a less stable resonator, i.e. with a slightly longer resonator.

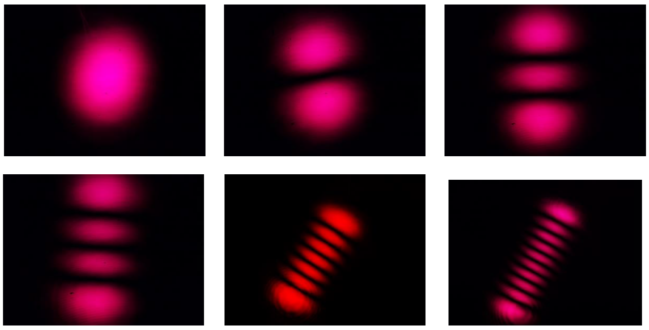


Fig. 4: Hermite-Gauss modes (rectangular)

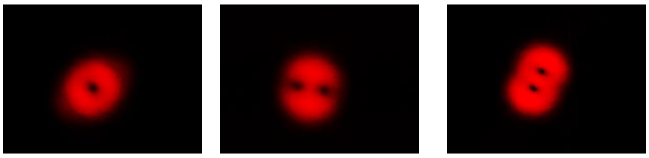


Fig. 5: Laguerre-Gauss modes (cylindrical)

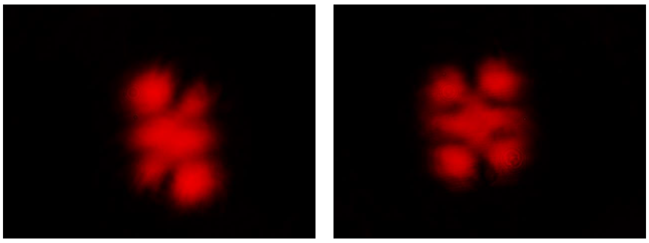


Fig. 6: Ince-Gauss modes (elliptical)

1.1.9 Spiking, coherence and interference, coherence length

If the ruby laser is pumped in a pulsed manner, one observes that the laser process only begins with a delay of approx. 0.5 ms after the start of the pump pulse. When resolved in time, you can see that the laser radiation initially consists of a series of so-called "spikes" (flashes of light).

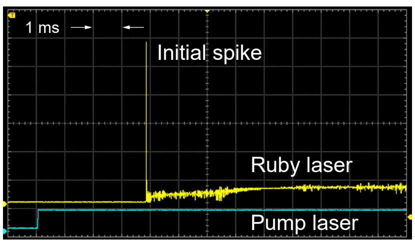


Fig. 7: Dynamic behavior of the ruby laser

Interference requires coherent wave trains that overlap constructively or destructively. One speaks of spatial coherence when the radiation emanates from the same point. In addition, the quantum emission acts are time-limited. The individual (photon-like) wave trains therefore have a limited length and are subsequently only capable of interference within a coherence time. With classic light sources, interference can be observed on thin layers of oil on water, but due to their thickness it can no longer be observed on a plane-parallel window pane. Coherence length and coherence time are related as follows:

$$\Delta l = c\Delta t = c / \Delta \nu$$

Hence the coherence length of the pulsed pumped ruby laser depends on the spike duration. The spikes are more or less irregular and sometimes come from different parts of the ruby crystal. Continuous wave (cw) lasers have significantly longer coherence lengths because of the stimulated, in-phase emission.

1.2 Lifetime measurement of the metastable level E3

1.2.1 Exponential decay and decay of ruby fluorescence

About the lifetime τ of the metastable level E_3. To measure the time behavior of the fluorescence must be examined without laser operation. The ruby fluorescence is excited using square-wave pulses. Each time the excitation is switched off (after the end of the respective square-wave pulse), the metastable level E_3 empties with the time constant $1/\tau$. The balance equation after the intensity is switched off (i.e. after the end of the pump pulse) is:

$$\frac{dN_3}{dt} = -\frac{N_3}{\tau}.$$

Separation of variables: $\dfrac{dN_3(t)}{N_3(t)} = -\dfrac{1}{\tau}$

Solution: $N_3(t) = N_{30} \exp\left(-\dfrac{t}{\tau}\right)$

Half-life: $\displaystyle\int_{N_3}^{\frac{1}{2}N_3} \frac{dN_3(t)}{N_3(t)} = \int_0^{t_{HWZ}} \left(-\frac{1}{\tau}\right) dt$

$$\ln(N_3/2) - \ln(N_3) = -\frac{1}{\tau} t_{HWZ} \quad \text{or.} \quad 0{,}69\,\tau = t_{HWZ}$$

The point in time at which the population density or the fluorescence intensity has fallen to half is called the half-life. From this, the time constant of the exponential function and thus the lifetime of the metastable laser level E_3 can be calculated immediately.
Likewise, the onset of the E_3 -population (according to the onset edge of the square wave pulse) can be measured. This process is analogous to charging a capacitor. The solution is given through the function,

$$N_3(t) = N_{30}(1 - \exp\left(-\frac{t}{\tau}\right)$$

where N_{30} is the maximum population density that can be generated by the pump intensity and pulse length in state E_3. Since the material is not lasing here, but rather its fluorescence is examined at low excitation intensity, $N_3 \ll N_1$ applies, so that the emptying of N_1 does not have to be taken into account.
The same time constants can therefore be observed during the onset and decay of the fluorescence.

1.3 Balance equations – at least three levels for population inversion

In a two-level system, a maximum of almost equal population densities can be achieved. The balance equation contains absorption, stimulated emission (proportional to the Einstein coefficient B) and the pump radiation field (intensity) as well as spontaneous emission.

$$\frac{dN_1}{dt} = -\frac{dN_2}{dt} = -B(N_2 - N_1)I + A_{21}N_2 ,$$

A clear justification may suffice: As soon as half of all electrons are in the upper level, the probabilities for absorption (1 → 2) and stimulated emission (2 → 1), which depend on the population density of the respective state, are the same. The population of the excited state is additionally reduced by the spontaneous emission, so that even the case of equal population densities cannot be achieved.
At least a three-level system is necessary for a population inversion . A rapid, radiation-free depletion of the level E_2 excited by pump radiation into a metastable (long-lived) level E_3 occurs in the range of picoseconds. Then the competitive process takes place, emptying of E_2 according to E_1 no longer plays a role due to stimulated and spontaneous emission. The population density in state E_3 then increases compared to the state E_1, which becomes empty through pumping . In this way a population inversion $N_3 > N_1$ can be achieved. The laser transition then takes place between the levels E_3 and E_1 (3 → 1).
Since the state E_2 immediately is emptied to state E_3, so that

$$N \approx N_1 + N_3$$

$$\frac{dN_3}{dt} = -\frac{dN_1}{dt} = BIN_1 - \frac{N_3}{\tau} .$$

In contrast to the two-level system, the stimulated emission from E_2 to E_1 due to the pumping process, is now missing from the balance equation according to E_1 . A rewrite with $\Delta N = N_1 - N_3$ and with N as well as the search for a minimum of ΔN ultimately delivers in contrast to the two-level system

$$\Delta N = N \frac{1 - I/I_S}{1 + I/I_S} ,$$

so that now above a saturation intensity I_S a population inversion can be achieved.

literature
[1] W. Luhs and B. Wellegehausen, “Diode pumped cw ruby laser,” OSA Continuum 2, 184-191 (2019)
[2] W. Luhs et al. , (2021) J. Phys. Commun. 5, 085 012
[3] J. Eichler, HJ Eichler, Laser designs, beam guidance, applications, Springer-Verlag, 7th edition 2020

2 Description of components

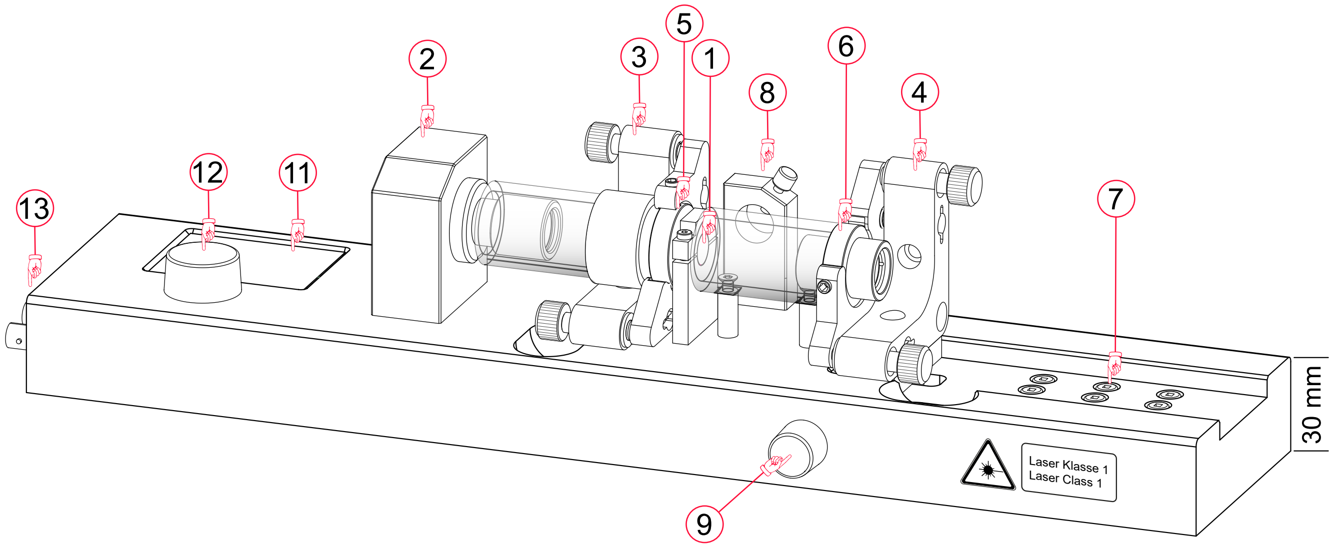


Fig. 8: Ruby Experimental Laser

The cw Ruby experimental laser is a class 1 laser. It is therefore a completely safe laser and thus can be used in internships and high school education without any further protective measures, i.e. even without laser safety goggles, for experimenting with and within the laser.

A safety concept ensures that no radiation can escape from the laser or when experimenting with the laser. If an experimental element is inserted incorrectly (7), the laser switches off immediately. The optical axis runs in the middle of acrylic glass tubes (A), so that everything can be easily observed and no objects of any kind can be brought into the beam path.

The device is compact and just under 40 cm long. The power is supplied via USB-C with a power delivery plug-in power supply or via a suitable power bank. The laser has complete adjustable resonator mirrors (3, 4) and a length-adjustable resonator. The decoupling mirror can be moved in the direction of the optical axis by approximately 6 mm using a rotary knob (9) on the front of the base block. The magnitude of the displacement of the output mirror or the resonator length is determined using a caliper (see Fig. 13). The selected position is fixed with the locking screw (F).

The ruby crystal (1) is located close behind the flat coupling mirror (5). The decoupling mirror (5) has a radius of curvature of 50 mm and is located in the adjustment holder (4). Behind the output mirror (4) there are three plug-in panels (7) into which various experiment modules can be plugged. Each of these modules contains an EPROM that is read by the microprocessor. Only when the right module is plugged into the right place, the laser diode can be switched on. If a module is removed during operation, the laser diode is switched off immediately.

A photodetector for measuring the fluorescence decay or a holder for an optical fiber can be inserted into the holder (8) in order to analyze the fluorescent light of the ruby crystal.

After entering the security code, operational readiness is established via the touch screen (11) of the display. The menu is self-explanatory, but is described in detail on page 12. The "Diode Laser" button is used to select cw laser operation. Adjustable parameters such as diode laser current, modulation frequency, photodiode parameters are set with the real rotary knob (12).

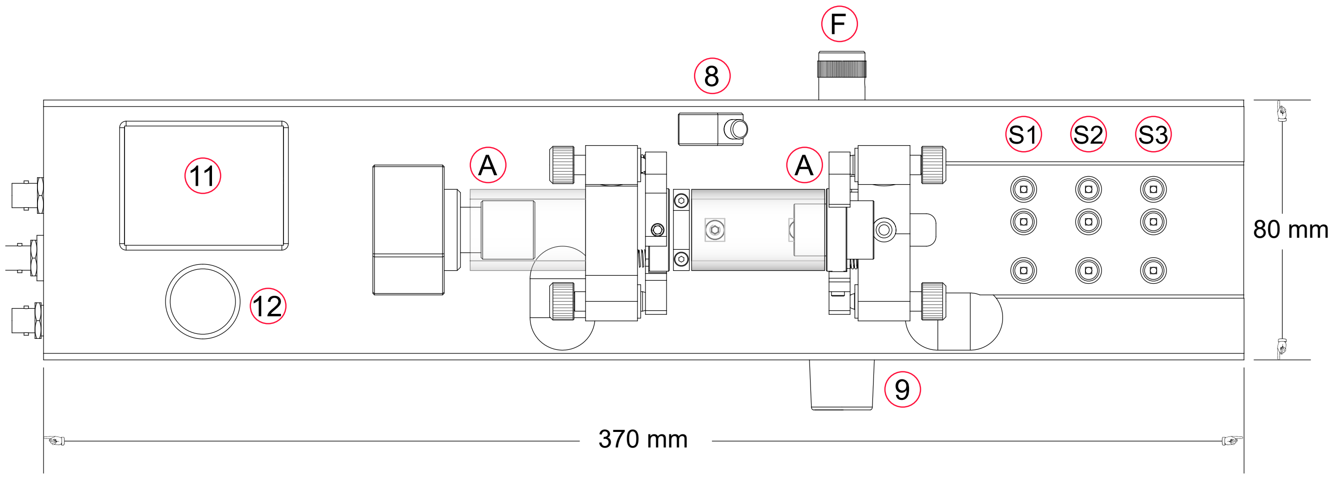


Fig. 9: Ruby experimental laser in top view

Experimental setup

2.1 The electronics

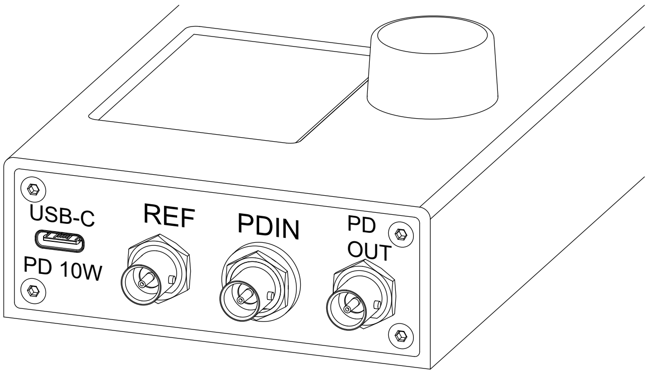


Fig. 10: The connections of the RL400

The power is supplied via the included USB-C power adapter with Power Delivery Technology. The electronics of the RL4000 require the USB-C power supply at a voltage of 9V. The digital signal from the pump laser diode is available at the "REF" BNC socket. If the laser diode is switched on, there will be a "High" signal, and if it is switched off there will be a "LOW" signal. If the laser diode is modulated, a corresponding TTL signal is available with which an oscilloscope can be triggered. The photodiodes are connected to the "PDIN" input with their mini BNC sockets. The electronics of the RL4000 convert the photocurrent into a linear voltage, which is available at the "PDOUT" output.

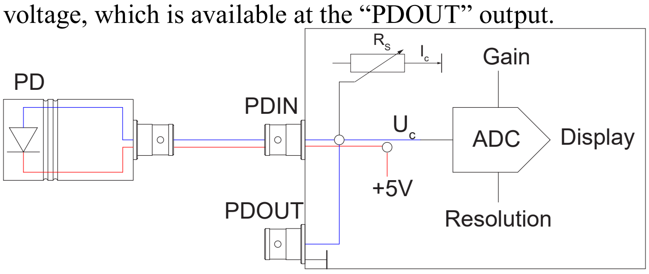
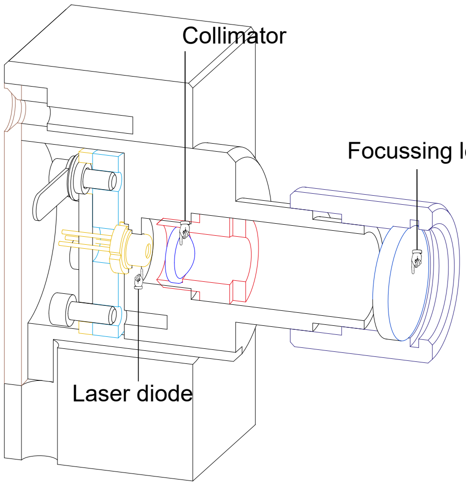


Fig. 11: Photodetector circuit

The photodiode (PD) is connected to 5V in the reverse direction. The photocurrent flows through the resistor R_S and creates a voltage drop U_C, which is available at the PDOUT socket. At the same time, the photovoltage UC is processed by an analog/digital converter (ADC). The internal microprocessor allows the shunt resistance to be adjusted as well as the gain of the ADC via the display.

2.2 The pump laser diode



The laser diode is operated with an adjustable current, the maximum of which is limited to 600 mA. The laser diode housing is a TO18 type, where the cooling flange has a diameter of only 5.6 mm. Therefore, a very precise mechanical holder is necessary to safely dissipate the resulting heat. The divergent radiation from the laser diode is set almost parallel with a collimator and then focused with a plano-convex lens with a focal length of 50 mm. The focusing lens is located in an adjustable lens so that the resulting focus point lies exactly in the ruby crystal. These settings are made at the factory and cannot be changed by the user.

2.2.1 The resonator

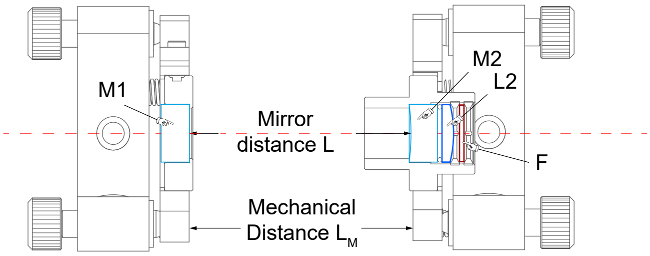


Fig. 12: Resonator structure

The plane mirror M1 has a mirror layer that has a high transmission for the pump wavelength of 405 nm (>90%) and a high reflection (>99.98%) for the ruby laser wavelength of 694 nm. The mirror M2 has a radius of curvature of 50 mm and the mirror layer is highly reflective for the pump wavelength and has a transmission of 1% for the ruby laser wavelength.

For the ruby laser beam transmitted through the mirror, the mirror M2 acts as a diverging lens with a focal length of approx. -50 mm and simulates a greater laser divergence. Therefore, directly behind the mirror M2 there is a plano-convex lens (L2) with a focal length of 50 mm. To completely suppress unwanted residual pump radiation, a red filter (F) is also used, which only allows radiation above 635 nm to pass through.

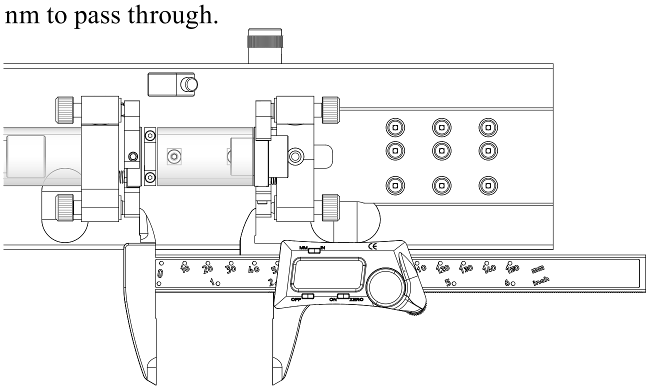


Fig. 13: Measuring the mechanical distance L_M

To precisely determine the mirror distance and thus the resonator length, a caliper is used to determine the mechanical distance L_m between the mirror holders.

The desired mirror distance L then results in L_M-1 mm. For example, L_M determined to be 51.2 mm, the mirror distance L=50.2 mm.

For calculating the optical resonator length L_{opt} it must be taken into account that the ruby crystal has a thickness of 5 mm and a refractive index of 1.7.

The optical resonator length is then calculated as:

$$L_{opt} = L_{Rubin} \cdot n_{Rubin} + (L - L_{Rubin}) \cdot n_L$$

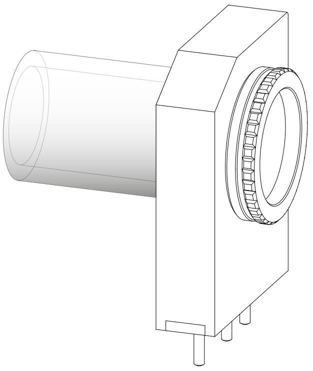
With the stability criterion for the ruby laser

$$L_c \le L_{opt} = 5 \cdot 1.7 + 45 = 53.5\,\text{mm}$$

Experimental setup

This results in a maximum resonator length for stable laser operation of 53.5 mm. The adjustment range of the RL4000 resonator is 49 -54 mm.

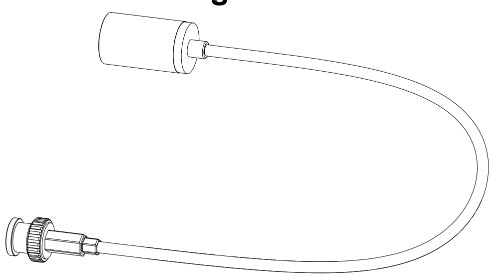
2.3 The visualization screen



This module contains a transparent disk on which the ruby laser beam or just its fluorescence is imaged. The module belongs in the first slot and is recognized as a "shield".

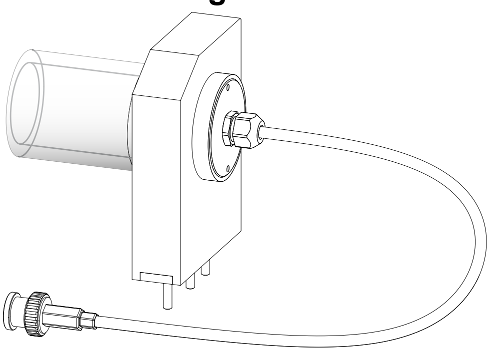
2.4 Photodetectors

2.4.1 For measuring fluorescence



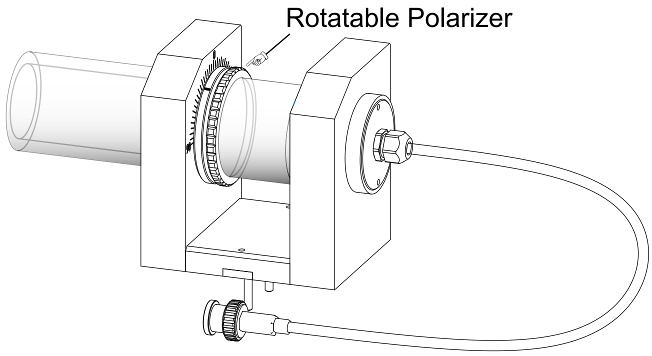
This photodetector is intended for measuring the fluorescence of the pumped ruby crystal. The detector is inserted into the side detector holder (8) and fixed with the adjusting screw, see Fig. 8. The BNC cable is connected to the "PDIN" BNC socket (see Fig. 10).

2.4.2 For measuring laser emission



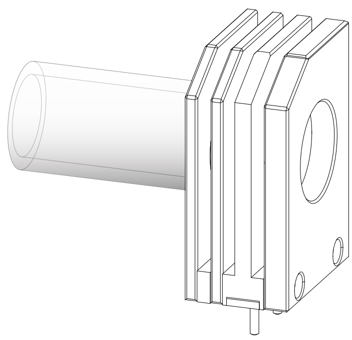
This photodetector module is inserted into slot 1 and is intended to detect the ruby laser emission. The BNC cable is connected to the "PDIN" BNC socket (see Fig. 10).

2.4.3 The polarization module



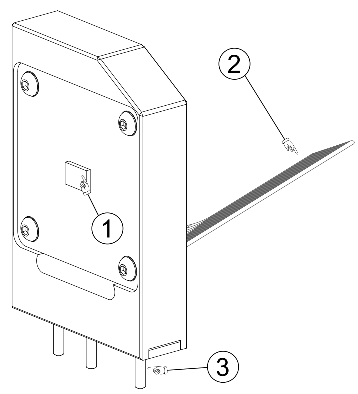
This module is used in slot 2. In the front mounting plate with a scale (-90 to +90°) there is a rotatable polarizer with a graduation mark. The BNC cable is connected to the "PDIN" BNC socket (see Fig. 10).

2.5 The filter box



The filter box is used to hold 50x50 mm filters and slide frames with optical structures.

2.6 The camera module

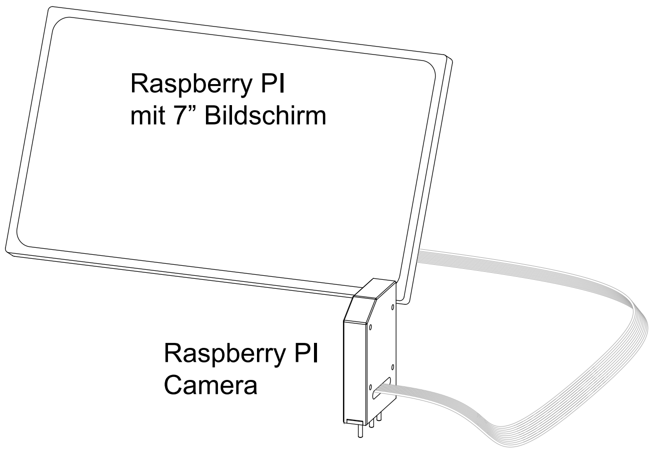


This module uses the Raspberry Pi 12 MP camera and is designed for industrial and consumer applications, among others, allowing the highest level of visual fidelity and/or the integration of special optics. In this experiment only the 12 MP chip without IR cut filter is used.

Technical data

- Compatible with all Raspberry Pi models
- Sony IMX477R sensor (1)
- 12.3 megapixel resolution
- 7.9 mm sensor diagonal
- 1.55 µm × 1.55 µm pixel size
- 750 mm FPC cable (2) for connection to a Raspberry PI

The camera module is operated in slot 3 and at the same time requires the filter module in slot 2. The module is permanently connected to the Raspberry Pi with screen using a ribbon cable.



To start the Raspberry Pi, the USB-C power supply is connected to the connection cable. To operate the camera, the software PiCam2023.py is located in the /HOME/LE1600/LUHS directory. To make things easier, there is a button in the start menu that starts the software directly.

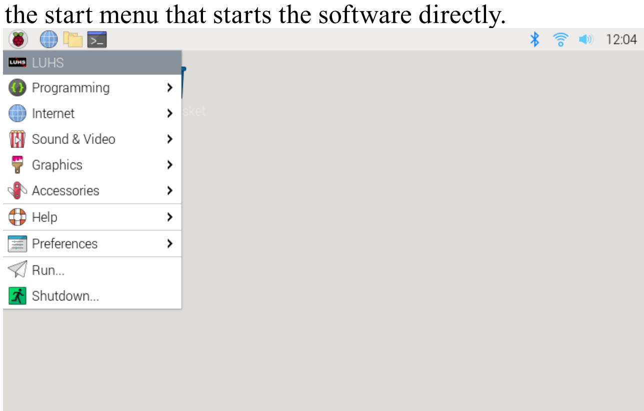


Fig. 14: Start screen, select menu entry “LUHS”.

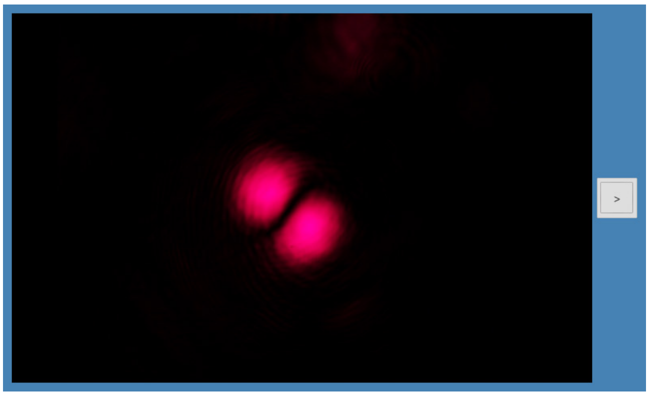
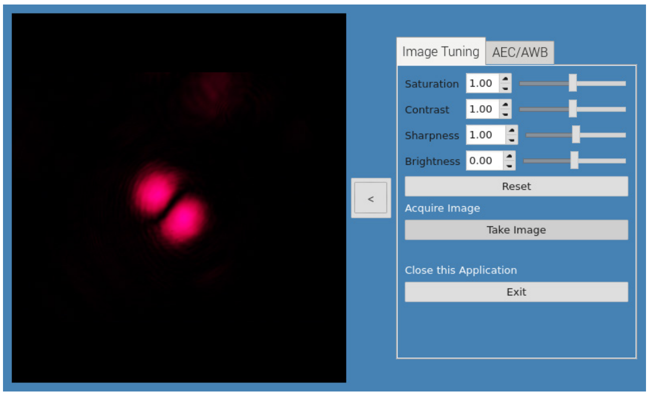
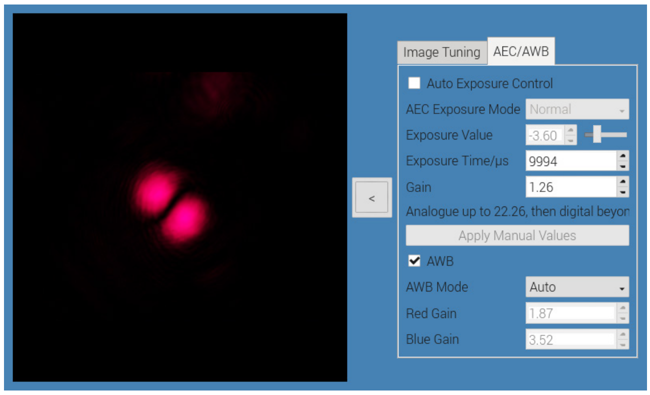


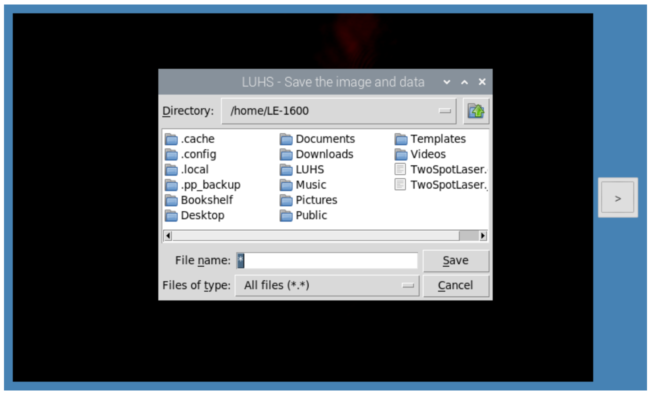
Fig. 15: The camera image is displayed. After clicking on the button with an arrow, another menu appears to the right of the image with parameters for image adjustment.



The Tabulator Element has two cards, “Image Tuning” and AEC/AWB. AEC stands for “Automatic Exposure Control” and AWB stands for “Automatic White Balance”. Both can be switched off and adjusted manually.



Once you have found sensible settings, you can save the camera image.
To do this, click on the “Take Image” button and the following file dialog is displayed:



You can also select a connected USB stick. Just enter a file name (without an extension) and press “Save”.
A JPG graphic of the camera image is saved in the highest resolution (4056 x 3040 = 12.33MB) and a numerical file that contains the intensity values of each individual pixel. This file is a CSV (Comma Separated Values) file and can be opened with various evaluation programs. This file has a size of 70.6 Mbytes and it takes a few 10 seconds to complete the saving process.

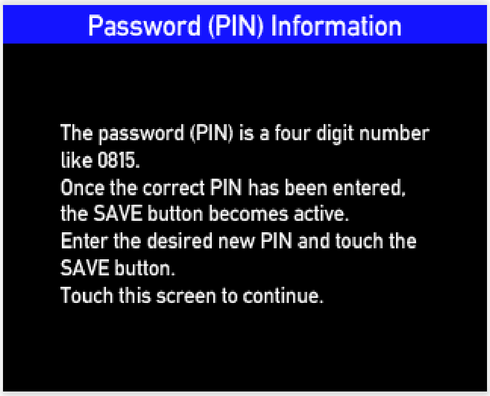
2.7 The control

The RL4000 Laser has two fast processors, one constantly monitoring the plug-in modules and the other reacting to user input.

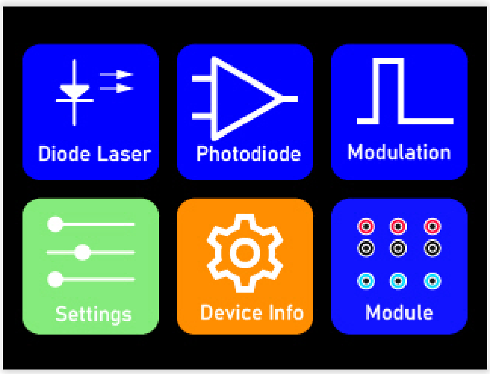
2.7.1 The display

After connecting the USBC power supply, the start screen appears and after a few seconds asks the user to touch the screen to continue.

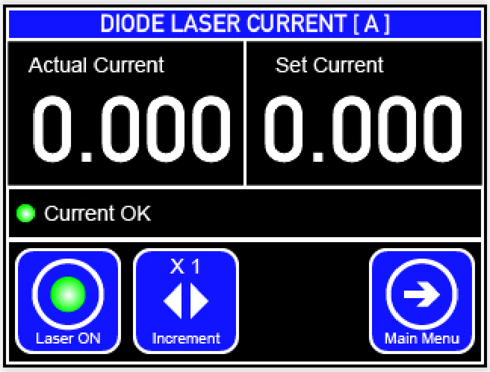
The screen for entering the 4-digit PIN codes then appears. Touching the “HOW TO?” button leads to the help screen.



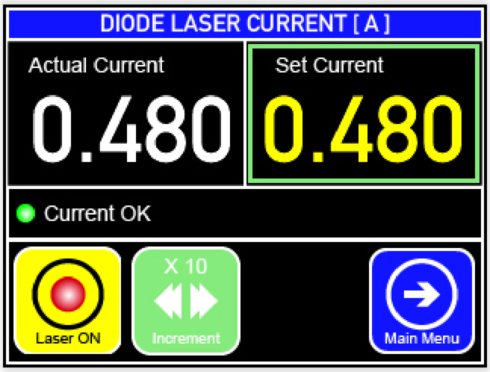
After entering the correct PIN, the main menu appears.



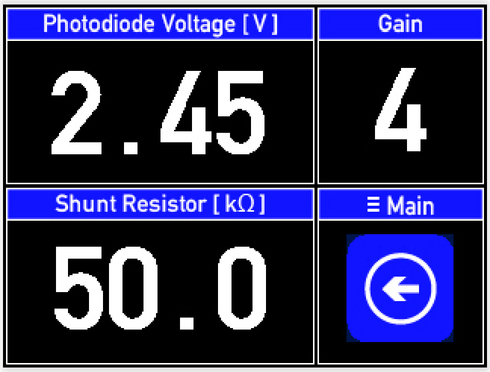
There are 6 choices offered here, which are explained below.



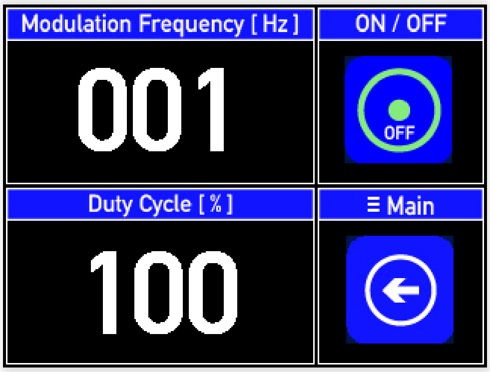
The laser diode menu shows the actual value (Actual Current) of the set current (Set Current). By touching the “Set Current” field, this is activated and the desired value is set by turning the adjustment knob. With the “Increment Button” the step size can be increased from 1mA to 10 mA. After tapping the “Laser ON” button, the digital PI controller starts and regulates the diode laser current to the set target value.



The diode laser current is set to 480 mA, the laser is switched on and the step size is set to 10.



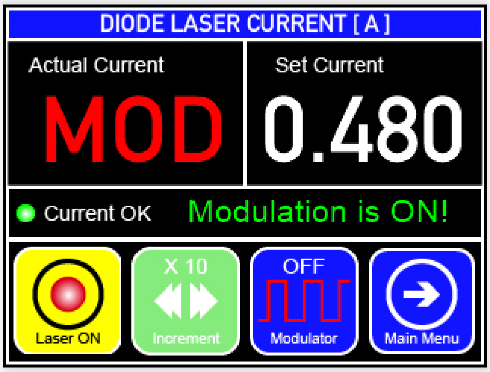
After touching the “Photodiode” button in the main menu, the setting screen for the connected photodetector appears. By repeatedly tapping the “Gain” field, the gain of the analog/digital converter is set to 1, 2, 4 or 8 and the measured value is displayed. By touching the “Shunt Resistor” field, it is activated and the shunt resistance of the photodiode is adjusted from 50 Ohm to 50 kOhm by turning the adjustment knob.



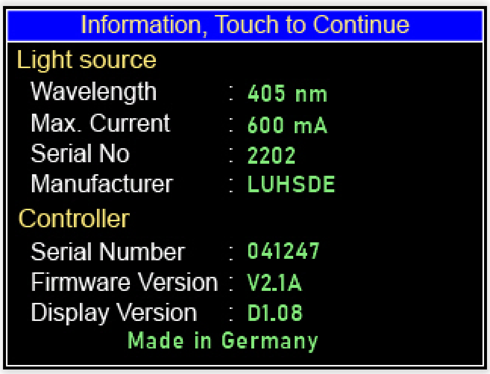
After touching the “Modulation” button in the main menu, the screen as shown above appears.

With this menu the laser diode can be periodically switched on and off and modulated. After tapping the “Modulation Frequency” field, this is activated and the modulation frequency can be set in a range of 1 - 999 Hz using the rotary knob. The “duty cycle” is the duty cycle of the on-time to the off-time. If both are the same length, the duty cycle is 100%. At a value of 50%, the on time is half the off time. The smaller the duty cycle, the more “lightning-like” the pump diode laser emission becomes. The modulation is switched on or off by touching the “ON/OFF” button.

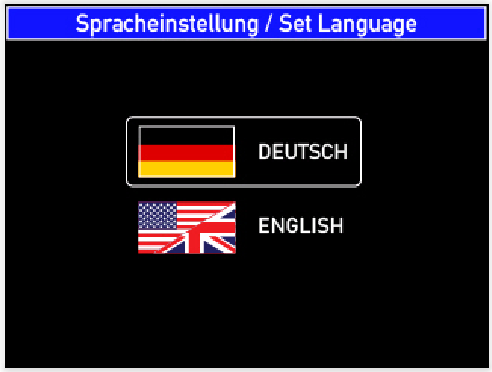
As soon as the modulation of the pump laser diode is active, the PI control is switched off and the last fixed value is retained. If you now switch to the laser menu, the following picture emerges:



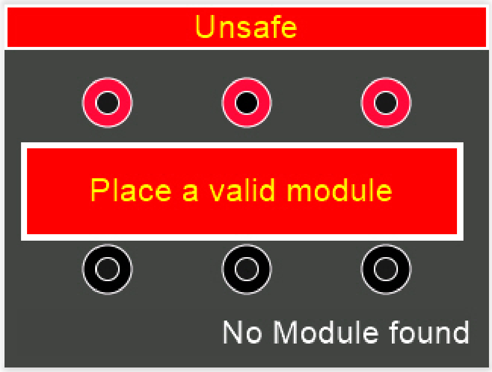
The current measurement is switched off due to the modulation. An extra button “OFF Modulator” appears with which the modulation can be switched off again.



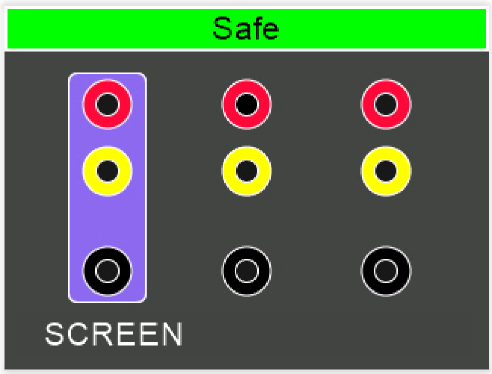
The Device Info information menu displays versions and hardware settings.



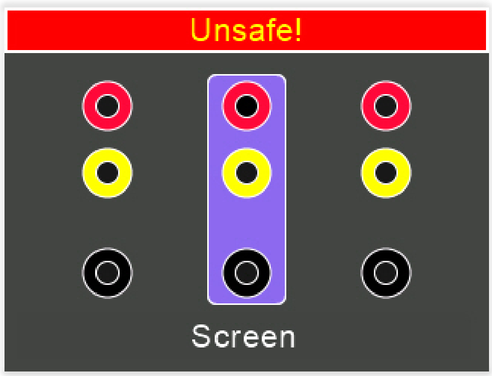
The language German or English can be selected in the “Settings” menu item.



After calling up the “Modules” menu item, corresponding information appears depending on the modules inserted. If no module or no secure arrangement of modules is inserted, no further menu items can be accessed



In this case, the screen is inserted in the correct place, which is considered safe.



However, if the screen is inserted into the wrong place, the module name “Screen” appears with the message “Unsafe”, i.e. incorrect position. The laser switches off or cannot be switched on.

2.8 The photodiodes

The properties of the photodiodes used are listed below.

parameter	symbol	Value	Unit
Rise and fall time of the photo current at: R_L=50Ω; v_R=5V; λ=850 nm and I_p=800 µA	t_r, t_f	20	ns
Capacitance at V_R = 0, f = 1MHz	C_0	72	pF
Wavelength of max. sensitivity	λ_{Smax}	850	nm
Spectral sensitivity S 78% of S_{Max}	λ	694	nm
Dimensions of radiant sensitive area	L × W	7	mm^2
Spectral sensitivity, λ = 850 nm	S(λ)	0.62	A/W

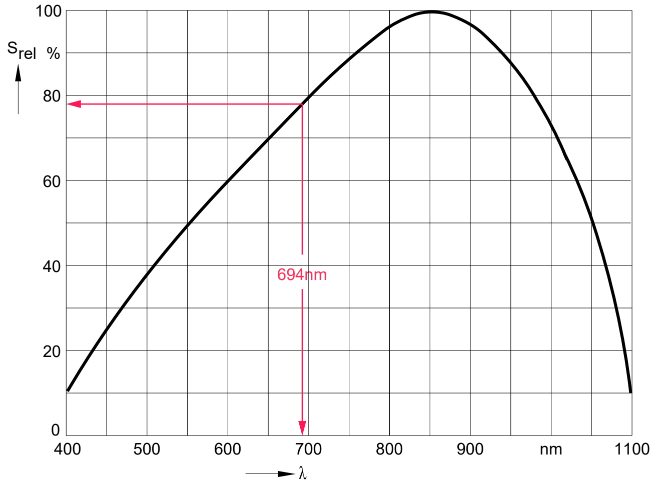


Fig. 16: Spectral sensitivity curve

For the ruby laser wavelength of 694 nm, the detectors have a spectral sensitivity of

$$S = 0.78 \cdot 0.62 = 0.48 \frac{A}{W}$$

This means that a photocurrent of 0.48 A flows for every 1 W of light output.

Assuming a voltage drop of 1 V is measured across the shunt resistor of 1000 ohms, the photocurrent is 1 mA (Ohm's law). The associated light output is therefore 2.08 mW. This means that the optical power of the ruby laser can be determined as long as the entire laser radiation falls on the relatively large detector area.

Measurements

3 Demonstrations and Measurements

3.1 Measurement of the lifetime of the excited level

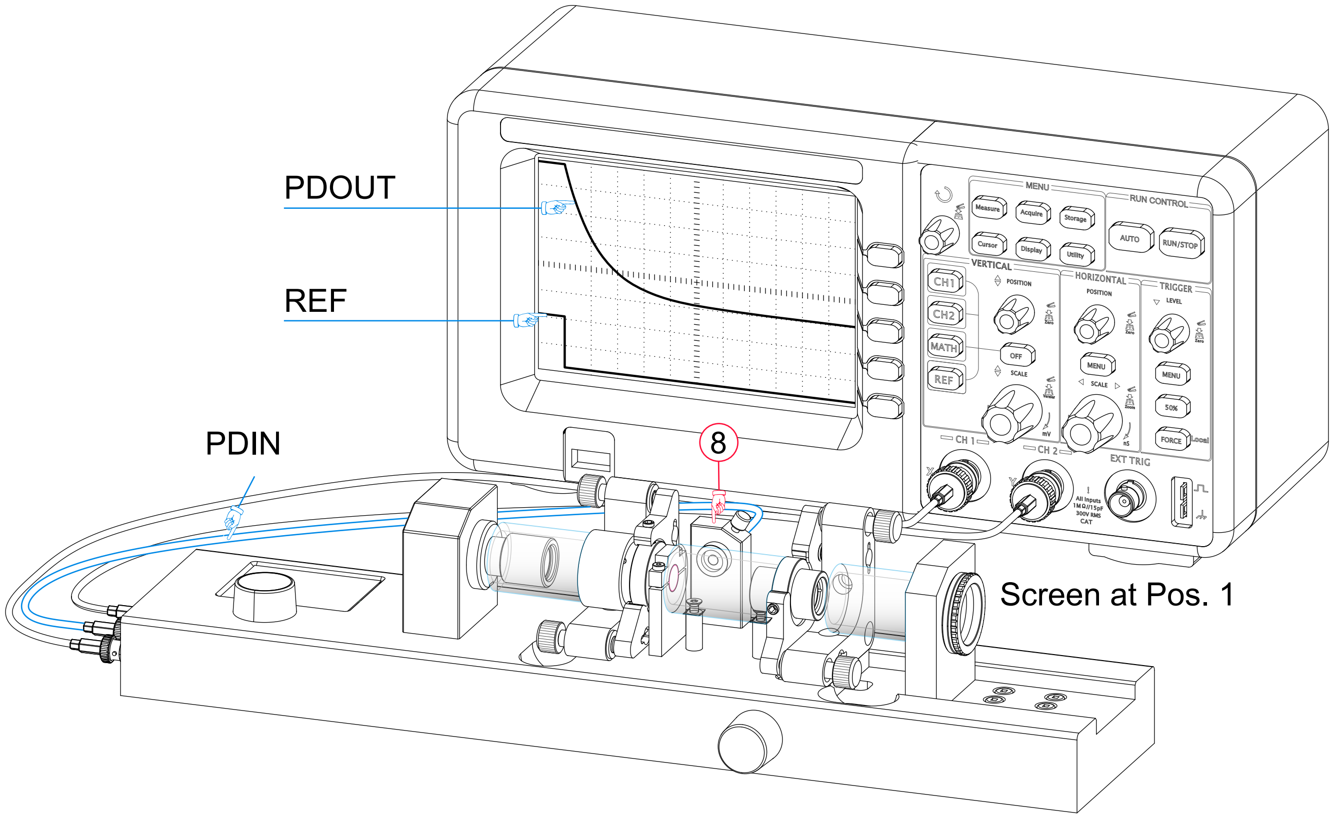


Fig. 17: Setup for measuring the lifetime of the excited level

For this experiment, the photodetector is inserted into the holder (8) and fixed with the locking screw. The detector should be pushed in as far as possible in order to get as close as possible to the ruby crystal. An oscilloscope with two channels is also required. A digital oscilloscope is preferable as this allows the screen to be saved as a graphics or data file.

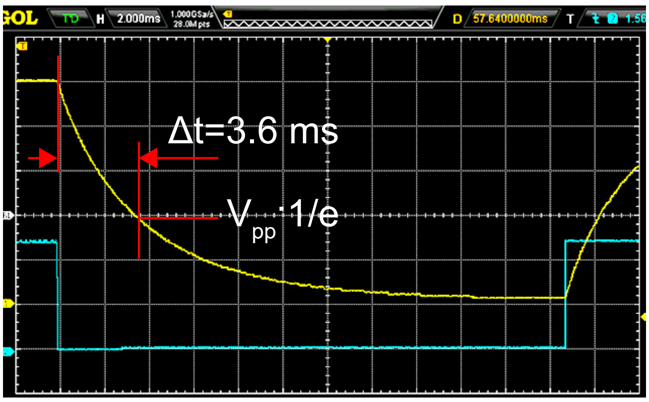


Fig. 18: Oscillogram of the fluorescence decay curve

In order for the pump laser to be switched on, at least the shield must be plugged into position 1. The photodiode signal (PDOUT) is connected to the first channel and the reference signal (REF) of the modulation to the second channel of the oscilloscope. The triggering is set for the second channel with a falling edge, i.e. the switch-off signal of the photodiode. The shunt resistance of the photodiode should not be greater than 10 kOhm and the modulation frequency should be approximately 30 Hz. With these parameters and a current of 600 mA for the laser diode, an oscilloscope image should appear as shown above.

Starting from the decay curve:

$$I(t) = I_0 \cdot e^{-\frac{t}{\tau}}$$

for $t = \tau$

$$I(t=\tau) = \frac{I_0}{e}$$

So exactly when the intensity (or photovoltage on the oscilloscope) has decayed to the value of 1/e is the lifespan τ reached. In this example, a lifespan of 3.6 ms is measured. For this measurement, the pump diode laser must excite the ruby crystal, but laser operation is not necessary. The measurement can therefore also be carried out if the laser resonator is not adjusted.

3.2 Fluorescence spectrum

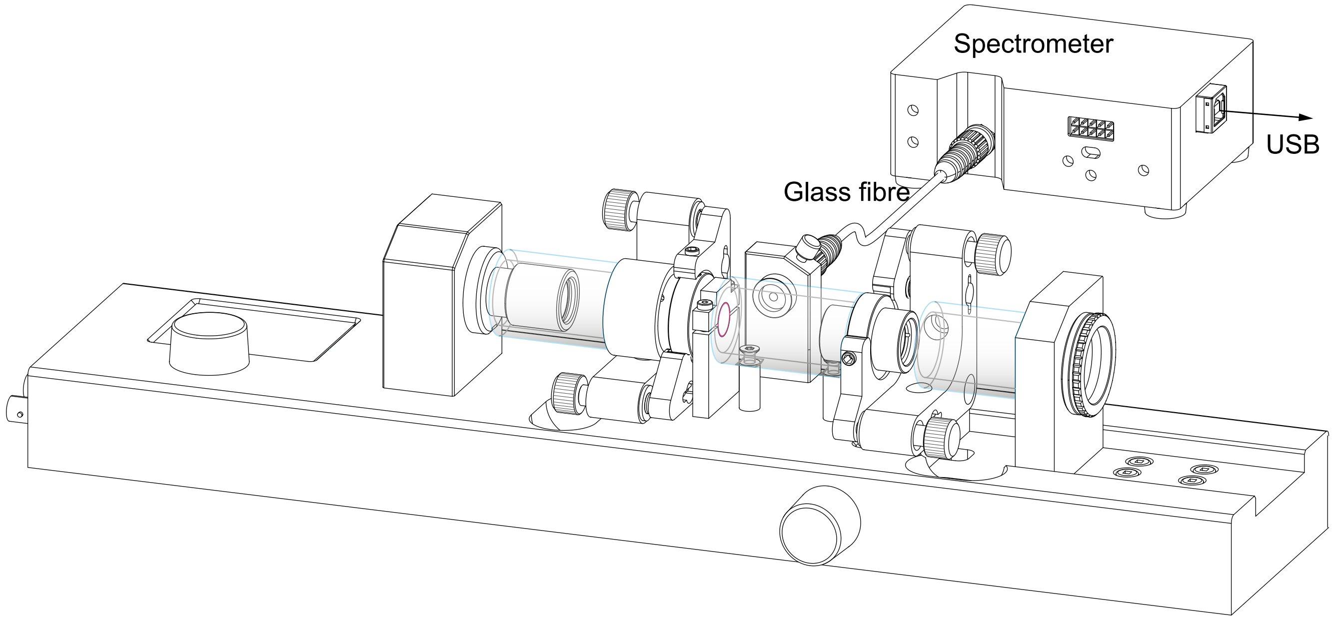


Fig. 19: Measurement of the excitation spectrum with a fiber-coupled spectrometer

Instead of the photodetector, an adapter is introduced containing a connection for an F-SMA fiber. A fiber optic cable with F-SMA connectors on both sides connects the adapter to the spectrometer. The fluorescence intensity is sufficiently high so imaging optics are not required. To evaluate the recorded spectra, the spectrometer must be connected to a PC via its USB bus.

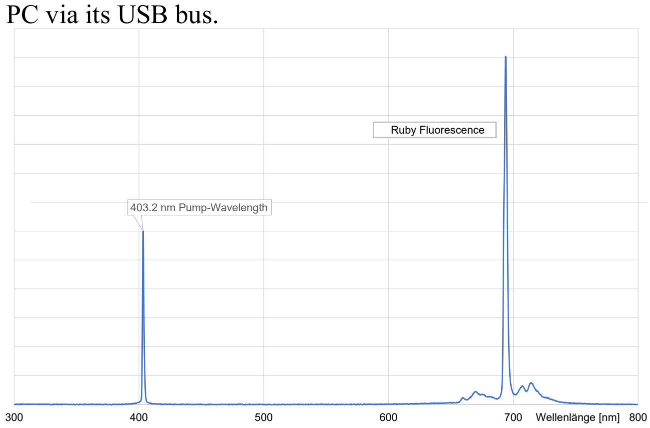


Fig. 20: Excitation spectrum of the ruby crystal

In addition to the pump wavelength at 405 nm, the strong spectrum around 694 nm can be seen. In addition to the main peak at 694 nm, some weaker secondary lines can be observed.

3.3 Adjusting the ruby laser

Laser adjustment means the alignment of the resonator mirrors parallel to each other. For this purpose, the mirrors are installed in precise adjustment holders with which the respective mirror can be tilted independently in horizontal or vertical orientation by turning the adjustment screws. If the mirrors are set in parallel and other relevant parameters such as pump power and resonator length are selected appropriately, the laser emission will “start”. The pump power is then first set to the maximum value. This is done by setting the diode laser current to the maximum value.
How can you tell whether the resonator mirrors are aligned parallel to each other and perpendicular to the pump radiation?
At maximum pump power, the focused radiation from the pump laser diode causes a sharp fluorescence line in the ruby crystal (A). The position of the track (A) is specified by the fixed laser diode. The radiation reflected back from the opposite mirror (M2) also creates a fluorescence trace (B) in the ruby crystal. The M2 adjustment holder is now adjusted until the track (B) lines up with (A).

This step can be sufficient enough for the laser oscillation to begin, but this is relatively rare. Another step is required to achieve this.

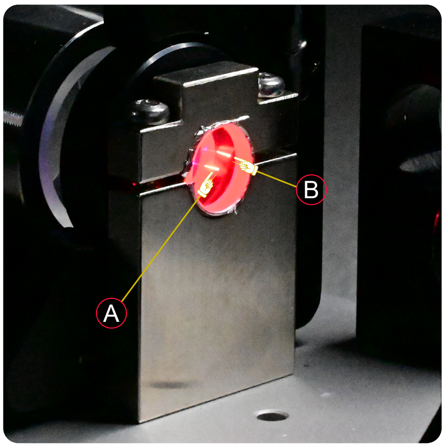
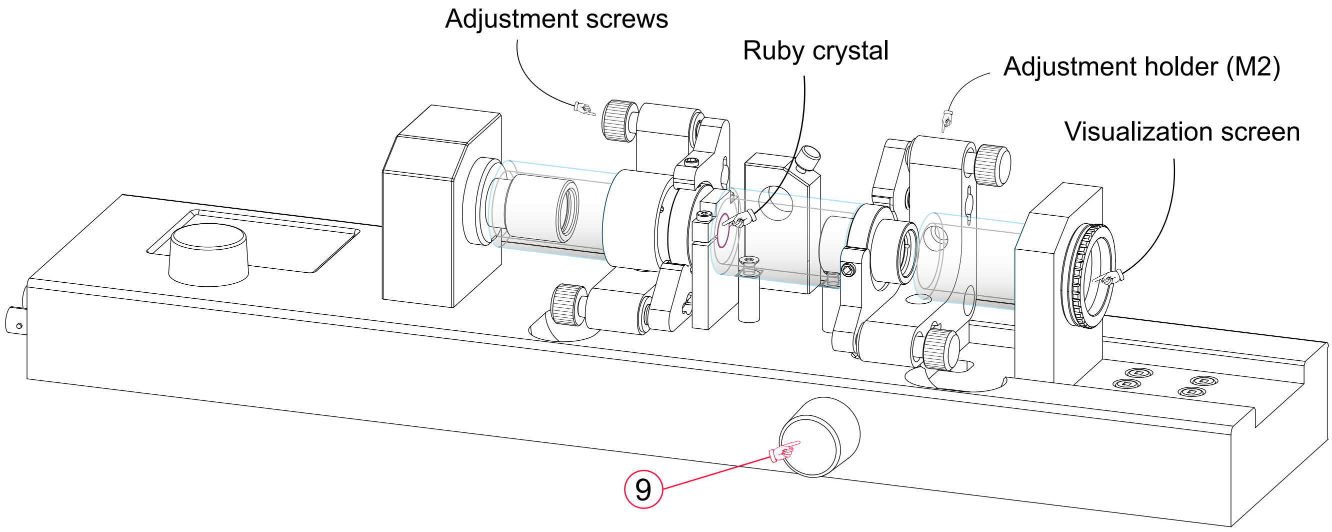


Fig. 21: Traces of fluorescence in the ruby crystal

This step can be carried out using the visualization screen or with the camera module. Both methods are based on the idea of using the fluorescent radiation circulating in the resonator.

3.3.1 With the visualization screen



To do this, look at the visualization screen. In a darkened environment, two fluorescent spots (a) and (b) are observed. Because the mirror M2 has a transmission, albeit a low one, of 1%, a corresponding portion of the fluorescence radiation will emerge from the resonator and be visible on the screen (Fig. 22).
If the fluorescent spots are not as clearly visible as in the Fig. 22, the resonator length can be reduced by turning the adjustment knob (9) accordingly.
By adjusting the mirror M2 you now bring both spots on top of each other.

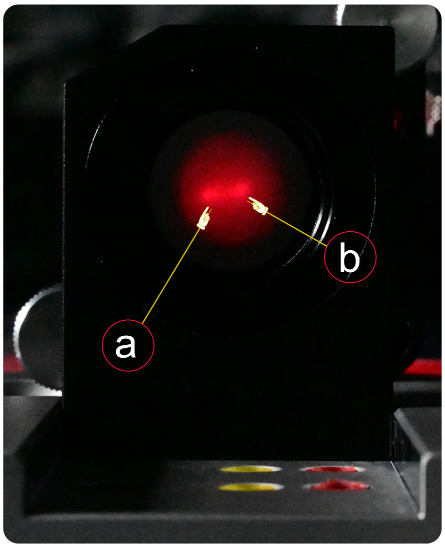


Fig. 22: Fluorescence spots on the visualization screen

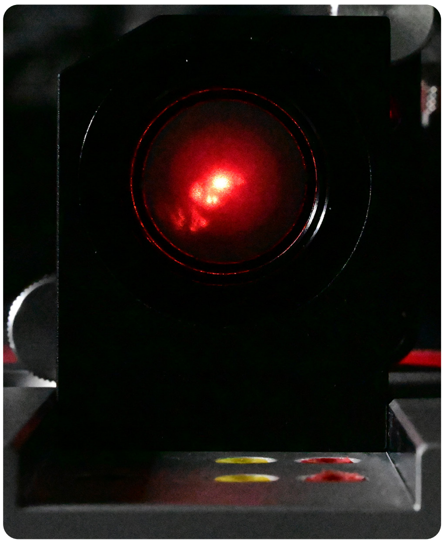
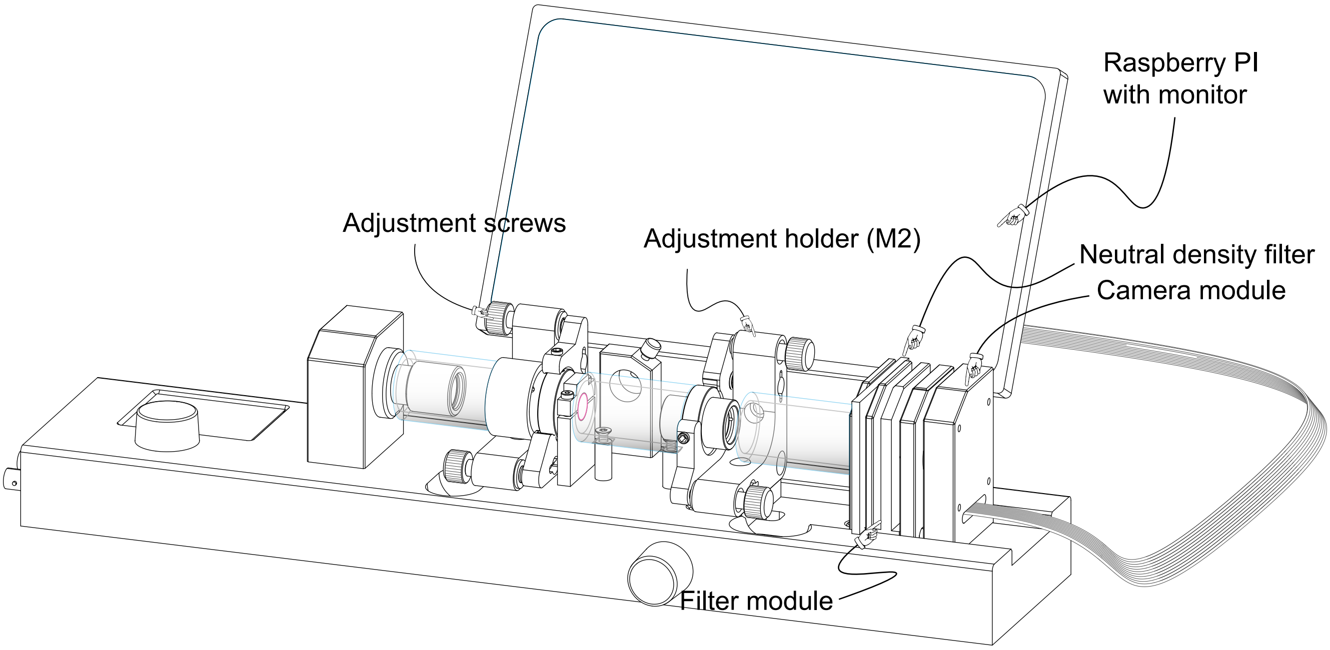
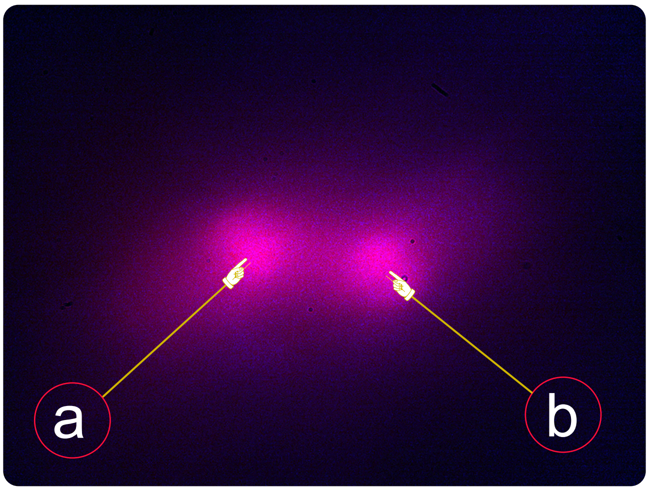


Fig. 23: The laser is “on”!

3.3.2 Adjustment with the camera module



In this setup, the filter module is used in slot 2 and the camera module in slot 3. To prevent the camera from being overload, one or more of the three neutral density filters is inserted into the filter module as required.



Instead of the visualization screen, the CCD chip of the Raspberry PI camera is used here watch the image on the screen. Here, too, the two fluorescence spots can be observed, which must be adjusted about each other using the adjustment holder (M2).

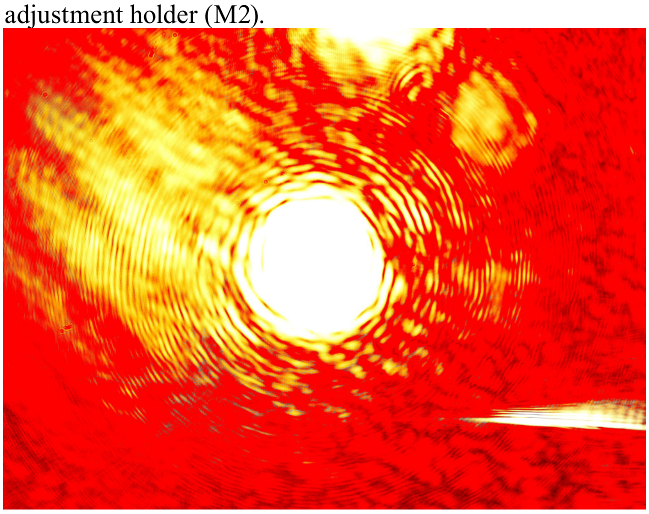
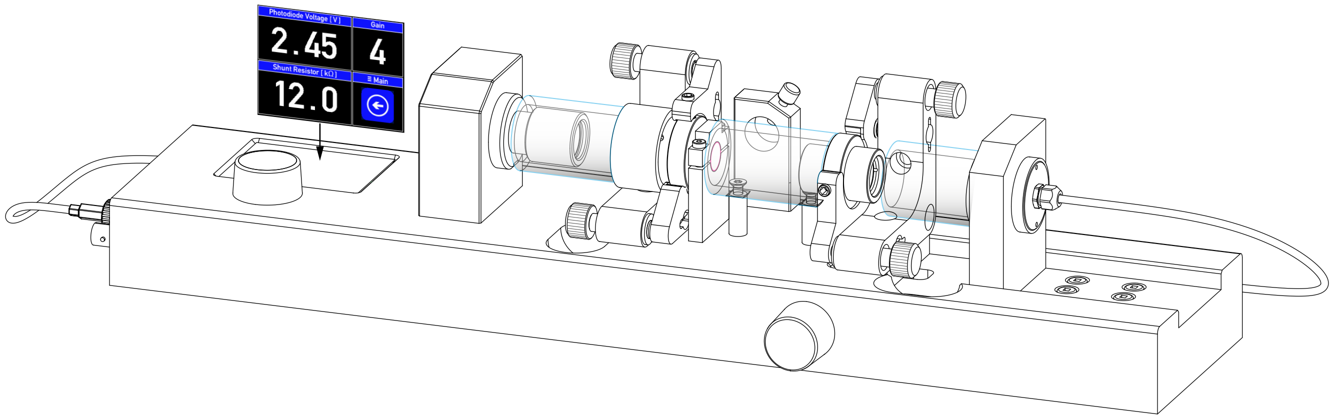


Fig. 24: As soon as the spots are aligned one above the other, intense laser radiation is created.

3.4 Measurement of laser power, slope efficiency, threshold



For these measurements you use the photodetector module, which is inserted into slot 1. The values for the shunt resistance and the gain are set in the photodiode menu. An example measurement is shown in the table below.

Current [mA]	Voltage [V]	gain	Shunt [kOhm]	Photocurrent [mA]
200	0.22	1	1	0.22
250	1.06	1	1	1.06
300	1.60	1	1	1.60
350	1.31	1	0.7	1.87
400	1.51	1	0.7	2.16
450	1.60	1	0.7	2.29
500	1.70	1	0.7	2.43
550	1.80	1	0.7	2.57
600	2.02	1	0.7	2.89

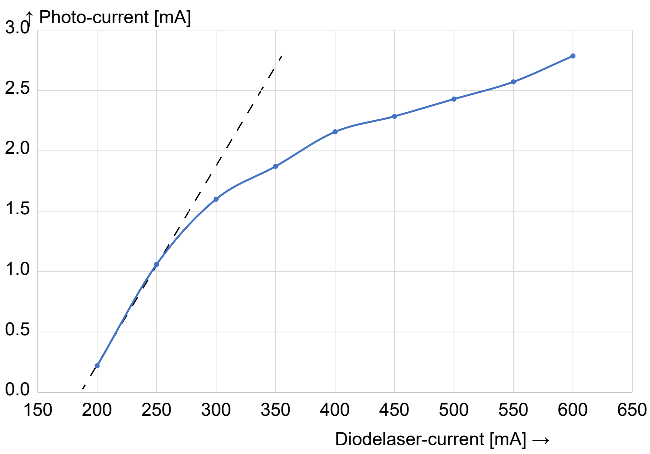


Fig. 25: The measured photocurrent as a function of the diode laser current

It can be seen that the photodetector becomes nonlinear from around 270 mA pump current due to saturation effects. However, this effect could be avoided by choosing a more suitable shunt resistance. The dashed curve would result if the photodetector were not saturated. The zero crossing of the dashed curve results in a laser threshold of 180 mA. With the value of 0.48 A/W (Fig. 16) we can use the photocurrent I_{phot} in Optical Performance P_{opt} convert:

$$P_{opt} = \frac{I_{phot}}{0.48}$$

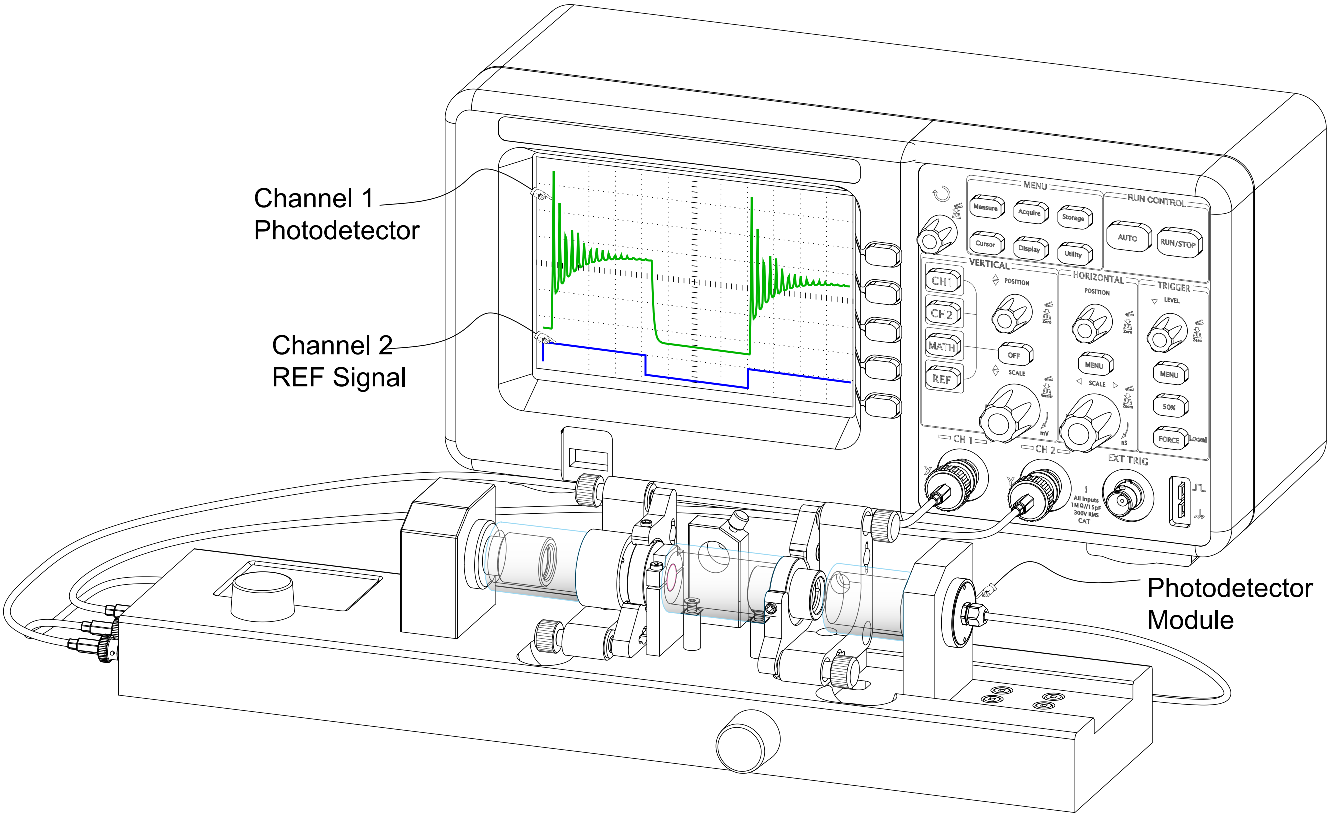
The "slope efficiency" α_s is the slope of the linear curve and gives:

$$a_S = \frac{P_{opt}^2 - P_{opt}^1}{I_2 - I_1} = \frac{2.7 \cdot 10^{-3} - 0.22 \cdot 10^{-3}}{0.48 \cdot (350 - 200)} = \frac{2.48 \cdot 10^{-3}}{72}$$

$$= 0.034 \cdot 10^{-3} \frac{W}{mA}$$

With a laser diode current of 600 mA, the ruby laser emits an impressive 20.4 mW.

3.5 Dynamic measurements, spiking



This setup is used to investigate the dynamic behavior of the ruby laser. The photodetector module is plugged into slot 1 and the BNC cable is connected to the "PDIN" BNC socket. The output socket (PDOUT) is connected to the first channel of the oscilloscope (yellow trace), and the "REF" output is connected to the second channel (blue trace). This signal serves as a trigger. Depending on the task, the trigger is set on the rising or falling edge of the "pump signal".

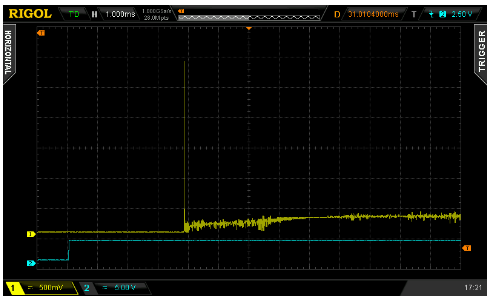


Fig. 26: Typical "initial spike" and transition to cw operation during the pump pulse

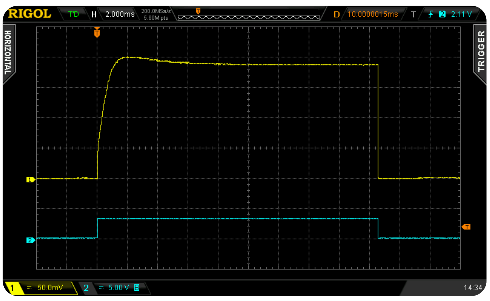


Fig. 27: Laser response at high pump power

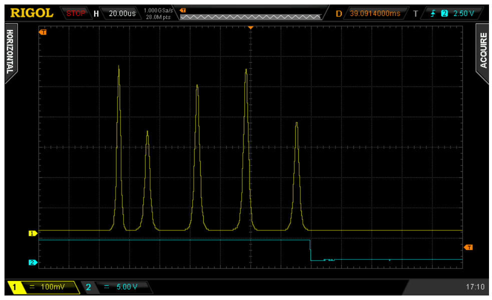
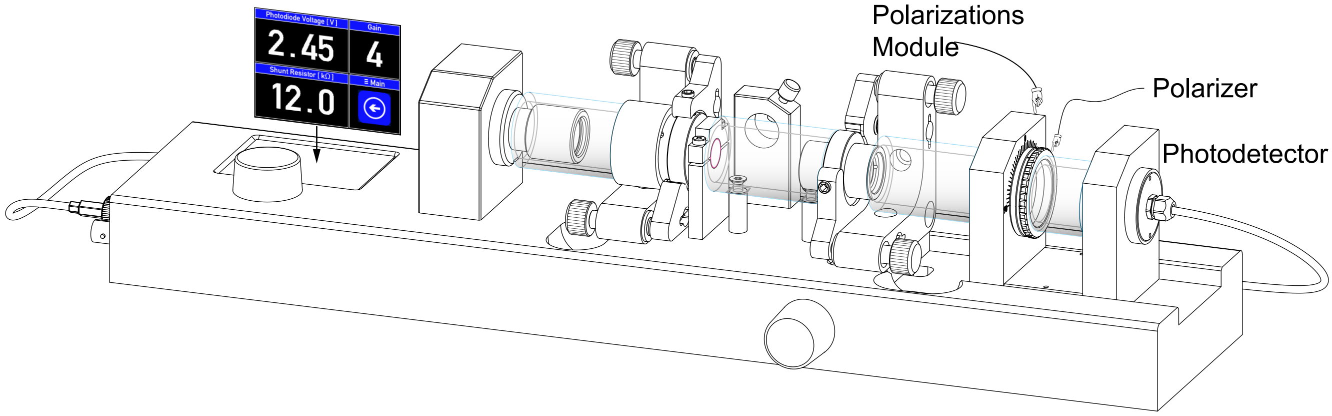


Fig. 28: Laser response at low pump power. The coherence length can also be calculated from the temporal width of these spikes at the end of the pump pulse.

Depending on the choice of pump power and modulation parameters, different laser responses will be observed.

3.6 Measuring polarization - Malus' law



This setup is used to measure the polarization of the ruby laser. To do this, the polarization module is plugged into the second slot. The module has a rotatable polarizer and a photodetector, which is connected to the "PDIN" socket with its BNC cable.
Suitable parameters are selected in the photodetector menu. To do this, turn the polarizer to maximum voltage and ensure that no "overload" of the voltage is signaled. Now turn the polarizer to the dark position and observe whether smaller voltage values are displayed. Please also note that the laser power is not set too high to avoid saturation of the photodetector in the bright position.

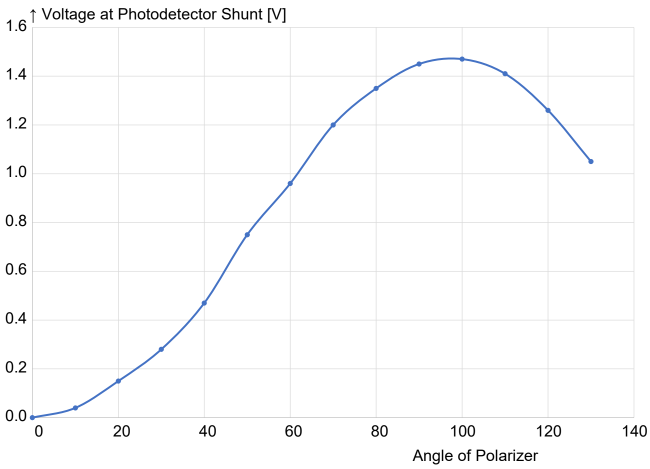
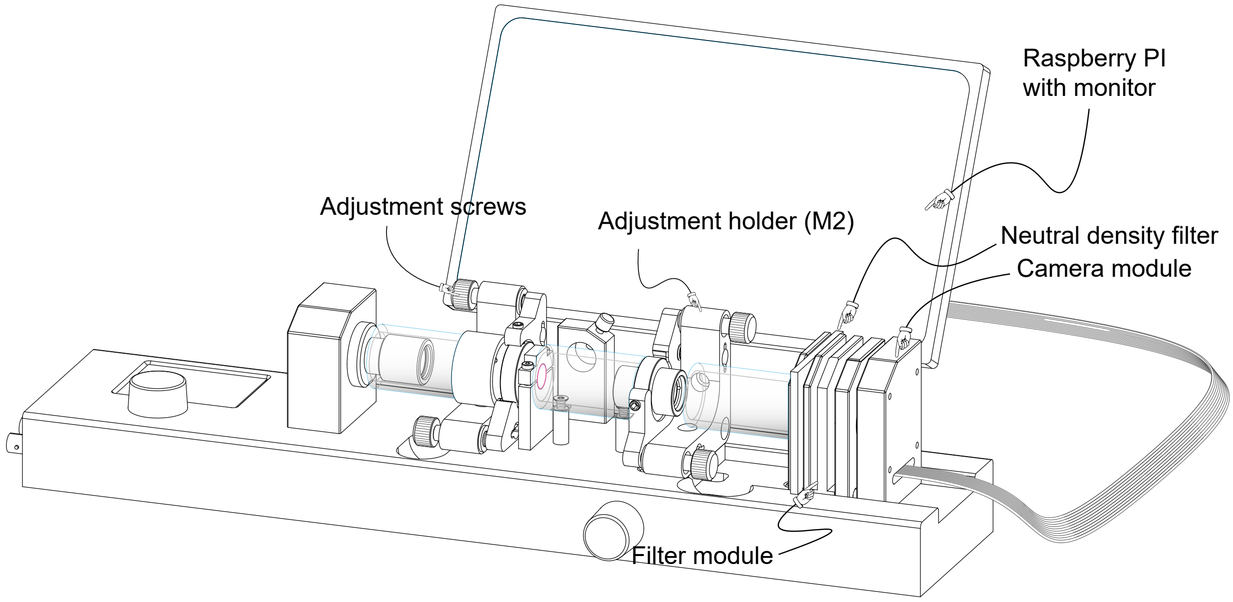


Fig. 29: Measured photo-voltage as a function of the adjustment angle of the polarization filter acting as an analyzer

Add: To check the Malus law, the measured curve should be fitted against a $\cos^2$ function. A plot in polar coordinates is also very clear. The position of the crystal axis of the ruby crystal can be determined from the position of the "eight" in the polar coordinate diagram.

3.7 Demonstration of transversal modes



The same setup is used as we used to adjust the ruby laser. One can observe that the number of transverse modes increases near the largest adjustable resonator spacing. You will choose this setting if you want to observe higher transverse modes. On the other hand, low modes or especially the TEM_{00}, smaller resonator spacings will be set. Other parameters that can be used to influence the occurrence of transversal modes are the pump power and the adjustment state of the mirror M2. The closer the laser works to the threshold, the fewer transverse modes occur.
The following photos show a selection of such modes.

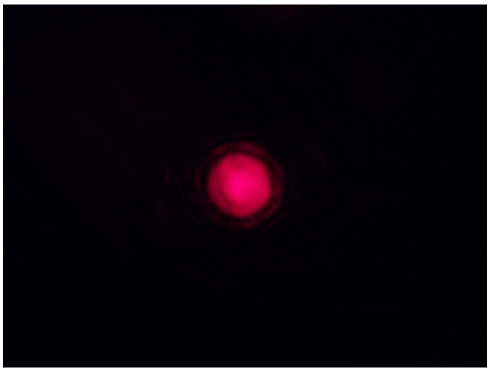


Fig. 30: TEM_{00} Mode

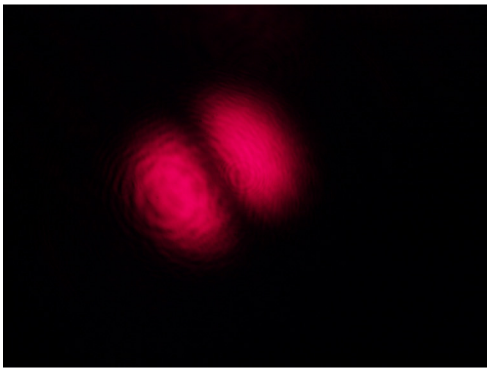


Fig. 31: TEM_{01} Mode

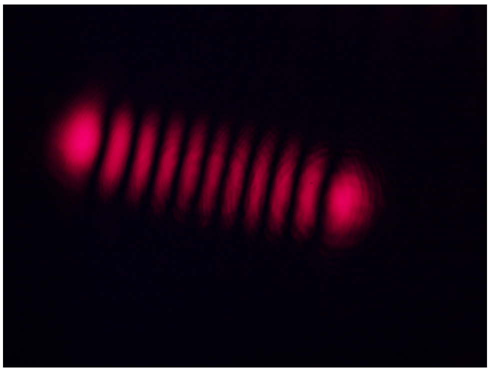


Fig. 32: TEM $_{010}$ Mode

In addition to the image file (jpeg), the Raspberry PI also saves a data file (csv) as a matrix of the image. This can be read in and analyzed in numerical evaluation programs such as MatLab or others.

3.7.1 Recording and Gaussian fitting of the TEM_{00} Mode

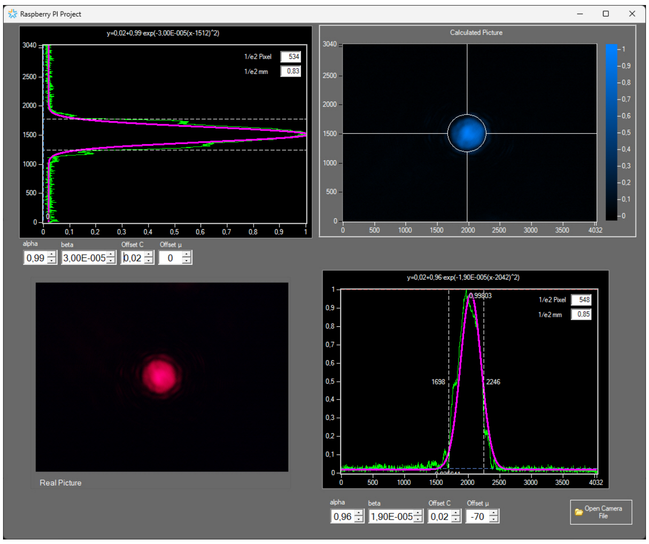


Fig. 33: Example of self-made software to adapt the Gaussian fundamental mode.

The image file is read in at the bottom left and the matrix at the top right. For the maxima in the X and Y directions, the intensity (top left and bottom right) is plotted and approximated with Gaussian curves.