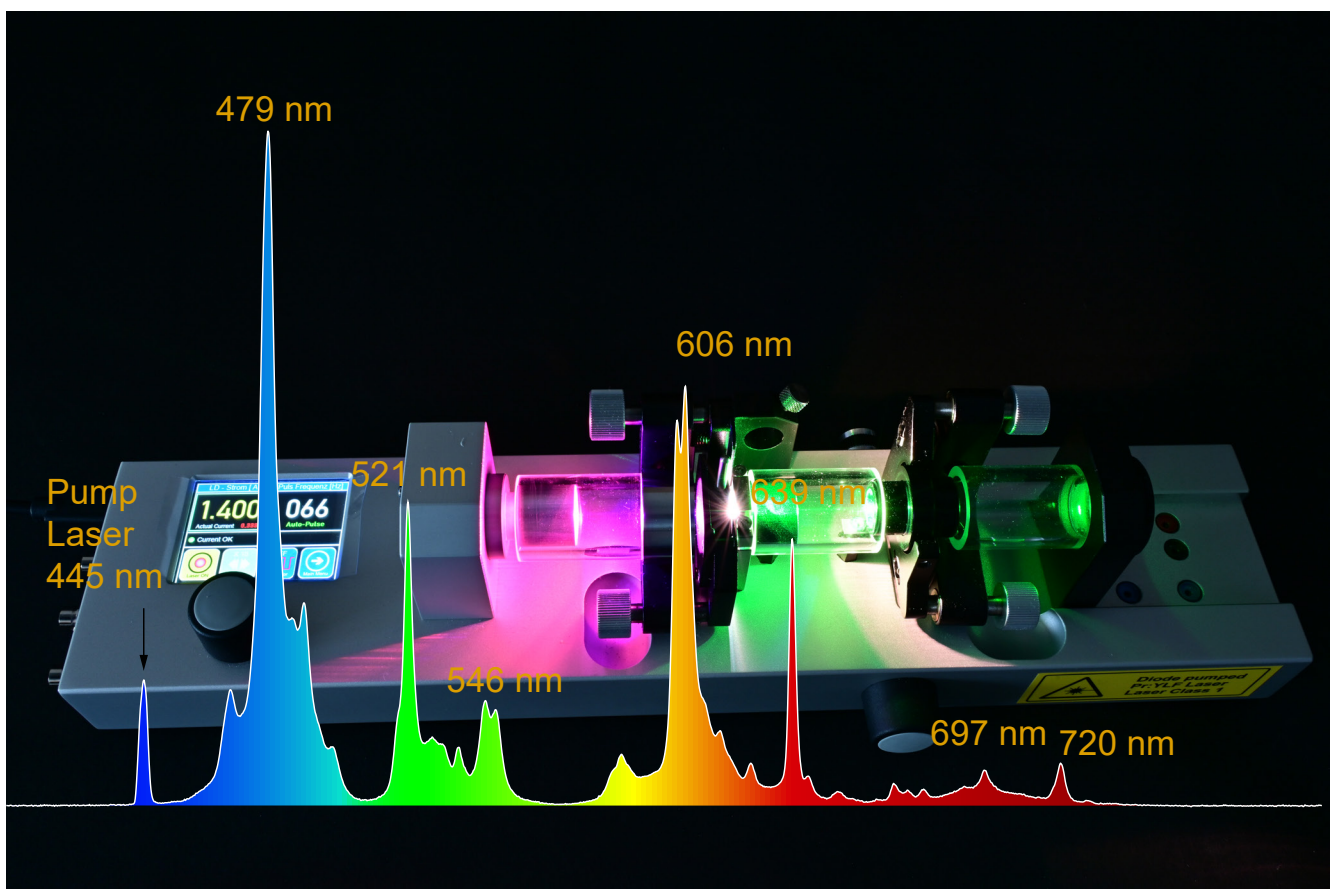


UM-18 Manual for the Pr:YLF PL4000 Laser



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1 Theory Section – Compendium of Key Fundamentals

1.1 To start off, a bit about the history

Einstein's 1917 work on the absorption and emission of light laid the theoretical foundation for the later development of the MASER and LASER, as it described not only spontaneous emission but also the possibility of stimulated emission. This led to the development of the ammonia maser oscillator in 1954 (Townes, Gordon, Zeiger). The theory they subsequently developed in 1958 for optical frequencies demonstrated the possibility of generating coherent light via stimulated emission within an optical resonator. In 1960, Theodore Maiman presented the very first laser oscillator using a flashlamp-pumped ruby crystal. That same year saw the development of the gas laser (He-Ne laser) by Javan and Bennett. As early as 1962, Basov built the first semiconductor injection laser (diode laser).

1.2 Three Conditions for Laser Oscillation

Several things are needed to generate laser radiation:

- An **active material** in which light amplification via stimulated emission is possible. To achieve this, **population inversion** must be created within the material. This requires at least a third, metastable electronic level with a long lifetime that can be effectively—that is, very quickly or at a high rate—populated when the active material is excited. Therefore, only certain materials are suitable.
- A **pumping process** used to excite the active medium. This can be done optically (solid-state lasers, dye lasers), electrically (injection lasers), or, for example, through a chemical process (excimer lasers).
- A **laser resonator** that feeds back light emitted in a specific direction into the active and excited amplifying medium in such a way that it repeatedly passes through it, being further amplified each time by stimulated emission. As with acoustic feedback between a speaker and a microphone in an amplifier, the system then begins to oscillate at its natural frequencies. The laser resonator consists of two dielectric mirrors with very high reflectivity (99.9% and, for the output mirror, only 98 to 99%) for the wavelength of the laser light.

1.3 Difference Between Three-Level and Four-Level Lasers

Suitable active materials for solid-state lasers include, for example, chromium (ruby laser) or rare earth elements such as neodymium (Nd), praseodymium (Pr), (e.g., Nd:YAG or Pr:YLF lasers). These atoms or ions are incorporated into transparent crystal lattices in such low concentrations (approx. 0.05 wt.%) that they are virtually isolated from one another, and interaction between them is possible only through light. This results in sharp atomic emission. While the ruby laser—which uses a chromium-doped sapphire crystal ($\text{Cr}^{3+}:\text{Al}_2\text{O}_3$)—is a three-level laser, the Nd:YAG laser (yttrium aluminum garnet) and the Pr:YLF (yttrium lithium fluoride) laser are four-level lasers.

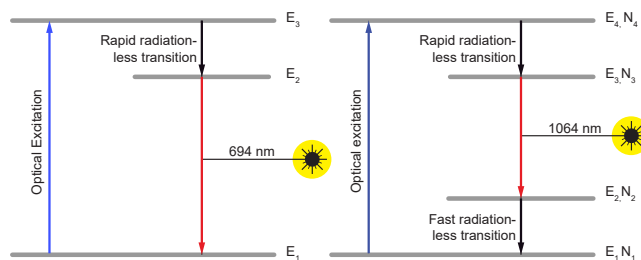


Fig. 1: Ruby Laser

Fig. 2: Nd:YAG Laser

Schematic representation of the three-level energy scheme of the ruby laser and the four-level scheme of the Nd:YAG laser

In both cases, a radiationless transition—which is significantly faster than the lifetime of the electrons in the pump level (approximately 10 ns)—causes the pump level to be immediately depleted into the metastable level, that is, into the upper lasing level. In a four-level laser, an equally rapid radiative transition always depopulates the lower lasing level. As a result, population inversion between the upper and lower lasing levels is easier to achieve in a four-level laser than in a three-level laser, in which the lower lasing level is identical to the ground state.

1.4 Spectral Diversity of the Fluorescence of the Pr:YLF Crystal

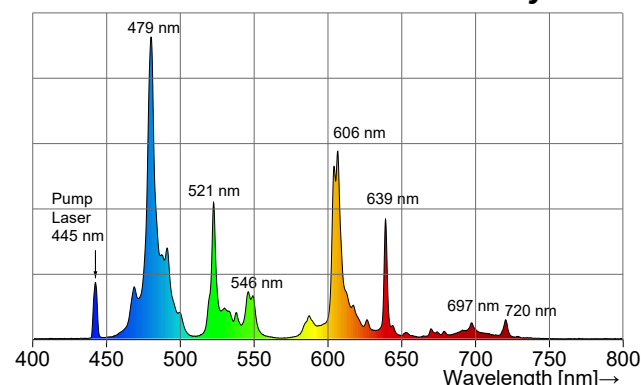


Fig. 3: Fluorescence spectrum of a Pr:YLF crystal

The Fig. 3 shows the fluorescence spectrum of a praseodymium YLF crystal when excited by blue light from a 445-nm laser diode, with lines at 479 nm, 521 nm, 546 nm, 606 nm, 639 nm, and 697 nm. If we add the blue pump radiation at 445 nm generated during laser operation, the Pr:YLF laser in multi-line mode becomes a candidate for a white-light laser.

Wavelength (nm)	Transition	Effective cross-section 10^{-19} cm^2
479	$^3\text{P}_0 \rightarrow ^3\text{H}_4$	1.9
523	$^3\text{P}_1 \rightarrow ^3\text{H}_5$	0.3
607	$^3\text{P}_0 \rightarrow ^3\text{H}_6$	1.4
639	$^3\text{P}_0 \rightarrow ^3\text{F}_2$	2.2
698	$^3\text{P}_0 \rightarrow ^3\text{F}_2$	0.5
721	$^3\text{P}_0 \rightarrow ^3\text{F}_4$	0.9

Table 1: Cross-section of the main lines and their transitions, taken from the reference 4

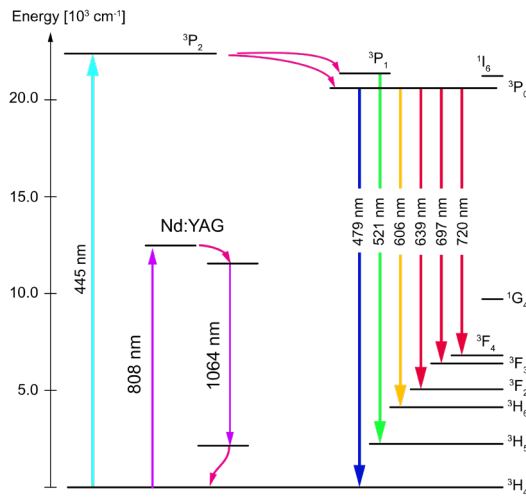


Fig. 4: Energy Level Diagrams for Pr:YLF and Nd:YAG

While the Nd:YAG laser has only one wavelength in the infrared spectral range—which is often doubled or tripled to 532 nm and 355 nm, respectively, using nonlinear optical crystals—the Pr:YLF laser has several lines in the visible range that are suitable for four-level laser operation. These are the lines at 521 nm (green), 606 nm (orange), 639 nm (red), and 697 nm (red).

The laser radiation is linearly polarized due to the crystal geometry (uniaxial crystal). It should be noted that the green line (521 nm) originates from a different upper laser level than the orange and red lines and therefore has a polarization direction rotated by 90°.

1.5 Quantum-like Transitions

1.5.1 From Bohr to Einstein

Absorption, Spontaneous and Stimulated Emission Einstein Coefficients

Electrons possess quantized energies, meaning they have only discrete, allowed energy states, which are referred to as energy levels. In Bohr's classical atomic model, these energy states correspond to circular orbits of different radii. Orbits with larger radii represent higher energy states—in accordance with the equivalence of the radial force and the Coulomb force. The electronic transition between two orbits—for example, between the ground state n and an excited state m —occurs abruptly. For this to happen, a photon with the energy difference must be absorbed $h \cdot \nu = E_m - E_n$. The photon disappears, and the electron transitions to the excited state m . After its lifetime of approximately 10 ns (10^{-8} s) in the excited state, the electron returns to the ground state, emitting a photon with exactly this energy difference. This is referred to as spontaneous emission of a photon. The spontaneous transition probability A_{mn} (transitions per unit time) is the reciprocal of the lifetime.

If there are many atoms with electrons in an excited state, the excited electrons in the active medium can be stimulated to immediately transition to the ground state by irradiating them with photons of the same frequency. This is referred to as stimulated emission. It can be triggered by a spontaneously emitted photon. Stimulated emission is proportional to the radiation density $u(\nu)$ of the incident field that causes it. The total transition probability to the ground state is then $P_{mn} = A_{mn} + u(\nu) \cdot B_{mn}$. The phase of the stimu-

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

1.5.2 Occupation numbers, spontaneous and stimulated emission

In thermal equilibrium, for a system with energy levels E_1 (ground state) and E_2 (excited state) with occupation numbers N_1 and N_2 , the Boltzmann relation holds

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

The occupation numbers refer to the electron density in the respective states.

Since absorption, which is proportional to N_1 , and (spontaneous plus stimulated) emission, which is proportional to N_2 , are in thermal equilibrium, the following holds:

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

If we solve the equation for the radiation density $u(\nu)$ and substitute N_2 according to the Boltzmann relation, then—based on the comparison of coefficients with Planck's radiation formula, first performed by Einstein—we obtain, on the one hand, $B_{21} = B_{12} = B$ and, on the other hand, the ratio

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

This then yields the ratio of spontaneous emission (incoherent radiation) to stimulated emission (coherent radiation) as

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

For optical frequencies at room temperature, spontaneous emission is about 10^{38} times more intense. At longer wavelengths, the ratio for stimulated emission becomes much more favorable, approaching one at 70 μm . This explains why the MASER (Microwave Amplification ...) was developed first, followed later by the LASER.

To operate a laser, the population in the upper laser level must be greater than that in the lower level. This requires a non-equilibrium state known as population inversion, which can only be achieved by using an additional metastable level as the upper laser level. Population inversion can be generated with less pumping power in a four-level laser if there is an additional level below the lower lasing level that is constantly and rapidly depleted.

1.6 Optical Resonator and Axial Modes

The active medium in a non-equilibrium state acts as an optical amplifier that uses spontaneously emitted photons to stimulate additional excited atoms to emit light coherently—albeit in random directions. This amplifier alone is not sufficient to generate laser emission. A feedback mechanism with a filter is required to obtain an oscillator at the desired frequency. The necessary feedback is provided by the optical resonator—also known as a cavity. The resonator consists of two mirrors that repeatedly send the stimulated radiation back and forth through the active medium in a selected direction, thereby further amplifying it. At the output mirror, a certain fraction (approximately 1 to 2%) is transmitted as a usable laser beam.

Between the two mirrors, which are spaced a fixed distance apart—also known as a Fabry-Perot interferometer—only standing waves can exist, with their nodes located at the

mirrors. The distance between the mirrors must therefore correspond to half a wavelength or an integer multiple of half a wavelength: $L = n \cdot \frac{\lambda_n}{2}$. The possible resonance (or natural) frequencies—also known as axial or longitudinal resonator modes—are then given by

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

where n^* is the refractive index of the medium between the mirrors.

Since the light wavelength is very small compared to the resonator length, the order number n is a very large number. Therefore, only the frequency spacing $\Delta\nu$ between neighboring axial modes is of interest.

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

For our experimental laser ($L \approx 5$ cm, $n^* \approx 1$), the axial mode spacing is 3 GHz. However, this can only be measured using a fast photodiode and a frequency analyzer or an FP etalon.

1.7 Line widths, gain profile, and resonator modes—how monochromatic is a laser?

Despite being quantum-like transitions, spectral lines are not sharp. The so-called homogeneous or natural line width (half-width at half-maximum of the line) follows from the uncertainty principle, $\Delta E \cdot \Delta t = \frac{\Delta E}{\Delta\nu} \approx h$ where $\Delta\nu$ denotes the frequency uncertainty. It follows from the lifetime of excited states that

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

A wavelength of 521 nm corresponds to a light frequency of 575.8 THz. This results in a frequency uncertainty of 5.7 MHz.

Other factors, such as the residence time of the photons in the resonator (resonator decay time), the number of modes in the gain profile of the active medium, and the output power, influence the actual spectral laser linewidth.

The gain profile of solid-state lasers ranges from 300 to 500 GHz, which corresponds to a line half-width of 0.5 to 1 nm. Consequently, several natural frequencies of the resonator (axial modes), spaced 3 GHz apart, can be amplified by the active medium. In addition, there are the non-axi-

al modes—which will be discussed in more detail later—that are high-energy and lie at a small distance from the axial modes. As a result, the laser beam contains several different frequencies. If exactly one axial mode is amplified, the radiation is monochromatic. For this to occur, the frequency spacing $\Delta\nu$ between the axial modes must be greater than the width of the gain profile.

1.8 Resonator quality and its resolution capability

The quality factor of a resonator depends on its losses—that is, on how much energy leaves the resonator per oscillation period at the resonator frequency. The main loss results from the transmission T of the output mirror. From the quality factor

$$Q = \frac{2\pi\nu_R L}{c \cdot T} = \frac{\nu_R}{\Delta\nu_R}$$

This yields the resonator's resolution $\Delta\nu_R$. For our laser, which has 1% mirror transmission, a wavelength of 521 nm, and a resonator length of approximately 0.05 m, $\Delta\nu_R = 9.5$ MHz.

This makes the axial mode spacing of 3 GHz very easy to observe.

1.9 Resonators, Stability, Gaussian Modes

There are various types of resonators, each with its own stability range [3]. The following are worth mentioning here:

- Resonator with two plane-parallel mirrors (very difficult to align),
- A confocal resonator with two concave mirrors having identical mirror radii R , with focal points located at $R/2$, respectively, and a stable resonator length of $L < 2R$.
- A symmetric concentric resonator, which is a special case of the confocal resonator, in which both mirror surfaces lie on the surface of a sphere and a diffraction-limited spot is formed at the center (stable for $L \leq 2R$).
- An asymmetric concentric resonator consisting of a concave mirror and a flat mirror, stable for $L < 2R$. Here, half of the concentric resonator is replaced by its reflection formed on the flat mirror.

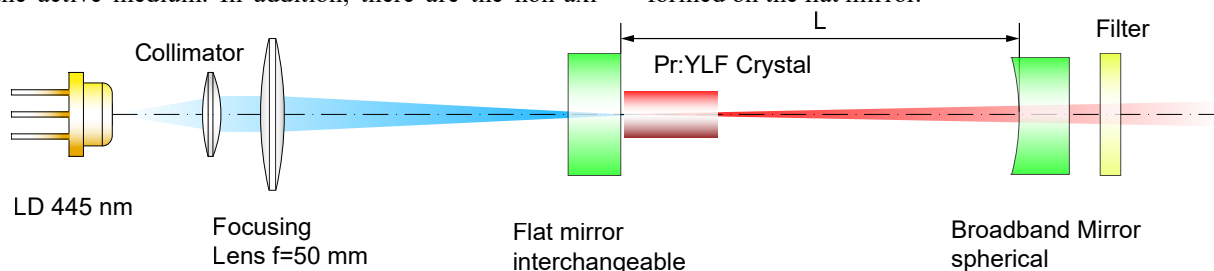


Fig. 5: Asymmetric concentric resonator

Both Class 1 experimental lasers—the Pr:YLF laser and the ruby laser—use a semi-concentric resonator (Fig. 5). This can be recognized from the outside by the fact that the respective laser crystal is positioned directly next to the flat input mirror. Both mirrors are dielectric mirrors, each consisting of several dielectric layers deposited onto the mirror glass. The layer thicknesses and their refractive indices are calculated such that multiple interferences produce the desired spectral transmission and reflection properties.

Thus, the input mirror is always transparent to the respective pump radiation of the diode laser, but highly reflect-

tive—with $R = 99.9\%$ —only for the desired laser emission line. The broadband output mirror reflects all wavelengths with $R = 99\%$. Behind the output mirror is an additional filter that absorbs any residual pump radiation.

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

$$I(r) = I_0 \cdot e^{-2r^2/w^2}$$

where r is the distance from the axis and w is the beam cross-section. In a concentric resonator, the minimum beam

cross-section—the beam waist—is located at the center, whereas in a semi-concentric resonator, it is located at the input mirror (see image above).

In the experiment, the Gaussian shape of the axial mode (also known as $_{\text{TEM}00}$) can be verified, recorded, and adjusted using a camera and a Raspberry Pi, with the help of specialized software.

1.10 Selective Resonator

Mirrors for optical resonators are dielectric mirrors that, unlike metal mirrors, do not absorb light but instead reflect light of the desired wavelengths and transmit other wavelengths through constructive and destructive interference effects. To achieve this, multiple dielectric layers with different refractive indices and thicknesses are designed and then deposited, for example, onto quartz glass. For example, if you look through a yellow-reflecting mirror, you will see blue light in the transmitted beam. This allows you to build resonators that function selectively only for certain wavelengths—that is, they amplify only those wavelengths. The choice of resonator mirrors therefore determines which fluorescence line of the Pr:YLF crystal is used for laser operation. In the Pr:YLF Class 1 experimental laser, a semi-concave resonator was used, whose curved output mirror reflects 99% of all wavelengths in the visible spectrum. Wavelength selection is therefore handled by the planar mirrors. These mirrors are transparent to the pump wavelength of 445 nm, which must reach the laser crystal, but they are highly reflective for the respective desired laser wavelength. Although the Pr:YLF crystal appears white when excited—since it fluoresces on all lines—only the line selected by the mirror configuration is amplified as the laser line within the resonator.

In general, selective resonators can also use a Littrow prism (argon laser), a grating (dye laser), or a birefringent Lyot filter (dye laser, He-Ne laser) instead of a mirror. However, when using two broadband reflective mirrors, multi-line laser operation—as seen, for example, in the argon laser—cannot be achieved because, with the exception of the green line, all other lines share a common output level. Due to homogeneous broadening, only the strong red line at 648 nm will oscillate.

1.11 TEM modes (non-axial or transverse electromagnetic modes)

Since the laser beam generated in the resonator also has a lateral extent, non-axial modes—known as TEM modes—occur, particularly as power increases and when the resonator is not optimally aligned. The reason for this is that the phase of the light wave is no longer constant across the entire mirror surface. The phase varies in different regions of the mirror surfaces, resulting in the presence of multiple beam bundles within the laser beam. For circular mirrors (radius r_s), the resonance frequencies of these modes are given by

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

$X_{m,l}$ refers to the l th zero of the m th-order Bessel function. The TEM modes are therefore high-energy modes with a small frequency spacing—which depends on m and l and increases as m increases—and are located adjacent to the

axial modes. Since their order numbers n are very large, they are not specified for the TEM modes.

Depending on the geometry of the laser beam (circular, 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 various 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 finesse, you can produce a wide variety of TEM mode images. These are particularly easy to observe near the laser threshold and when the resonator is less stable—that is, when the resonator is slightly elongated.

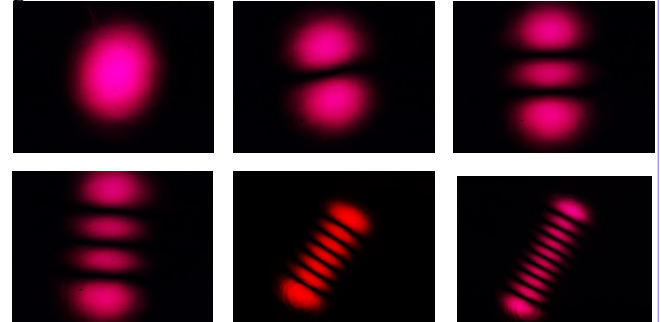


Fig. 6: Hermite-Gauss modes (rectangular)

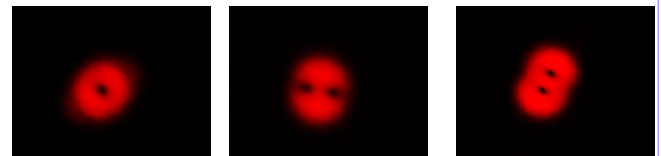


Fig. 7: Laguerre-Gauss modes (cylindrical)

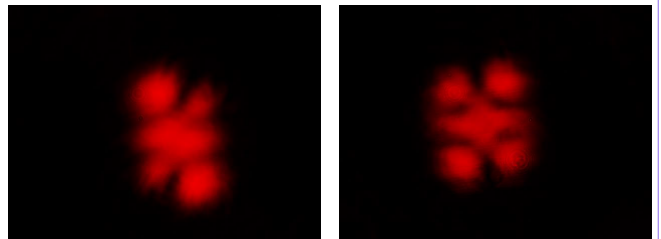


Fig. 8: Ince-Gauss modes (elliptical)

1.12 Spiking, Coherence, and Interference; Coherence Length

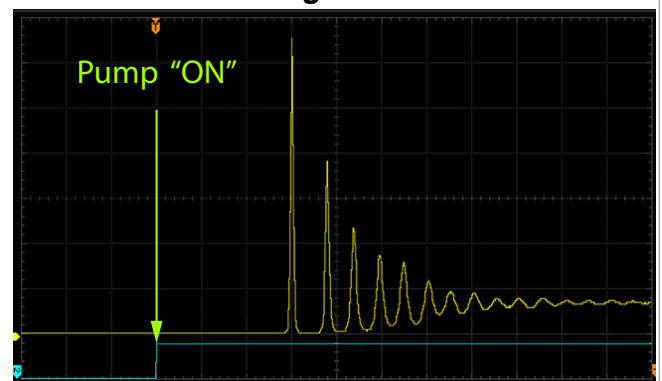


Fig. 9: Turn-On Behavior of the Pr:YLF Laser

When the Pr:YLF laser is pulsed-pumped, it is observed that the laser process begins with a delay after the start of the pump pulse. When analyzed in terms of time resolution,

it can be seen that the laser radiation initially consists of a series of so-called “spikes” (flashes of light) (Fig. 9).

Interference requires coherent wave trains that interfere constructively or destructively. We speak of spatial coherence when the radiation originates from the same point. In addition, the quantum-like emission events are limited in time. Thus, the individual (photon-like) wave trains have a finite length and are therefore capable of interfering only within a coherence time. For example, while interference can be observed with classical light sources on thin layers of oil on water, it can no longer be observed on a plane-parallel window pane due to its thickness. The coherence length and coherence time are related as follows:

$$\Delta l = c \cdot \Delta t = \frac{c}{\nu}$$

It follows that the coherence length of a pulsed-pumped laser depends on the pulse duration. Initially, the pulses are more or less irregular and originate, in part, from different locations within the laser crystal. Continuous-wave (cw) lasers have significantly longer coherence lengths due to stimulated, in-phase emission.

1.13 Measuring the lifetime of the metastable level—exponential decay and rise

To measure the lifetime τ of the metastable laser output level in Pr:YLF, the temporal behavior of the fluorescence must be investigated without laser operation. The Pr:YLF fluorescence is excited using square-wave pulses. Each time the excitation is turned off (at the end of the respective square-wave pulse), the metastable E₃ level decays with a time constant of $1/\tau$. The balance equation after the intensity is turned off (i.e., after the end of the pump pulse) is:

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

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

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

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

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

The time at which the population density or fluorescence intensity has fallen to half its original value is called the half-life. From this, the time constant of the exponential function—and thus the lifetime of the metastable laser level E₃—can be calculated immediately.

Similarly, the rise time of the E₃ waveform (following the start of the square wave pulse) can be measured. This process is analogous to charging a capacitor. The solution is given by 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 in the E₃ state given the pump intensity and pulse duration. Since the material is not being excited to produce laser light here, but rather its fluorescence is being studied at low excitation intensities, $N_3 \leq N_1$, so the depopulation from N₁ does not need to be taken into account. Thus, the same time constants can be observed for the rise and decay of the fluorescence.

1.14 Balance Equations – At Least Three Levels for Inversion of Terms

In a two-level system, at most, only one population equilibrium can be achieved. The balance equation includes absorption, stimulated emission (proportional to the Einstein coefficient B and to the pump radiation field (intensity)), and spontaneous emission.

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

A clear explanation should suffice here: As soon as half of all electrons are in the upper level, the probabilities of absorption ($1 \rightarrow 2$) and stimulated emission ($2 \rightarrow 1$)—which depend on the occupation density of the respective state—are equal. The population of the excited state is further reduced by spontaneous emission, so that even the case of equal population densities cannot be achieved.

At least a three-level system is required for population inversion. Rapid, radiationless depopulation of the E₂ level—excited by pump radiation—into a metastable (long-lived) E₃ level occurs within the order of picoseconds. At this point, the competing process—depopulation from E₂ to E₁ via stimulated and spontaneous emission—no longer plays a role. The population density in the E₃ state then increases relative to the E₁ state, which is becoming emptier due to pumping. In this way, population inversion ($N_3 > N_1$) can be achieved. The laser transition then occurs between the E₃ and E₁ levels ($3 \rightarrow 1$).

Since state E₂ is immediately transitioned to state E₃—and

thus is $N \approx N_1 + N_3$ —, the following holds:

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

In contrast to the two-level system, the stimulated emission caused by the pumping process—that is, from E₂ to E₁—is now missing from the balance equation. Rewriting the equation using $\Delta N = N_1 - N_3$ and N , and then finding a minimum of ΔN , ultimately yields—in contrast to the two-level system—

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

so that an occupation inversion can now be achieved above a saturation intensity I_s .

2 Bibliography

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3 Description of the Components

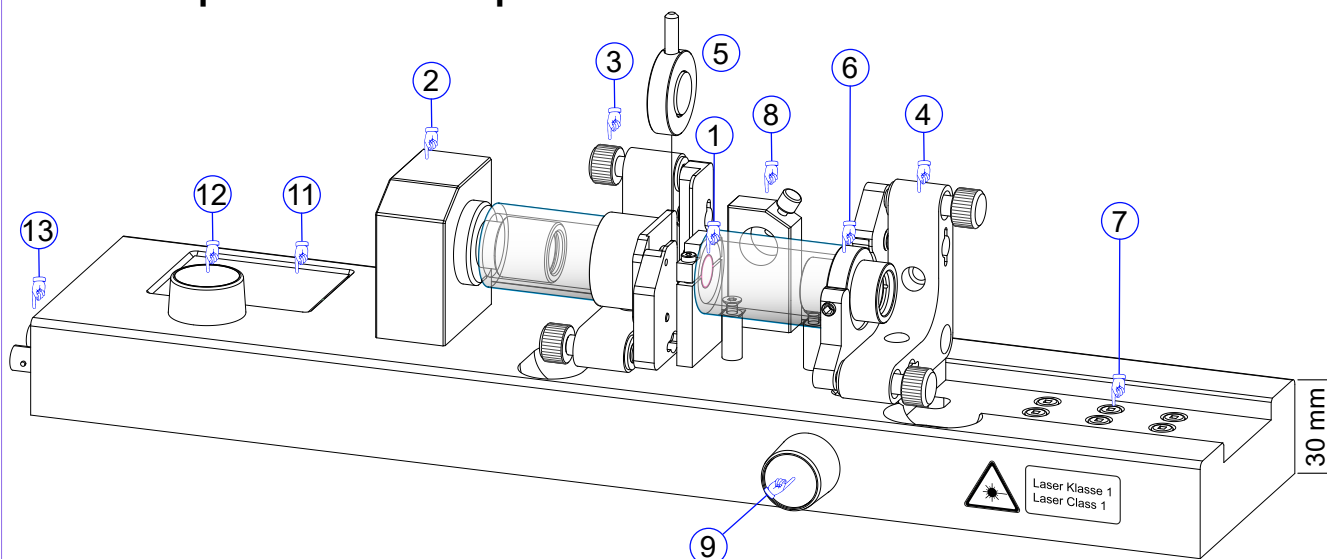


Fig. 10: The Pr:YLF Experimental Class 1 Laser

The Pr:YLF experimental laser is a Class 1 laser. This makes it a completely safe laser, and it can therefore be used in laboratory courses, student labs, and high school education for experiments involving the laser without any additional protective measures—including laser safety goggles.

A safety system ensures that no radiation can escape from the laser or be emitted during experiments with the laser. If an experimental component is connected incorrectly or the selective resonator mirror (5) is removed, the laser shuts off immediately. The optical axis runs through the center of an acrylic tube, so that everything is clearly visible and no objects of any kind can enter the beam path.

The device is compact and approximately 40 cm long; it is powered via USB-C using a Power Delivery AC adapter or a compatible power bank. The laser features a fully adjustable resonator with a length adjustment range of approximately 6 mm, and one of the mirror holders (3) can be used with any of three different selectively reflective mirrors (5). The resonator's length is adjusted by moving the broadband-reflective output mirror along the optical axis using a rotary knob on the front of the base block (9).

The unit is prepared for operation by entering the security code via the display's touch screen (11). The menu is self-explanatory; however, it is described in detail on page XX. Select "Diode Laser" to switch to CW laser operation. Next, press the green power button in the menu, then use the physical rotary knob to set the desired current for the 445 nm diode laser, which continuously pumps the laser crystal. Currents of up to 1400 mA are possible here. With a well-adjusted resonator, stable laser operation is possible for the red lines starting at approximately 350 mA and for the green line starting at approximately 700 mA. The current value is displayed digitally in the menu.

The laser has a safe experimental area with three slots for inserting the five different components: (1) screen, (2) photodiode A, (3) filter box, (4) analyzer, and (5) camera.

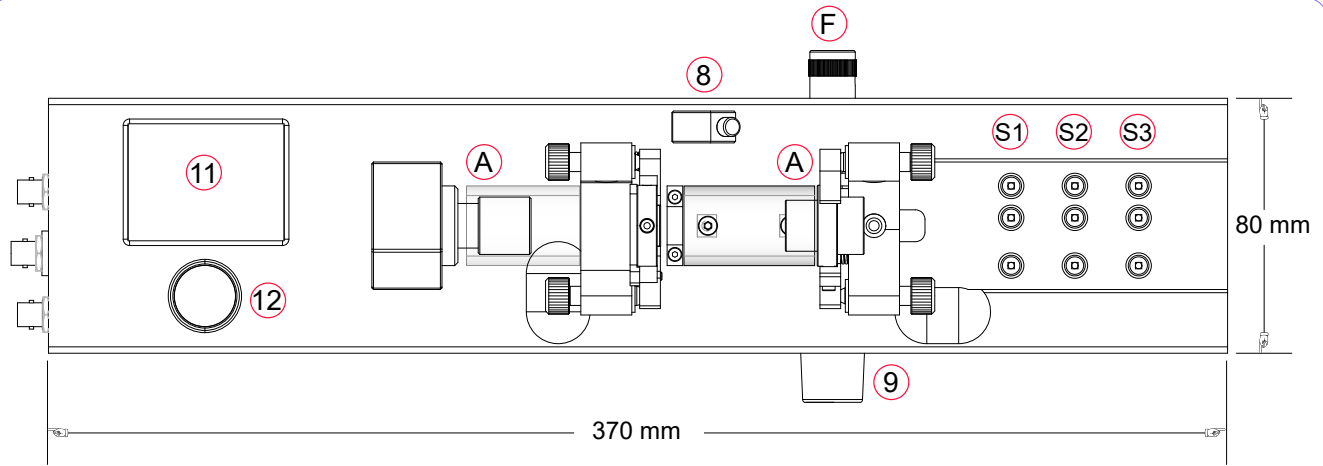
The "Modulation" option in the menu allows you to select a modulated pump mode. In this mode, the 445 nm pump diode laser is driven by square-wave pulses of adjustable frequency, so that

- when the resonator is out of tune (without laser operation), it is possible to measure the time behavior of the fluorescence of the metastable level using the side-mounted "Photodiode B," and
- With the resonator adjusted—that is, in laser operation with "Photodiode A" in the first slot of the experimental section—the delayed onset of laser activity, the initial spike, and the spiking can be observed.

In the menu, you can use the "Photodiode" option to adjust the sensitivity of the photodiode amplifier.

The menu also displays which experimental components are inserted in which slots and whether the respective combination is permitted or prohibited from a safety standpoint. Prohibited combinations are labeled "incorrect" in the menu. The experimental components are encoded via EPROM and are thus identified by the electronics. Incorrect insertion, which could lead to the unintended emission of laser radiation, results in the immediate automatic shutdown of the laser. The laser can only be turned on again after the arrangement of the components has been corrected accordingly. The wavelength-selective plane mirrors (5), which can be inserted into the mirror holder (3), are detected by magnetic sensors. When the mirror is removed from the holder, the diode laser that generates the pump radiation shuts off immediately.

The laser can be shut down immediately by pressing the rotary knob.



The laser has a secure experimental area with three slots—S1, S2, and S3—for inserting the five different components: (1) screen, (2) photodiode A, (3) filter box, (4) analyzer, and (5) camera. The following combinations of experimental components are possible:

- Shield in position S1
- Photodiode in position S1
- Analyzer with a photodiode in position 2
- "Filter holder" in position 2 and camera in position S3

"Photodiode B" or an "optical fiber" can be inserted into a side-mounted holder (8).

3.1 Electronics

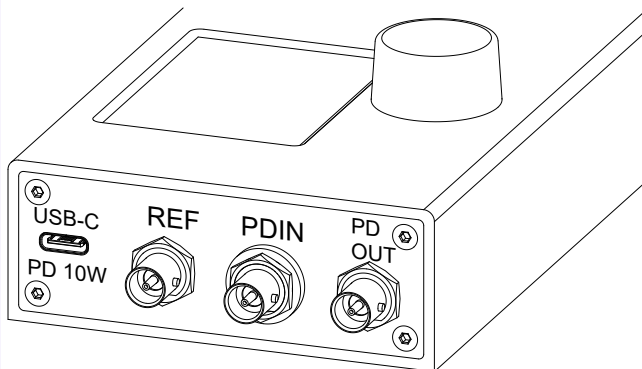


Fig. 11: The Connectors on the RL4000

Power is supplied via the included USB-C AC adapter with Power Delivery technology. The RL4000's electronics require a 9V voltage from the USB-C AC adapter. The digital signal from the pump laser diode is available at the "REF" BNC jack. When the laser diode is on, a "High" signal is present; when it is off, a "Low" signal is present. If the laser diode is modulated, a corresponding TTL signal is available that can be used to trigger an oscilloscope. The photodiodes are connected via their mini-BNC jacks to the "PDIN" input. The RL4000's electronics convert the photocurrent into a linear voltage, which is available at the "PDOUT" output.

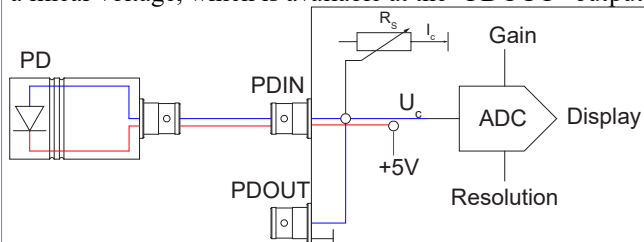
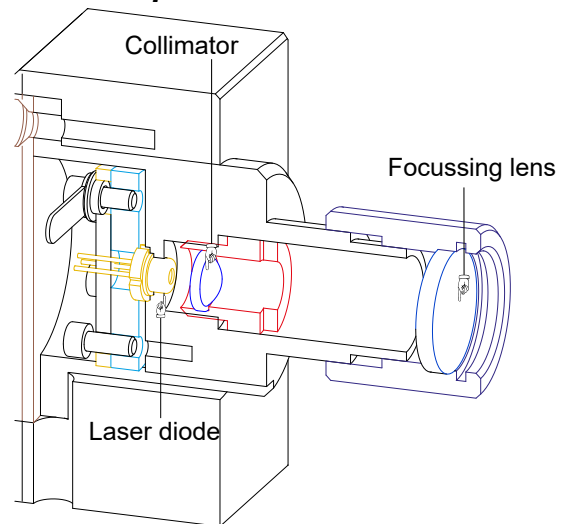


Fig. 12: Photodetector Circuit

The photodiode (PD) is connected in the reverse bias direction to 5V. The photocurrent flows through the resistor R_s

and generates a voltage drop U_c , which is available at the PDOUT connector. At the same time, the photovoltage U_c is processed by an analog-to-digital converter (ADC). The internal microprocessor allows the shunt resistor and the ADC gain to be adjusted via the display.

3.2 The Pumped Laser Diode



The laser diode is operated at an adjustable current, with a maximum limit of 600 mA. The laser diode is housed in a TO18 package, in which the cooling flange has a diameter of only 5.6 mm. Therefore, a very precise mechanical mounting is required to safely dissipate the generated heat. The divergent radiation from the laser diode is adjusted to be nearly parallel using a collimator and then focused by a plano-convex lens with a focal length of 50 mm. The focusing lens is housed in an adjustable objective so that the resulting focal point lies exactly within the Pr:YLF crystal. These settings are factory-set and cannot be changed by the user.

3.2.1 The Resonator

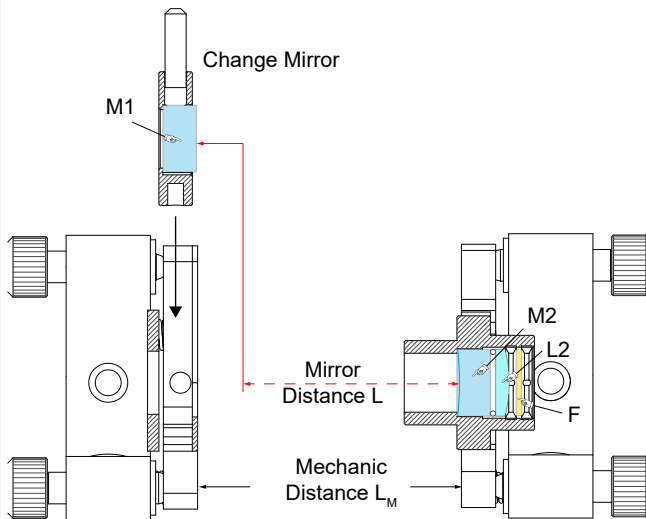
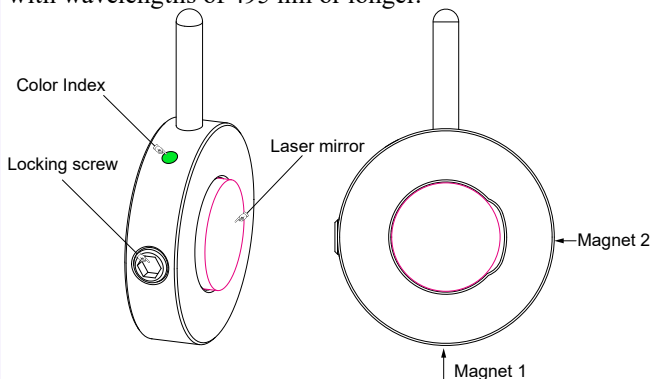


Fig. 13: Resonator Design

The flat mirror M1 has a mirror coating that provides high transmission for the pump wavelength of 405 nm (>90%) and high reflection (>99.98%) for the respective Pr:YLF laser wavelength. Mirror M2 has a radius of curvature of 50 mm; its coating is highly reflective for the pump wavelength and has a transmission of 1% for the Pr:YLF laser wavelengths.

For the laser beam transmitted through mirror M2, the mirror acts as a diverging lens with a focal length of approximately -50 mm, giving the appearance of greater laser divergence. For this reason, a plano-convex lens (L2) with a focal length of 50 mm is positioned directly behind mirror M2. To completely suppress unwanted residual pump radiation, a yellow filter (F) is also used, which transmits only radiation with wavelengths of 495 nm or longer.



Three interchangeable, wavelength-selective plane mirrors are available for the left resonator mirror holder, allowing for laser operation with either the green, orange, or red line. After changing the mirror, only minor readjustments are required, and the current may need to be readjusted.

The M1 plane mirror is mounted in a holder and secured with a locking screw; it can be removed and reinstalled for cleaning purposes. The holder has two built-in radial permanent magnets: magnet (1) holds the mirror in place within the adjustment holder, and magnet (2) is used for detection by a magnetic sensor in the adjustment holder. The mirrors are distinguished by a color code:

Red vapor deposition 500–700 nm
 Yellow selective evaporation for the 608 nm line
 Green-selective evaporation for the 521 nm line

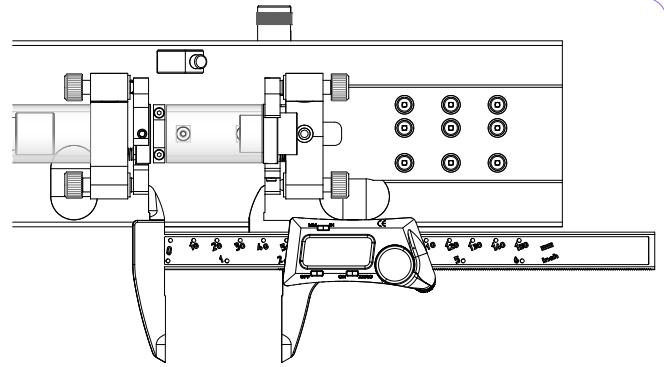


Fig. 14: Measuring the mechanical distance L_M

To precisely determine the mirror spacing—and thus the resonator length—a vernier caliper is used to measure the mechanical distance L_M between the mirror mounts.

The mirror distance L is then calculated as L_M minus 1 mm. For example, if L_M is determined to be 51.2 mm, the mirror distance is $L = 50.2$ mm.

When calculating the optical resonator length L_{opt} , it is important to note that the Pr:YLF crystal has a thickness of 5 mm and a refractive index of 1.45.

The optical resonator length is then calculated as follows:

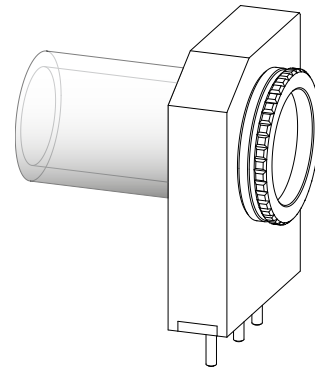
$$L_{opt} = L_{Rubin} \cdot n_{Pr:YLF} + (L - L_{Pr:YLF}) \cdot n_L$$

Using the stability criterion for the laser resonator

$$L_c \leq L_{opt} = 5 \cdot 1.45 + 45 = 52.3 \text{ mm}$$

This results in a maximum resonator length of 52.3 mm for stable laser operation. The RL4000's resonator adjustment range is 49–54 mm.

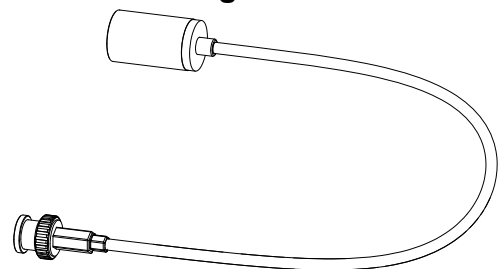
3.3 The display screen



This module contains a transparent plate onto which the laser beam—or even just its fluorescence—is projected. The module goes into the first slot and is recognized as a “screen.”

3.4 Photodetectors

3.4.1 For measuring fluorescence

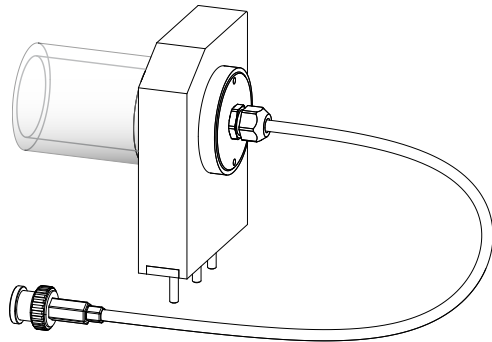


This photodetector A is designed to measure the fluorescence of the pumped Pr:YLF crystal. The detector is inserted into the side detector mount (8) and secured with the set screw; see Fig. 10. If available, an optical fiber can also be

inserted into this mount to record the fluorescence spectrum using a spectrometer. Both experiments can be performed without laser operation—that is, without an aligned resonator.

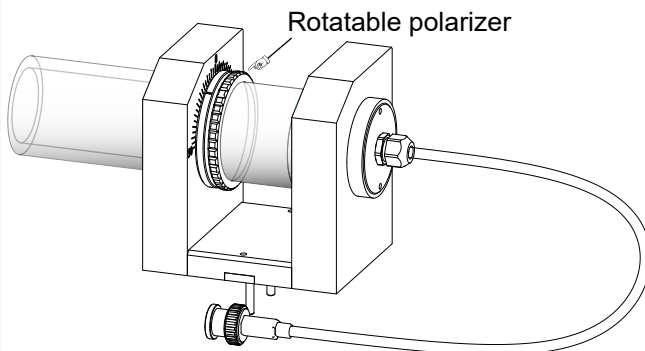
The BNC cable is connected to the “PDIN” BNC jack (see Fig. 11). The amplifier for photodiode A, whose gain must be set in the menu, is located in the laser’s base unit. Photodiode A must be connected via its BNC cable to the amplifier’s input (mini-BNC jack on the left side of the base block). The mini-BNC jack for the photodiode amplifier output is also located there. Measuring instruments, such as an oscilloscope or multimeter, can be connected there (Fig. 11).

3.4.2 For measuring laser emission



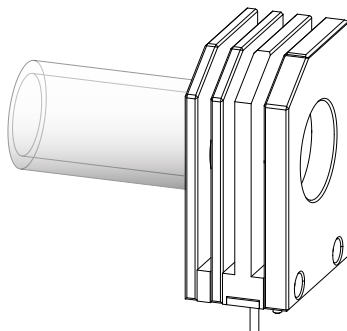
This photodetector module is inserted into slot 1 and is designed to detect laser emission. The BNC cable is connected to the “PDIN” BNC jack (see Fig. 11).

3.4.3 The Polarization Module



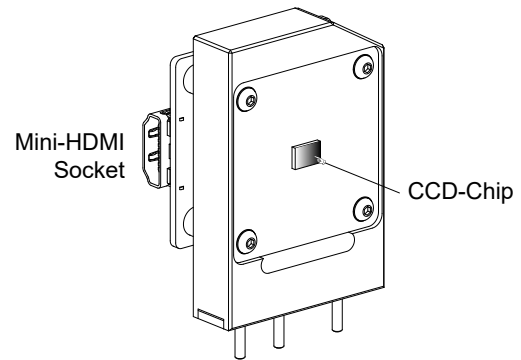
This module is used in slot 2. The front mounting plate, which features a scale (-90 to $+90^\circ$), contains a rotatable polarizer with a scale mark. The BNC cable is connected to the “PDIN” BNC jack (see Fig. 11).

3.5 The Filter Box



The filter box is designed to hold 50x50 mm filters as well as slide frames with optical structures. The “filter box” element has three slots for inserting, for example, neutral density filters or optical elements such as gratings,

3.6 The Camera Module



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

Technical Specifications

- Compatible with all Raspberry Pi models
- Sony IMX477R Sensor (1)
- 12.3-megapixel resolution
- 7.9 mm sensor diagonal
- $1.55 \mu\text{m} \times 1.55 \mu\text{m}$ pixel size
- 1-meter Mini HDMI cable for connecting to the Raspberry Pi

The camera module operates in slot 3 and requires the filter module in slot 2 at the same time. The module is connected to the Raspberry Pi via an HDMI (mini) cable; the Raspberry Pi is equipped with a screen for observing the fluorescence spots, the laser spot, the TEM modes, and the diffraction patterns, etc. The camera software automatically adjusts the detector sensitivity according to the light intensity. This provides a wide dynamic range, which is necessary, for example, when switching from observing fluorescence spots to laser activity. Depending on the intensity, an additional ND filter (OD -1, OD -2, and/or OD -3) may be required.

3.7 Camera Control Unit (CC)



The camera control unit uses a Raspberry Pi 5 Proprocessor with the standard Linux distribution. The official Raspberry Pi 7-inch Display 2 is used as the display.



The Raspberry Pi is housed in a metal enclosure, and the communication ports—such as USB 2.0, USB 3.0, and LAN—are accessible on the back of the enclosure. The camera is connected to the control unit via an HDMI cable.

A USB-C cable and a USB-C power adapter supply the Raspberry Pi and the display with the necessary operating voltage. A mouse and a keyboard are each plugged into the USB 2.0 port.

As soon as the USBC power adapter is plugged in and the switch is set to the “On” position, the control unit starts up. After a few seconds, the startup desktop appears.

To operate the camera, the PiCam2023.py software is located in the /HOME/LE1600/LUHS directory. For convenience, a button has been added to the Start menu that launches the software directly.

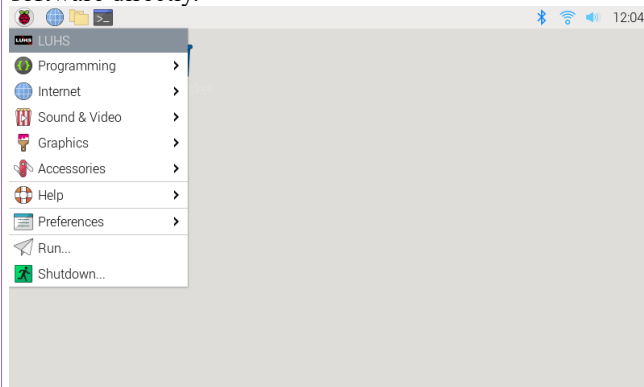


Fig. 15: Home screen: Select the "LUHS" menu item.

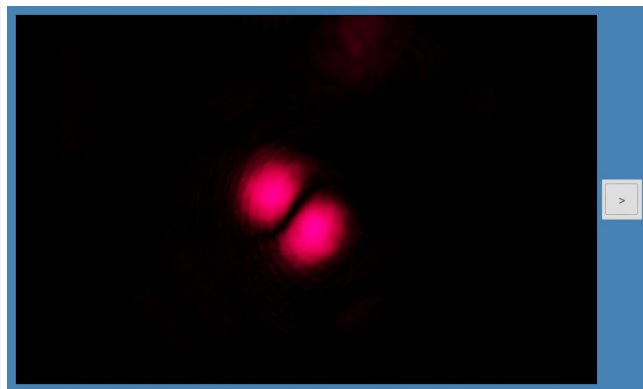
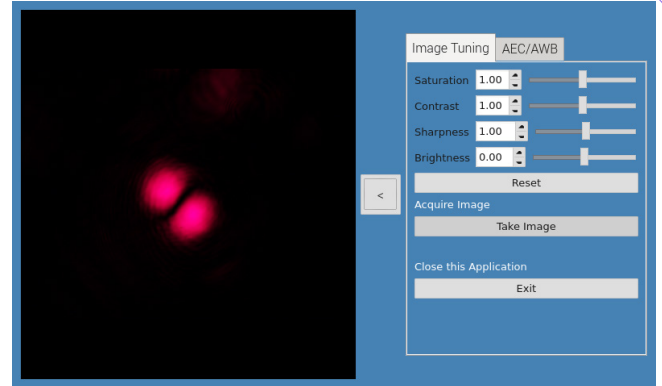
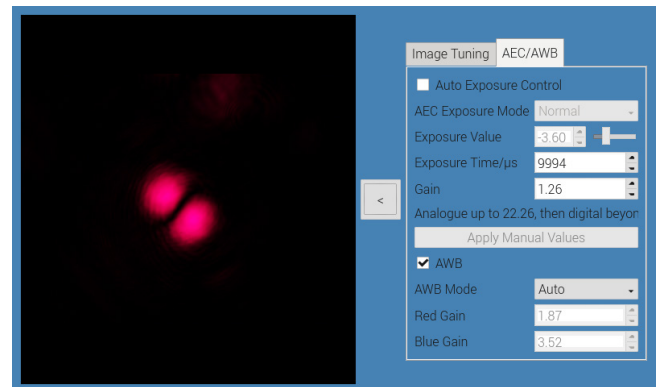


Fig. 16: The camera image is displayed. When you click the button with the arrow, another menu appears to the right of the image, containing image adjustment settings.

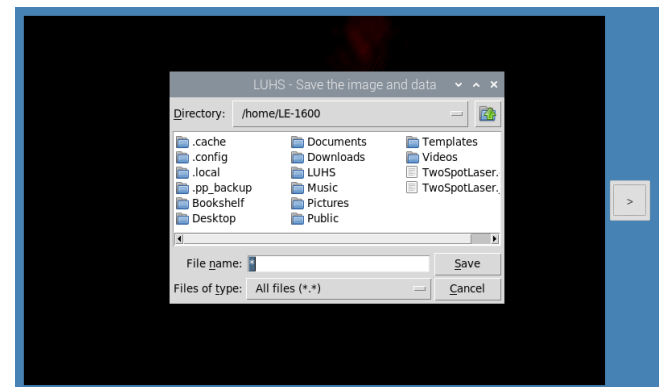


The Tabulator element has two tabs: “Image Tuning” and AEC/AWB. AEC stands for “Automatic Exposure Control” and AWB for “Automatic White Balance.” Both can be turned off and adjusted manually.



Once you've found the right settings, you can save the camera image.

To do this, click the "Take Image" button, and the following file dialog will appear:



You can also select a connected USB flash drive. Simply enter a filename (without the extension) and click “Save.”

A JPG image of the camera view is saved at the highest resolution ($4056 \times 3040 = 12.33$ MB), along with a numerical file containing the intensity values of each individual pixel. This file is a CSV (Comma Separated Values) file and can be opened with various analysis programs. This file is 70.6 MB in size, and it takes about 10 seconds for the saving process to complete.

3.8 The Control System

The RL4000 laser has two high-speed processors; one continuously monitors the plug-in modules, while the other responds to user input.

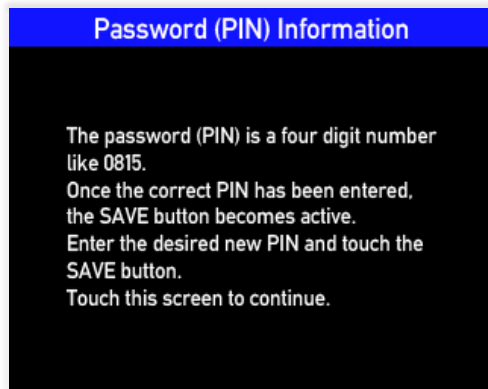
3.8.1 Display



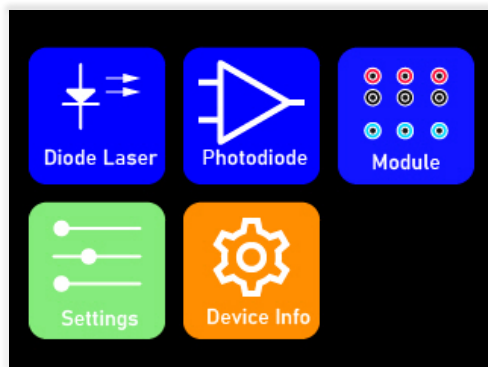
After connecting the USB-C power adapter, the startup screen appears and, after a few seconds, prompts the user to touch the screen to continue.



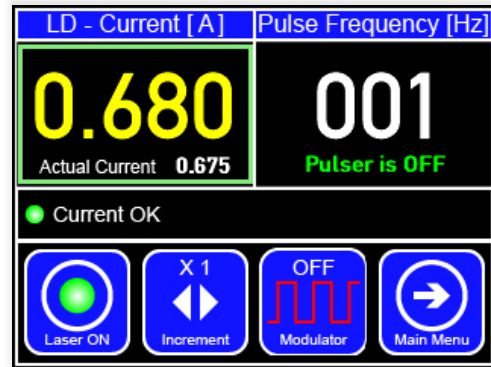
Next, the screen for entering the 4-digit PIN code will appear. Tapping the “HOW TO?” button will take you to the help screen.



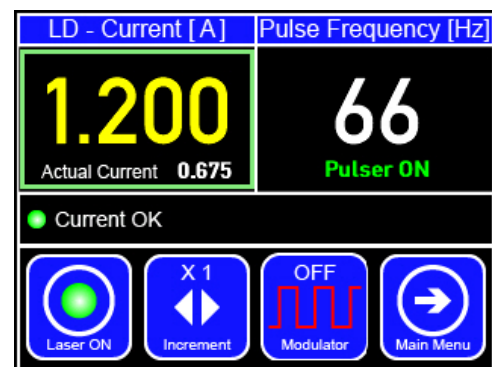
After entering the correct PIN, the main menu appears.



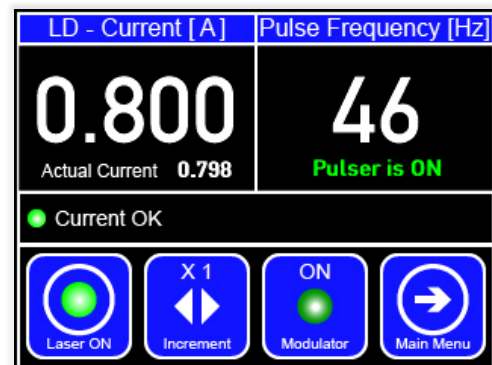
There are 5 options available here, which are explained below.



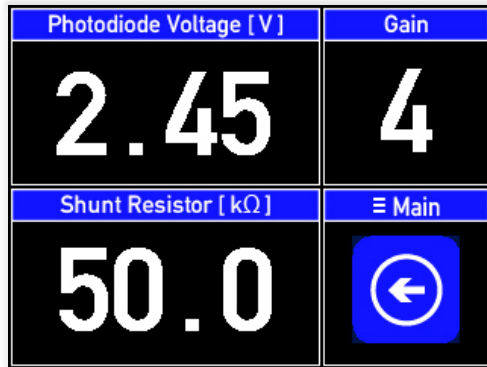
The laser diode menu displays the actual current (Actual Current) for the set current (Set Current). Touch the “Set Current” field to activate it, and turn the adjustment knob to set the desired value. Use the “Increment Button” to increase the increment from 1 mA to 10 mA. After tapping the “Laser ON” button, the laser diode turns on.



To reduce the thermal load on both the laser diode and the Pr:YLF crystal, automatic modulation at a frequency of 66 Hz is enabled when the current exceeds 1000 mA.



After tapping the “Modulation” button in the main menu, the following settings screen appears. This menu allows you to periodically turn the laser diode on and off—that is, to modulate it. Tapping the “Pulse Frequency” field activates it, and you can use the rotary knob to set the modulation frequency within a range of 1–100 Hz. The modulation is turned on or off by tapping the “ON/OFF Modulator” button.



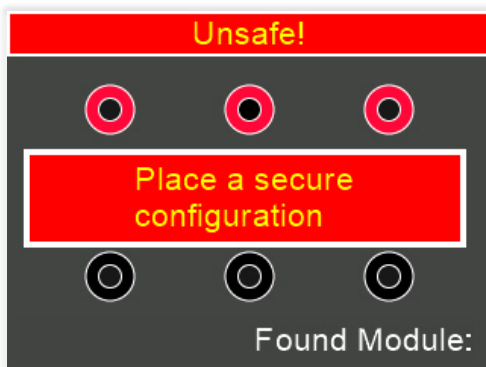
After tapping the “Photodiode” button in the main menu, the settings screen for the connected photodetector appears. By repeatedly tapping the “Gain” field, the gain of the analog-to-digital converter is set to 1, 2, 4, or 8, and the measured value is displayed. Tapping the “Shunt Resistor” field activates it, and the photodiode’s shunt resistance can be adjusted from 50 ohms to 50 kOhms by turning the adjustment knob.



The "Device Info" menu displays version information and hardware settings.

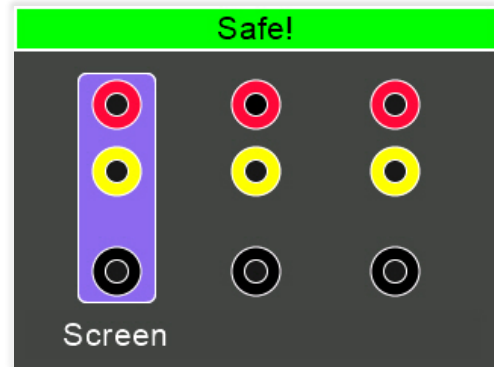


In the "Settings" menu, you can select either German or English as the language.

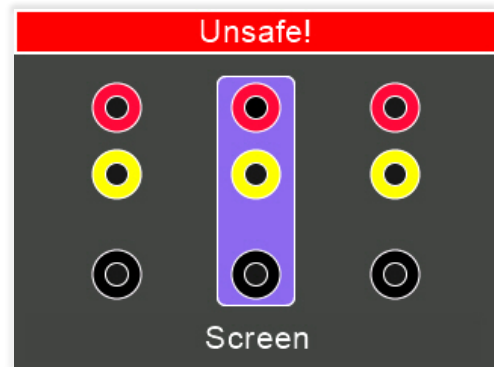


When you select the “Modules” menu item, information corresponding to the installed modules will appear. If no

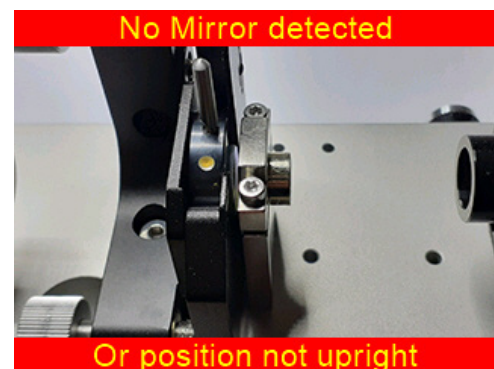
module or no valid combination of modules is installed, no additional menu items will be available.



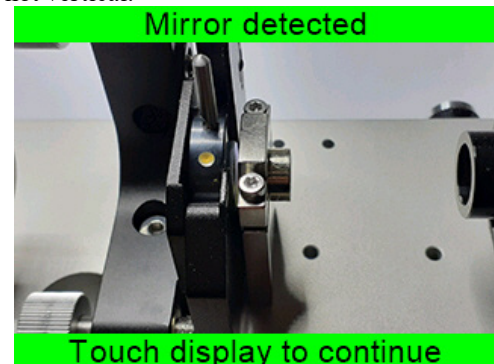
In this case, the screen is plugged into the correct slot, which is considered safe.



If, on the other hand, the screen is inserted into the wrong slot, the module name “Shield” appears along with the message “unsafe,” indicating an incorrect position. The laser turns off or cannot be turned on.



This message appears if no laser mirror is installed or if the pin is not vertical.



Once a mirror has been set up correctly, the message above appears. When you tap the screen, you'll be taken back to the page that was active before the mirror was changed.

3.9 The Photodiodes

The specifications of the photodiodes used are listed below.

Parameters	Symbol	Value	Unit
Rise and fall times of the photocurrent at: $R_L = 50\ \Omega$; $V_R = 5\text{ V}$; $\lambda = 850\text{ nm}$; and $I_p = 800\ \mu\text{A}$	t_r, t_f	20	ns
Capacitance at $V_R = 0$, $f = 1\text{ MHz}$	C_o	72	pF
Wavelength at which sensitivity is greatest	λ_{Smax}	850	nm
Spectral sensitivity S : 78% of S_{max}	λ	694	nm
Dimensions of the radiant-sensitive area	$L \times W$	7	mm ²
Spectral sensitivity, $\lambda = 850\text{ nm}$	$S(\lambda)$	0.62	F/W

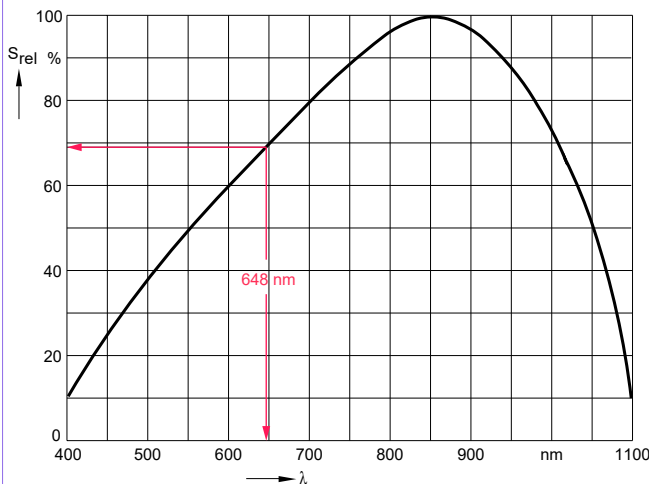


Fig. 17: Spectral sensitivity curve

For the 648 nm wavelength of the Pr:YLF laser, the detectors have a spectral sensitivity of

$$S = 0.69 \cdot 0.62 = 0.43 \frac{\text{A}}{\text{W}}$$

This means that for every 1 W of luminous power, a photocurrent of 0.43 A flows.

Assuming a voltage drop of 1 V is measured across the 1000-ohm shunt resistor, the photocurrent is 1 mA (Ohm's law). The corresponding light power is therefore 2.32 mW. Thus, the optical power of the Pr:YLF laser can be determined as long as the entire laser radiation strikes the relatively large detector area.

4 Demonstrations and Measurements

4.1 Measurement of the lifetime of the excited level

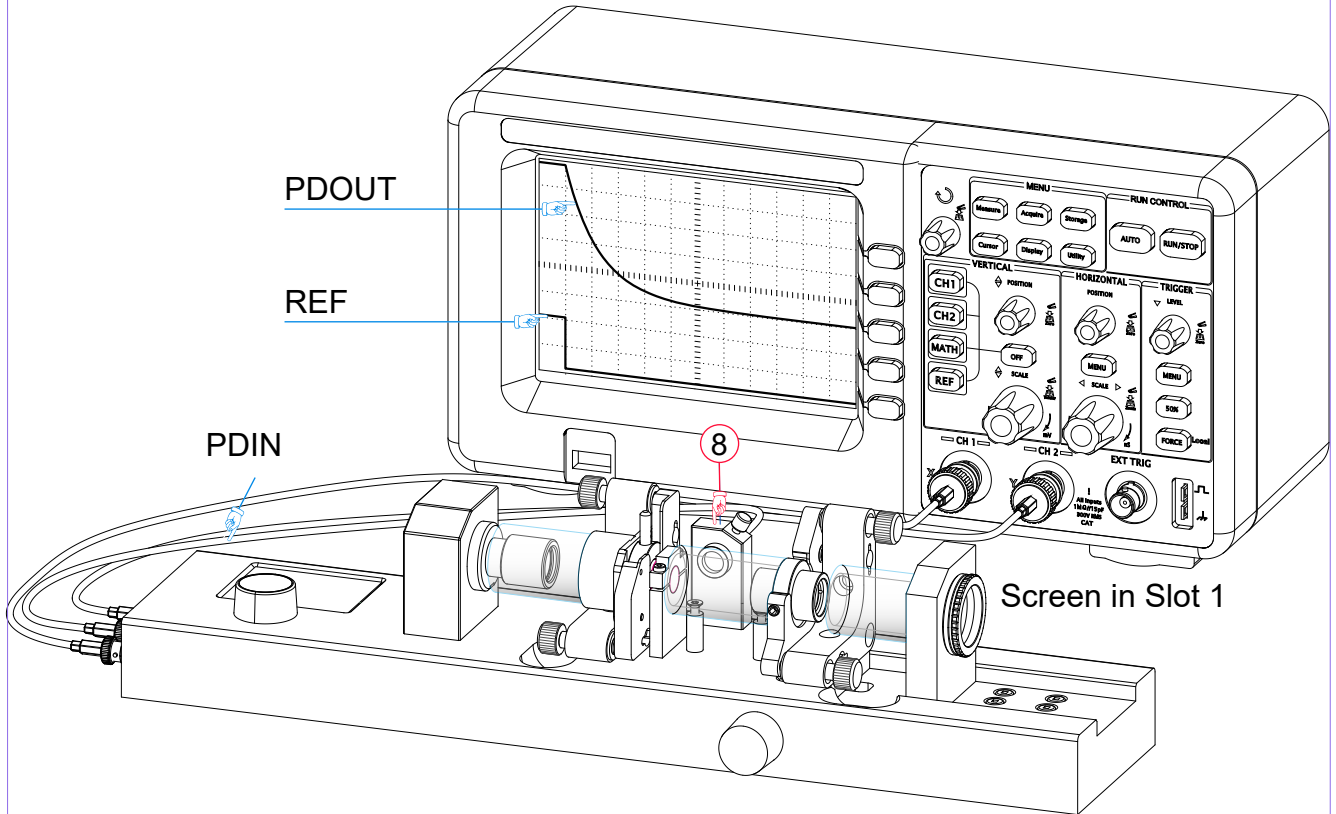


Fig. 18: Setup for Measuring the Lifetime of the Excited Level

For this experiment, insert the photodetector into the holder (8) and secure it with the locking screw. The detector should be inserted as far as possible to position it as close as possible to the Pr:YLF crystal. You will also need a two-channel oscilloscope. A digital oscilloscope is preferable, as it allows you to save the screen display as a graphic or data file.

Based on the decay curve:

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

for $t = \tau$

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

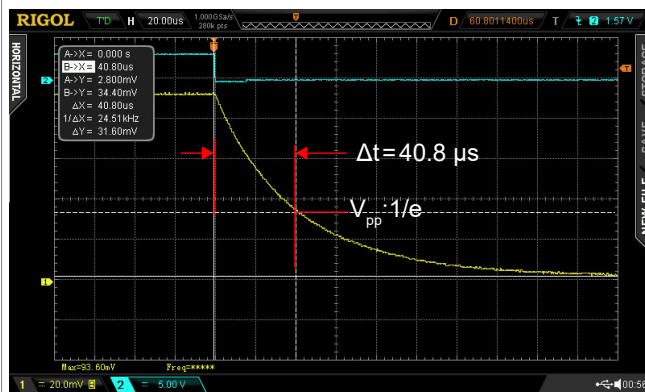


Fig. 19: Oscillogram of the fluorescence decay curve

To turn on the pump laser, at least the shield must be set to position 1. The photodiode signal (PDOUT) is connected to the first channel of the oscilloscope, and the reference signal (REF) for modulation is connected to the second channel. Triggering for the second channel is set to the falling edge, i.e., the photodiode's turn-off signal. The shunt resistor for the photodiode should not exceed 10 kOhm, and the modulation frequency should be approximately 30 Hz. With these parameters and a current of 600 mA for the laser diode, the oscilloscope waveform should look as follows:

So, exactly when the intensity (or photovoltage on the oscilloscope) has decayed to a value of $1/e$, the lifetime τ is reached. In this example, a lifetime of $40.8 \mu\text{s}$ is measured. For this measurement, the pumped diode laser must excite the Pr:YLF crystal, but laser operation is not necessary. The measurement can therefore be performed even if the laser resonator has not been aligned.

4.2 Fluorescence spectrum

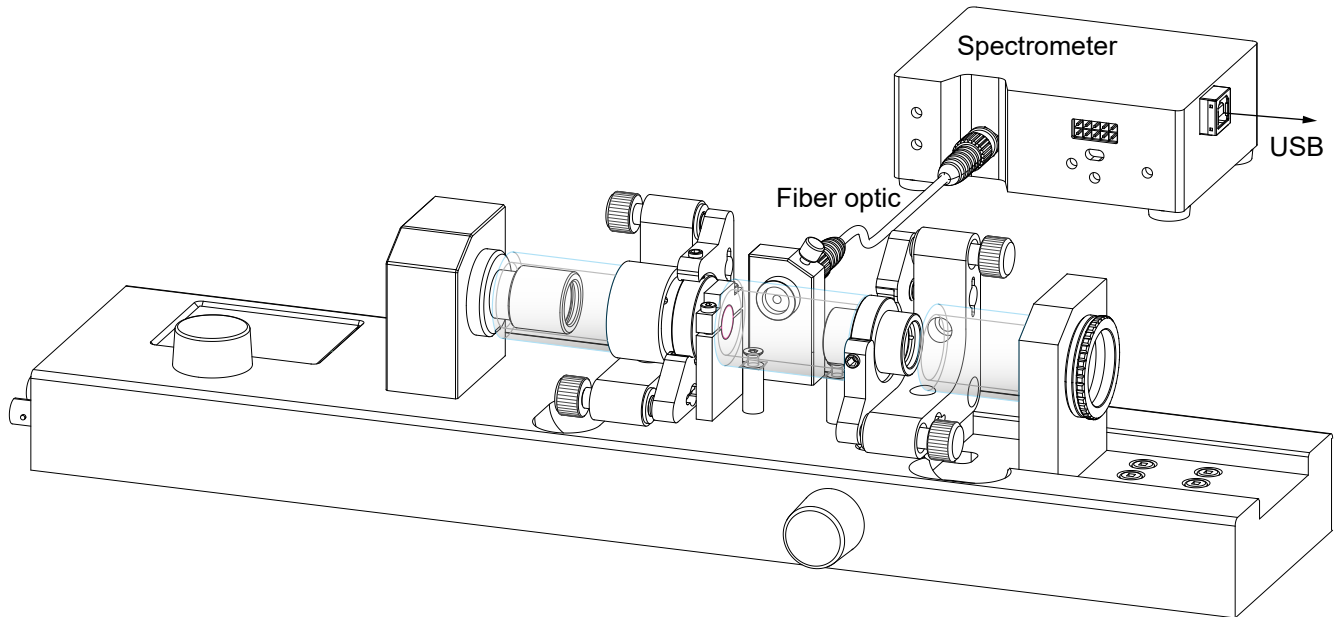


Fig. 20: Measurement of the excitation spectrum using a fiber-coupled spectrometer

An adapter with an F-SMA fiber connector is inserted in place of the photodetector. A fiber-optic cable with F-SMA connectors on both ends connects the adapter to the spectrometer. The

fluorescence intensity is high enough that imaging optics are not required. To analyze the recorded spectra, the spectrometer must be connected to a PC via its USB bus.

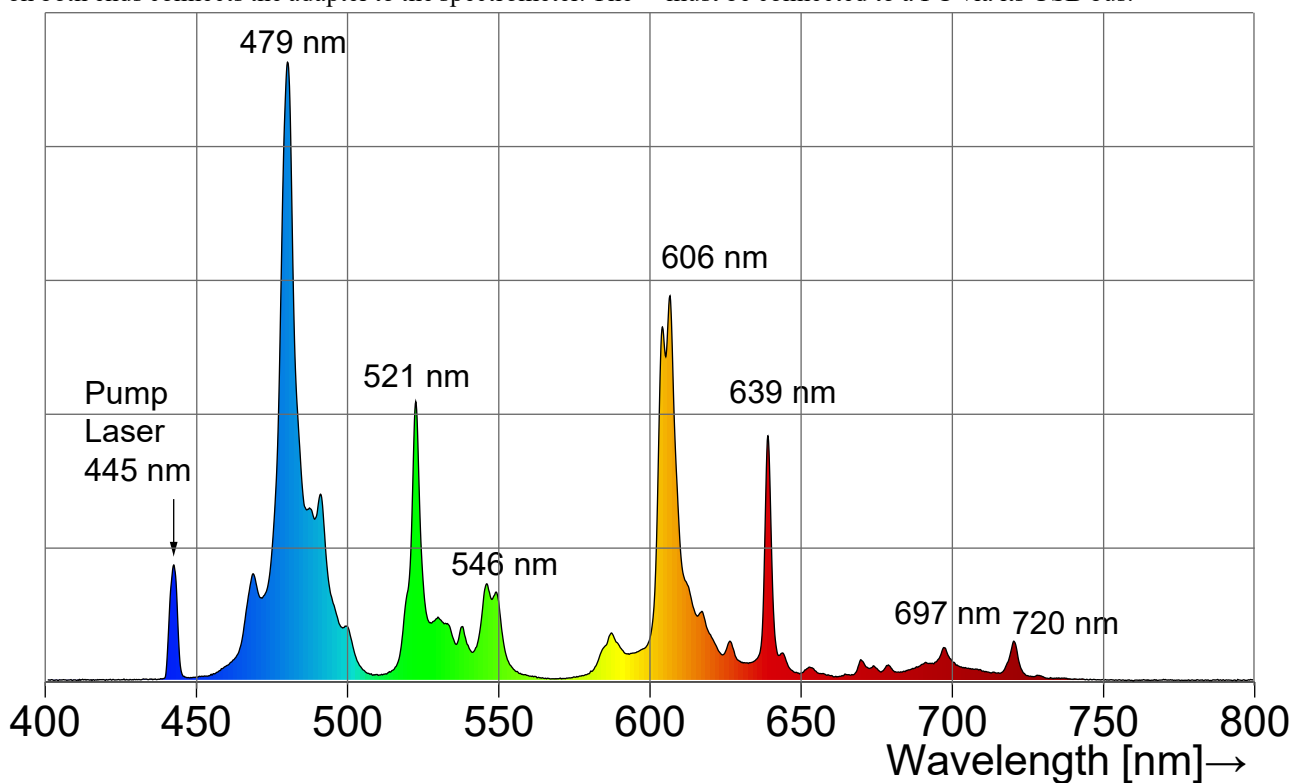


Fig. 21: Excitation spectrum of the Pr:YLF crystal

In addition to the pump wavelength at 445 nm, a large number of intense spectral lines can be observed. One might think that laser oscillation should be possible on all of these lines. Take, for example, the strong line at 479 nm; however, this line ends in the ground state, and population inversion is therefore difficult to achieve. The following table lists the most important lines. For the wavelengths marked with an asterisk (*), laser oscillation is achieved in this experiment.

Wavelength (nm)	Transition	Effective cross-section 10^{-19} cm^2
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

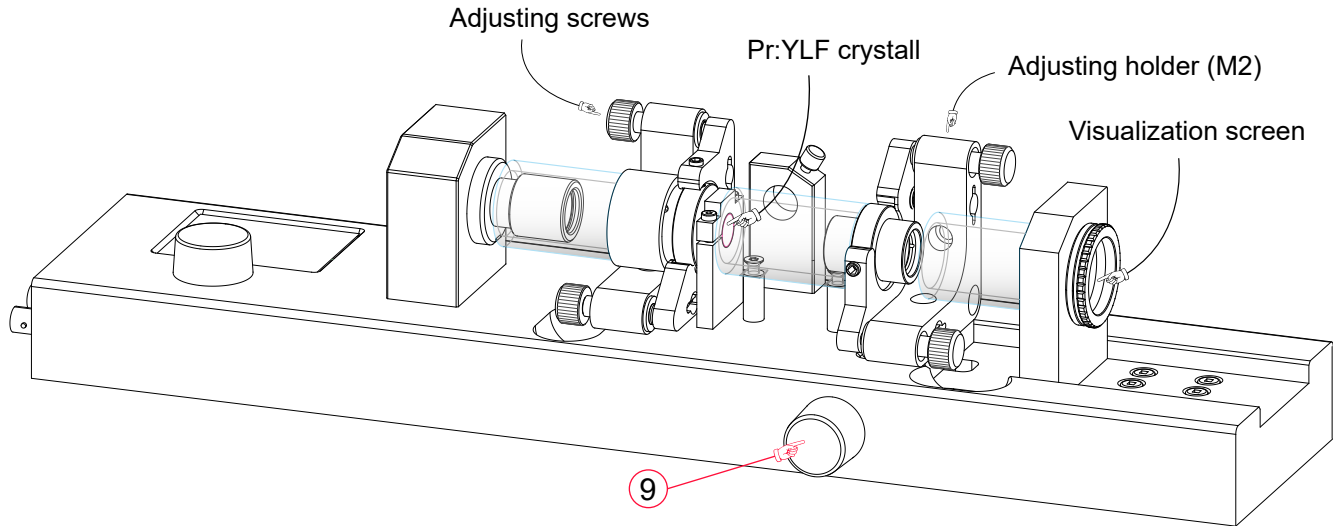
Table 2: Cross-sections of the main lines and their transfers, by reference 4

4.3 Adjustment of the Pr:YLF Laser

Laser alignment refers to the process of aligning the resonator mirrors so that they are parallel to one another. For this purpose, the mirrors are mounted in precision alignment holders that allow each mirror to be tilted independently in the horizontal or vertical plane by turning the adjustment screws. Once the mirrors are aligned parallel to each other and other relevant parameters, such as pump power and resonator length, have been selected appropriately, the laser will “start up.” The pump

power is then first set to its maximum value. This is done by setting the diode laser current to its maximum value. So how can you tell if the resonator mirrors are aligned parallel to each other and perpendicular to the pump radiation? This step can be performed using the visualization screen or the camera module. Both methods are based on the principle of utilizing the fluorescent radiation circulating within the resonator.

4.3.1 Using the display screen



To do this, look at the visualization screen. In a darkened environment, you will observe two fluorescent spots (a) and (b). Because mirror M2 has a transmission of 1%—albeit a small one—a corresponding portion of the fluorescent radiation will escape from the resonator and become visible on the screen (Fig. 22).

If the fluorescent spots are not as clearly visible as in the Fig. 22, reduce the resonator length by turning the adjustment knob (9) accordingly.

By adjusting mirror M2, you can now align the two spots so they are superimposed.

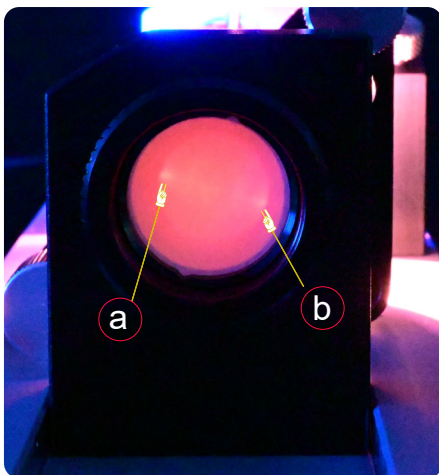


Fig. 22: Fluorescent spots on the visualization screen

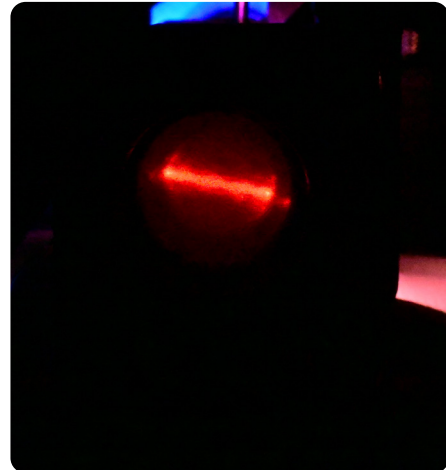
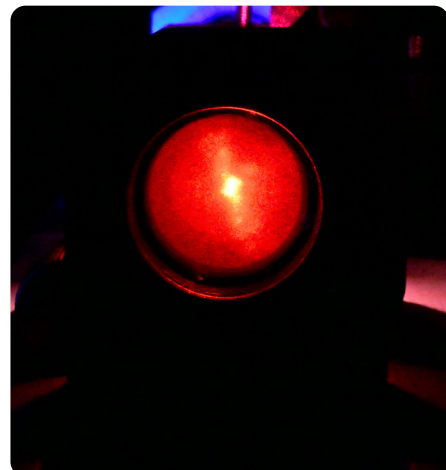


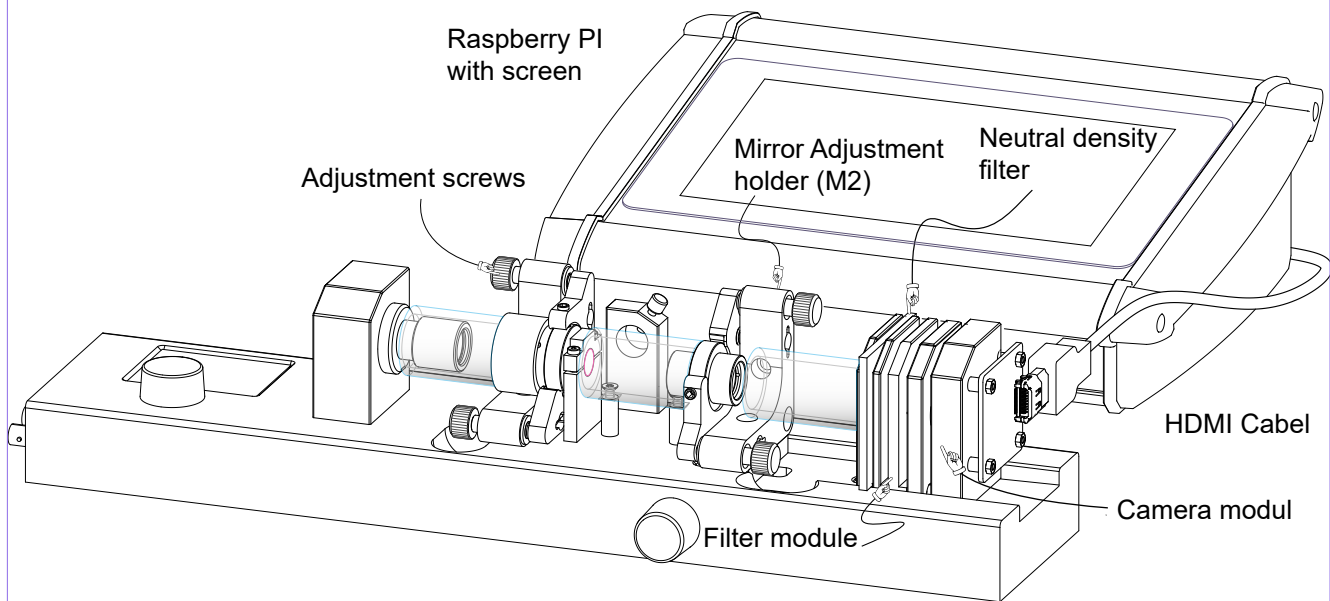
Fig. 23: The laser is “on”!

Due to the high gain of the Pr:YLF material, all possible transverse modes are excited.

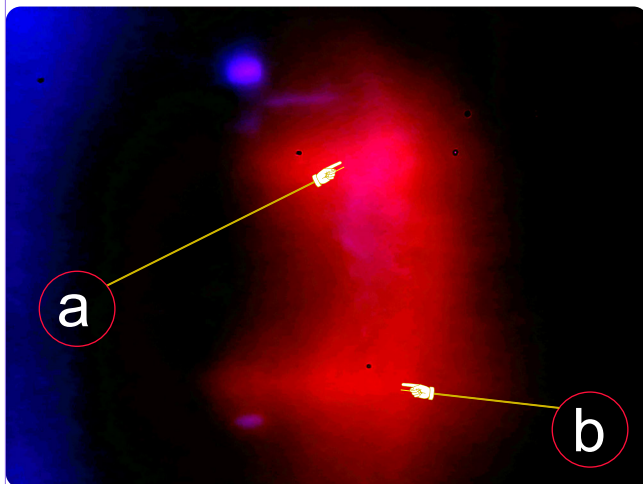


By making fine adjustments, you can achieve modes that are nearly identical to TEM_{00} .

4.3.2 Adjustment Using the Camera Module



In this configuration, the filter module is installed in slot S2 and the camera module in slot S3. To prevent the camera from being overexposed, one or more of the three neutral density filters are inserted into the filter module as needed.



Instead of the visualization screen, we use the CCD chip of the Raspberry Pi camera here, and we view the image on the screen. Here, too, we can see the two fluorescent spots (a) and (b), which must be aligned one above the other using the adjustment bracket (M2).

Because the intensity distribution of the laser diode is elliptical, we observe "non-circular" fluorescence spots.

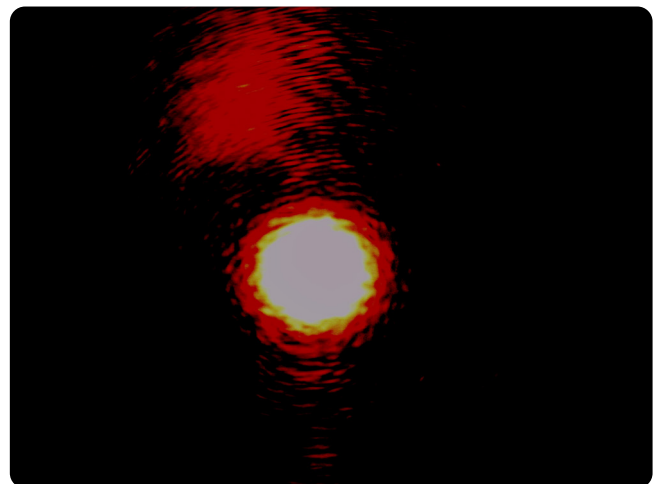
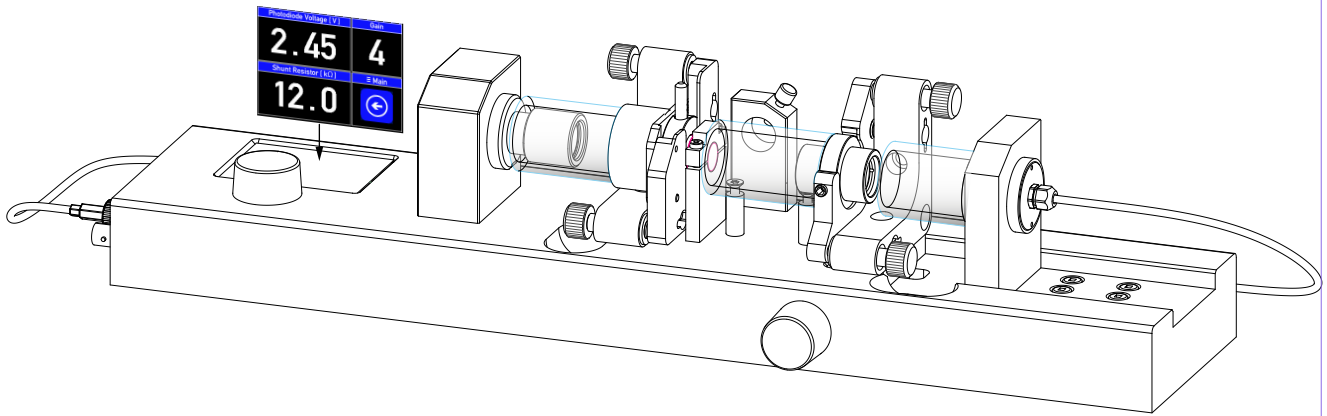


Fig. 24: Once the spots are aligned on top of each other, intense laser radiation is produced.

4.4 Measurement of laser power, slope efficiency, threshold



For these measurements, use the photodetector module, which is inserted into slot 1. In the photodetector menu, set the values for the shunt resistor and the gain. 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

$$a_s = \frac{P_{opt}^2 - P_{opt}^1}{I_2 - I_1} = \frac{2.7 \cdot 10^{-3} - 0.22 \cdot 10^{-3}}{0.48 \cdot (350 - 200)} = \frac{2.48 \cdot 10^{-3}}{72} = 0.034 \cdot 10^{-3} \frac{W}{mA}$$

At a laser diode power of 600 mW, the Pr:YLF laser emits a remarkable 20.4 mW (example).

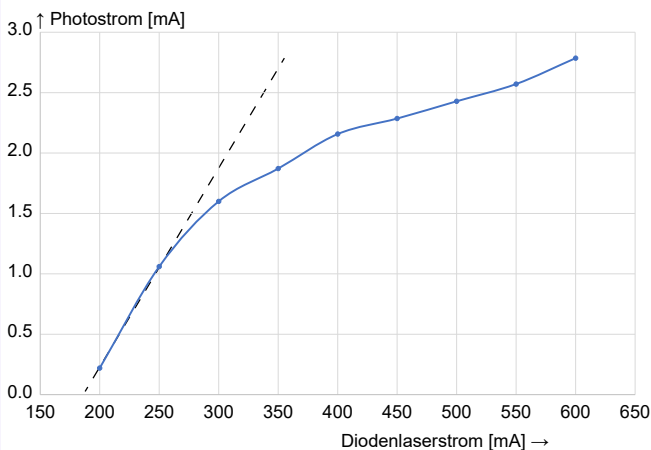


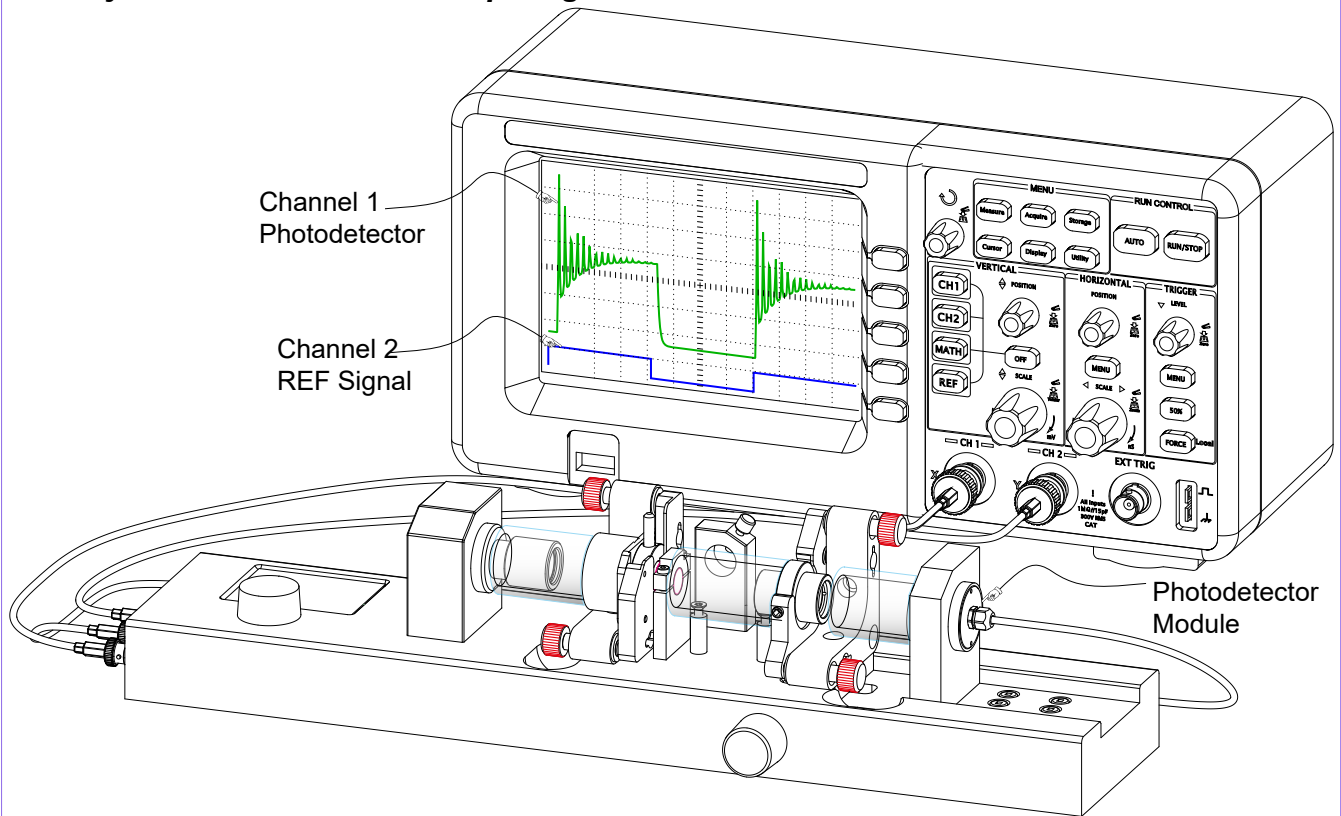
Fig. 25: The measured photocurrent as a function of the diode laser current

It can be seen that the photodetector becomes nonlinear due to saturation effects at a pump current of approximately 270 mA. However, this effect could be shifted by selecting a more appropriate shunt resistor. The dashed curve would result if the photodetector were not saturated. The zero-crossing point of the dashed curve indicates a laser threshold of 180 mA. Using the value of 0.43 A/W (Fig. 17), we can convert the photocurrent I_{phot} to optical power P_{opt} :

$$P_{opt} = \frac{I_{phot}}{0.43}$$

The "slope efficiency" a_s is the slope of the linear curve and is calculated as follows:

4.5 Dynamic Measurements, Spiking



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

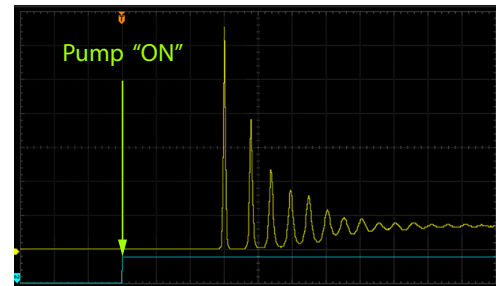


Fig. 28: Laser Response at Low Pump Power

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

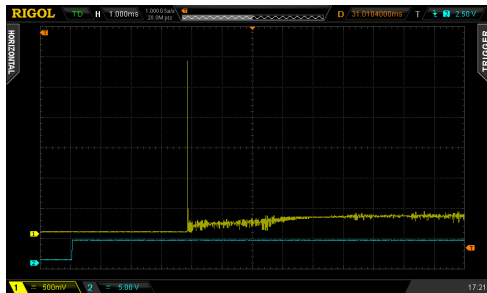


Fig. 26: Typical "initial spike" and transition to CW operation during the pump pulse

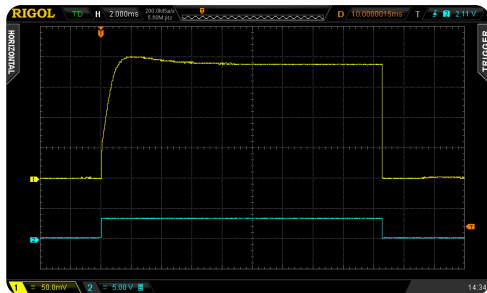
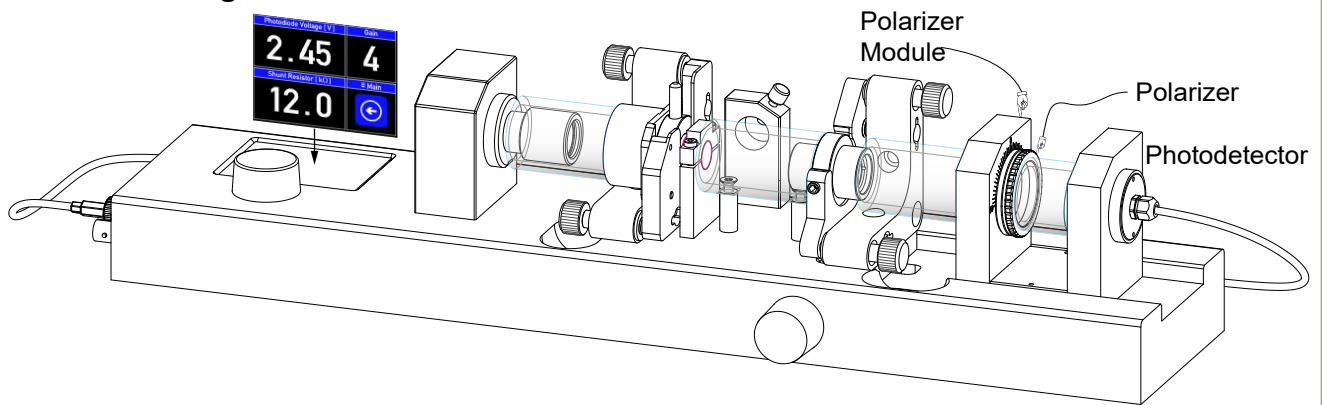


Fig. 27: Laser Response at High Pump Power

4.6 Measuring Polarization - Malus's Law



This setup is used to measure the polarization of the Pr:YLF laser. To do this, insert the polarization module into the second slot. The module features a rotatable polarizer and a photodetector, which is connected to the “PDIN” jack via its BNC cable.

Select the appropriate parameters in the photodetector menu. To do this, set the polarizer to maximum voltage and ensure that no “overload” is indicated. Now turn the polarizer to the “dark” position and observe whether lower voltage values are displayed. Also note that the laser power should not be set too high to prevent the photodetector from saturating in the “light” position.

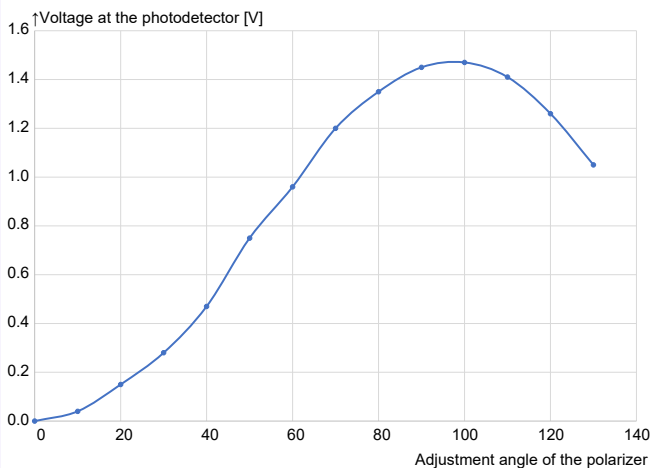
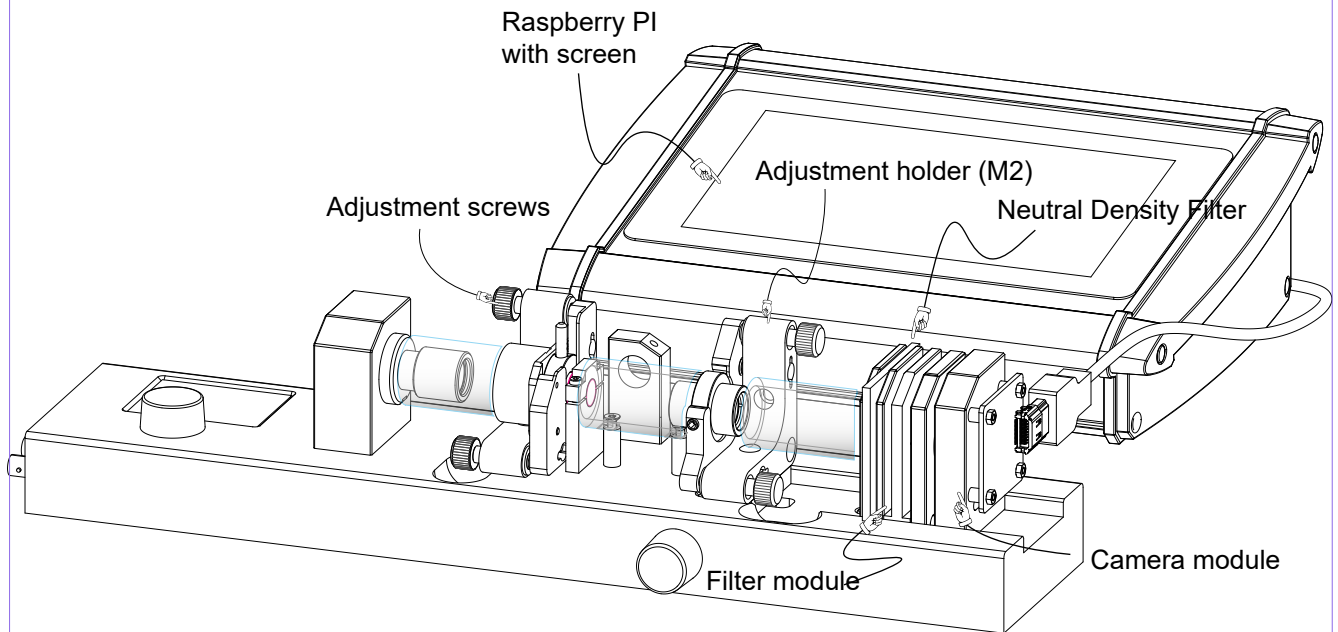


Fig. 29: Measured photovoltage as a function of the angle of rotation of the polarization filter acting as an analyzer

Addition: To verify the Malus law, the measured curve should be fitted with a $\cos^2$ function. Plotting the data in polar coordinates is also very illustrative. The position of the “eight” in the polar coordinate diagram can be used to determine the orientation of the crystal axis of the Pr:YLF crystal.

The measurements are performed for each of the laser wavelengths. It is shown that the polarizations of the green and red lines are perpendicular to each other.

4.7 Demonstration of Transverse Modes



We will use the same setup that we used to adjust the Pr:YLF laser.

It can be observed that the number of transverse modes increases near the maximum adjustable resonator spacing. This setting should be chosen when one wishes to observe higher transverse modes. If, on the other hand, lower modes—or, in particular, the TEM_{00} mode—are desired, smaller resonator spacings should be set. Other parameters that can influence the occurrence of transverse modes are the pump power and the alignment of mirror M2. The closer the laser operates to the threshold, the fewer transverse modes occur.

The following photos show a selection of such styles.

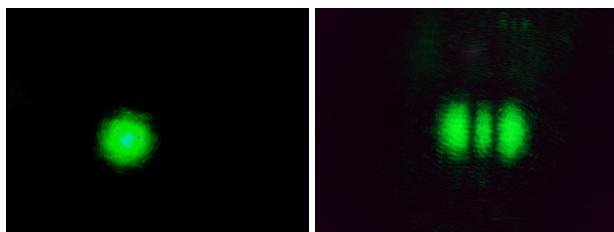


Fig. 30: TEM_{00} Mode and TEM_{20} of the Green Line

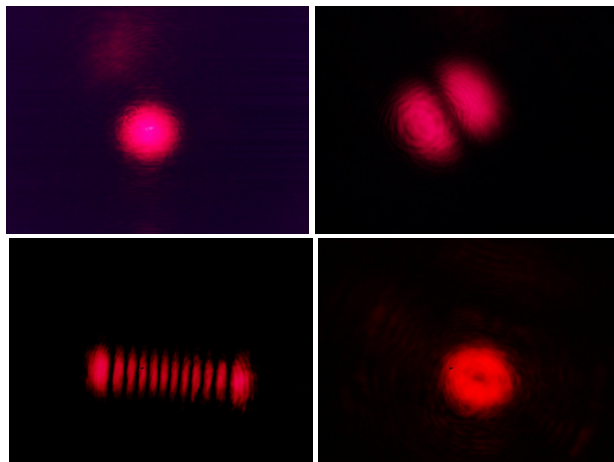


Fig. 31: TEM and Dough Nut Mode on the Red Line

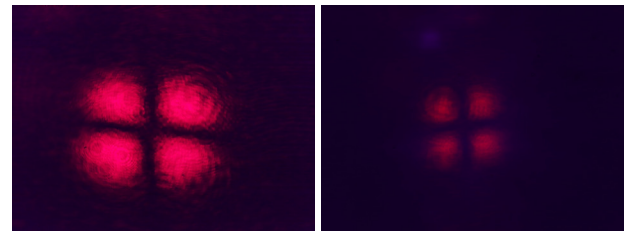
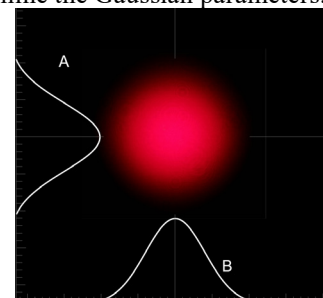


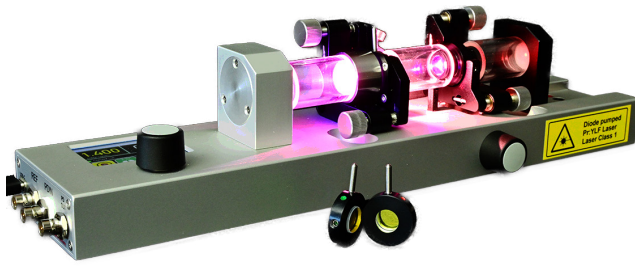
Fig. 32: "Cloverleaf" fashion from the red (left) and orange lines

The intensity distribution of the TEM_{00} mode is now captured by the camera ("take picture") and saved to a memory stick. Using the camera software, the "color saturation" and "brightness" can be adjusted. If the camera's dynamic sensitivity control is insufficient to reduce intensity that may still be too high in the center of the mode, a neutral density filter (OD=2 or 3) is also inserted into the filter box.

The recorded image can then be analyzed using the Gaussian Fit program on another computer to verify its shape and determine the Gaussian parameters.



4.8 Wavelength Change by Changing Mirrors



Three interchangeable, wavelength-selective flat mirrors are available for the left resonator mirror holder, allowing the laser to operate with either a green, orange, or red line. After changing the mirror, only minor readjustments are required, and the current may need to be readjusted. Once the laser has been optimally adjusted for red or green, the wavelength of the laser radiation can be changed. To do this, the selective plane mirror must be replaced accordingly. The three available plane mirrors are marked with colored dots and can thus be assigned to the green, orange, and red wavelengths.



After replacing a mirror, the laser should still be properly aligned and should “start up” immediately. Only a minor readjustment is needed to optimize the power again. In general, it is important to understand that the laser has different gain levels at different wavelengths. As a result, the pump current may need to be readjusted after changing mirrors. For example, if you switch from red to green, you must first increase the pump current after changing the mirrors until the laser “kicks in” again. The image shows the laser with a red line and the two switchable mirrors. The laser thresholds for the three wavelengths should also be determined here.

Due to the large number of fluorescence lines emitted by the excited Pr:YLF crystal and the blue pump radiation, the laser crystal emits white light. If you look at it from the side and at an angle from above through a grating with approximately 300 lines per centimeter, you can see the impressive spectrum ranging from blue to red. In this case, you are not looking in a straight line, but rather in the direction of the first-order diffraction through the grating. Without a slit, the lines are naturally smeared and blend into one another. The lines can be separated using a handheld spectrometer. The best results are obtained with a spectrometer connected via an optical fiber. The optical fiber is plugged into the side connector next to the crystal.

4.9 Observation of Rayleigh scattering and its polarization dependence

A beam of light becomes visible only through scattering. The green laser beam, in particular, is very intense—and, of course, about 100 times more intense inside the resonator than outside it when viewed on a screen or through a camera, since the output mirror transmits only 1%. If you look at the resonator from the side, you can see this beam quite clearly. The cause is Rayleigh scattering off air molecules. Similar to the blue color of the sky, which is also caused by Rayleigh scattering, this scattering is polarized. You can verify this immediately by holding a polarizing filter up to your eye. The spontaneous flashes visible in the laser beam are caused by dust particles passing through the beam.

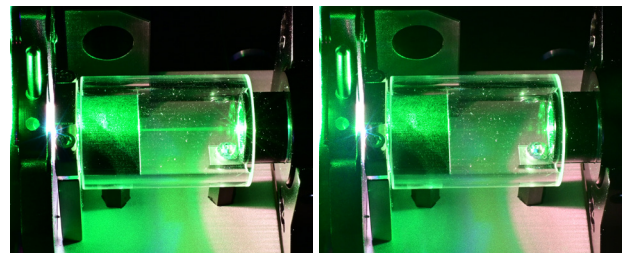


Fig. 33: Rayleigh scattering in the resonator (left), observed with a vertical polarizer (right)

Using the polarization filter, you can just as quickly verify whether the linear polarization of the Rayleigh-scattered light and the linear polarization of the laser line are indeed oriented perpendicular to each other.

4.10 Determining the laser wavelength via diffraction at the grating

Filter box, camera, continuous-wave (cw) operation,

Once again, generate a TEM₀₀ mode that is as symmetrical as possible by optimally adjusting a resonator that is as short as possible and using strong pumping. This is a prerequisite for clearly observing diffraction phenomena on various small structures.

Use the camera and the Raspberry Pi to capture diffraction patterns of a 100-line grating (100 lines/mm) when the grating is placed once in the front slot (maximum distance from the camera) and once in the third (rear) slot of the filter box. For both cases, measure the distances of the grating from the detector surface. (Note: The detector surface is 2 mm below the edge of the camera slot.)

Determine the distances between the diffraction orders from the recorded diffraction pattern (image width: 6 cm; width of the 7.4" CCD detector in the camera module: 6.5 mm). Use a ruler to measure the distances between the 1st and 2nd diffraction orders. Dividing these values by two, applying the rule of three, and using the tangent function will give you the diffraction angles. Use the known formula to determine the laser wavelength (where is the diffraction order and is the grating constant).

4.10.1 Reading Image Data

The diffraction images recorded with the Raspberry Pi can be captured and saved using the “take picture” command. The image data can be read out in defined horizontal and/or vertical directions, for example, to (1) measure distances between diffraction maxima or (2) perform adjustments using MATLAB or other programs on a different computer. The image below illustrates examples of how image data can be extracted and displayed in corresponding charts.

