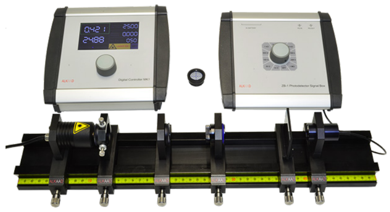
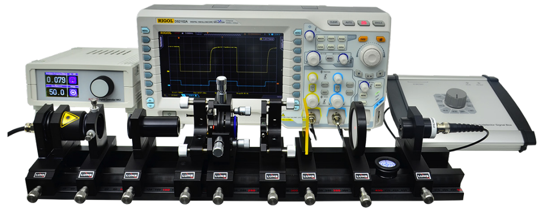
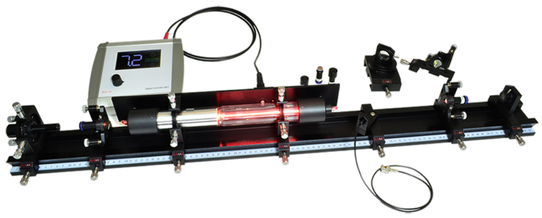
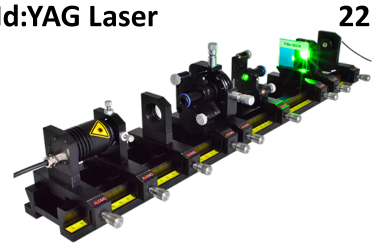
Photonic Experiments

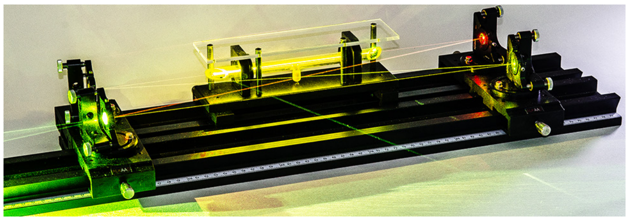
LE - Laser Experiments



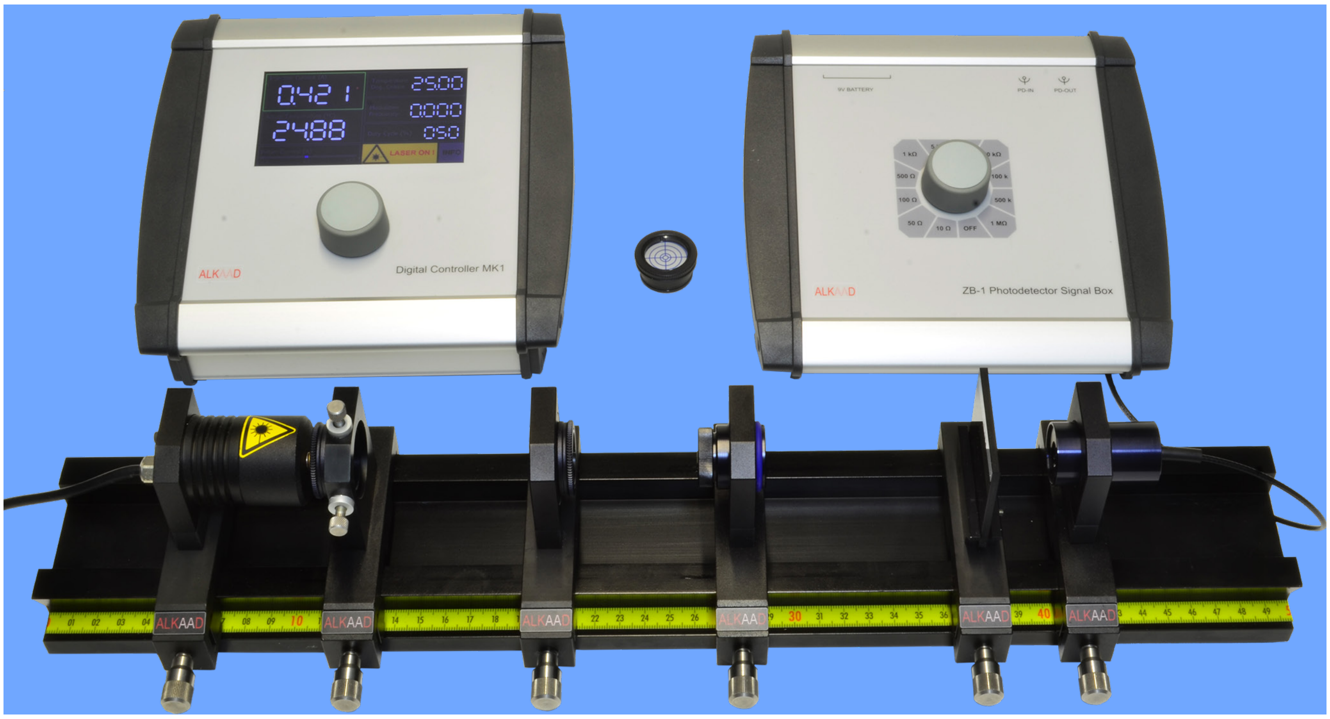








LE-0100 Emission and Absorption



Keywords

Optical Pumping
Absorption Spectra of Nd:YAG
Spontaneous Emission
Diode Laser
Lifetime of Excited States
Real Time Fluorescence Spectra
Nd:YAG Crystal
Einstein Coefficient

Introduction

Optical pumping is a process in which an electron of an atom or a molecule is excited (or "pumped") from a lower to a higher energy level. Within this experiment we are using as pump light source a diode laser and Neodymium (Nd) atoms which are hosted in a crystal lattice formed by an Yttrium Aluminium Garnet (YAG). This material (abbreviated Nd:YAG) is one of the most important laser materials. At the beginning Nd:YAG has been pumped by flash lamps. To improve the efficiency, diode lasers are used whose emission wavelength is almost completely absorbed whereby the light of the flash lamps to an extent of only about 5%.

The experiment provides a diode laser which is mounted onto a Peltier element. Changing the temperature tunes the wavelength of the diode laser with 0.25 nm / °C. Within the temperature range of 10 - 60°C a spectral range of 12.5 nm is covered allowing the measurement of the spectral absorption of the Nd:YAG crystal. By using the well known absorption peaks of the Nd:YAG, the emission wavelength of the diode laser is determined. Furthermore, the injection current of the diode laser can be periodically be switched on and off to allow the recording of the temporal decay of the fluorescence of the Nd:YAG crystal with an oscilloscope. The inverse value of the measured lifetime is the Einstein coefficient for spontaneous emission. By means of the optional spectrometer the fluorescence spectrum of the Nd:YAG crystal as well of the diode laser can be recorded and printed.

How it works

Fig. 2.1: Measuring the output power

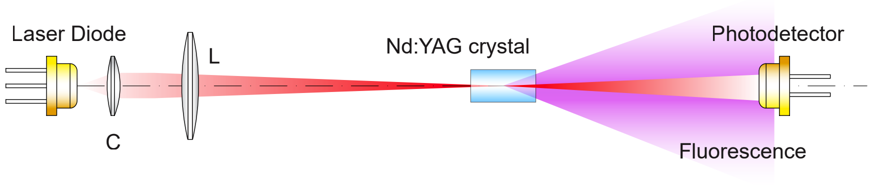


Fig. 2.2: Absorption Measurement

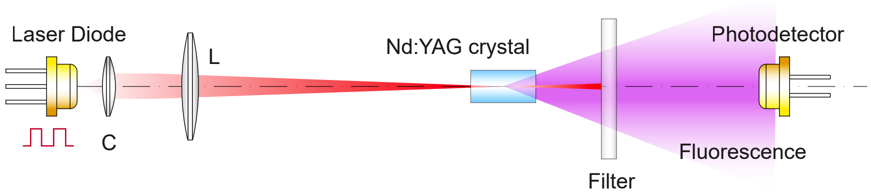


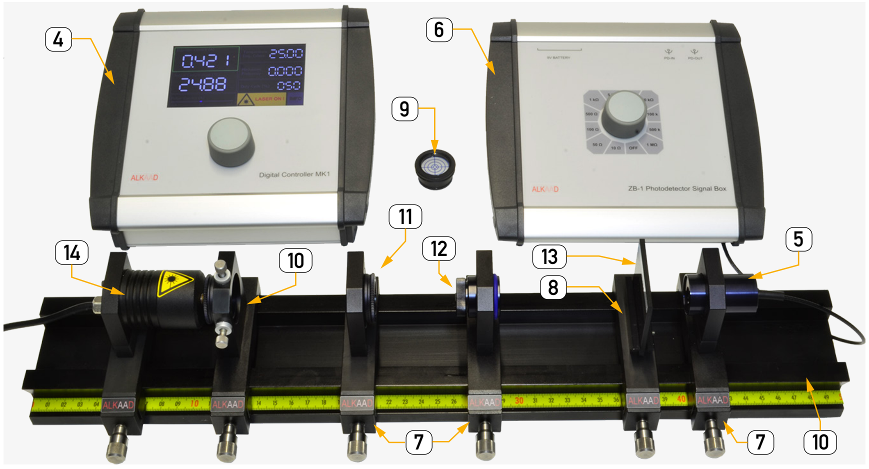
Fig. 2.3: Fluorescence Measurement

The laser diode emits a wavelength of 808 ±3 nm and is mounted onto a Peltier element allowing the temperature to be varied from 10 to 50°C to study the thermal effect on the laser properties. A change the temperature affects the emitted wavelength as well as the output power. The setup as shown in Fig. 2.1 measures the relative output power of the laser diode versus the injection current with the temperature as parameter. The beam divergence is controlled by the collimating lens (C) and is set to a suitable intensity without saturating the photodetector.

The setup according to Fig. 2.2 is used to measure the spectral property of the laser diode using the well known absorption lines of a Nd:YAG crystal. In this arrangement a focusing lens is added to create a tight focus inside the Nd:YAG crystal. The photodetector sees the unabsorbed pump light as well as the created fluorescence. However, its intensity is comparably small and will not affect the measurement.

In the setup of Fig. 2.3 a filter is added which blocks the pump radiation and only the fluorescence will be seen by the photodetector. Furthermore, the injection current of the pump laser is modulated and allows the measurement of the temporal build up and decay of the fluorescence using an oscilloscope. From the results the important lifetime of the excited state is determined. The inverse value is also defined as Einstein coefficient for spontaneous emission.

Description of the components



The laser diode (14) is connected to the controller (4) which is used to set the injection current, the temperature, the modulation frequency as well as duty cycle. Depending on the experimental requirement the radiation of the diode laser (14) is collimated (10) and focused (11). To study absorption and emission effects by optical pumping a Nd:YAG rod (12) is used. A filter (13) blocks the pump radiation and passes the created fluorescence light which is detected by the photodetector (5). The photo current is converted into a voltage by the signal box (6). At the rear this signal is available and can be measured either by the provided digital voltmeter or for faster signals with the optional oscilloscope (16). For the initial alignment a crossed hair target is used to align (10) the collimated beam of the diode laser (14) with respect to the optical axis of the optical bench (10).

Measurements

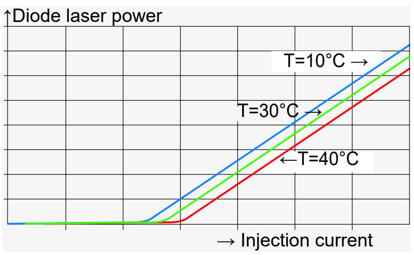


Fig. 2.4: Diode laser power versus injection current and temperature

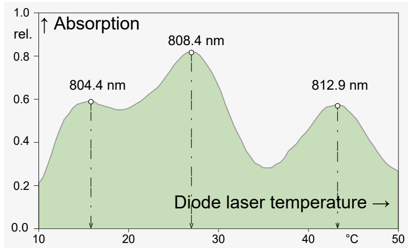


Fig. 2.5: Absorption versus diode laser temperature or wavelength

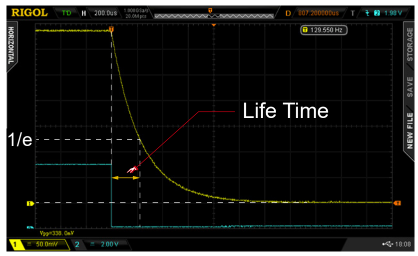


Fig. 2.6: Measure the life time of the excited state

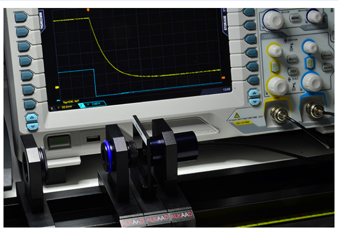


Fig. 2.7: Measure the fluorescence decay

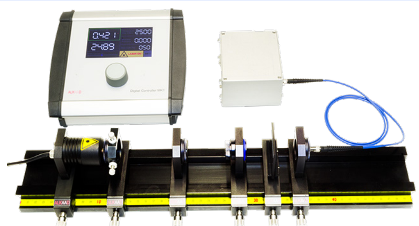


Fig. 2.9: Taking the fluorescence spectrum

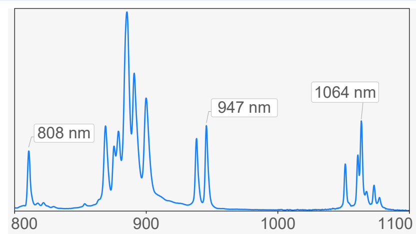


Fig. 2.10: Emission spectrum

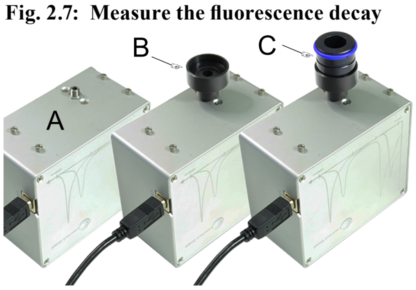


Fig. 2.8: Taking the absorption spectrum

The optional spectrometer (17) can also be used to measure the absorption spectrum of the Nd:YAG rod (12). For this purpose a white light spectrum from the daylight or a tungsten desktop lamp is taken as reference. By placing the Nd:YAG rod with its holder (C) into the provided adapter (B) the resulting spectrum is recorded and divided subsequently by the reference spectrum to obtain the net transmission. Applying the relation T=1-A where A is the absorption and T the transmission we obtain the absorption spectrum of the Nd:YAG rod as shown in Fig. 2.11.

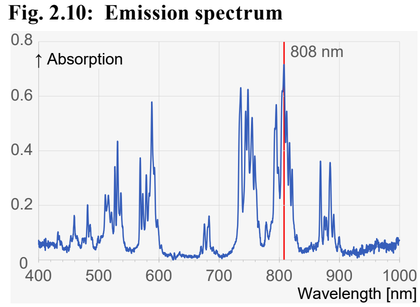


Fig. 2.11: Absorption spectrum

LE-0100 Emission, Absorption & Optical Pumping consisting of:

Item	Code	Qty.	Description	Details page
1	CA-0060	1	Infrared display card 0.8 -1.4 µm	64 (10)
2	CA-0220	1	Multimeter 3 1/2 digits	66 (21)
3	CA-0410	1	BNC - banana adapter cable, 1m	67 (27)
4	DC-0040	1	Diode laser controller MK1	58 (4)
5	DC-0120	1	Si-PIN Photodetector, BPX61 with connection leads	60 (15)
6	DC-0380	1	Photodetector Junction Box ZB1	62 (31)
7	MM-0020	3	Mounting plate C25 on carrier MG20	30 (1)
8	MM-0060	1	Filter plate holder on MG20	31 (7)
9	MM-0100	1	Target Cross in C25 Mount	31 (9)
10	MP-0150	1	Optical Bench MG-65, 500 mm	30 (8)
11	OC-0060	1	Biconvex lens f=60 mm in C25 mount	36 (5)
12	OC-0550	1	Nd:YAG rod in CR25 mount	39 (33)
13	OC-0950	1	Filter RG1000 50x50x3 mm	41 (54)
14	OM-L500	1	Diode laser module 808 nm on C20	55 (56)
15	UM-LE01	1	Manual Emission and Absorption	
	Option (order separately)			
16	CA-0200	1	Oscilloscope 100 MHz digital, two channel	66 (19)
17	CA-0270	1	Fibre coupled spectrometer 200 - 1200 nm, USB	67 (26)

Highlights

Basic, advanced, and top level ★★★ experiments

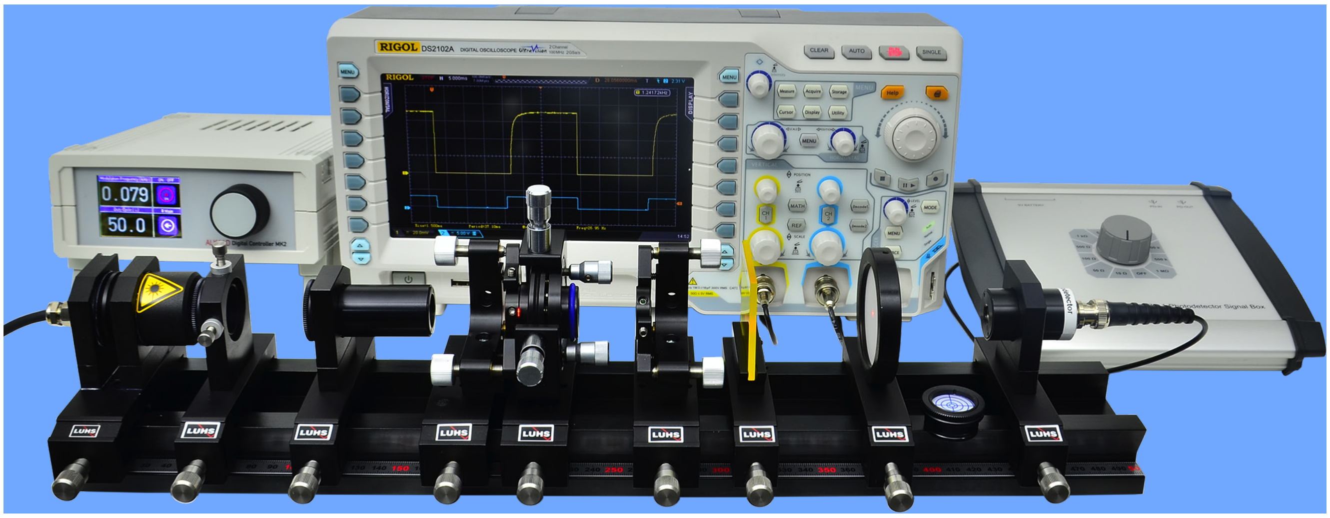
Outstanding features for fundamental quantum optics:

- ★★★ Einstein coefficient
- ★★★ Lifetime of excited state
- ★★★ Fluorescence spectrum
- ★★★ Absorption spectrum

Intended institutions and users:

- Physics Laboratory
- Engineering department
- Electronic department
- Biophotonics department
- Physics education in Medicine

LE-0200 Ruby Laser



Keywords

Theodore Maiman
Absorption spectra
Laser threshold
Three-level laser
Emission spectra
Laser spiking
Blue diode pumping
Excited lifetime measurement
CW and pulsed Ruby laser

Introduction

In 1960 T. Maiman realized the first laser, the Ruby laser, which started a tremendous and still ongoing development of laser sciences and optical technologies. Looking back into laser history, Maiman's famous Ruby laser initiated a fascinating start, which also led to the invention of the powerful tiny diode laser used here to pump the Ruby laser, allowing now a compact and low-cost laser setup, well suited for demonstration and education purposes.
This experimental Ruby laser allows to study the observation of the fluorescence and laser spectrum with oscillation of both R lines. The dynamic of the three level laser system is studied by modulating the pump diode laser. It seems so, as if with this system "The Laser Odyssey" will find its happy end.

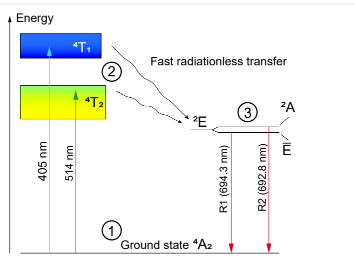


Fig. 2.12: Three level diagram of Ruby

When Maiman proposed the Ruby as active materiel for an "optical maser" he already had a deep insight of the spectral properties of Ruby. Although colleagues and other high ranked scientist like Townes declared, that "maser operation" (the word "laser" was not yet created) is impossible because the maser start and end level is the ground state (1). To achieve the necessary population inversion an extremely high pump intensity is required. However, Maiman succeeded, favoured by the long lifetime of about 3.5 ms of the upper laser state (3) and the broad absorption bands (2) for pumping. The first laser ever was born and it was a pulsed one and it still serves in medicine and holography. In 1962 the Ruby laser was operated in continuous mode pumped by a mercury lamp and later on with an Argon ion laser. However, the efficiency did not reach values which made the ruby laser attractive as cw source. In early 2018 we demonstrated for the first time cw Ruby laser operation by pumping the $^4T_1$ state with a diode laser. The goal of our effort was to create a Ruby laser for the practical education of students. For historical reasons and because of its three level system, the Ruby laser is worldwide subject of each course in photonics.

How it works

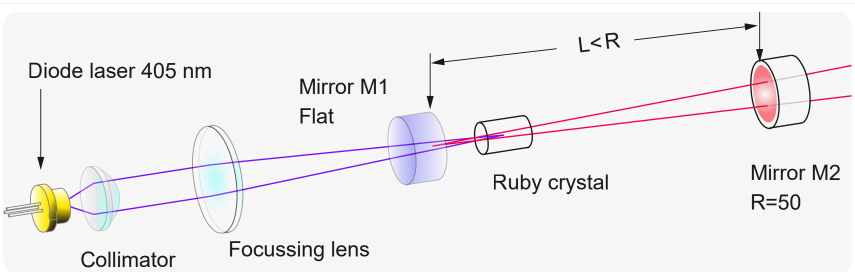


Fig. 2.13: Semi-concentric resonator

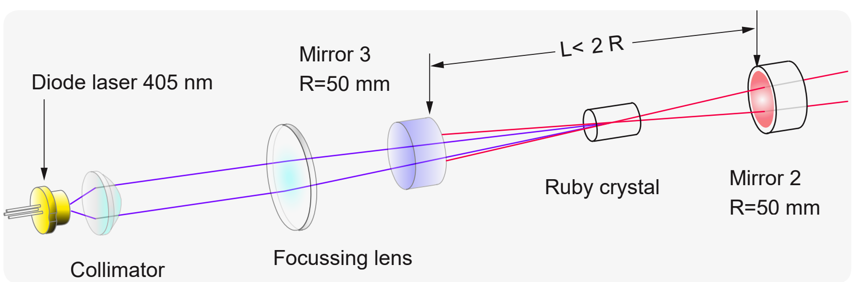
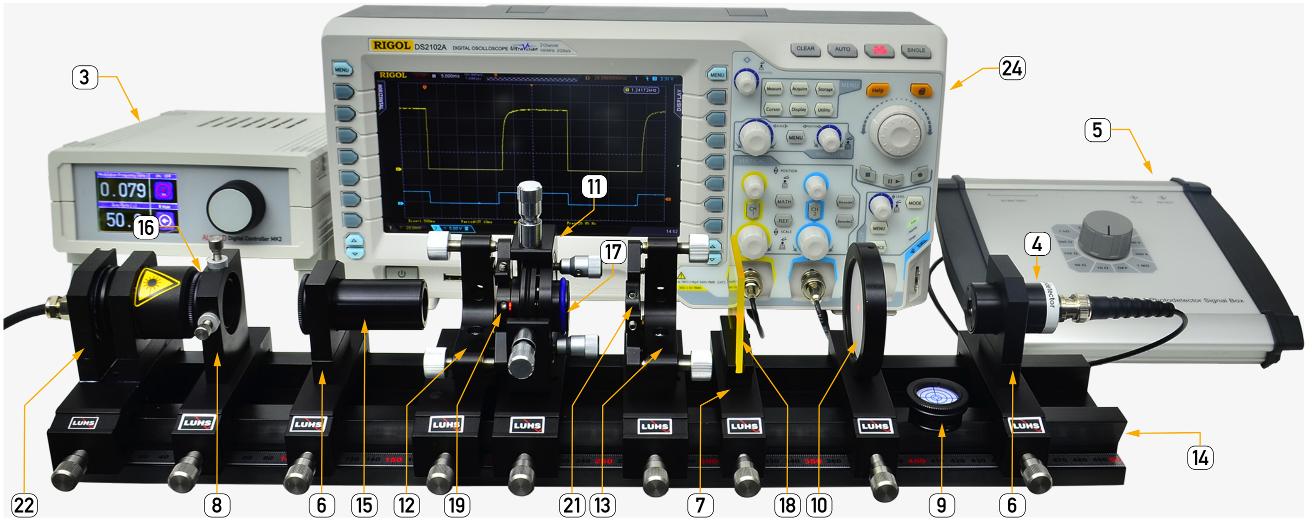


Fig. 2.14: Concentric resonator

The Fig. 2.13 shows the setup using a semi-concentric resonator consisting of the flat mirror (M1) and the curved mirror (M2). The Ruby crystal has a diameter of 6 mm and a length of 6 mm and is located as close as possible to the mirror (M1). Both sides are antireflection coated for the pump wavelength of 405 nm and the Ruby laser wavelength 694 nm.
The strong divergent radiation (405 nm) of the pump diode laser is collimated by an aspheric lens. The now almost parallel beam is focused by the focussing lens close behind the entrance face into the Ruby crystal. It is important that the pumped volume fits well to the mode volume of the cavity which is achieved by selecting a suitable focal length of the focussing length. The focus location is adjusted by moving the position of the lens.
The Fig. 2.14 shows the setup of a concentric resonator consisting of two spherical mirrors (M3 and M2) with same radii of curvature. The Ruby crystal is placed in the centre of the resonator and the focussing lens is positioned in such a way that the pump focus lies within the crystal.

Description of the components



The pump laser diode (22) emits 1 W at a wavelength of 405 nm which perfectly fits into the $^4T_1$ absorption band of the Ruby crystal. The laser diode is connected to the controller (3) which controls its injection current, temperature and modulation.
The laser diode emission is collimated with the adjustable collimator (8) and focused with a lens (15) through the flat laser mirror (19) into the Ruby crystal (17). The flat resonator mirror is mounted into a kinematic adjustment holder (12). The Ruby crystal is set into a 5 axes adjustment holder (11) which has two fine pitch screws to adjust the XY position and two fine pitch screws for the kinematic alignment. The fifth axis allows the turning of the Ruby crystal with its mount. The mirror (21) is the second resonator mirror and is mounted into a kinematic adjustment holder (13).
The filter (18) blocks the blue pump radiation which is not absorbed by the Ruby crystal. However, the deep red Ruby laser radiation is transmitted and the spot is visible on the translucent screen (10). The crossed-hair target (9) is used as alignment aid for the adjustment of the collimated pump radiation with respect to the optical axis of the setup.
The photodetector (4) is connected with a BNC cable to the signal box(5), where the photocurrent is converted into a linear voltage.
The oscilloscope (24) displays the modulation signal of the pump laser diode and the optical radiation detected by the photodiode (4).

The Ruby crystal (17)

Fig. 2.17: Ruby crystal with its mount

The efficient pumping of the blue band of the Ruby crystal requires an optimised Cr^{3+}dopant level as well a special orientation of the crystal's c-axis with respect to the mechanical axis of the Ruby rod. The Ruby rod is gently clamped by the mounting disk (1). The crystal is set into the housing (3) and fixed therein with the retaining ring (2).

The pump diode laser (22)

Fig. 2.18: Pump diode laser

A laser diode which emits an optical power of 1 W at a wavelength of 405 nm is built into a round housing. A Peltier element removes the excess heat via the mounting plates and the carrier and finally by the optical rail. The 15 pin SubD connector contains an EEPROM, where the critical data of the laser diode are stored.

Diode laser controller (3)

Fig. 2.19: Digital diode laser controller

When the pump laser diode is connected to the controller, it reads the stored values and sets the maximum values of the injection current and temperature range. The controller allows the setting of the injection current and the temperature of the laser diode. The modulator enables the pulsed operation. The modulation frequency as well as the duty cycle can be set, allowing the simulation of the laser diode as flash lamp.

Measurements

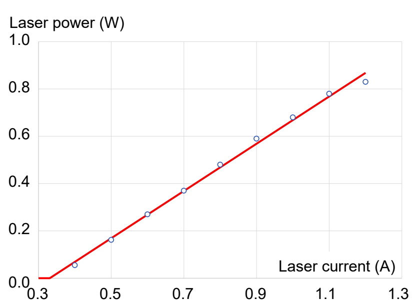


Fig. 2.15: Pump laser power versus the injection current

The optical power is measured with an optical power meter

The pump laser diode is built onto a Peltier element into a round housing (22). It is connected to the controller (3) which controls the temperature, the injection current and the modulation of the pump laser diode. If a power meter is available, the output power of the laser diode is measured directly. If not, the photodetector (4) provided may be taken to measure the output power in relative units. However, care must be taken not to saturate the detector, which can be ensured by enlarging the beam divergence of the pump diode laser with the collimator or even with removed collimator. The Fig. 2.16 shows such a setup without collimator. The photo current is linear to the incident power and provides a reliable alternative for a power meter.

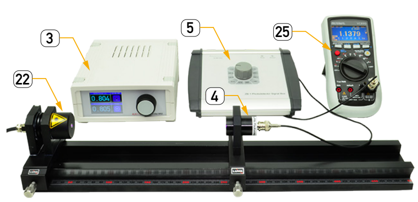


Fig. 2.16: Setup to characterize the pump laser diode.

A digital voltmeter (25) is used to measure the voltage drop across the photodetector's shunt resistor and therewith the photo current. The maximum current of the controller is read from the laser diode's EEPROM and is related to the optical power of 1 W.

Absorption spectrum of Ruby

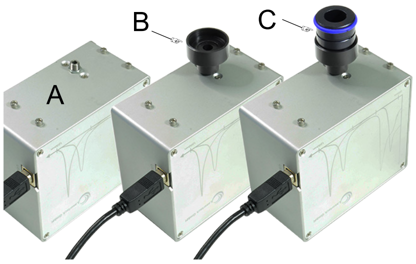


Fig. 2.22: Spectrometer with crystal adapter (B) and Ruby rod (C)

The optional spectrometer (24) is used to measure the absorption spectrum of the Ruby rod (17). For this purpose a white light spectrum from the daylight or a tungsten desktop lamp is taken as reference. By placing the Ruby rod with its holder (C) into the provided adapter (B) the resulting spectrum is recorded and divided subsequently by the reference spectrum to obtain the net transmission. Applying the relation $T=1-A$ where A is the absorption and T the transmission, we obtain the absorption spectrum of the Ruby rod as shown in Fig. 2.23. One strong absorption band occurs with a peak wavelength of 405 nm and a weaker one at 544 nm.

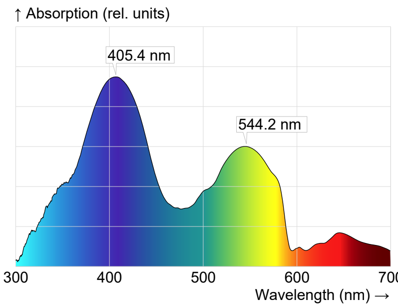


Fig. 2.23: Ruby absorption spectrum

Fluorescence spectrum of Ruby

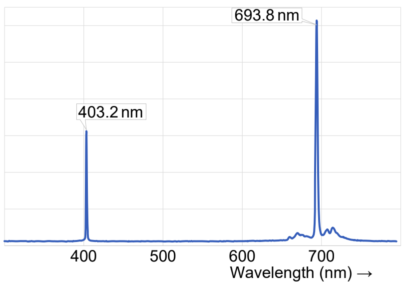


Fig. 2.24: Measured fluorescence spectrum of the Ruby rod

The Fig. 2.24 shows the fluorescence spectrum of the Ruby rod excited by the 405 nm pump laser diode. The actual wavelength of the laser diode depends on its temperature and injection current. For the measurement the settings resulted in a wavelength of 403.2 nm. The used spectrometer (26) has a resolution of 1 nm, thus the R1 and R2 lines are not separated since their spectral difference is just 1.4 nm. The structured bands left and right from the maximum peak round 694 nm are vibronic sidebands of the R1 and R2 transitions.

The Fig. 2.25 shows the experimental setup. The collimated pump laser light is focused with the focussing lens (15) into the Ruby rod (17). The fibre of the spectrometer (26) is attached to the articulated arm (27) and placed in such a way, that besides the strong deep red emission also a fraction of the violet pump laser light falls into the front face of the optical fibre.

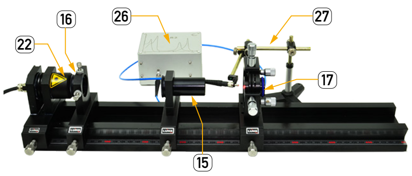


Fig. 2.25: Experimental setup to take the fluorescence spectrum of the Ruby rod

The lifetime of the ^2E state

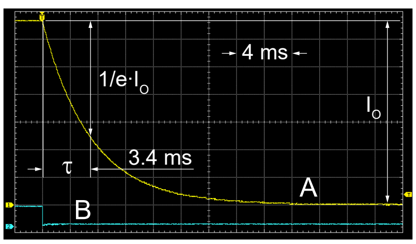


Fig. 2.20: Oscilloscope picture of the fluorescence decay of the ^2E state

The ^2E state is populated by the absorption of the pump radiation by the $^4T_1$ band and by the fast radiationless transfer in less 1 ns. Only due to the very long lifetime of the ^2E state Maiman was able to achieve the required population inversion to the ground state. The goal of this experiment is to measure this lifetime. The pump laser diode is periodically switched on and off (trace B), while the decay of the fluorescence is measured with the photodetector and displayed as trace A.

The lifetime τ is defined at the time, when the fluorescence intensity drops the 1/e fraction of its initial intensity I_0. From the Fig. 2.20 we estimate the lifetime τ to be 3.4 ms.

The theoretical laser-line width $\Delta\omega=1/\tau$ is 286 Hz only, which explains why the ruby laser is still the best for pulsed holography!

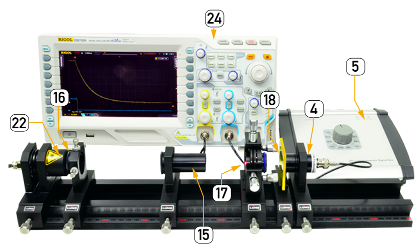


Fig. 2.21: Experimental setup to measure the lifetime of the excited state ^2E

Laser line spectrum

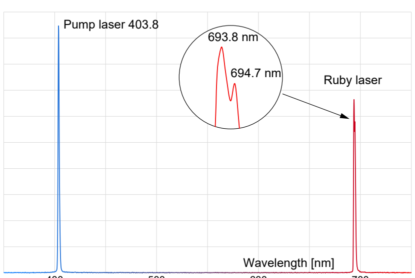


Fig. 2.26: Laser line spectrum showing the pump and Ruby laser

Once the Ruby laser is aligned and oscillates, we want to know what is lasing! The fibre of the spectrometer (26) is attached to the articulated arm (27) and positioned in such a way that beside the Ruby laser emission also a small fraction of the pump light enters the fibre. The human skin has a high penetration depth of light with a wavelength of 694 nm. Therefore the Ruby Laser is still very useful in medical applications.

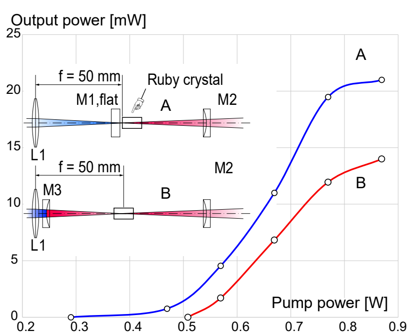


Fig. 2.27: Output power of the Ruby laser versus the pump power

We compare the performance of a semi-concentric and a concentric resonator. The output power of the semi-concentric resonator (A) is higher as for the concentric one, above 0.8 W of pump power higher transverse modes occur. However, the concentric resonator mainly shows TEM_{00} modes.

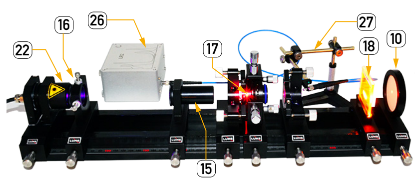


Fig. 2.28: Experimental setup to measure the ruby laser line spectrum

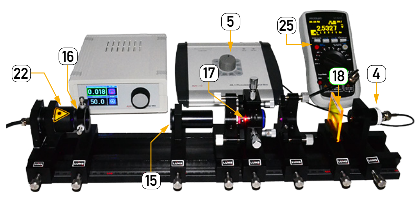


Fig. 2.29: Experimental setup to measure the ruby laser output power

To determine the optical power of the Ruby laser we make use of the known spectral properties of the photodetector.

Dynamic measurements

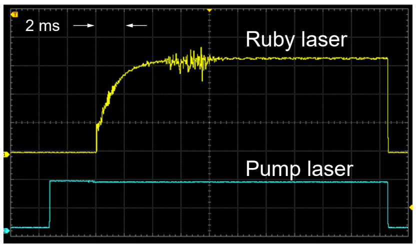


Fig. 2.30: The switch on behaviour

The Fig. 2.30 shows the the ruby laser output after switching on the pump laser diode. It shows the typical build up of the laser output with some spiking and reaches the continuous steady state after 10 ms.

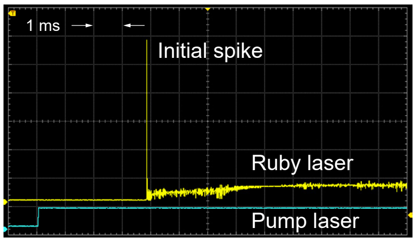


Fig. 2.31: Demonstration of initial spike

To demonstrate the initial spike, the pump laser power is reduced and a giant spike occurs when the Ruby laser starts up. For this example the pump power has been reduced and the laser mirror a bit misaligned.

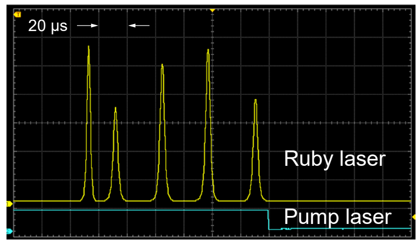


Fig. 2.32: Selected and resolved spikes

The oscilloscope picture of the Fig. 2.32 shows a few spikes. The time base of the oscilloscope is set in this example to 20 µs/division to resolve the individual spikes. Furthermore the pump power is further reduced to obtain just a few spikes.

Flash lamp simulation

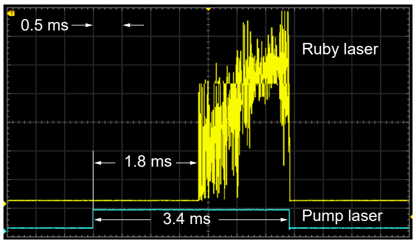


Fig. 2.33: Operating the pump laser as flash lamp

For this experiment the modulation frequency and pulse duration (duty cycle) of the injection current of the laser diode is set in such a way, that the timing of a xenon flash lamp is achieved. This experiment is the historical reproduction of the famous flash lamp pumped Ruby laser as T. Maiman performed in 1960. It clearly shows the spiking during the laser pulse which is typical due to the long lifetime of the excited state of 3.5 ms.

Dynamic Pump absorption

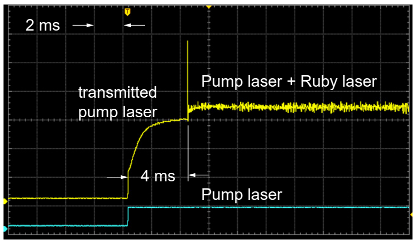


Fig. 2.34: Non linear pump absorption and laser inset

For the measurement as shown in Fig. 2.34, we removed the filter (17) which blocks the pump radiation. The photodetector now sees the pump as well the Ruby laser emission simultaneously. After a delay of 4 ms the population inversion is reached and the Ruby laser starts with a significant initial spike. After that, the ruby laser reaches a steady state with almost continuous output power.

Experimental setup for dynamic measurements

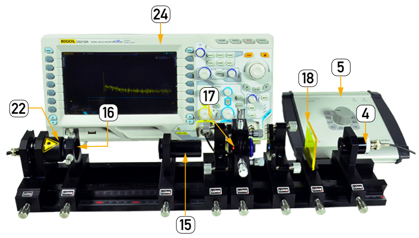


Fig. 2.35: Setup for dynamic measurements

For the dynamic measurements we make use of the modulation facilities of the diode laser controller. It allows us to set the modulation frequency and the duty cycle of the pulsed injection current of the laser diode. In addition the pulse peak power can be controlled to observe the behaviour at the threshold or slightly above. This experiment reveals a variety of effects which are typical for three level laser

LE-0200 Ruby Laser consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	CA-0080	1	Optics cleaning set	65 (12)
2	CA-0450	3	BNC connection cable 1 m	67 (28)
3	DC-0048	1	Diode laser controller MK2	59 (5)
4	DC-0120	1	Si-PIN Photodetector, BPX61	60 (15)
5	DC-0380	1	Photodetector Junction Box ZB1	62 (31)
6	MM-0020	2	Mounting plate C25 on carrier MG20	30 (1)
7	MM-0060	1	Filter plate holder on MG20	31 (7)
8	MM-0090	1	XY adjuster on MG20	31 (8)
9	MM-0100	1	Target Cross in C25 Mount	31 (9)
10	MM-0110	1	Translucent screen on carrier MG20	31 (10)
11	MM-0420	1	4 axes adjustment holder on 20 mm carrier	33 (25)
12	MM-0440	1	Kinematic mount ø25.4 mm on MG20, left	33 (26)
13	MM-0442	1	Kinematic mount ø25.4 mm on MG20, right	33 (27)
14	MP-0150	1	Optical Bench MG-65, 500 mm	30 (8)
15	OC-0068	1	Biconvex lens f=60 mm in C25 extended	36 (6)
16	OC-0160	1	Collimator 445 nm in C25 mount	36 (12)
17	OC-0560	1	Ruby crystal in CR25 mount	39 (34)
18	OC-0970	1	Filter GG495, 50 x 50 x 3 mm	41 (55)
19	OC-1160	1	Laser mirror 1/2” in 1” mount, ROC flat, HT405-HR694 nm	44 (80)
20	OC-1164	1	Laser mirror 1/2” in 1” mount, ROC 50, HT405-HR694 nm	44 (81)
21	OC-1168	1	Laser mirror 1/2” in 1” mount, OC 50, HR405 nm-HR 694 nm	44 (82)
22	OM-L405	1	Diode laser module 405 nm, 1 W	55 (54)
23	UM-LE02	1	Manual Ruby Laser	
	Option (order separately)			
24	CA-0200	1	Oscilloscope 100 MHz digital, two channel	66 (19)
25	CA-0220	1	Multimeter 3 1/2 digits	66 (21)
26	CA-0270	1	Fibre coupled spectrometer 200 - 1200 nm, USB	67 (26)
27	MM-0360	1	Fibre holder with articulated arm	33 (22)

Highlights

Basic, advanced, and top level ★★★ experiments

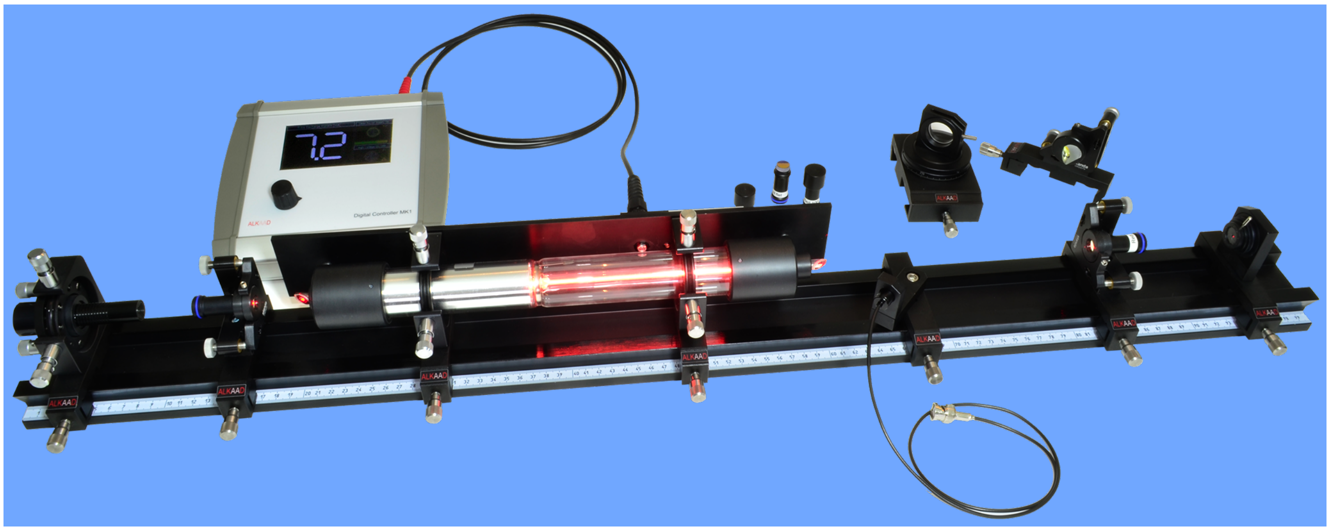
Outstanding features for a Ruby Experimental Laser:

- ★★★ Blue diode laser pumped
- ★★★ Ruby crystal
- ★★★ Absorption & Emission
- ★★★ Continuous Ruby laser
- ★★★ Lifetime of excited state
- ★★★ Demonstration of spiking

Intended institutions and users:

- Physics Laboratory
- Engineering department
- Electronic department
- Biophotonics department
- Physics education in Medicine

LE-0300 Helium Neon Laser



Keywords

HeNe Energy Level Diagram	**ABCD Law & Resonator**	**Optical Gain**
Optical Stability Criteria	**Cavity Alignment**	**Output Power, Discharge Current**
Gaussian Beams	**Line & Mode Selection**	**Crystal Optics**
Birefringent Filter	**Single Mode Etalon**	**Spectrum Analyser**
Free Spectral Range	**Lamb Dip**	**Longitudinal and Transverse Modes**

Introduction

The humble Helium Neon (HeNe) laser still has many applications, due to its superior beam quality and coherence. In all physics text books this laser represents the class of the gas laser and was the first gas laser invented by Ali Javan in 1960 right after Theodore Maiman demonstrated the first operation of the ruby laser. Since the HeNe laser was continuously operating and easy to build in a laboratory, it served as specimen for a lot of scientific work and proof for theoretical predictions. It starts with the theory of optical resonator, Doppler broadened laser active material in a cavity, spectral hole burning (Lamb dip), single mode operation, coherence and intra-cavity absorption (inverse Lamb dip) just to name a few. For technical applications the HeNe laser is still in use due to its outstanding beam quality and coherence as secondary meter standard and is present in each air plane or ship as laser gyroscope for navigation. This experiment is designed as an open frame setup in such a way that all components can be arranged freely on a stable optical rail. A Helium Neon tube with Brewster windows on both ends is used to perform a variety of fundamental experiments. Verification of mode selection properties, the optical stability range and the ABCD matrix formalism of the cavity used are discussed. A birefringent filter as well as a Littrow prism is used for the wavelength selection and the effect of an etalon used inside the cavity are investigated. A photo detector for measuring the relative output power and an alignment laser are supplied with a 1 metre long optical rail, along with all necessary mounts and adjusters.

For the visualisation of the mode structure a „Fabry Perot“ extension is available or an electronic spectrum analyser is used to measure the modes beat frequency. The optical resonator is formed by two precision adjustment holders for common 1/2 “ exchangeable mirrors having different radii of curvature. For ease of adjustment, at the beginning a “green” pilot laser is attached as an alignment aid. The laser tube is mounted into XY-adjustments to align the tube with respect to the pilot laser.

How it works

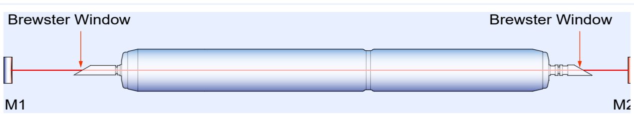


Fig. 2.36: Open frame Helium Neon laser

A glass tube terminated on both sides with Brewster windows contains an optimised mixture of Helium and Neon gas. The mirror M1 and M2 form the optical cavity or resonator. The Brewster windows prevent reflection losses and force the laser to oscillate in linear polarisation. The cavity can be setup as hemispherical, spherical and concentric.

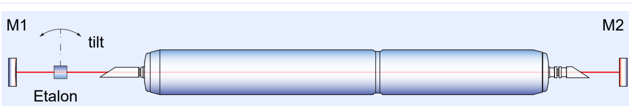


Fig. 2.37: Adjustable etalon for single mode operation

The gain profile of gas laser are Doppler broadened resulting in general in multimode oscillation. An uncoated cylindric glass body with precisely parallel ground surfaces forms a Fabry Perot etalon. Its length is chosen in such a way, that the superimposition of the laser modes and the etalon modes allows only one mode to oscillate

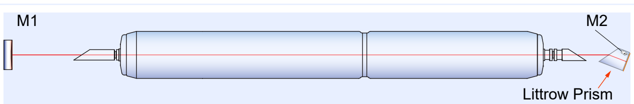


Fig. 2.38: Line selection with a Littrow prism

A Littrow prism is a combination of a prism and a mirror and is shaped such that the laser beam enters the prism under the Brewster angle and hits the mirror (M2) at the rear side exactly under 90°. This is fulfilled for one wavelength only. For another one, the prism needs to be tilted accordingly.

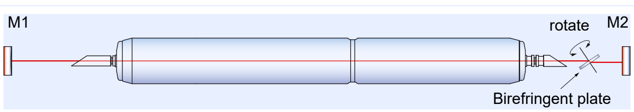
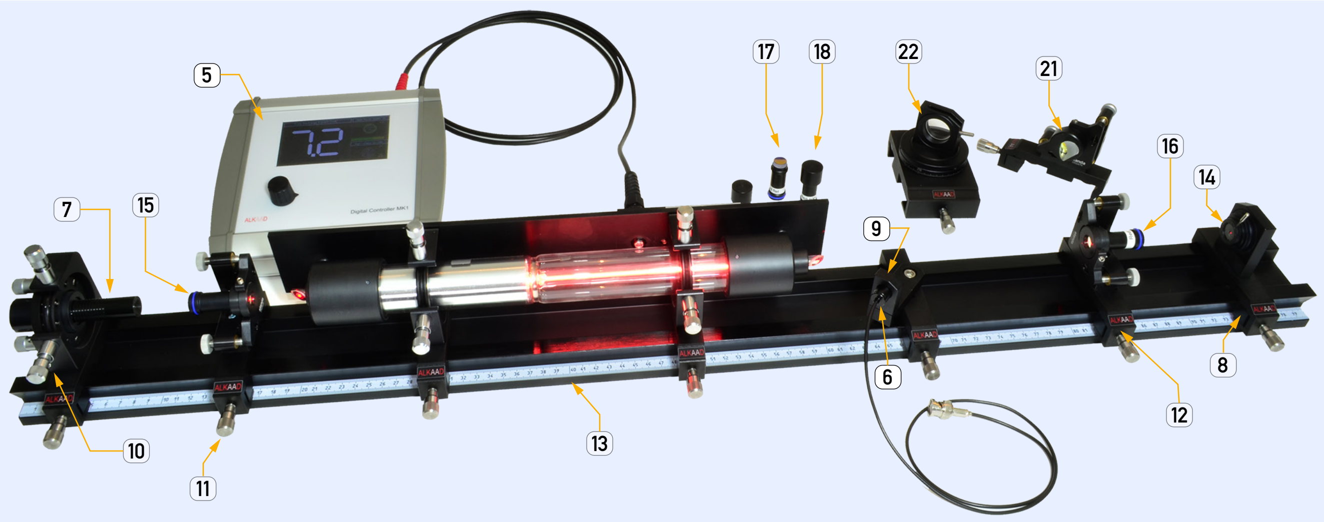


Fig. 2.39: Line selection with a birefringent plate

By rotating the birefringent plate, its optical retardation δ is changed. If the retardation of two passes is a multiple integer of the wavelength λ, this wavelength undergoes no losses at the Brewster window and will oscillate. All other possible lines will be elliptically or circular polarised and the losses at the Brewster prevents their laser oscillation.



LE-0300 HeNe-Laser, description of the components

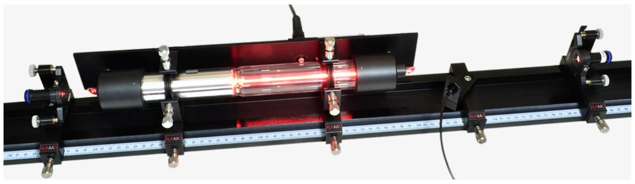


Fig. 2.40: Fundamental setup

The basic experiments like

1. Cavity alignment
2. Power measurement
3. Stability criteria of a hemispherical cavity
4. Gaussian beam diameter distribution

are performed with the basic setup. A green pilot laser (7) is mounted into a 4 axes adjustment holder (10) and in combination with the adjustable iris (14) the optical axis is aligned with respect to the mechanical centre line.

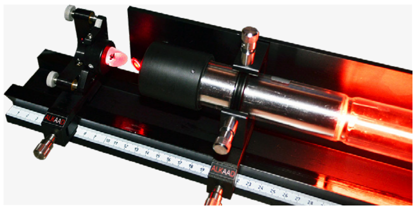


Fig. 2.41: Line tuning with Littrow prism

A way to select different lines of a laser is to use a Littrow prism. Within this experiment we are using such a module to tune the lines of the Helium Neon laser. The Littrow prism is made from fused silica which is the required substrate for IBS (Ion Beam Sputter) coating. The spectral range of the IBS coating covers 580..720 nm with a reflectivity of >99.98 %. The prism is mounted into a precise adjustment holder where it can be smoothly tilted in vertical or horizontal direction.
The prism is used instead of the left mirror (11,15). Before the setup is modified for the Littrow prism experiments, the Littrow prism is adjusted by using the output beam of the still running HeNe laser. After that, the left mirror with its adjustment holder (11,15) is removed and the laser continues to oscillate with the Littrow prism as mirror M1 (see the principle as shown in Fig. 2.14.

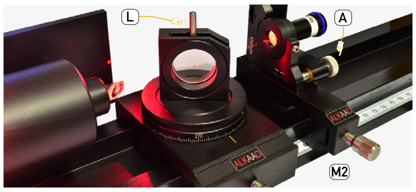


Fig. 2.42: Line tuning with birefringent tuner (BFT)

Another way to select different lines is done by using a birefringent optical plate inside the cavity. The birefringent plate is set to the Brewster angle (57°) and placed in front of mirror M2. When rotating the birefringent plate by tilting the lever (L) laser emission should occur. If not lift the lever up and down while adjusting the knob A to compensate the beam deviation caused by the quartz plate. Then gently tune to the maximum of performance and optimise the alignment of the mirror M2. By tilting the lever some other wavelength should show up. In total 5 different lines will be observed.
It will be noted that the line selection with a BFT requires no change of the geometrical path of the laser cavity as it is the case with the Littrow prism.

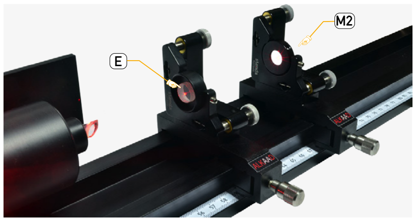


Fig. 2.43: Single mode etalon

Commonly, gas laser oscillate due to the Doppler broadening of the laser transitions on many longitudinal modes. To force the operation on only one longitudinal mode an etalon (E) is inserted into the cavity. It consists of a quartz cylinder with its end faces ground precisely parallel within a few arc seconds. The length is designed so that the convolution of its free spectral range with the Helium Neon laser cavity favours only one mode. The alignment is quite simple, before the etalon is placed into the cavity, it is aligned out side the cavity (behind M2) by using the laser output as alignment beam. The etalon is aligned perpendicular to the laser beam. Once inserted inside the cavity laser oscillation should continue. If not, small alignments of the fine pitch screws lets the laser flash up and further alignment comes to a stable oscillation again. The etalon is then tilted by turning let's say the screw for vertical tilt. The laser oscillation ceases, but turning further the laser starts to oscillate again and the etalon is tilted to its first order.

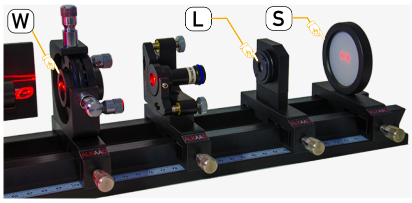


Fig. 2.44: Excitation of transverse modes

Setting up a nearly concentric cavity by using two mirrors with radii of curvature of 700 mm (16) and positioning the laser tube in the centre of both mirrors one can observe a multitude on non-axial, or transverse modes. For better viewing the laser beam is expanded by the lens (L) and imaged on a translucent screen (S). To get a better mode separation and a clearer image a wire (W) is inserted into the cavity which can be rotated and adjusted in X and Y direction. Depending on the adjustment state, position of the tube and of the wire a great variety of transverse modes can be observed, even the famous doughnut mode.

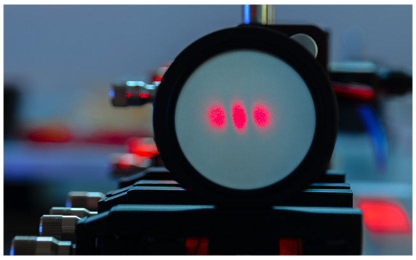


Fig. 2.45: Photographed transverse modes

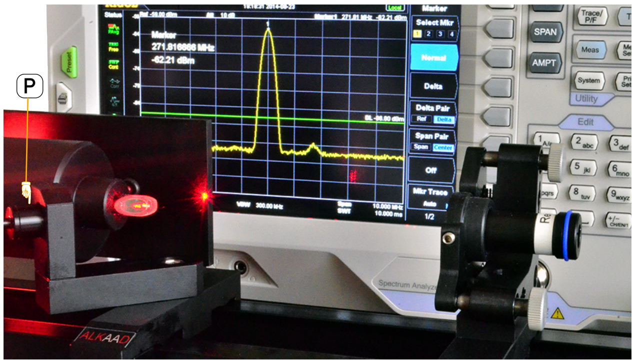
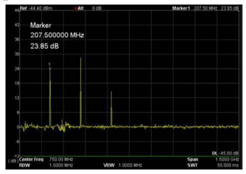


Fig. 2.46: Mode beat frequency measurement

Multimode emission consists of a number of simultaneously oscillating longitudinal modes with a frequency difference δν to each other, which depends on the cavity length L as δν=c/2L. For a length L of 0.75 m and the speed of light c, this frequency difference will be 200 MHz. The experiment comes with a fast photodetector (P). Connecting the photodetector to an electronic spectrum analyser this beat frequency



appears as a strong peak on the analyser. Depending on the number of oscillating longitudinal modes, multiples of the beat frequency will be observed. The number of harmonics tells us on how many modes the laser is oscillating. The gain bandwidth of the Helium Neon laser is 1.5 GHz. Under ideal conditions a cavity with a free spectral range of 200 MHz can have 7 to 8 modes. Since modern spectrum analysers with a range of 1 GHz are economically available, this method of measuring the beat frequency is very attractive

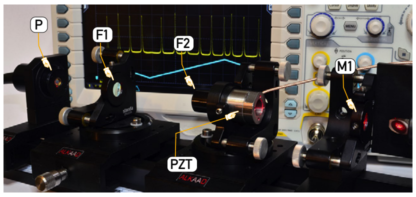


Fig. 2.47: Measuring the mode spectrum with the Fabry Perot Extension LE-0350

The classical way to measure the mode spectrum of a laser is to use a Fabry Perot. Such a Fabry Perot (FP) consists of two curved mirrors (F1 and F2) and are operated in the confocal configuration. One of the mirrors (F2) is mounted to a piezoelectric transducer (PZT). A triangular voltage applied to the PZT moves the mirror periodically forth and back. Each time the wavelength fits to the free spectral range of the FP it becomes transparent and the photodetector detects the change of intensities. Each peak of the oscilloscope represents a mode of the laser. The FP is placed behind the flat mirror (M1) of the Helium Neon laser cavity. For this experiment a mirror with a output coupling of 3% is used to increase the intensity for the FP. Otherwise the signal behind the FP is too close to the noise figure.

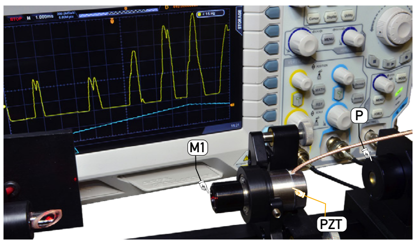


Fig. 2.48: Power intensity profiles, Lamb dip

A great extension to the Helium Neon laser experiments is a PZT to which one of the cavity mirror (M2) is attached. This allows the scanning of the cavity length periodically by some orders. The provided photodiode (P) detects the intensity changes of the HeNe laser during the scanning. Both signals, the PZT voltage and the photodiode signal are shown simultaneously on an oscilloscope whereby the PZT signal is used as trigger signal. Since the PZT movement follows almost linearly the PZT voltage the time axis of the oscilloscope track is equivalent to cavity resonance frequency. In case this frequency equals a multiple integer of half of the laser wavelength the laser starts to oscillate. The signal of the photodiode shows the power profile of such a mode as function of the cavity frequency. In this way the famous Lamb dip can be measured and displayed.
Furthermore this way of scanning the Helium Neon laser cavity provides information of the gain bandwidth as well the number of actual lasing modes. A great idea to scan the Helium Neon laser cavity!

LE-0300 HeNe-Laser, advanced consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	CA-0080	1	Optics cleaning set	65 (12)
2	CA-0220	1	Multimeter 3 1/2 digits	66 (21)
3	DC-0060	1	High voltage supply 4.0 - 7 mA adjustable	59 (7)
4	DC-0140	1	Mini SiPIN photodetector with connection lead	60 (17)
5	DC-0380	1	Photodetector Junction Box ZB1	62 (31)
6	LQ-0030	1	Green (532) pilot laser25 with USB power supply	56 (2)
7	MM-0020	1	Mounting plate C25 on carrier MG20	30 (1)
8	MM-0230	1	Photodetector mount on rotary arm on MG20	32 (18)
9	MM-0420	1	Four axes kinematic mount on carrier MG20	33 (25)
10	MM-0460	1	Kinematic mirror mount M16, left	34 (30)
11	MM-0462	1	Kinematic mirror mount M16, right	34 (31)
12	MP-0100	1	Optical Bench MG-65, 1000 mm	29 (4)
13	OC-0400	1	Adjustable iris mounted in C25	37 (19)
14	OC-1000	1	Laser mirror M16, flat, T 3% @ 632 nm	41 (57)
15	OC-1005	1	Laser mirror M16, flat, HR @ 632 nm	41 (58)
16	OC-1020	1	Laser mirror M16, ROC 700 mm, HR @ 632 nm	42 (61)
17	OC-1030	1	Laser mirror M16, ROC 1000 mm, HR @ 632 nm	42 (62)
18	OM-0560	1	HeNe laser tube with XY and wobble alignment	50 (25)
19	OM-0570	1	Littrow Prism Tuner	51 (26)
20	OM-0580	1	Birefringent Tuner	50 (24)
21	OM-0590	1	Single Mode Etalon with kinematic mount	51 (28)
22	OM-0596	1	Transverse Mode Enhancer	51 (29)
23	UM-LE03	1	Manual HeNe Laser	
	Option (order separately)			
24	CA-0060	1	Infrared display card 0.8 -1.4 µm	64 (9)
25	CA-0200	1	Oscilloscope 100 MHz digital, two channel	66 (19)
26	CA-0210	1	Spectrum Analyzer 100 kHz - 500 MHz	66 (20)
27	CA-0270	1	Fibre coupled spectrometer 200 - 1200 nm, USB	67 (26)
28	CA-0510	1	Laser safety goggles 632 nm	67 (29)
29	DC-0120	1	Si-PIN Photodetector, BPX61 with connection leads	60 (15)
30	LE-0350	1	HeNe Fabry Perot Mode Analyser	69 (1)
31	OC-1040	2	Laser mirror M16, ROC 700 mm, HR @ 1180 nm	42 (63)
32	UM-LM03	1	Manual Fabry Perot Resonator	

Highlights

Basic, advanced, and top level ★★★ experiments

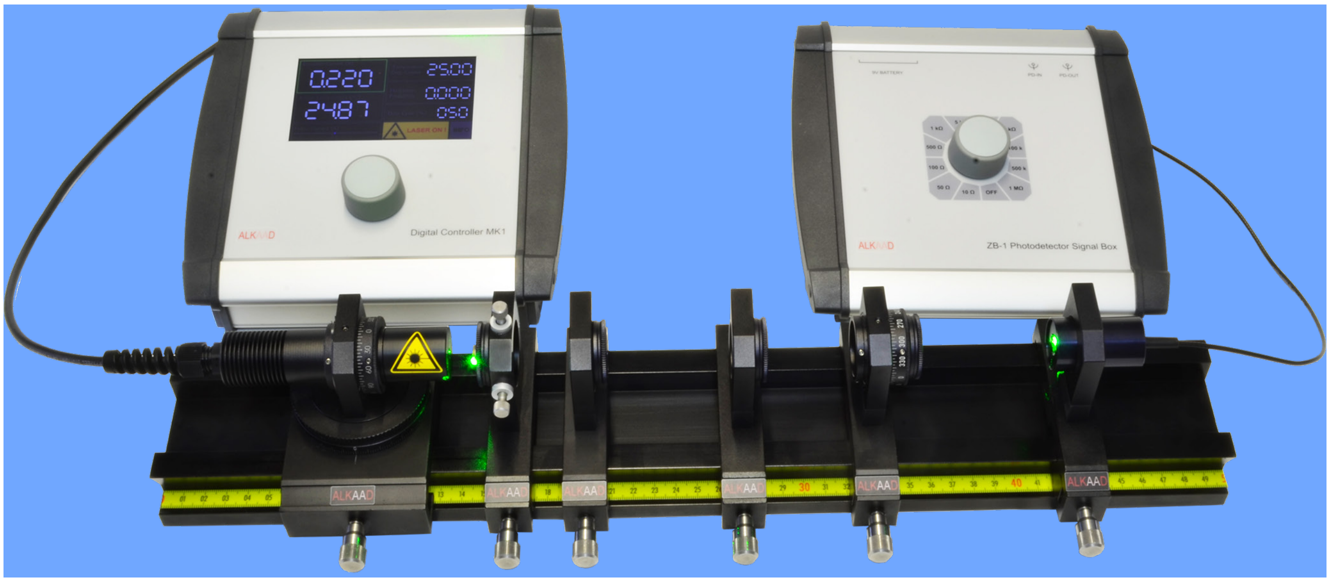
Outstanding features for a Helium Neon Experimental Laser:

- ★★★ Scanned Laser Cavity
- ★★★ Power Profile
- ★★★ Lamb Dip
- ★★★ Beat Frequency Measurement
- ★★★ Excitation of transverse modes

Intended institutions and users:

- Physics Laboratory
- Engineering department
- Electronic department
- Biophotonics department
- Physics education in Medicine

LE-0400 Diodelaser



Keywords

Fermi Distribution
Green (525 nm) Laser Diode
Beam Shaping
Inversion in Semiconductors
Spatial Intensity Distribution
Polarisation Properties
Types of Laser Diodes
Spectral Properties

Introduction

Laser diodes differ from most "classical" lasers in two distinct ways:

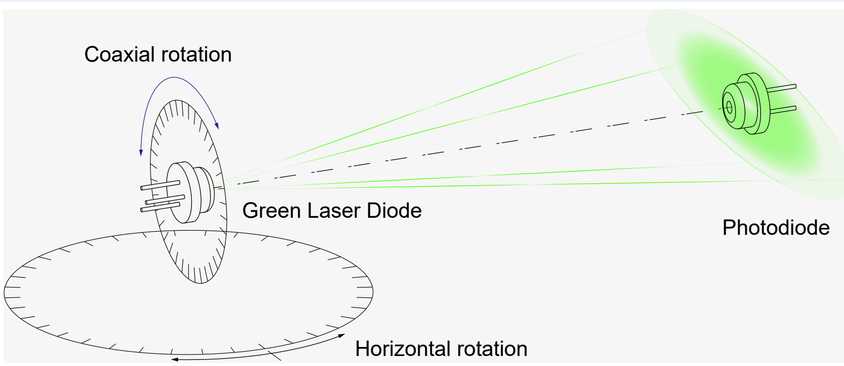
Firstly, they do not posses an inherently defined wavelength. Instead of two defined energy levels, the lasing transition occurs between two energy bands.

Secondly, the pn junction of the diode defines the lasing volume, instead of the resonator in a classical laser.

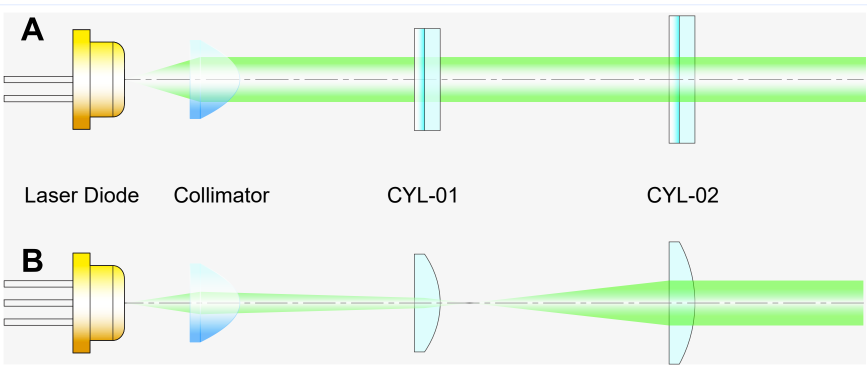
These experiments investigate the variation of the emitted laser wavelength versus temperature and current. The divergence and polarisation of the laser emission are examined. The set-up comprises a modern 30 mW green (525 nm) emitting laser diode, with integrated Peltier cooler, mount and driver. Collimating optics, lenses and a polarisation analyser are provided, along with a photodiode detector. A spectrum analyser is available as an option. All optical mounts and positioners are included. The laser diode is mounted in a rotational stage which allows the independent rotation around the beam propagation axis as well as perpendicular to this axis to measure the spatial distribution of the emitted laser light. The polarisation for different values of the injection current is analysed by means of a polarizer.

The spectrum analyser will be used to measure the change of wavelength by varying the temperature and injection current. The shift is app. 0.05 nm per °C. The temperature range of the diode laser controller can be varied from 10 to 60° C which results in a shift of 2.5 nm. Temperature and injection current are stabilised and displayed by the controller. The use of an oscilloscope is recommended to suppress disturbing environmental light. In this case some of the measurements are carried out with modulated diode laser light.

How it works



A laser diode emitting visible green radiation at a wavelength of 525 nm is used as probe laser. The laser diode is attached to a Peltier cooler which allows a controlled temperature change from 10-50 °C. Furthermore, the injection current can be set from zero to the maximum permissible value. The laser diode and the attached Peltier cooler are integrated into a round housing which is mounted into a twofold rotary stage for horizontal and coaxial rotation. This allows the measurement of the spatial intensity distribution of the emitted visible green light. The incident light from the laser diode is detected and measured with a fixed photodiode.



The emission of a laser diode is in general strongly divergent and asymmetric concerning the spatial propagation. The light appears to have two points of origin (astigmatic difference) and two orthogonal axes, each with different divergence. Most application however, require a round beam. To achieve this, a pair of cylindrical lenses are used as shown in the figure on the left. The case (A) shows the collimation of one direction using the collimator to create an almost parallel beam which is not affected by the cylindrical lenses. The orthogonal emission direction (B) is treated by the cylindrical lenses to obtain an almost round beam

Measurements

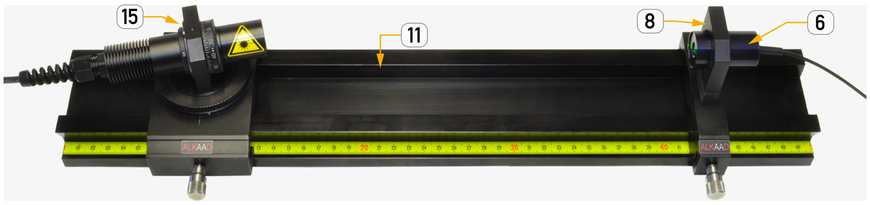


Fig. 2.49: Setup to characterise the green laser diode

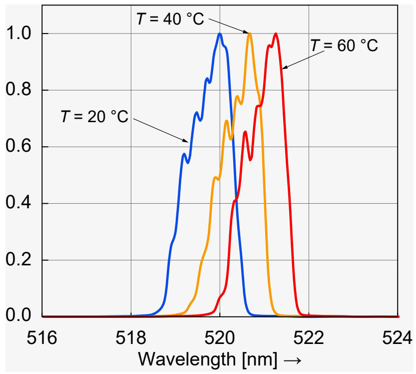


Fig. 2.50: Wavelength versus temperature

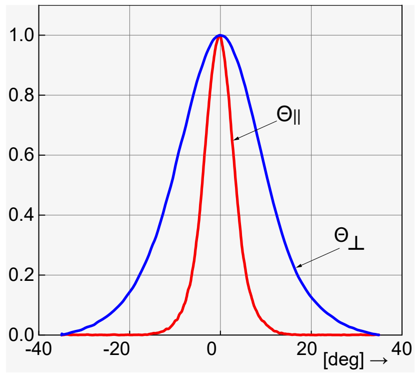


Fig. 2.51: Spatial intensity distribution

The green laser diode is mounted into the two-fold rotary unit (14). It can be rotated around its horizontal as well as coaxial axis. At the beginning the horizontal angle of the laser diode is set to zero, the diode laser illuminates the photodetector (6) fully. In this arrangement the output power versus the injection current is measured with the temperature as parameter. The temperature can be set by the MK1 controller in a range from 10 to 50°C and the injection current from zero up to the maximum permissible value for the laser diode. Each laser diode contains an EEPROM in its connector where these values are stored. Once connected to the MK1 controller the values are read and the maximum current is limited to it. Even more, these values are displayed by request on the MK1 controller's touch display. In the same setup the optional spectrum analyser is applied. The fibre adapter is clicked into the mounting plate instead of the photodetector. For different temperatures the spectral curves are recorded and the wavelength change $d\lambda/dT$ determined. In addition the wavelength change $d\lambda/dI$ versus the injection current for a fixed temperature is determined.

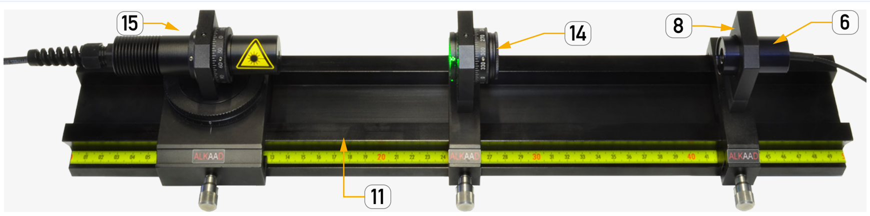


Fig. 2.52: Setup to measure the polarisation of the laser diode

The setup shown in Fig. 2.52 is used to measure the polarisation of the green laser emission. The polarisation analyser (13) is placed onto the optical bench (10) between the laser diode (14) and the photodetector (6). The detector is connected to the junction box (7) where the photocurrent is converted into a voltage and measured by the provided multimeter (3).

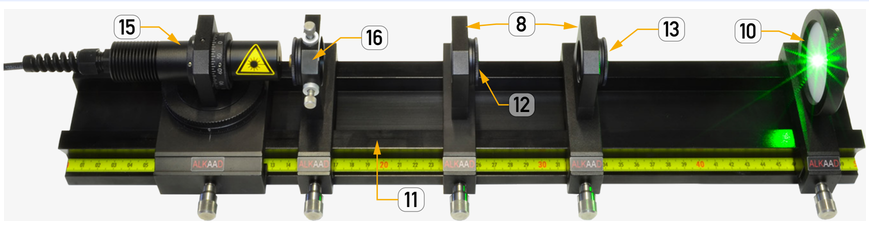


Fig. 2.53: Setup for beam collimation and shaping

The goal of this experiment is to transform the elliptical beam of the green emitting laser diode into the most perfect round shaped beam. This can be done either by just the two cylindrical lenses (12 and 13) or by the combination of the collimator (16) and the two lenses. The result can be seen on the translucent white screen. The image on the rear side can be photographed by any simple digital camera. The strategy can be either trial and error or educated guessing. In both cases, it is an exciting experience!

LE-0400 Diode laser Characterization consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	CA-0060	1	Infrared display card 0.8 -1.4 µm	64 (10)
2	CA-0080	1	Optics cleaning set	65 (12)
3	CA-0220	1	Multimeter 3 1/2 digits	66 (21)
4	CA-0410	1	BNC - banana adapter cable, 1m	67 (27)
5	DC-0040	1	Diode laser controller MK1	58 (4)
6	DC-0120	1	Si-PIN Photodetector, BPX61 with connection leads	61 (22)
7	DC-0380	1	Photodetector Junction Box ZB1	62 (31)
8	MM-0020	3	Mounting plate C25 on carrier MG20	30 (1)
9	MM-0100	1	Target Cross in C25 Mount	31 (9)
10	MM-0110	1	Translucent screen on carrier MG20	31 (10)
11	MP-0150	1	Optical Bench MG-65, 500 mm	30 (8)
12	OC-0220	1	Cylindrical lens f = 20 mm in C25 mount	37 (14)
13	OC-0280	1	Cylindrical lens f=80 mm in C25 mount	37 (15)
14	OM-0400	1	Rotary Polariser / Analyser 360° on Carrier 20 mm	49 (15)
15	OM-0510	1	Diode laser head in twofold rotary mount	50 (21)
16	OM-0620	1	Collimating optics on carrier MG20	51 (30)
17	UM-LE04	1	Manual diode laser	
	Option (order separately)			
18	CA-0200	1	Oscilloscope 100 MHz digital, two channel	66 (19)
19	CA-0270	1	Fibre coupled spectrometer 200 - 1200 nm, USB	67 (26)

Highlights

Basic and advanced level ★★ experiments

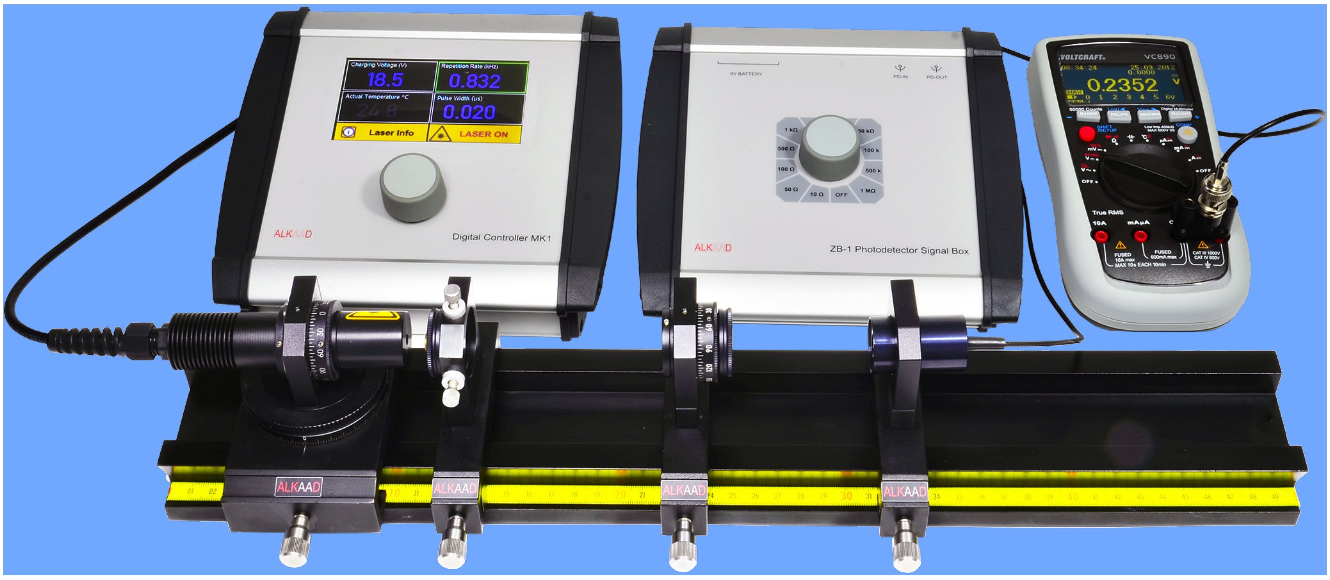
Outstanding features like visible green laser diode:

- ★★ Diode laser emission
- ★★ Polarisation
- ★★ Emission spectrum
- ★★ Beam shaping

Intended institutions and users:

Physics Laboratory
Engineering department
Electronic department
Biophotonics department
Physics education in Medicine

LE-0500 Pulsed Diode Laser



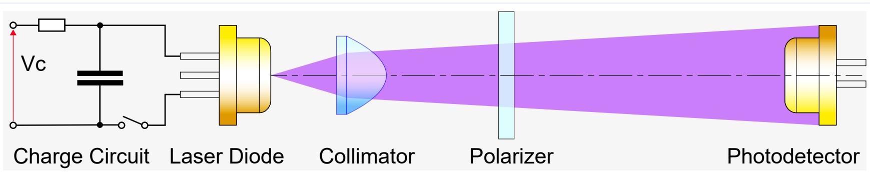
Semiconductor laser	**Types of pulsed diode laser**	**Laser pulse and Peak Power**
Duty cycle	**Repetition Rate**	**Average output power**
Spatial radiation distribution	**Polarisation Analysis**	**Energy measurement**

Continuously operating diode laser are available from a few milliwatt up to several hundreds of watt. They can also be operated in a pulsed mode, however the pulse power is slightly above the continuous power. Pulsed diode laser can only emit pulses but with extremely high peak power in the kilowatt range in a very short time of a couple of nanoseconds. Such diode laser are useful when a flash lamp like emission is required like for range finder, optical time domain reflectometer (OTDR) or light detection and ranging (LIDAR).

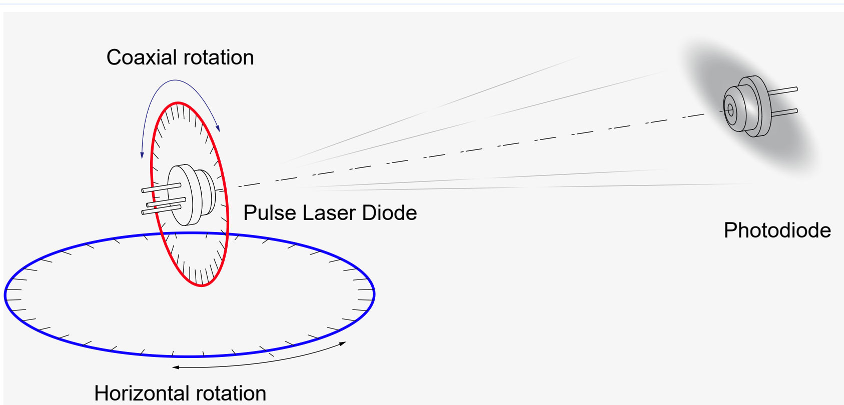
This experiment is equipped with a pulse diode laser emitting at 905 nm with a maximum peak power of 70 W and a pulse width of 100 nanoseconds. Both, the peak power as well the pulse width can be adjusted within a certain range. The students will study the parameter by displaying the timely behaviour on a digital oscilloscope. The optical as well as electrical discharge pulse is monitored. The diode laser is operated by the discharge of a pre-loaded capacitor. The influence of the charging voltage and discharge time on the emitted power is recorded and discussed.

The optical property of the diode laser like spatial beam distribution is measured and with subsequent collimation formed to an almost parallel beam. Further on the polarisation of the diode laser emission is measured using a polarisation analyser.

With an optical power meter the energy per pulse is measured in micro Joule. The energy sensor as well as display unit are optional and needs to be ordered extra.

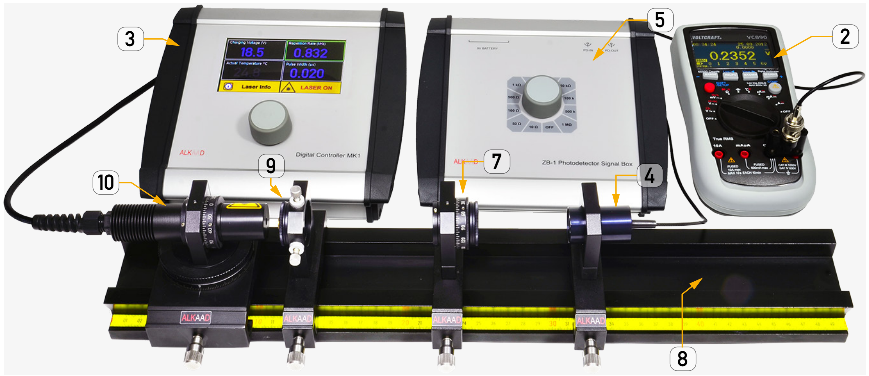


The pulse laser diode requires an electrical pulse to emit a laser pulse. It cannot operate in cw mode like other laser diodes. Their advantage is that they can deliver a peak power which is magnitudes higher than the cw power. The electrical pulse is generated by discharging a capacitor (closing of the switch). The capacitor is charged (open switch) to the desired voltage Vc. The attached controller manages the charging cycles and sets the desired voltage Vc. The output peak power depends on the stored energy by the capacitor and the repetition rate on the ON/OFF rate of the switch.



The pulse laser diode is built into a round housing which is mounted into a twofold rotary stage for horizontal and coaxial rotation. This allows the measurement of the spatial intensity distribution of the emitted laser light. The incident light from the laser diode is detected and measured with a fixed photodetector. The polarisation property of the laser light is measured by placing a polarisation analyser in front of the fast photodetector. The detector is connected to a circuit which converts the photocurrent into a voltage which can be displayed on an oscilloscope to observe the dynamic parameter like repetition rate, pulse width and peak power. An optional energy meter is available which measures the energy of a single pulse. Using the pulse width, the optical peak power can be calculated.

Description of the components



The pulse diode laser (8) is connected to the controller (3) which allows the setting of the charge voltage Vc, the pulse width as well as the pulse repetition rate. A collimator (8) is used to control the divergence of the laser radiation and a polarisation analyser (6) allows the measurement of the polarisation property of the laser radiation. The photodetector (4) is connected to the junction box (5) which converts the photocurrent into a linear voltage. The signal is available at a BNC connector and can be displayed on an oscilloscope (11) or the provided digital voltmeter (2). To monitor the fast signals with rise times in the nanosecond range the photodetector is operated with a 50 Ohms shunt.

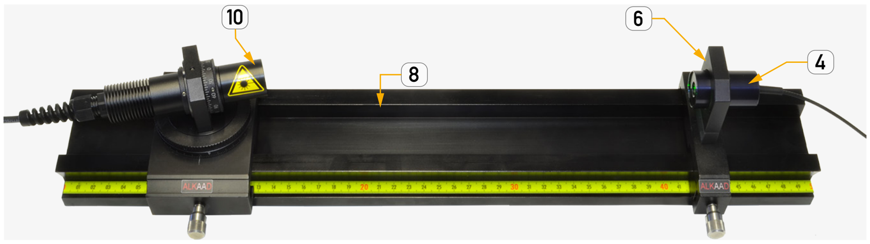


Fig. 2.54: Setup to measure the far-field distribution

The arrangement shown on the left is used to measure the spatial intensity or far-field distribution. The pulse laser diode (10) is rotated horizontally step by step and the intensity measured with the photodetector (4). Then the laser is rotated by 90° around its optical axis (coaxial) and again step by step the intensity is recorded (see. Fig. 2.55). To measure the peak power versus the charge voltage Vc (Fig. 2.54) the pulse diode is directed to the photodetector.

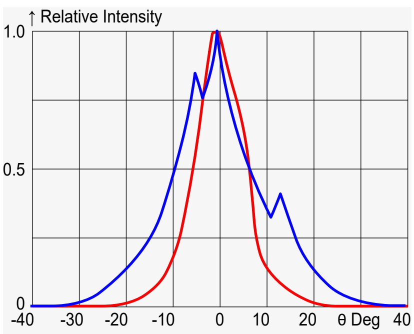


Fig. 2.55: Far-field distribution

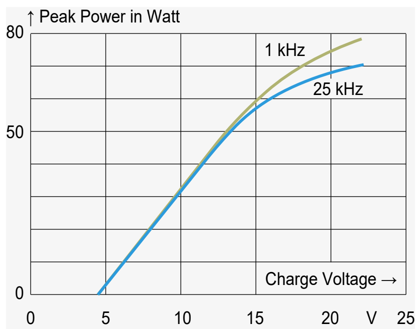


Fig. 2.56: Peak power versus charge voltage

With the same setup as shown in Fig. 2.54 the dynamic and temporal intensity of the pulse laser diode is measured. The shunt resistor of the junction box is set to 50 Ohms to achieve a fast response of the photodiode. The trigger signal from the controller as well as the photo voltage from the junction box are connected to the oscilloscope. The Fig. 2.57 shows the screen dump of the measurement of the periodic time and repetition rate of the pulse train of the laser diode whereas Fig. 2.58 shows the resolution of a single pulse. The electronic reference pulse of the controller is used as trigger (blue trace). The optical pulse (yellow trace) is analysed with respect the width and peak value.

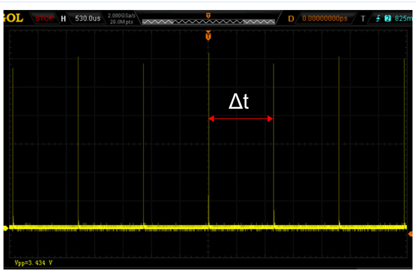


Fig. 2.57: Pulse train of the laser diode, measurement of the periodic time and determination of the repetition rate

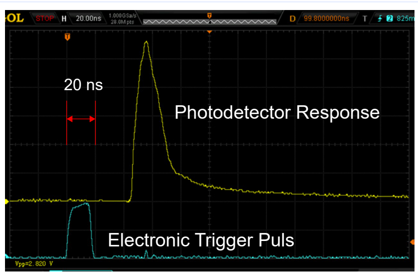


Fig. 2.58: Measuring the pulse width and the peak power

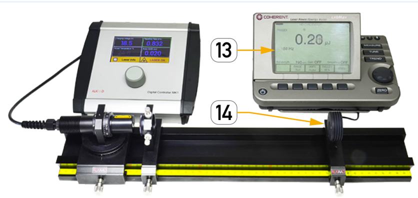


Fig. 2.59: Measuring the energy of a single pulse

Instead of the photodetector the optional energy sensor (14) is used in conjunction with the display unit (13). By knowing the energy per pulse and the pulse width, the optical peak power can be calculated.

LE-0500 Pulsed Diode Laser consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	CA-0060	1	Infrared display card 0.8 -1.4 µm	64 (10)
2	CA-0220	1	Multimeter 3 1/2 digits	66 (21)
3	DC-0050	1	Pulsed laser diode controller MK1	59 (6)
4	DC-0120	1	Si-PIN Photodetector, BPX61 with connection leads	60 (15)
5	DC-0380	1	Photodetector Junction Box ZB1	62 (31)
6	MM-0020	1	Mounting plate C25 on carrier MG20	30 (1)
7	MM-0410	1	Rotary Polarisation Analyzer 40 mm	33 (24)
8	MP-0150	1	Optical Bench MG-65, 500 mm	30 (8)
9	OC-0170	1	Collimator 808 nm in C25 mount	36 (13)
10	OM-0520	1	Pulsed diode laser head in twofold rotary mount	50 (22)
11	UM-LE05	1	Manual Pulsed diode laser	
	Option (order separately)			
12	CA-0200	1	Oscilloscope 100 MHz digital, two channel	66 (19)
13	CA-0260	1	Laser power meter LabMax-TO	66 (22)
14	CA-0262	1	Energy sensor head 300 nJ - 600 µJ	66 (22)

Highlights

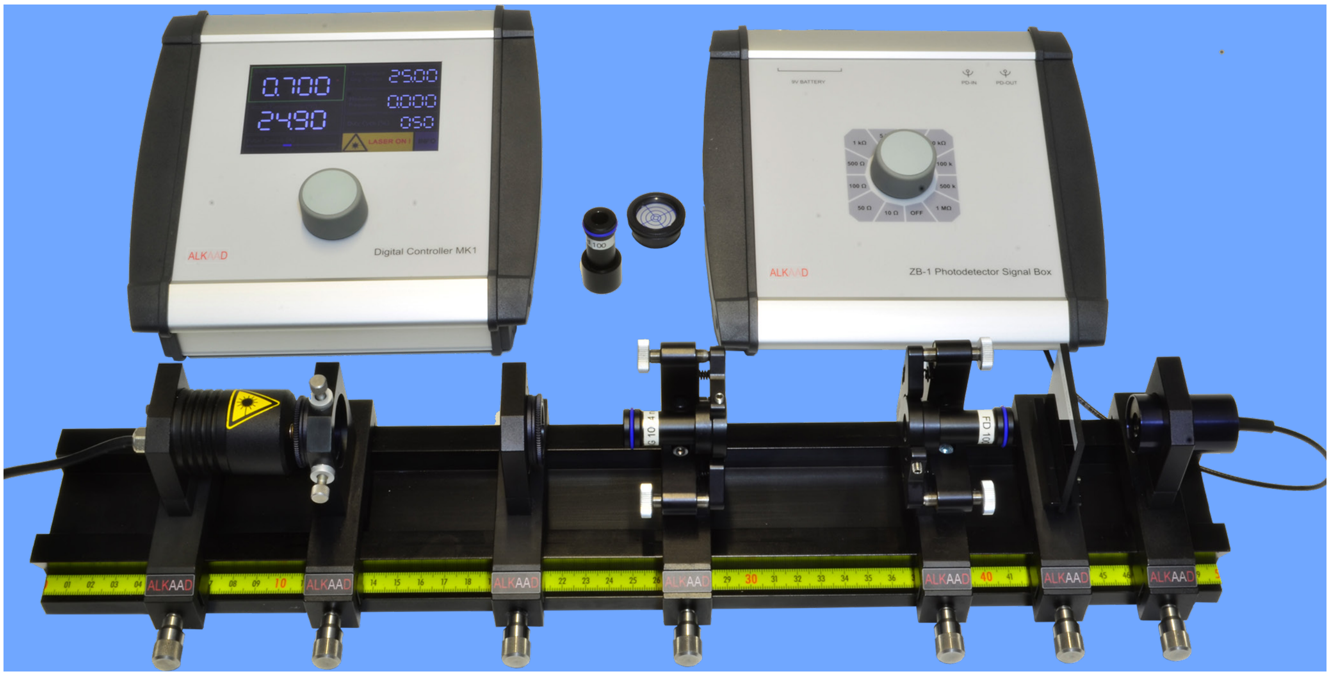
Basic and advanced level ★★ experiments, introduction to pulse laser application

- ★★ Pulse diode laser emission
- ★★ Polarisation
- ★★ High peak power
- ★★ Far-field pattern

Intended institutions and users:

- Physics Laboratory
- Engineering department
- Electronic department
- Biophotonics department
- Physics education in Medicine

LE-0600 Diode pumped Nd:YAG Laser



Keywords

Properties of Diode laser
Static and dynamic behaviour
Resonator Stability Criterion
Hemispherical Resonator
Optical Pumping
Output Power
Transversal Modes
Spherical Resonator
Rate Equation Model
Optical Resonator
Spiking
Laser Line Tuning

Introduction

Optical pumping in conjunction with Nd:YAG lasers is of particular interest, because these have become widely accepted for industrial use, along with the CO_2 laser. The laser-active material which, in the case of the Nd:YAG laser, is excited by optical pumping, consists of Neodymium atoms that are accommodated in a transparent YAG host crystal (Yttrium Aluminium Garnet).
Whereas up to a few years ago Nd:YAG lasers were always excited using discharge lamps, optical pumping with laser diodes is becoming more and more significant. This is because laser diodes are available economically and they emit narrow band light at high optical powers, which matches the energy levels of the Nd:YAG crystal. The advantage over the discharge lamp is that the emission of laser diodes is nearly completely absorbed by the Nd:YAG, whereas the very wide spectral emission of discharge lamps is absorbed to only a small extent.
The four level system is explained, a theoretical analysis of the Nd:YAG laser is performed, and a rate equation model derived. The steady state solution is presented, and the dynamic situation considered to investigate spiking.
The experiments contains all components necessary to assemble a diode pumped Nd:YAG laser - a 1W diode with driver and Peltier controller, collimating and focusing optics, Nd:YAG crystal, laser mirrors, a photodiode detector and all necessary mounts etc.
The stability criterion of the resonator are verified experimentally. The dependence of the pump wavelength on diode temperature and drive current are proven, and the absorption spectrum of Nd:YAG derived. By using a few additional modules, this basic set-up can be upgraded to LE-0700 „Frequency Doubling with KTP“ or LE-0800 „Generation of short pulses“. Furthermore the components for the oscillation at 1.3 µm including frequency doubling to “red” or an active or passive Q-switch are available as options.

How it works

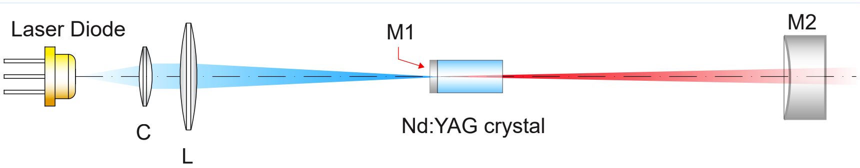


Fig. 2.60: Hemispherical Nd:YAG laser cavity

One side of the Nd:YAG crystal is coated and forms the first mirror (M1) for the laser cavity. The second mirror (M2) is a curved mirror resulting in a hemispherical cavity. The Nd:YAG crystal is pumped by the radiation of 808 nm emitted from the laser diode. The divergent radiation is collimated (C) to an almost parallel beam and afterwards focused (L) in such a way that the focus lies within the Nd:YAG crystal.

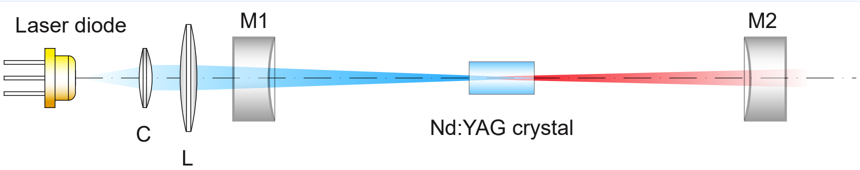


Fig. 2.61: Concentric Nd:YAG laser cavity

Another concept is to use a Nd:YAG rod which has no mirror coating. With such a rod other cavity configurations can be realized. One of it is the concentric cavity which uses two curved mirror (M1 and M2) of same radii of curvature. This concept allows a much better mode matching and gives more intracavity space for more experimental freedom

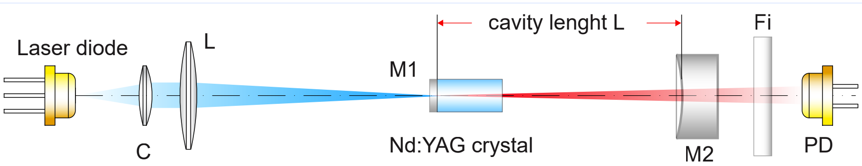
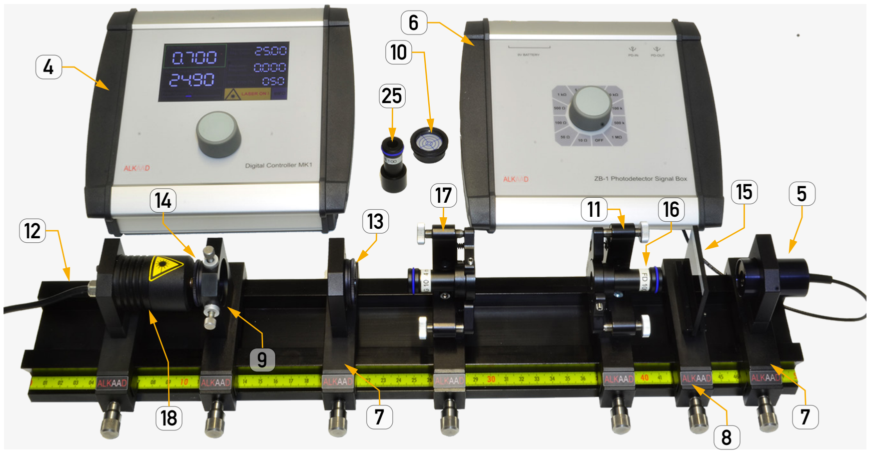


Fig. 2.62: Measurement setup

Independent of the choice of the cavity, a photodetector and a NIR long pass filter is used to measure either the power of the Nd:YAG laser or without the NIR filter the absorption of the pump laser. With the removal of the Nd:YAG crystal and NIR filter the radiation of the pump laser is measured for various values of the temperature or injection current.

Description of the components



The Nd:YAG rod is mounted to a M16 mirror mount and screwed into the mirror adjustment holder of (17). The rod is optically pumped by the diode laser (18) which is mounted to a Peltier cooler inside the housing of (18). The laser emits a power of 1 W at a wavelength of 808 ± nm at 25°C. The divergent light is collimated by a precision aspheric lens (14) to an almost parallel beam. The XY- adjuster (9) is used to align the beam with respect to the mechanical axis of the rail which is given by the target screen (10) when plugged in to the mounting plate (7) at the end of the rail (12). The lens (13) focuses the beam into the Nd:YAG rod (17). The Nd:YAG laser cavity is formed by the coated back side of the Nd:YAG rod and the mirror (16) which is screwed into the adjustment mount (11). The optical signals are detected by the photodiode of (15) which is connected to the junction box (6) where the photo current is converted into a voltage.

Measurements

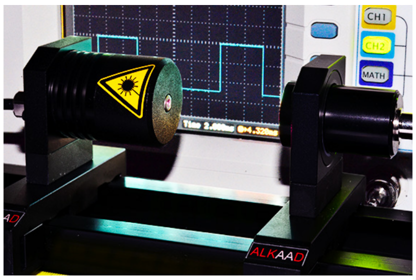


Fig. 2.63: Characterising the laser diode

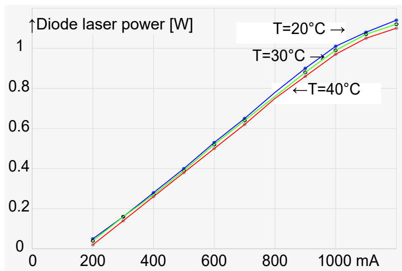


Fig. 2.64: Diode laser power versus injection current

One of the first measurement may be the characterization of the pump laser diode concerning the power and spectral properties. The Fig. 2.64 shows the diode laser power versus the injection current with the temperature as parameter. The power has been measured using an optional power meter (20, 21). The measurement can also be done by using the provided photodetector (5) in connection with the junction box (6). In this case the power values are given in relative units. In a next step the spectral property is measured. That means the dependence of the wavelength on the temperature and injection current.

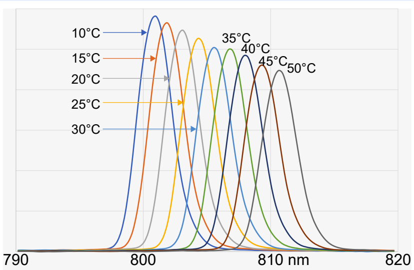


Fig. 2.65: Wavelength versus temperature

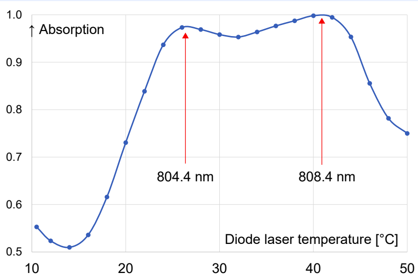


Fig. 2.66: Absorption spectrum

These experiments are related to the spectral property of the pump laser diode, which means the wavelength as function of the injection current or temperature. The Fig. 2.65 shows the emission spectrum taken with the fibre coupled optional spectrometer (22) at constant injection current for different temperatures from 10 to 50°C in steps of 5 °C. The Fig. 2.66 shows the absorption spectrum of the Nd:YAG rod for different temperatures of the pump laser diode. From literature it is known that the maximum absorption occurs at 808.4 nm.

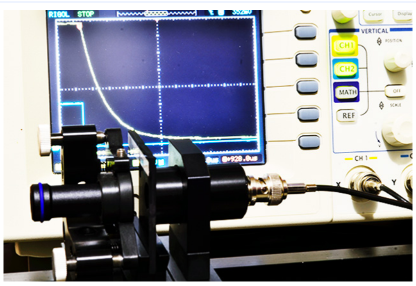


Fig. 2.67: Fluorescence decay

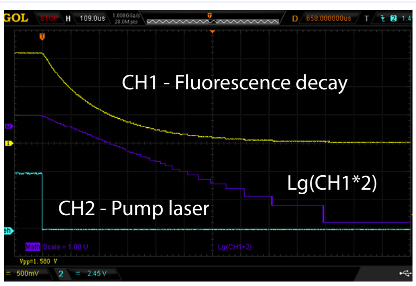


Fig. 2.68: Determination of the lifetime of the excited state

This experiment is addressed to the optical pumping of the Nd:YAG rod. The Fig. 2.67 shows the arrangement, the Nd:YAG rod is excited by the pump laser in pulse mode and the photodetector (5) senses the created fluorescence intensity. To block the residual pump power, a filter (15) is used. The photodetector is connected to the junction box (6) where the photo current is converted into a voltage, which is displayed on an oscilloscope. The Fig. 2.68 shows the screen dump of the oscilloscope (28) with an extra math track which linearises in real time the fluorescence decay to evaluate the lifetime of the excited state as its slope.

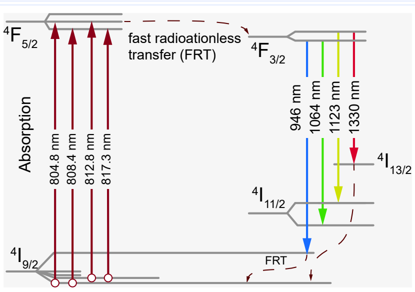


Fig. 2.69: Relevant Nd:YAG energy level diagram

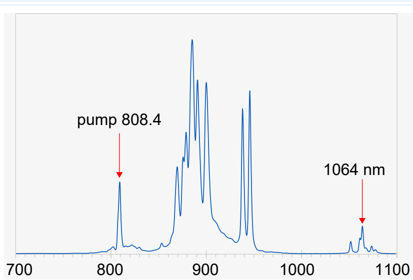


Fig. 2.70: Fluorescence spectrum taken in the range from 700 - 1100 nm

With the fibre coupled spectrometer (22) the fluorescence spectrum is easily obtained (see Fig. 2.70). The peak at 808.4 nm stems from the pump laser which is tuned to this wavelength. The absorption around 808 nm belongs to the $^4I_{9/2} \rightarrow {}^4F_{5/2}$ manifold and the fluorescence manifold in the range of 850-950 nm to the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transitions. The fluorescence intensity is quite high, laser oscillation is hardly possible, since the laser transition would end in populated ground state levels. The main wavelength is the 1064 nm, the fluorescence intensity appears to be low, also due to the spectrometer sensitivity

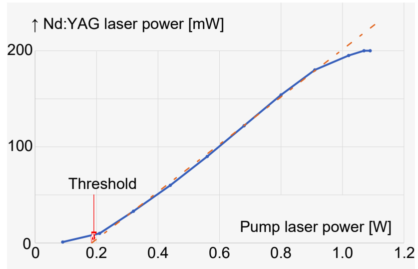


Fig. 2.71: Output versus pump power measured with power meter

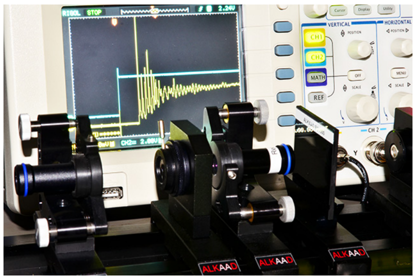
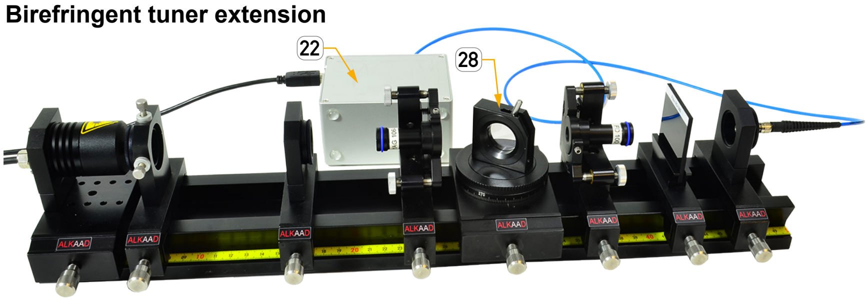


Fig. 2.72: Laser spiking (yellow curve) as a result of modulated pump power (blue)

After performing the characterization of the laser diode, absorption and fluorescence spectra, the laser cavity is setup and its properties studied. By using for the mirror M2 the output coupler with 2% transmission for 1064 nm the laser output power is measured as function of the pump power. From this, the laser threshold and efficiency is determined. Enabling the modulator of the controller MK1 (4) allows the study of the dynamic behaviour of the Nd:YAG laser like the so called spiking (Fig. 2.72). Extending the length of the cavity by moving the mirror M2 allows the study of the optical stability criterion.

Birefringent tuner extension



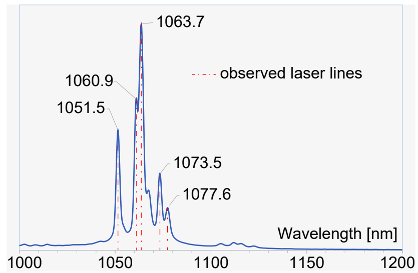
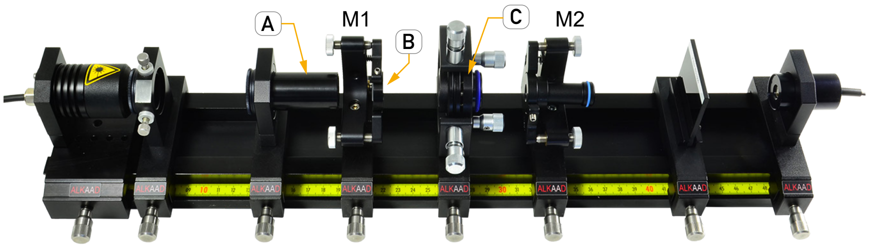


Fig. 2.73: Fluorescence spectrum and laser lines in the range from 1000 to 1200 nm

The fluorescence spectrum of Fig. 2.70 and Fig. 2.73 shows next to the traditional 1064 nm line a couple of some more lines which are candidates for laser operation. However, they can only oscillate if the strong 1064 nm is suppressed significantly which is obtained by using the birefringent tuner (28) inside the laser cavity. By means of the fibre coupled spectrometer (22) the laser lines are identified. For almost each fluorescence line laser operation can be achieved.

The concentric cavity extension



Within this exciting experiment the hitherto hemispherical setup is interchanged against a concentric or confocal one. For this purpose the Nd:YAG rod (17) is exchanged against a spherical mirror (B). The Nd:YAG rod used (C) has no (except antireflection) coatings and is positioned in the centre between M1 and M2. For best performance the rod can be adjusted in all directions. Instead of the focusing lens (13) a lens in an extended housing is used to create the focus in the centre of the cavity. This design enhances the study of optical cavities as well as the respective stability ranges. The arrangement of the mirrors M1 and M2 can be concentric (mirror distance L=100 mm) or confocal can with L=50 mm.

LE-0600 Diode pumped Nd:YAG Laser consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	CA-0060	1	Infrared display card 0.8 -1.4 µm	64 (10)
2	CA-0080	1	Optics cleaning set	65 (12)
3	CA-0450	2	BNC connection cable 1 m	67 (28)
4	DC-0040	1	Diode laser controller MK1	58 (4)
5	DC-0120	1	Si-PIN Photodetector, BPX61 with connection leads	60 (15)
6	DC-0380	1	Photodetector Junction Box ZB1	62 (31)
7	MM-0020	2	Mounting plate C25 on carrier MG20	30 (1)
8	MM-0060	1	Filter plate holder on MG20	31 (7)
9	MM-0090	1	XY adjuster on MG20	31 (8)
10	MM-0100	1	Target Cross in C25 Mount	31 (9)
11	MM-0462	1	Kinematic mirror mount M16, right	34 (31)
12	MP-0150	1	Optical Bench MG-65, 500 mm	30 (8)
13	OC-0060	1	Biconvex lens f=60 mm in C25 mount	36 (5)
14	OC-0170	1	Collimator 808 nm in C25 mount	36 (13)
15	OC-0950	1	Filter RG1000 50x50x3 mm	41 (54)
16	OC-1070	1	Laser mirror M16, ROC 100 mm, HR @ 1064 nm	42 (65)
17	OM-0624	1	Nd:YAG rod in 2 axes kinematic mount	52 (32)
18	OM-L500	1	Diode laser module 808 nm on C20	55 (56)
19	UM-LE06	1	Manual for Nd:YAG Laser	
	Option (order separately)			
20	CA-0260	1	Laser power meter LabMax-TO	66 (22)
21	CA-0266	1	Power sensor PM3 0.5 mW to 2W	67 (25)
22	CA-0270	1	Fibre coupled spectrometer 200 - 1200 nm, USB	67 (26)
23	LE-0620	1	Concentric Cavity Extension	69 (2)
24	LE-0710	1	“Green” 532 nm SHG extension	page 24
25	LE-0720	1	“Red 660 nm” SHG Extension	page 24
26	LE-0810	1	Passive Q-Switch Extension	69 (3)
27	LE-0820	1	Active Q-switch Extension	69 (4)
28	OC-1060	1	Laser mirror M16, ROC 100 mm, T 2% @ 1064 nm	42 (64)
29	OM-0580	1	Birefringent Tuner	51 (27)
30	CA-0200	1	Oscilloscope 100 MHz digital, two channel	66 (19)

Highlights

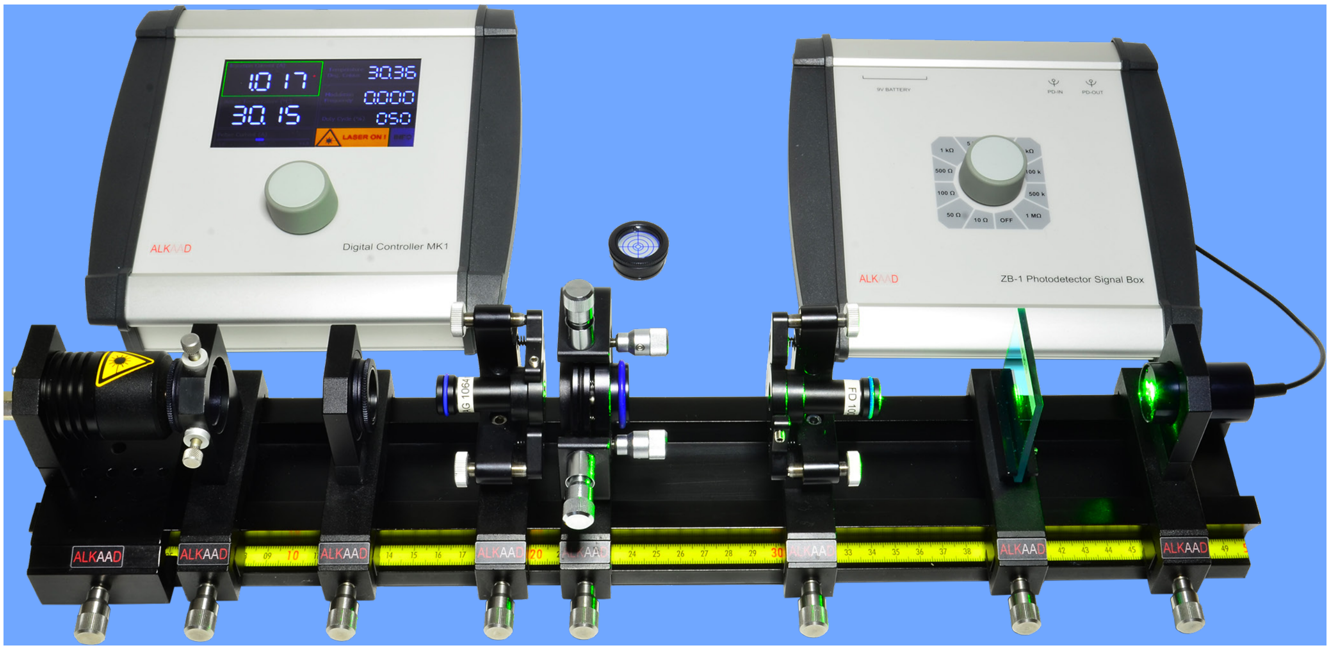
Basic, advanced and top level ★★★ experiment

★★★	Classical Nd:YAG laser
★★★	Laser spectroscopy
★★★	Hemispherical cavity
★★★	Concentric and confocal cavity
★★★	Lifetime and Einstein coefficients
★★★	Optical Stability Criteria
★★★	BFT Line tuning

Intended institutions and users:

- Physics Laboratory
- Engineering department
- Electronic department
- Biophotonics department
- Physics education in Medicine

LE-0700 "Green" SHG with Diode pumped Nd:YAG Laser



Keywords

Interaction of Light and Matter
Second Harmonic Generation
Nd:YAG Laser
Crystal Optics
Phase Matching Condition
High Order Transverse Modes
Non-linear Optics
KTP Crystal
BFT Green Line tuning

Introduction

Lasers which emit light in the short wavelength spectral range are expensive and not sufficiently reliable for many applications. A more economically way to generate such radiation is achieved by frequency doubling. Especially the generation of green laser radiation is an important requirement of the lithographic industry. At present the argon ion laser is being displaced more and more by frequency doubled diode pumped Nd:YAG lasers. The principles of the generation of frequency doubled light will be explained and simultaneously the possibilities of non linear optics learnt in this experiment. The understanding of non linear effects is very important for laser technology, since the processes of generation of short pulses are also based on non linear effects. Within the experiment the phase matching condition will be presented and analysed. The efficiency of frequency doubling will be determined and hints for an optimised conversion rate will be evaluated in the experiment. For the first time the subject of frequency doubling can be followed up in a certain manner by a practical experiment. The theoretical understanding of the non linear optics grows by practical verification. Incidentally the understanding of birefringent crystals grows by experience of phase matching. The fundamental wave is generated by a diode laser pumped Nd:YAG laser with an open resonator structure. The non - linear crystal is placed into the resonator and intra - cavity SHG is carried out. The reflectivity of the output coupler of the Nd:YAG laser is chosen as high as possible to obtain several watts of power of the fundamental wave inside the cavity.

How it works

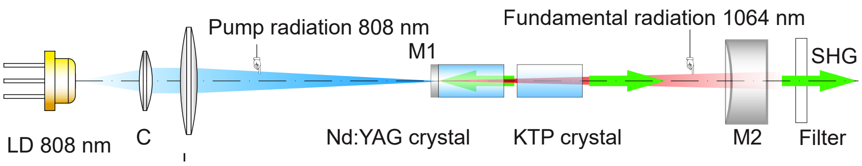


Fig. 2.74: "Green" Second Harmonic Generation (SHG)

One side of the Nd:YAG crystal is coated and forms the first mirror (M1) for the laser cavity. The second mirror (M2) is a curved mirror resulting in a hemispherical cavity. The Nd:YAG crystal is pumped by the radiation of 808 nm emitted from the laser diode. The divergent radiation is collimated (C) to an almost parallel beam and afterwards focused by the lens (L) in such a way that the focus lies within the Nd:YAG crystal. The KTP crystal is inserted into the cavity close to the Nd:YAG crystal where the beam waist is at smallest and thus the intensity of the fundamental radiation (1064 nm) at highest for efficient second harmonic generation (SHG). A filter is used to suppress the residual fundamental and pump radiation and to transmit the "green" SHG only.

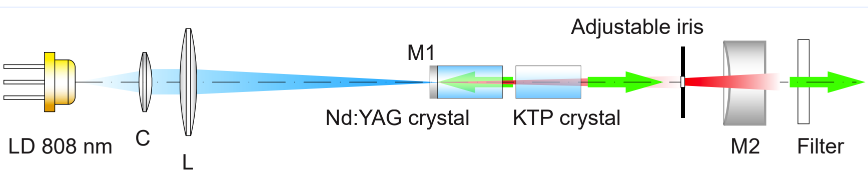


Fig. 2.76: Adjustable iris to reduce transverse modes down to TEM_{00}

Due to the high gain and asymmetric pump beam a large number of transverse modes are excited. Each of these modes generates a second harmonic which gives a visible pattern on a screen. To reduce the large multitude of modes, an adjustable iris is placed close to the output coupler mirror M2. Clear structured, beautiful transverse modes are achieved!

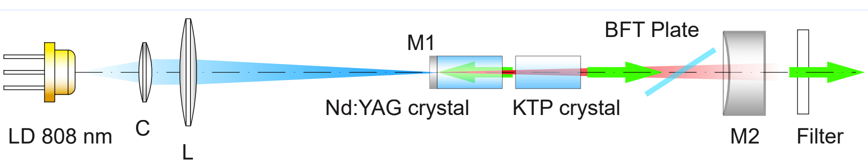
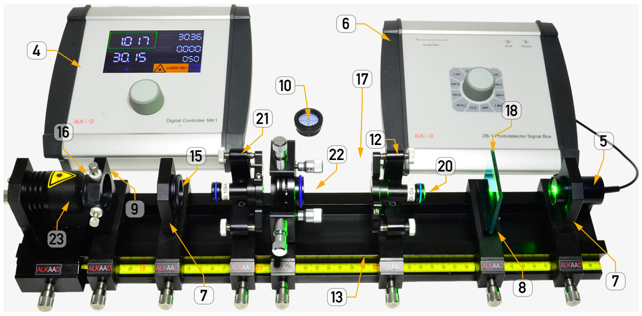


Fig. 2.75: Tuning different "green" lines from 526 up to 539 nm

This unique experiment uses a birefringent tuner (BFT) to select one of the manifold of lines of the Nd:YAG laser around 1064 nm (see) resulting in the same number of frequency doubled lines from 526 to 539 nm. The BFT is placed under the Brewster angle along with the KTP crystal inside the cavity. The change of the colour is not sufficient to distinguish the lines, thus the use of a spectrometer is recommended.

Description of the components



The Nd:YAG rod is mounted to a M16 mirror mount and screwed into the mirror adjustment holder of (21). The rod is optically pumped by the diode laser which is mounted to a Peltier cooler inside the housing of (23). The laser emits a power of 1 W at a wavelength of 808 ± nm at 25°C. The divergent light is collimated by a precision aspheric lens (16) to an almost parallel beam. The XY- adjuster (9) is used to align the beam with respect to the mechanical axis of the rail which is given by the target screen (10) when plugged in to the mounting plate (7) at the end of the rail (13). The lens (15) focuses the beam into the Nd:YAG rod (21). The Nd:YAG laser cavity is formed by the coated back side of the Nd:YAG rod and the mirror (20) which is screwed into the adjustment mount (12). The optical signals are detected by the photodiode of (5) which is connected to the junction box (6) where the photo current is converted into a voltage. For the frequency doubling or second harmonic generation a KTP crystal (22) is used, which is mounted into a 4 axes adjustment holder with a rotary mount to achieve best phase matching. A BG 39 filter (18) is used to transmit only the green radiation to the photodetector (5) or translucent white screen (11). To control the number of transverse modes an intracavity adjustable iris (17) is placed into the cavity.

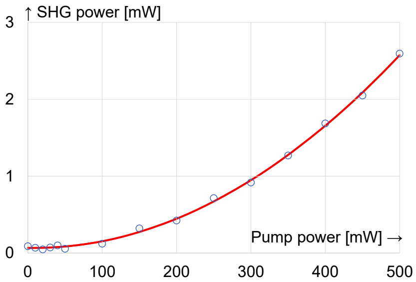


Fig. 2.78: SHG power versus pump power

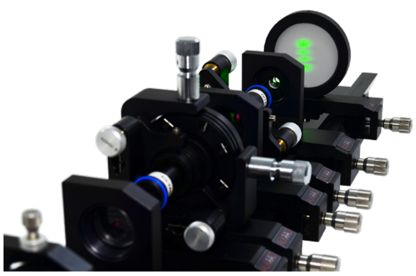
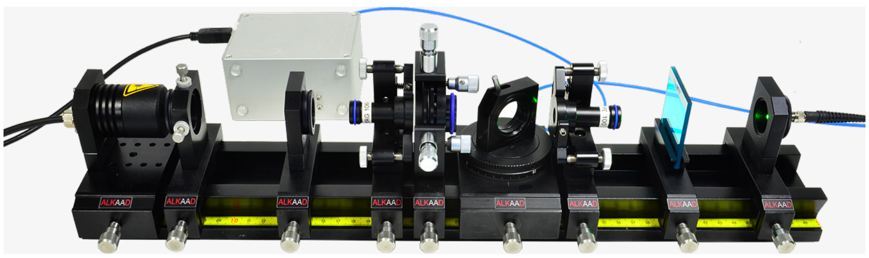


Fig. 2.79: Higher transverse modes, photograph of the translucent screen

The Fig. 2.78 shows the power of the second harmonic versus the pump power which reveals the non linear nature of the second harmonic generation. Furthermore, the SHG radiation is used to visualize the transverse mode structure (Fig. 2.79) of the Nd:YAG laser and is imaged by a short focal biconcave lens (14) onto the translucent white screen. The adjustable iris (15) is used to constrict the radial mode volume even down to the TEM_{00} mode.

Tuning green lines from 525.8 to 538.8 nm



The fluorescence spectrum of Fig. 2.77 shows next to the common 1064 nm line a couple of some more lines which are candidates for laser operation. However, they can only oscillate if the strong 1064 nm is suppressed significantly which is obtained by using the birefringent tuner (27) inside the laser cavity. By means of the fibre coupled spectrometer (26) the laser lines are identified. For almost each fluorescence line laser operation can be achieved. Each lasing line is frequency doubled by the KTP resulting in a respective manifold of green lines.

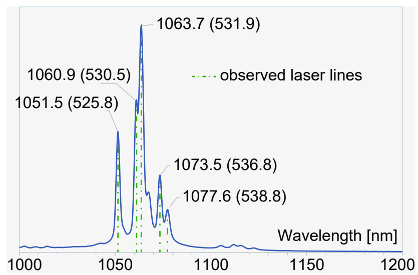


Fig. 2.77: Fluorescence and laser spectrum

The values in the brackets behind the lasing wavelength of the Nd:YAG laser are the frequency doubled lines ranging from 525.8 to 538.8 nm!

LE-0700 "Green" SHG with Diode pumped Nd:YAG Laser consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	CA-0060	1	Infrared display card 0.8 -1.4 µm	64 (10)
2	CA-0080	1	Optics cleaning set	65 (12)
3	CA-0450	2	BNC connection cable 1 m	67 (28)
4	DC-0040	1	Diode laser controller MK1	58 (4)
5	DC-0120	1	Si-PIN Photodetector, BPX61 with connection leads	60 (15)
6	DC-0380	1	Photodetector Junction Box ZB1	62 (31)
7	MM-0020	2	Mounting plate C25 on carrier MG20	30 (1)
8	MM-0060	1	Filter plate holder on MG20	31 (7)
9	MM-0090	1	XY adjuster on MG20	31 (8)
10	MM-0100	1	Target Cross in C25 Mount	31 (9)
11	MM-0110	1	Translucent screen on carrier MG20	31 (10)
12	MM-0462	1	Kinematic mirror mount M16, right	34 (31)
13	MP-0150	1	Optical Bench MG-65, 500 mm	30 (8)
14	OC-0005	1	Biconcave lens f=-5 mm, C25 mount	35 (1)
15	OC-0060	1	Biconvex lens f=60 mm in C25 mount	36 (5)
16	OC-0170	1	Collimator 808 nm in C25 mount	36 (13)
17	OC-0400	1	Adjustable iris mounted in C25	37 (19)
18	OC-0939	1	Filter BG39, 50 x 50 x 3 mm	41 (53)
19	OC-0950	1	Filter RG1000 50x50x3 mm	41 (54)
20	OC-1070	1	Laser mirror M16, ROC 100 mm, HR @ 1064 nm	42 (65)
21	OM-0624	1	Nd:YAG rod in 2 axes kinematic mount	52 (32)
22	OM-0650	1	KTP crystal SHG 532 nm, 5 axes mount on carrier MG20	52 (34)
23	OM-L500	1	Diode laser module 808 nm on C20	55 (56)
24	UM-LE06	1	Manual for Nd:YAG Laser	
	Option (order separately)			
25	CA-0200	1	Oscilloscope 100 MHz digital, two channel	66 (19)
26	CA-0270	1	Fibre coupled spectrometer 200 - 1200 nm, USB	67 (26)
27	OM-0580	1	Birefringent Tuner	51 (27)

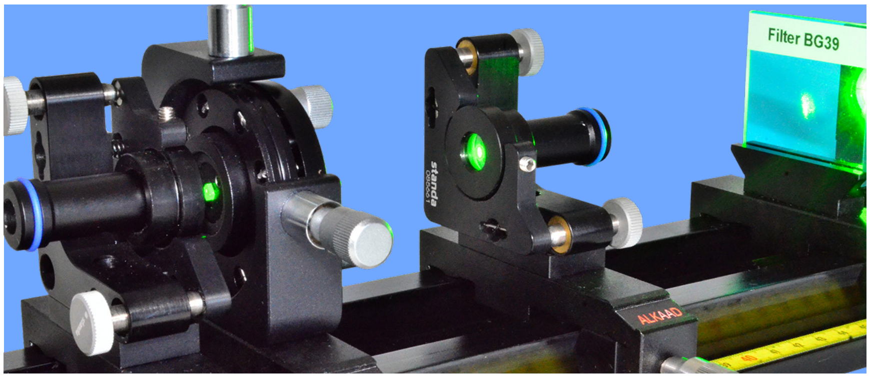
Highlights

Basic, advanced and top level ★★★ experiment

★★★	Classical Nd:YAG laser
★★★	Laser spectroscopy
★★★	Hemispherical cavity
★★★	Concentric and confocal cavity
★★★	Lifetime and Einstein coefficients
★★★	Optical stability criteria
★★★	BFT "green" line tuning
★★★	Nonlinear Optics
★★★	High order transverse modes

Intended institutions and users:
- Physics Laboratory
- Engineering department
- Electronic department
- Biophotonics department
- Physics education in Medicine

LE-0710 “Green” 532 nm SHG extension

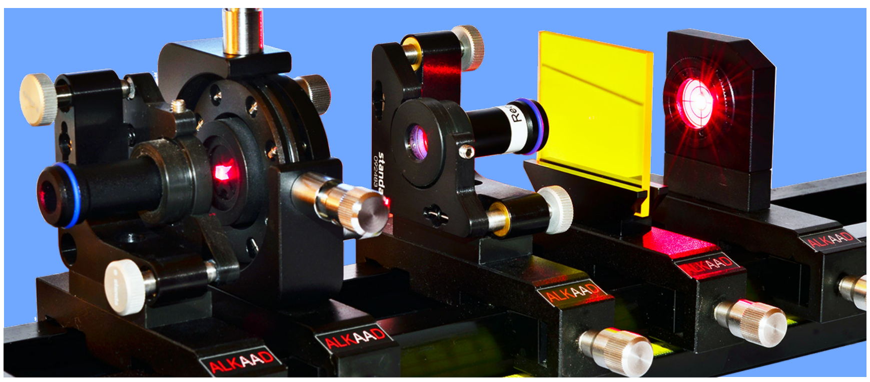


This extension comprises all necessary components to convert the “LE-0600 Diode pumped Nd:YAG Laser” into the “LE-0700 “Green” SHG with Diode pumped Nd:YAG Laser”. The main part is the KTP crystal (5) mounted into a 4 axes adjustment holder with a rotary mount allowing the KTP crystal to be rotated around its optical axis for best phase matching angle.

LE-0710 “Green” 532 nm SHG extension consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	MM-0110	1	Translucent screen on carrier MG20	31 (10)
2	OC-0005	1	Biconcave lens f=-5 mm, C25 mount	35 (1)
3	OC-0400	1	Adjustable iris mounted in C25	37 (19)
4	OC-0939	1	Filter BG39, 50 x 50 x 3 mm	41 (53)
5	OM-0650	1	KTP crystal SHG 532 nm, 5 axes mount on carrier MG20	52 (34)

LE-0720 “Red 660 nm” SHG Extension



This extension comprises all necessary components to operate the “LE-0600 Diode pumped Nd:YAG Laser” at 1330 nm instead of 1064 nm. For this purpose the provided Nd:YAG rod (1) and the cavity mirror (4) are coated for this wavelength. A KTP crystal (2) is provided to double the frequency of the fundamental wave of 1330 nm resulting in a red radiation. With the spectrometer (CA-0270) the spectrum of the visible red radiation is recorded and it shows three different lines (see Fig. 2.81). From this we can conclude that the Nd:YAG laser oscillates simultaneously on three lines 1318.8 1327.0 and 1337,6 nm. The Fig. 2.80 shows the relevant energy level diagram for the 1064 nm (532 nm) and the transition $^4F_{3/2} \rightarrow {}^4I_{13/2}$ for the 1330 nm manifold.

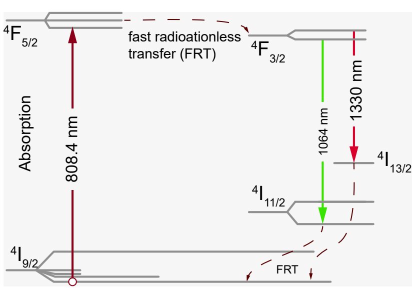


Fig. 2.80: The 1330 nm laser transition

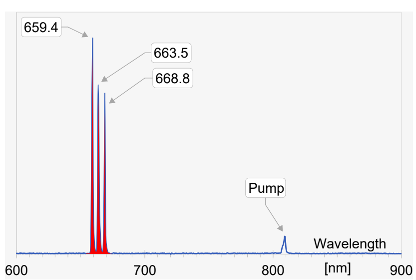


Fig. 2.81: Red SHG lines

LE-0720 “Red 660 nm” SHG Extension consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	OC-0860	1	Nd:YAG rod 1.3 µm coating, M16 mount	40 (48)
2	OC-0870	1	“Red 660 nm” SHG crystal mounted KTP in mount	40 (49)
3	OC-0910	1	Filter KG5, 50 x 50 x 3 mm	40 (51)
4	OC-1080	1	Laser mirror M16, ROC 100 mm, HR @ 1300 nm	42 (67)

LE-0800 Generation of Q-Switch Laser Pulses

Keywords

Nd:YAG-Laser	**Rate Equation Model**	**Steady State Solutions**
Time Dependent Solutions	**Spiking**	**Saturable Absorber**
Q - Switch	**Mechanical Chopper**	**Laser Pulse Width**
Peak Power	**Repetition Rate**	

Introduction

The use of short-pulse lasers enables the generation of high peak power pulses in a short time, which are useful for the investigation of non-linear effects and for the investigation of time dependant effects e.g. time resolved spectroscopy. In order to achieve extremely high peak power up to the Gigawatt range, laser systems are applied, which possess long lived excited states able to store energy and to emit it in an extremely short time. One of such lasers is e.g. the Nd:YAG laser. With q-switching in so called active or passive mode, it is possible to generate such short pulses. Here, in a first step the theory of laser operation with Nd:YAG is discussed and the steady state as well as time dependent solution of the four level rate equation is analysed. A two level rate equation model is introduced to explain the saturation behaviour of an optical absorber. The saturable absorber for passive q-switching is introduced. The dynamics of the pulse generation, like repetition rate, pulse width and peak power are determined. The experiment consists of the laser diode pumped Nd:YAG - laser as basic version with an additional passive q-switch (Cr:YAG) crystal. The time dependant signals are displayed and evaluated using an optional oscilloscope. Beside the generation of short pulses, the behaviour of the Nd:YAG laser can also be the subject of additional investigations, like measuring the threshold, slope efficiency and so on. By using the optional Pockels cell including the high voltage driver active q-switch can be performed and explored.

How it works

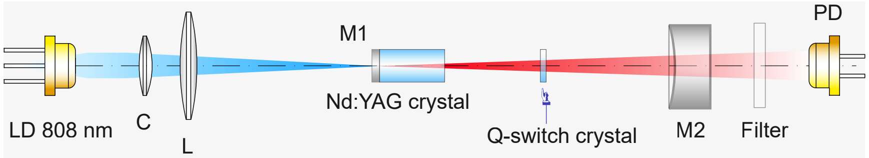


Fig. 2.82: Nd:YAG laser with saturable absorber crystal

The q-switch crystal is a saturable absorber whose absorption depends on the intensity of the incident light, the higher it is, the less the absorption will be. Placing such a crystal into the Nd:YAG laser cavity will prevent the laser to oscillate. However, the stimulated and spontaneous emission increases and reduces the absorption of the crystal to such an extend, that the laser reaches the threshold and emits a giant pulse. Immediately after the pulse ends, the crystal's absorption goes up again and prevents any laser action, until the crystal becomes transparent again under the influence of the strong fluorescence light. In this way a periodic pulse emission is created. Since the occurrence of the laser pulse depends on the systems parameter and its dynamics the pulse cannot predicted and thus this method is termed as passive q-switching opposed to the active q-switching where the operator controls the pulse release.

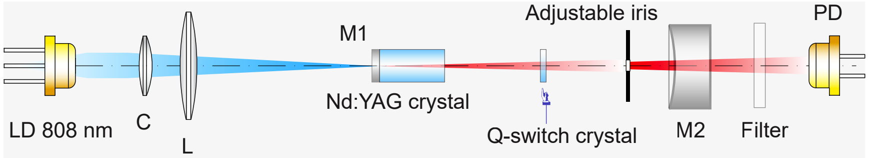
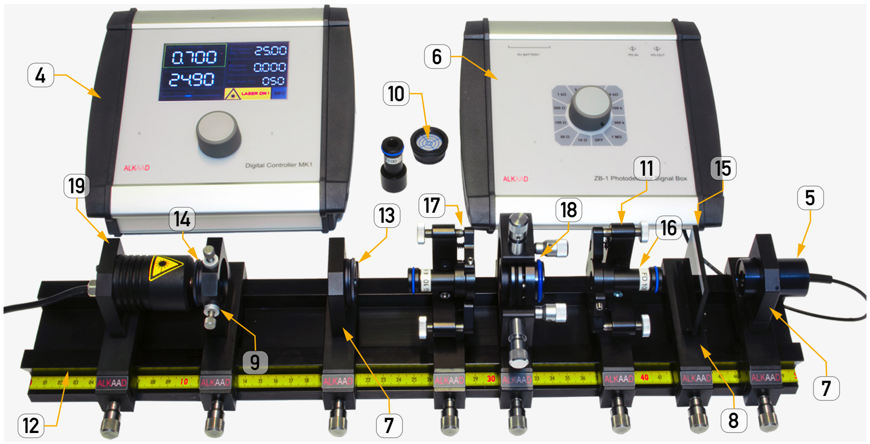


Fig. 2.83: Adjustable iris to reduce the number of transverse modes

To control the number of transverse modes an intracavity adjustable iris is placed into the cavity. By adjusting the free opening of the iris the diameter of the mode volume of the Nd:YAG laser is constricted, which in turn reduces the number of transverse modes. Even the fundamental Gaussian mode can be achieved in this way. Each transverse mode will build its own pulse and the less transverse modes exist, the clearer the pulse train will be. The pulses are detected by the fast photodiode PD and displayed on an oscilloscope. The expected pulse width is in a range of 50-100 ns and when using a cavity mirror with lowest output the cavity ring down effects can be observed as asymmetry of the pulse shape. The falling edge appears as a decay like curve.

Description of the components



The Nd:YAG rod is mounted to a M16 mirror mount and screwed into the mirror adjustment holder of (17). The rod is optically pumped by the diode laser which is mounted to a Peltier cooler inside the housing of (19). The laser emits a power of 1 W at a wavelength of 808 ± nm at 25°C. The divergent light is collimated by a precision aspheric lens (14) to an almost parallel beam. The XY- adjuster (9) is used to align the beam with respect to the mechanical axis of the rail which is given by the target screen (10) when plugged in to the mounting plate (7) at the end of the rail (13). The lens (13) focuses the beam into the Nd:YAG rod (17). The Nd:YAG laser cavity is formed by the coated back side of the Nd:YAG rod and the mirror (16) which is screwed into the adjustment mount (11). The optical signals are detected by the photodiode of (5) which is connected to the junction box (6) where the photo current is converted into a voltage. For the frequency q-switch pulse generation a Cr:YAG crystal (18) is used, which is mounted into a 4 axes adjustment holder to achieve best alignment with respect to the optical axis of the cavity. A RG 1000 filter (15) is used to transmit only the laser radiation to the photodetector (5). To control the number of transverse modes an intracavity adjustable iris (23) is placed into the cavity. For the performance of the measurements an oscilloscope is mandatory.

Measurements

Fig. 2.84: Free running q-switch pulse train

After optimising the output power of the Nd:YAG laser the Cr:YAG - crystal (19) is inserted into the resonator.

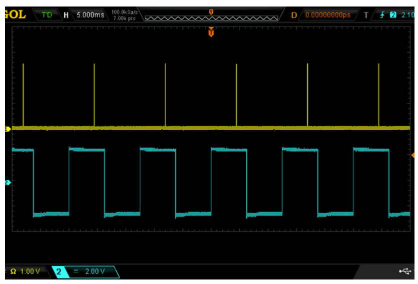


Fig. 2.85: Virtual q-switch by pump laser modulation

After slight re-adjustment one observes a train of needle-like pulses on the oscilloscope. Groups of amplitudes of different height show that there are also transversal modes as the result of the q-switching. The number of modes can be reduced by using the adjustable iris (23) leading to a more stable pulses with almost same amplitudes (Fig. 2.84).

A virtual active q-switch operation is obtained by modulating the pump laser diode and setting the duty cycle such, that only one of the laser pulse occurs (Fig. 2.85).

The repetition rate depends essentially on the losses and on the pump power. The higher the pump power is, the faster the saturation process for the q-switch will be, leading to a higher repetition rate. However, its upper limit is determined by the lifetime of the upper laser level.

LE-0800 Generation of Q-Switch Laser Pulses consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	CA-0060	1	Infrared display card 0.8 -1.4 µm	64 (10)
2	CA-0080	1	Optics cleaning set	65 (12)
3	CA-0450	2	BNC connection cable 1 m	67 (28)
4	DC-0040	1	Diode laser controller MK1	58 (4)
5	DC-0120	1	Si-PIN Photodetector, BPX61 with connection leads	60 (15)
6	DC-0380	1	Photodetector Junction Box ZB1	62 (31)
7	MM-0020	1	Mounting plate C25 on carrier MG20	30 (1)
8	MM-0060	1	Filter plate holder on MG20	31 (7)
9	MM-0090	1	XY adjuster on MG20	31 (8)
10	MM-0100	1	Target Cross in C25 Mount	31 (9)
11	MM-0462	1	Kinematic mirror mount M16, right	34 (31)
12	MP-0150	1	Optical Bench MG-65, 500 mm	30 (8)
13	OC-0060	1	Biconvex lens f=60 mm in C25 mount	36 (5)
14	OC-0170	1	Collimator 808 nm in C25 mount	42 (65)
15	OC-0950	1	Filter RG1000 50x3 mm	41 (54)
16	OC-1070	1	Laser mirror M16, ROC 100 mm, HR @ 1064 nm	42 (65)
17	OM-0624	1	Nd:YAG rod in 2 axes kinematic mount	52 (32)
18	OM-0660	1	Cr:YAG passive q-switch, 5 axis mount on MG20	52 (35)
19	OM-L500	1	Diode laser module 808 nm on C20	55 (56)
20	UM-LE06	1	Manual for Nd:YAG Laser	
	Option (order separately)			
21	LE-0820	1	Active Q-switch Extension	69 (4)
22	OC-0400	1	Adjustable iris mounted in C25	37 (19)
23	OC-1060	1	Laser mirror M16, ROC 100 mm, T 2% @ 1064 nm	42 (64)
	Required Option (order separately)			
24	CA-0200	1	Oscilloscope 100 MHz digital, two channel	66 (19)

LE-0820 Active Q-switch Extension consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	CA-0005	1	Allan key SW 0.9	63 (1)
2	DC-0356	1	Pockels Cell HV Driver DQ21, HV and Trigger Cable	62 (29)
3	OM-0030	1	Lithium Niobate Pockels Celle C-1043	47 (4)

Highlights

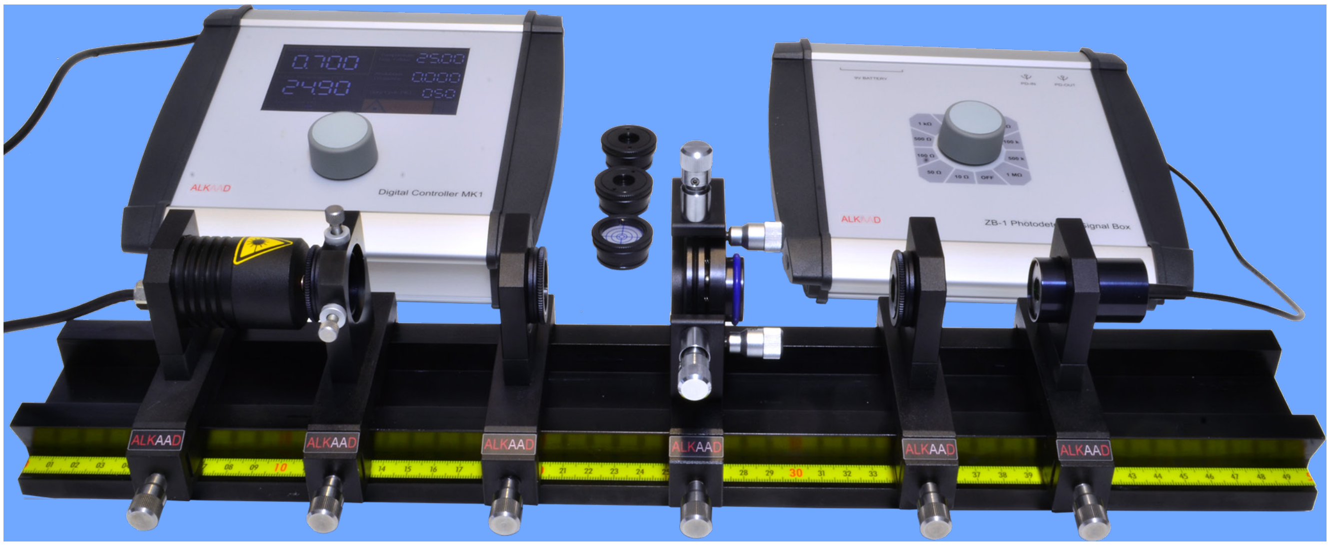
Basic, advanced and top level ★★★ experiment

★★★	Classical Nd:YAG laser
★★★	Hemispherical cavity
★★★	Lifetime and Einstein coefficients
★★★	Optical stability criteria
★★★	Saturable Absorber
★★★	Nonlinear Optics
★★★	Q-Switch Pulse train

Intended institutions and users:

- Physics Laboratory
- Engineering department
- Electronic department
- Biophotonics department
- Physics education in Medicine

LE-0900 Diode pumped Nd:YVO4 Micro Laser



Keywords

$Nd:YVO_4$ and KTP Crystal Compound | **Optical Pumping** | **$Nd:YVO_4$ Laser**
Laser Threshold | **Slope Efficiency** | **Pump Laser Characterization**
Laser Spiking | **Second Harmonic Generation** | **Nonlinear Optics**
Sum-Frequency Generation | **Green Problem** | **Single Mode Operation**

Introduction

Consider a cube of Neodymium doped Yttrium Vanadate ($Nd:VO_4$) with a length of 1 mm to which is bonded a KTP frequency doubler crystal with the same cross section but a length of 2 mm. Both opposite sides of the compound are coated with a mirror forming an optical cavity for the radiation of 1064 nm. When pumped with a small laser diode at 808 nm green radiation is produced. With a typical pump power of 200-300 milliwatt at 808 nm, green output power of around 10 milliwatt is obtained. Such a crystal compound (also termed as Green Laser Microchip GLM) allows the design of really small micro laser mainly used for laser imaging, green laser pointers, laser show, spectroscopy, medical diagnostics and a lot of other applications where the size of the laser source is of great importance.
Within this experiment we are using such a GLM and pumping it with the same setup as for the Nd:YAG laser (LE-0700). The GLM is mounted inside a 4 axes kinematic mount in order to align it to the focussed 808 nm pump radiation. As soon as the pump radiation hits the crystal, green emission is produced. By aligning the crystal the optimum of green power will be observed. Due to the possibility of tuning the temperature and output power of the pump diode laser, a series of measurements are carried out to demonstrate the quadratic relation between the green output and the fundamental power. The modulation capability of the diode laser driver allows the periodic switching on and off of the pump laser diode and to observe the "spiking" of the green radiation. Placing the provided laser line filter in front of the photodetector, only the 808 nm, 1064 nm or 532 nm radiation will be observed. This facilitates the separate characterization of the fundamental laser as well as the second harmonic.

How it works

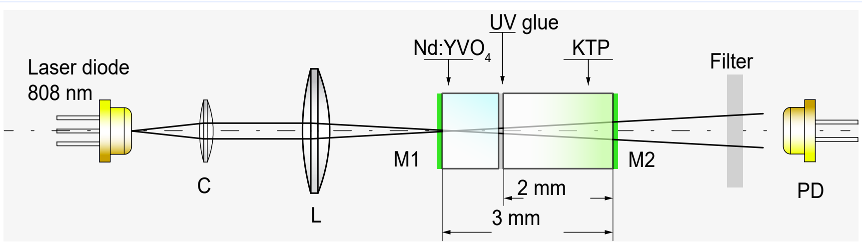


Fig. 2.86: Principle of the micro laser

The Green Laser Microchip consists of the $Nd:YVO_4$ crystal and the attached KTP crystal. The mirrors M1 and M2 form the cavity for the fundamental radiation at 1064 nm and are coated for highest reflectivity for this wavelength. In addition, M1 has a high transmission for the pump radiation at 808 nm and a high reflectivity for the second harmonic at 532 nm, while M2 has a high transmission for the second harmonic. The filter is used to suppress any residual radiation either at 808 nm or 1064 nm or to suppress the green emission to study the behaviour of the fundamental laser. The GLM is pumped by a separate laser diode. The pump laser radiation is collimated by a collimating lens (C) and focussed into the GLM by the lens (L). Considering the index of refraction for YVO_4 and KTP the optical cavity length is 5.4 mm, resulting in a spectral mode distance of the fundamental mode of about 28 GHz. The gain bandwidth of the $Nd:YVO_4$ crystal is 0.96 nm at 1064 nm or 254 GHz, allowing about 9 modes to oscillate. In principle each fundamental mode may create a second harmonic. However, due to the mainly homogeneously broadened gain profile, single frequency emission for the 1064 nm and 532 nm is expected. In case the $Nd:YVO_4$ is operating on more than one longitudinal mode, the KTP crystal also creates the sum-frequency of the longitudinal modes. This in turn couples the competing longitudinal modes and gives rise to chaotic fluctuation of the green emission. This phenomenon is also termed as "green problem" and also will subject of the experimental observations. By changing the injection current and / or temperature of the pump laser, the $Nd:YVO_4$ laser can be brought back to single mode operation which is indicated by the disappearance of the "green problem".

Measurements

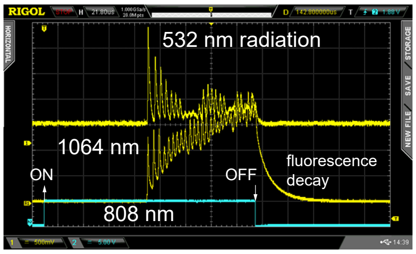


Fig. 2.87: Spiking of the 532 nm and 1064 nm and fluorescence decay

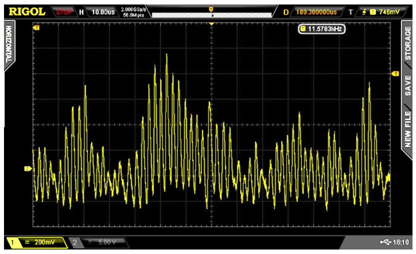


Fig. 2.88: The "Green Problem"

The gain medium (Nd:YVO$_4$), the nonlinear frequency doubler crystal (KTP) and the cavity are inseparably connected and thus forming a highly nonlinear structure. The Fig. 2.87 shows the laser and fluorescence response when pumping with a pump laser pulse. The initial spiking of the Nd:YVO$_4$ laser emission is damped by the second harmonic wave. After the sudden switch off of the pump laser, an exponential decay of the 1064 nm radiation is observed. The Fig. 2.88 shows undesired fluctuation of the green radiation caused by the sum-frequency generation by the KTP of competing longitudinal modes which occurs only if the Nd:YVO$_4$ laser is not operating in single mode.

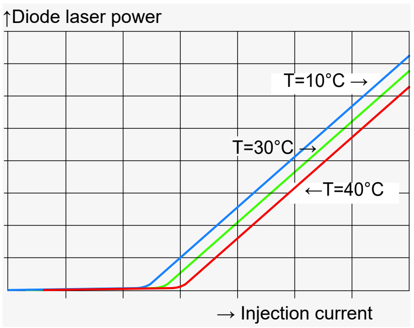
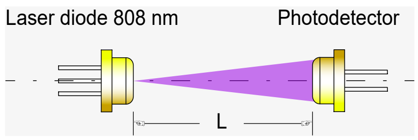


Fig. 2.89: Pump laser power versus injection current and temperature

The measurements may start with the characterization of the pump diode laser (16) which is connected and controlled by a microprocessor controller (4). The used laser diode is attached to a Peltier cooler which allows the temperature control from 10 to 50°C and the injection current control from 0 to 700 mA.



The photodetector is placed in front of the diode laser without any other optical components. The distance L is chosen such, that the photodetector is not saturated at maximum power and provides a sufficient signal at lower power values. The photodetector is connected to the junction box (5) where the photo current is converted into a linear voltage which is available at a BNC connector at the rear of (5).
For a set of temperature values the diode laser power for a series of injection current values is recorded and plotted. The resulting curves show the threshold and slope efficiency of the laser diode (Fig. 2.89).

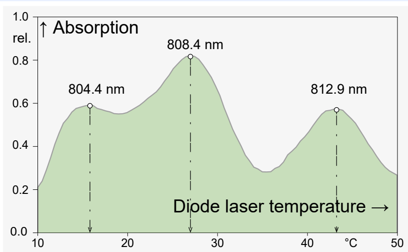
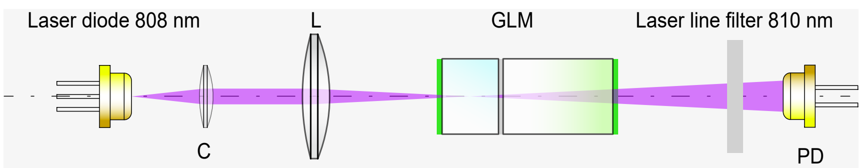


Fig. 2.90: Pump laser absorption versus temperature

The wavelength of the laser diode depends on the temperature of the emitting semiconductor chip and the injection current. To determine the wavelength of the laser diode and the absorption spectra of the GLM we are using a setup as shown in the figure below. To suppress the 1064 nm and the 532 nm we place a 810 ± 5 nm laser line filter (10) in front of the photodetector (5). For a fixed injection current, the non-absorbed pump radiation is recorded for a series of temperature values. The resulting graph (Fig. 2.90) shows two or more distinct maxima whereby one is higher than the other, which can be assigned to a wavelength of 808.4 nm.



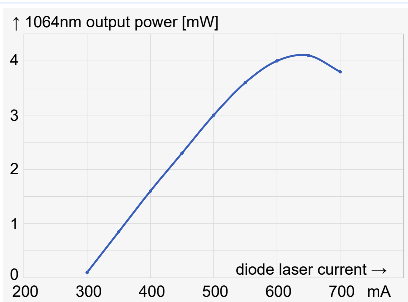
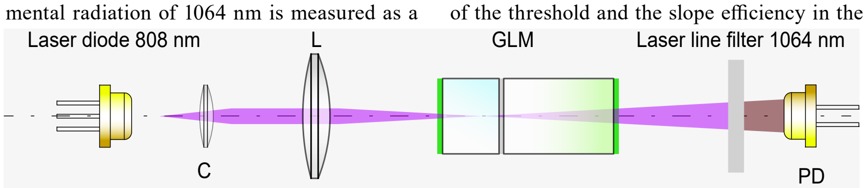


Fig. 2.91: Nd:VO$_4$ Laser power versus pump power

Once the optimum operating temperature has been estimated, the output power of the fundamental radiation of 1064 nm is measured as a function of the pump power or the injection current of the pump laser diode. To measure only the radiation at 1064 nm, the laser line filter (11) is applied. Although the mirror of the GLM has a high reflectivity, a small fraction is still transmitted. The Fig. 2.91 allows the determination of the threshold and the slope efficiency in the linear range of the curve for the Nd:YVO$_4$ laser. Above 550 mA the curve starts to saturate and even drops beyond 650 mA due to gain saturation and thermal effects.



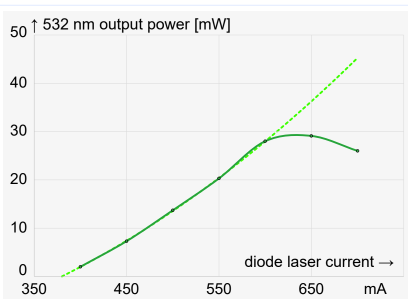
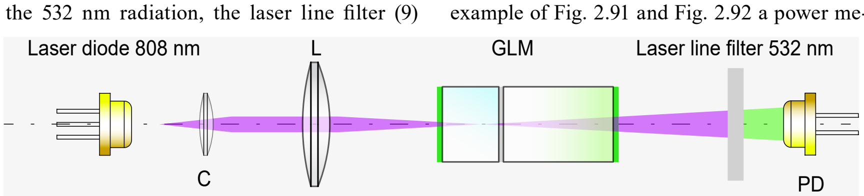
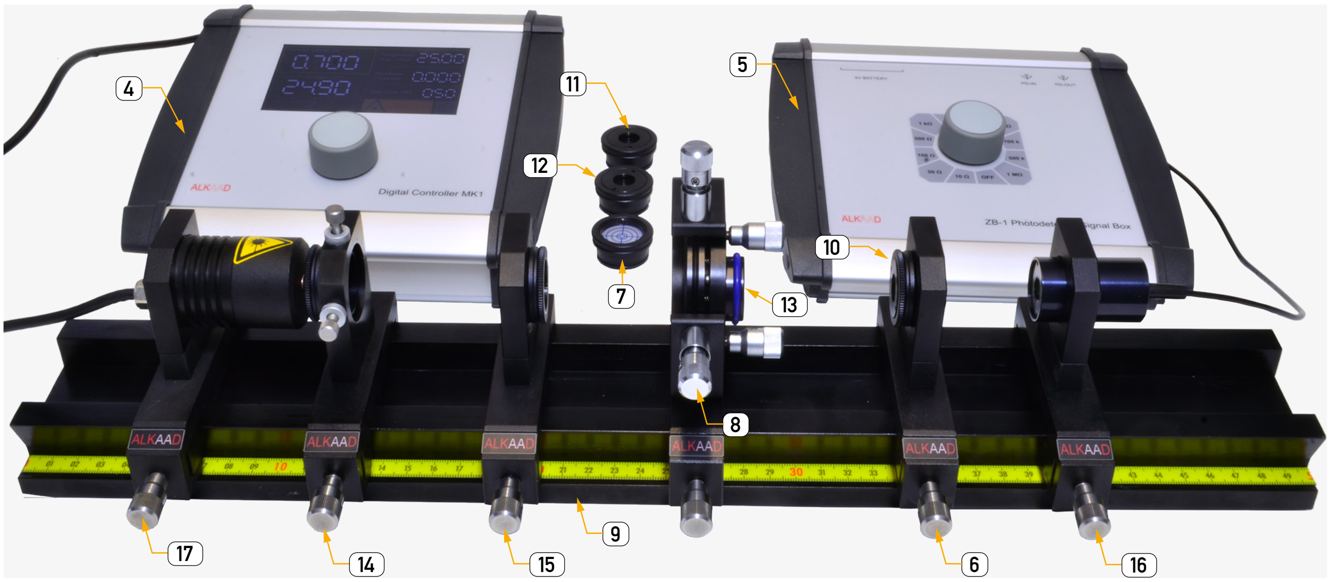


Fig. 2.92: SHG power versus fundamental power

The measurement of the "green" output power reveals the nonlinear character of the second harmonic generation process. To measure only the 532 nm radiation, the laser line filter (9) is applied. Since the fundamental power (Fig. 2.91) saturates beyond an injection current of 550 mA, it is expected that the same happens to the second harmonic radiation. Before the saturation takes place the "green" power depends quadratically on the fundamental power. In the example of Fig. 2.91 and Fig. 2.92 a power meter has been used to measure the absolute power values and it should be noted, that the green radiation attains almost 30 mW!



Description of the components



The heart of the setup is the Green Laser Module which has a size of only 1 x 1 x 3 mm. It is cemented into a slotted brass cylinder, which itself is mounted into the 5 axis adjustment holder (8). The GLM can be rotated around its axis, translated in X and Y and tilted in two orthogonal angles. The GLM is pumped by the temperature and current controlled diode laser (17). The controller (4) provides a fast modulation of the injection current along with variable duty values from 0 to 100%. This allows the reduction of the thermal load to the GLM and study the fundamental properties in a clearer manner. The emission of the diode laser is collimated (14) and centred to the mechanical axis of the optical bench (9). The focusing lens (15) having a focal length of 60 mm creates a small focus. The lens is positioned in such a way that the focus lies well within the GLM. As soon as the GLM is excited, the green (532 nm) laser radiation is observed behind the GLM. By adjusting the GLM with respect to the pump beam, the intensity of the green radiation is maximized. In addition to the green radiation, the 1064 nm Nd:VO_4 fundamental radiation as well as the unabsorbed residual pump power at 808 nm is present. To make each of the radiation accessible separately, laser line filter for 532 nm (10), 808 nm (11) and 1064 nm (12) are provided. These filters are placed into the mounting plate (6) in front of the photodetector (14).

Another essential device - not only for this experiment - is the MK1 digital controller. Modern micro processor solutions are combined with robust and precision experimental requirements. The MK1 provides a touch screen to activate the desired settings like temperature, injection current, modulation frequency and duty cycle of the modulation. The desired value is set by an precise knob operated electronic encoder. The temperature stabilisation has an outstanding accuracy of ±2 mK. Of course, the device is equipped with a USB bus and can be operated by the Windows© based computer or pads. The required software (ES-0040 MK1 controller software) is freely available. All of our LED, diode laser or DPSSL can be operated with the MK1. Each light source is equipped with a nonvolatile memory which is read by the MK1 and sets the maximum permissible limits of the temperature and operation current accordingly.

Highlights

Basic, advanced, and top level ★ experiments

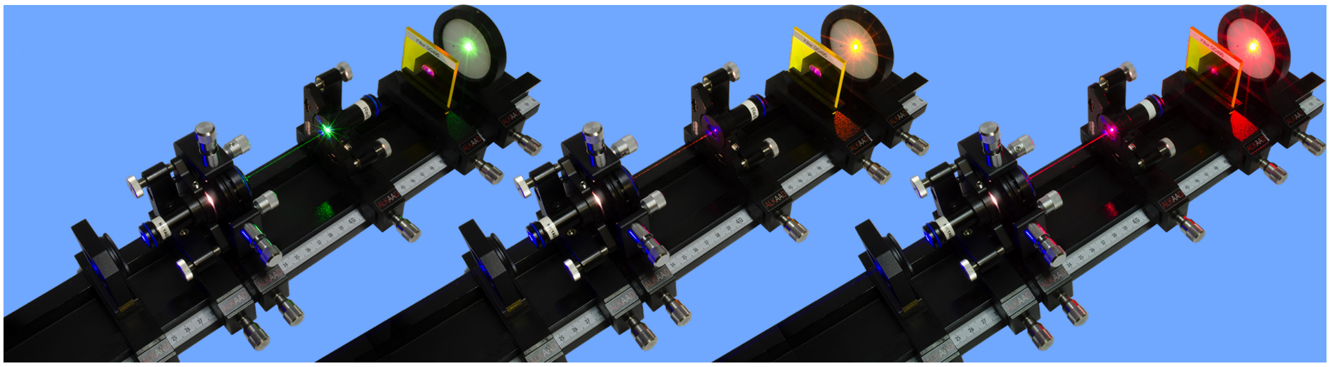
Outstanding features for a four level solid state experimental Laser with Frequency doubling.

Intended institutions and users:
- Physics Laboratory
- Engineering department
- Electronic department
- Biophotonics department
- Chemistry department
- Medical department

LE-0900 Diode pumped Nd:YVO4 Micro Laser consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	CA-0060	1	Infrared display card 0.8 -1.4 µm	64 (10)
2	CA-0080	1	Optics cleaning set	65 (12)
3	CA-0450	2	BNC connection cable 1 m	67 (28)
4	DC-0040	1	Diode laser controller MK1	58 (4)
5	DC-0380	1	Photodetector Junction Box ZB1	62 (31)
6	MM-0020	1	Mounting plate C25 on carrier MG20	30 (1)
7	MM-0100	1	Target Cross in C25 Mount	31 (9)
8	MM-0420	1	Four axes kinematic mount on carrier MG20	33 (25)
9	MP-0150	1	Optical Bench MG-65, 500 mm	30 (8)
10	OC-0750	1	Laser line filter 532 nm in C25 mount	39 (38)
11	OC-0754	1	Laser line filter 810 nm in C25 mount	39 (39)
12	OC-0756	1	Laser line filter 1064 nm in C25 mount	39 (40)
13	OC-0880	1	GCL in CR25 mount	40 (50)
14	OM-0620	1	Collimating optics on carrier MG20	51 (30)
15	OM-0622	1	Focussing optics, f=60 mm on carrier MG20	52 (31)
16	OM-0640	1	SiPIN photodetector on carrier MG20	52 (33)
17	OM-L500	1	Diode laser module 808 nm on C20	55 (56)
18	UM-LE09	1	Manual Micro laser	
	Option (order separately)			
19	CA-0200	1	Oscilloscope 100 MHz digital, two channel	66 (19)

LE-1000 Blue Diode pumped Pr:YLF Laser



Keywords

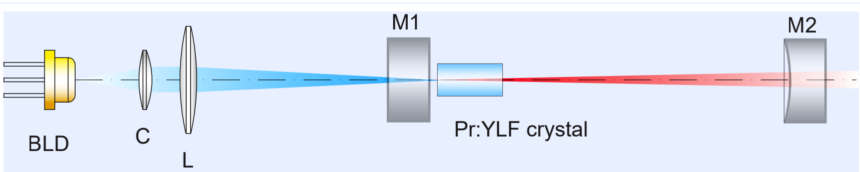
Blue Diode Laser 444 nm
Pr:YLF Excitation spectrum
Stability Criterion
Littrow prism line tuning
Demonstration of Spiking
SHG 640 nm → 320 nm UV
Wavelength dependency
Lifetime of excited state
Higher transverse modes
BFT line tuning
Active q-switch
Pockels cell
Pr:YLF Absorption spectrum
Hemispherical Cavity
Extended Cavity
Concentric Cavity
Operating of green and orange line
Operating of red and dark red lines

Introduction

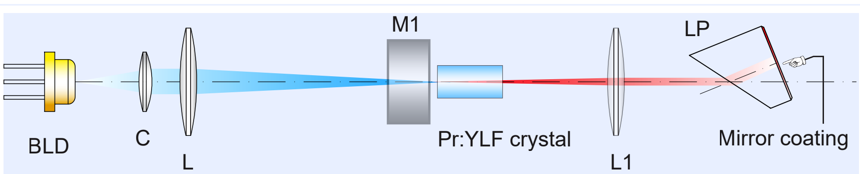
Due to the steadily increasing demand of the multimedia applications powerful RGB (red green blue) light sources came into the focus of industrial research. Along this road the Praseodymium laser has been reinvented again since this material has the potential to emit directly visible laser radiation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

The setup is designed in such a way that all components are accessible and can freely arranged on the optical rail. The measurement starts with the characterization of the blue laser diode which is connected to a digital controller allowing the settings of the injection current and temperature. In a next step the polarisation dependent absorption is measured. The Pr:YLF crystal is set into a mount which is inserted into a to a 4 axis kinematic mount allowing the crystal to be rotated around its axis. As soon as the crystal is exposed to the blue radiation of the laser diode a bright white fluorescence appears. By means of an optional spectrum analyser the emission lines are identified. By using the modulation capability of the controller the lifetime of the excited state is measured and related to the Einstein coefficient for spontaneous emission. The most exciting moment comes, when the laser cavity around the Pr:YLF crystal is setup. Due to the high gain, laser oscillation is obtained quite easily resulting in a strong red emission at 640 nm. To obtain laser oscillation also on other than the red line, either a Littrow prism, a birefringent tuner or selectively coated mirrors are used. Furthermore the generation of UV radiation with a wavelength of 320 nm as result of the intra cavity frequency doubling of the 640 nm line using a BBO crystal shows the great potential of such a laser system.

How it works



The radiation of the blue emitting laser diode (BLD) is collimated by the collimator (C) which is a high precision aspheric lens with a short focal length and a high numerical aperture. The resulting beam is parallel in one axis showing a more or less rectangular to elliptical intensity cross section. A focusing lens is used to focus the blue pump laser radiation into the Praseodymium doped YLF (Pr:YLF)crystal which is coated with a broadband anti reflection coating on both sides. The wavelength range for lowest reflection covers the entire emission range of the Pr:YLF material including the pump radiation at 444 nm. The optical cavity is formed by a flat mirror (M1) on the pump side and a curved mirror (M2) at the other cavity side. Due to the high gain, the alignment is achieved without external adjustment laser.



The figure on the right shows the main transitions within the energy level diagram of the 444 nm pumped Pr:YLF crystal. The strongest line is the emission with 640 nm. To operate the laser on other wavelengths, a Littrow prism (LP) is used instead the spherical mirror M2. To achieve again a stable hemispherical cavity the intracavity lens (L1) is required. The lens has a broadband anti reflection coating to keep the losses as low as possible. The Littrow prism (LP) is coated with a broadband coating having a high reflectivity > 99.98 % in a range of 580..725 nm. 5 visible lines can be obtained 606, 639, 676, 697 and 720 nm. If L1 is positioned correctly, the cavity length, or position of Littrow prism can virtually be in any position.

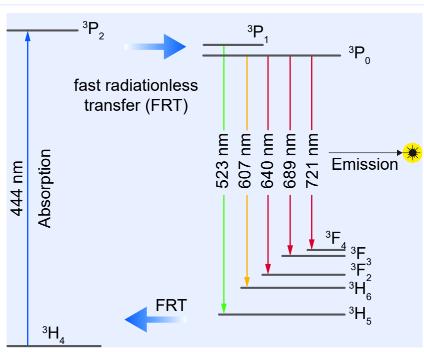
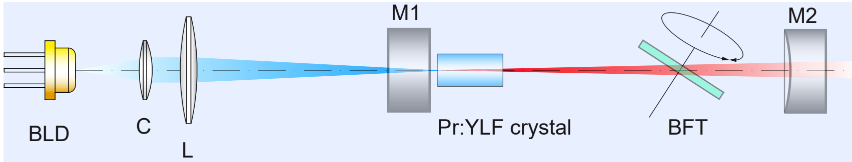
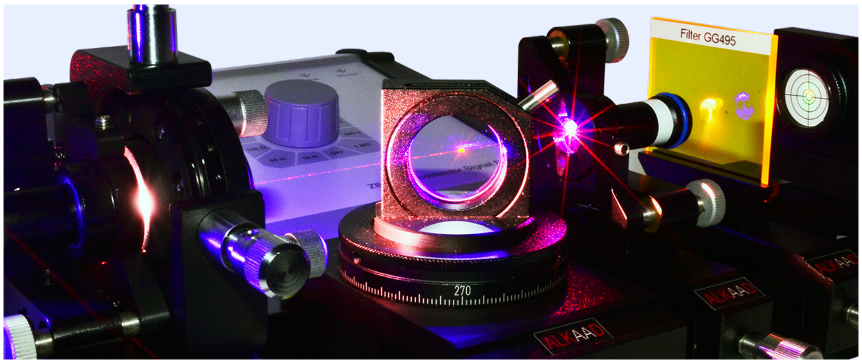


Fig. 2.93: Pr:YLF Energy level diagram

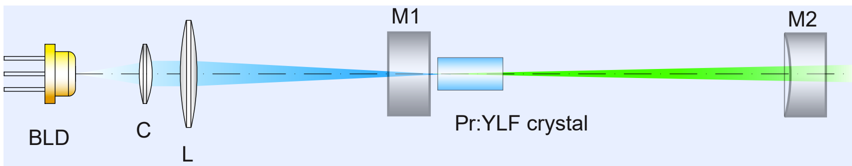


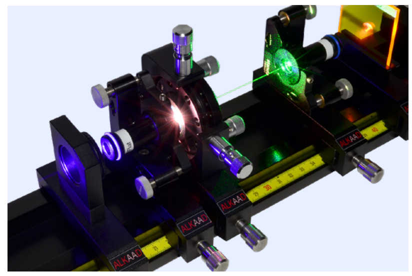


The birefringent tuner (BFT) is inserted into the hemispherical cavity. Although the beam is not that parallel as with the internal lens it works quite well. 5 visible lines can be obtained 607, 640, 676, 697 and 720 nm.

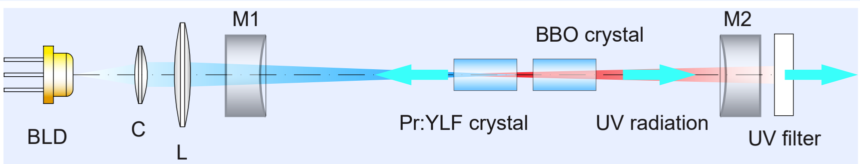
Wavelength (nm)	Strength (relative)
607	0.6
640	1.0
676	0.2
697	0.2
720	0.4

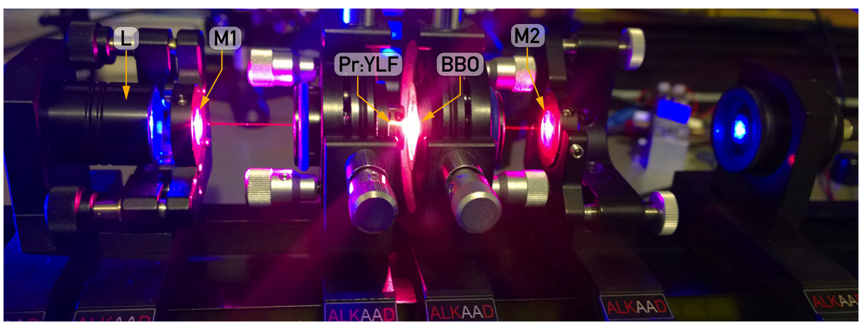
The picture on the left shows the operation of the 607 nm (yellow) line. The filter GG495 blocks the blue pump radiation and transmits all wavelengths above 495 nm. The BFT is mounted into a rotation table with an angle scale and is used to set the BFT to the Brewster's angle. The lever is used to turn the BFT plate in order to select the desired wavelength.





Another way to operate the Pr:YLF laser on a specific wavelength is to apply mirrors with selective coating. That means the coating is designed such, that the reflectivity is high only for the desired wavelength. The picture on the right shows the operation with mirrors (27) optimised for the green 523 nm line. Another set of mirror (28) allows only the yellow line at 607 nm.





The strong radiation at 640 nm allows the efficient frequency doubling or second harmonic generation of UV radiation to 320 nm. Such UV radiation is of great importance in Biophotonics. A LBO (Lithium Tri - Borate) or BBO (Beta Barium Borate) crystal is used as frequency doubler. It is 8 mm long with a quadratic cross section of 3 mm. The crystal is cut for type I phase matching for the wavelength of 640 nm. To achieve the necessary high intensity of the fundamental wave of 640 nm the cavity designed as confocal cavity where the Pr:YLF crystal is located in the centre of the cavity where the beam diameter of the fundamental wave has the smallest diameter. Furthermore, the focus of the blue pump radiation lies as well in the centre of the cavity. The frequency doubler crystal is mounted into a 5 axis adjustable mount like the Pr:YLF crystal.

Measurement Examples

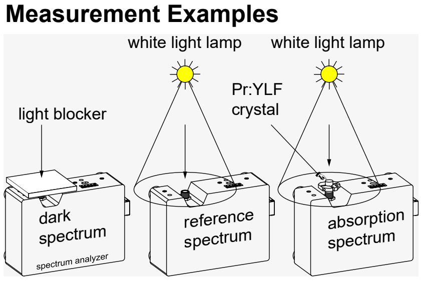


Fig. 2.94: Pr:YLF Absorption measurement

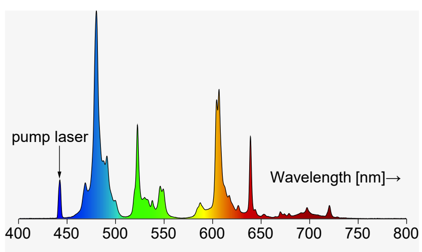


Fig. 2.96: Fluorescence Spectrum

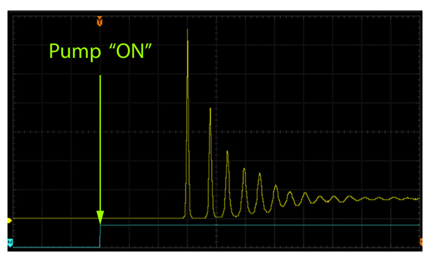


Fig. 2.98: Laser Spiking

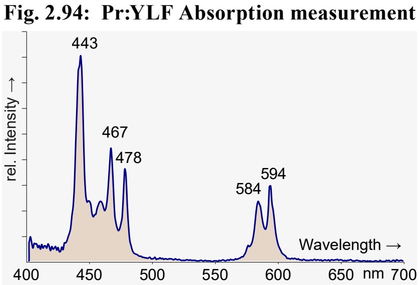


Fig. 2.95: Pr:YLF Absorption Spectrum

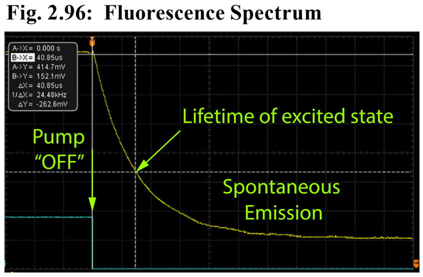
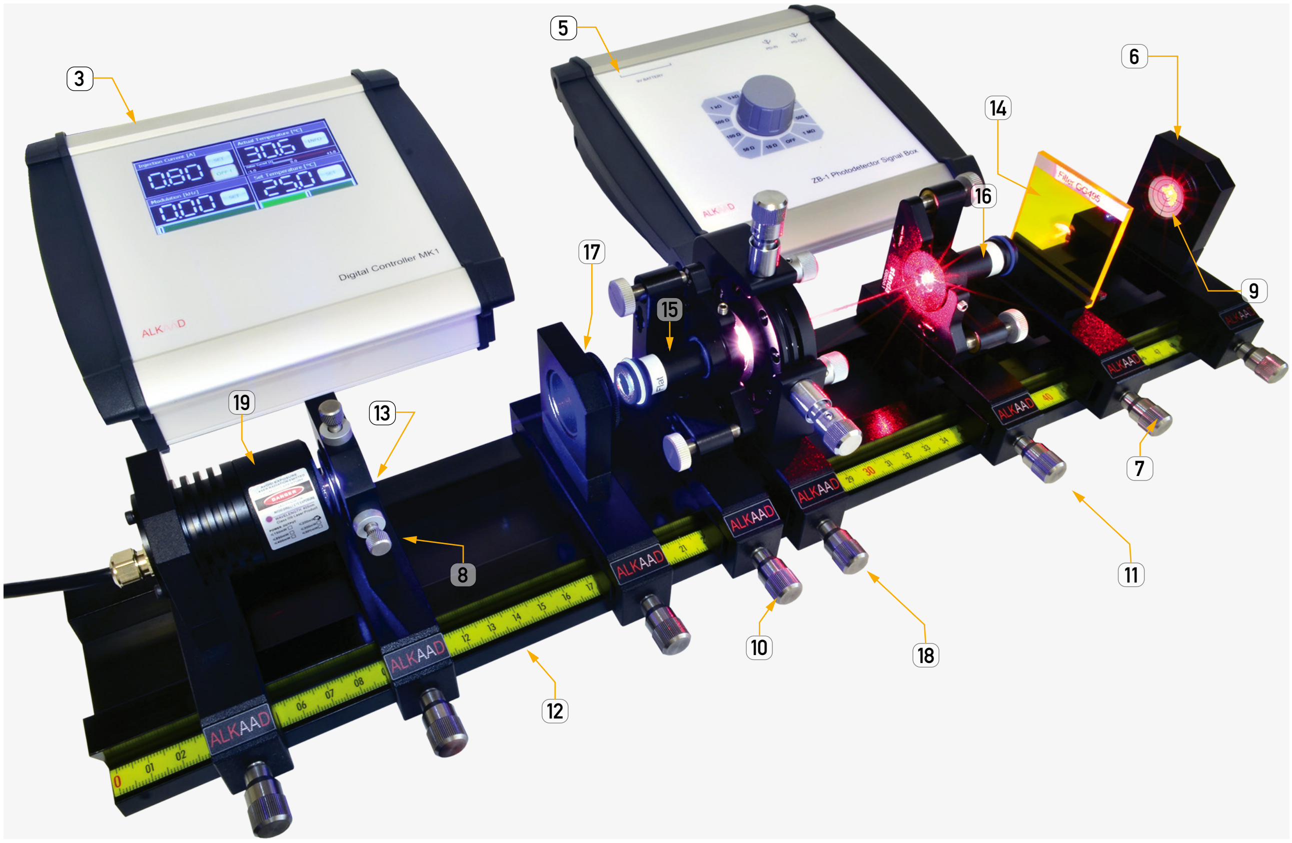


Fig. 2.97: Lifetime of excited state

The Fig. 2.94 to Fig. 2.98 show a few example of measurements by using a spectrometer and an oscilloscope. With the provided photodetector a variety of other measurements can be performed, like the characterization of the blue diode laser, measuring the output power of the Pr:YLF laser for different laser wavelength versus the injection current and temperature of the blue emitting pump laser. By using the provided white screen the rich transverse modes can be photographed by simple digital cameras.



Description of the components

The diode laser (19) emits radiation with a wavelength of 444 nm at 25°C and at maximum current. The laser diode is mounted on a Peltier element and the temperature as well as injection current is controlled and monitored by the digital controller MK1 (5). The divergent radiation is collimated by an precision aspheric lens (13) mounted into the XY adjuster (8). The almost parallel beam is focused (17) into the Pr:YLF crystal which is mounted into a 5 axes adjuster (18). The crystal can be turned in its holder which is important since the pump efficiency depends on its polarisation direction. Two adjustment screws are for the tilt and two for the XY translation. Once the laser is operating, the crystal is aligned for best performance. The cavity is formed by a flat mirror (15) which is screwed into a kinematic adjustment holder (10). The second mirror is a curved one (16) and is also screwed into an adjustment holder (11). The GG495 filter (14) is placed into the filter plate holder (7) and blocks the blue pump radiation. The mounting plate (6) serves to accommodate either the target cross (9) or the photodetector (5). The detector is connected to the junction box (5) which converts the photocurrent into a voltage.

LE-1000 Blue Diode pumped Pr:YLF Laser consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	CA-0080	1	Optics cleaning set	65 (12)
2	CA-0450	3	BNC connection cable 1 m	67 (28)
3	DC-0040	1	Diode laser controller MK1	58 (4)
4	DC-0120	1	Si-PIN Photodetector, BPX61 with connection leads	60 (15)
5	DC-0380	1	Photodetector Junction Box ZB1	62 (31)
6	MM-0020	1	Mounting plate C25 on carrier MG20	30 (1)
7	MM-0060	1	Filter plate holder on MG20	31 (7)
8	MM-0090	1	XY adjuster on MG20	31 (8)
9	MM-0100	1	Target Cross in C25 Mount	31 (9)
10	MM-0460	1	Kinematic mirror mount M16, left	34 (30)
11	MM-0462	1	Kinematic mirror mount M16, right	34 (31)
12	MP-0150	1	Optical Bench MG-65, 500 mm	30 (8)
13	OC-0160	1	Collimator 445 nm in C25 mount	36 (12)
14	OC-0970	1	Filter GG495, 50 x 50 x 3 mm	41 (55)
15	OC-1130	1	Laser mirror M16, ROC flat, HT 445, HR 580-725 nm	43 (75)
16	OC-1134	1	Laser mirror M16, ROC 100, HT 445, HR 580-725 nm	43 (76)
17	OM-0622	1	Focussing optics, f=60 mm on carrier MG20	52 (31)
18	OM-0670	1	Pr:YLF crystal in 5 axis mount on MG20	52 (36)
19	OM-L445	1	Diode laser module 445 nm, 1 W	55 (55)
20	UM-LE10	1	Manual PrYLF Laser	
	Option (order separately)			
21	CA-0200	1	Oscilloscope 100 MHz digital, two channel	66 (19)
22	CA-0270	1	Fibre coupled spectrometer 200 - 1200 nm, USB	
23	LE-0820	1	Active Q-switch Extension	69 (4)
24	LE-1020	1	SHG 640 to 320 nm (UV) extension	69 (5)
25	LE-1030	1	Birefringent tuner extension	69 (6)
26	LE-1040	1	Littrow prism tuner extension	69 (7)
27	OC-S010	1	Set of mirror (flat and 100 mm) for 520 nm operation	47 (107)
28	OC-S020	1	Set of mirror (flat and ROC 100) for 604 nm operation	47 (108)

Highlights

Basic, advanced, and top level ★★★ experiments

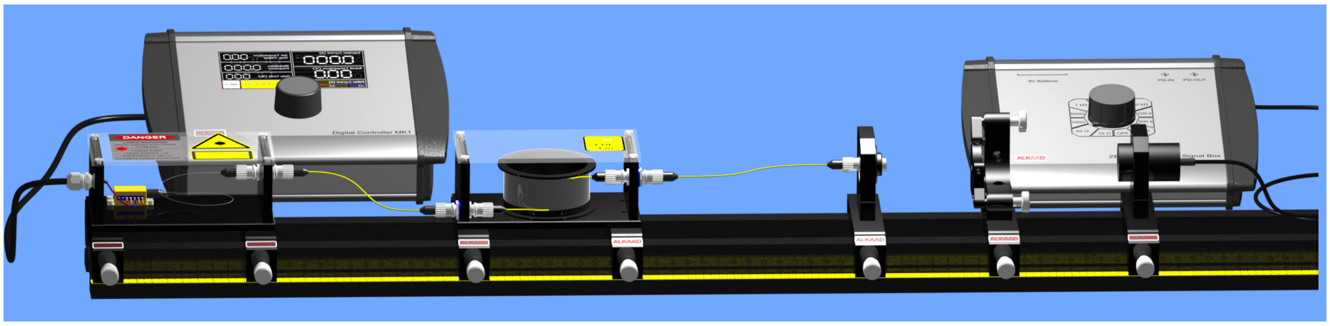
Outstanding features for an all visible four level solid state experimental Laser:

- ★★★ Visible excitation
- ★★★ High gain, easy alignment
- ★★★ 5 visible Laser Lines
- ★★★ UV (320 nm) generation by SHG
- ★★★ Impressive transverse modes

Intended institutions and users:

Physics Laboratory
Engineering department
Electronic department
Biophotonics department
Chemistry department

LE-1200 Erbium doped Fibre Laser



Linear Optical Resonator
WDM Coupler
Spiking
Amplified Spontaneous Emission
InGaAs Photodetector
Ring Resonator
Optical Pumping
Lifetime of Excited State
Longitudinal Modes
Modes Beat Frequency
EDF- Erbium Doped Fibre
Linear Fibre Laser
Accessible Beam
Optical Diode
Two Photon Absorption

Fibre Laser are a special class of Lasers differing from the "classic design". The optical resonator consists of an optical fibre which can be coiled onto a drum providing extremely long amplification lengths. Within this experiment the students are introduced to the basics of optical pumping with subsequent application by means of an Erbium doped optical fibre (EDF). This type of fibre is commonly used as amplifier in long distance telecommunication as so called EDFA (Erbium doped Fibre Amplifier). Due to its particular properties the EDF is a promising candidate also as laser source for telecommunication and remote sensing. The eye safe radiation makes such a device also useful for long range finding applications. This experiment allows to study the EDF in a linear as well as ring configuration. As pump source a diode laser emitting around 300 mW at a wavelength of 980 nm is applied. Via a wavelength division multiplexer (WDM) the pump light is coupled to the EDF. To close the ring, a fibre or an optical diode is connected to the WDM and the other end of the fibre. By means of a 4 port coupler - used as output coupler - a small fraction of the ring laser radiation is coupled out for further analysis. Herewith also counter propagating ring modes can be verified. With the provided photodetector and the modulator the time response like spiking, life time of excited states can be studied. Keeping in mind that the longest EDF used in the experiments has a length L of 8 m, the longitudinal mode spacing (c/2nL) is 13 MHZ for the linear laser and 26 MHz (c/nL) for the ring laser with n=1.45. Thus with a fast InGaAs photodiode and a simple oscilloscope or even better a spectrum analyser should be able to show the beat frequency of the modes.

At higher pump power and an 8 m long fibre green radiation with a wavelength of 544 nm is observed. It originates from a two photon (980 nm) excitation into higher lying states with subsequent laser emission.

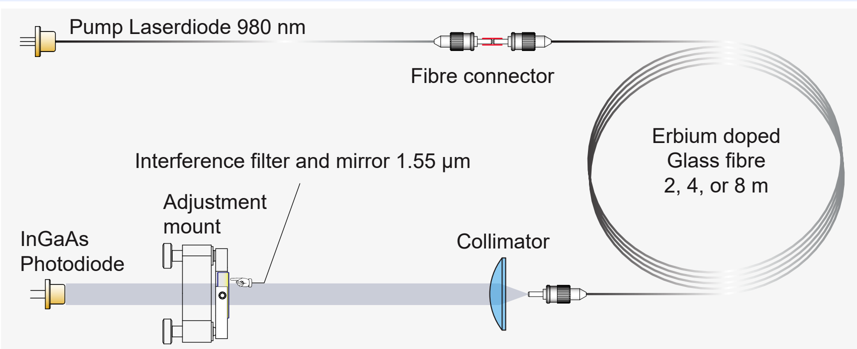
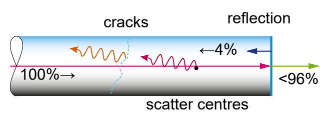


Fig. 2.99: Linear fibre laser

The pump laser diode has a so called single mode fibre pigtail, terminated with a fibre connector and is directly connected to the EDF fibre. The light inside the fibre is partially reflected at each end face due to Fresnel reflections. Despite the low reflectivity of 4% laser oscillation is built up between the two end faces of the EDF due to the high gain. A collimator with short focal length forms an almost parallel beam and an InGaAs photodetector is used to detect the emission of the fibre. The interference filter is mounted to an adjustment holder



and passes only the 1.55 µm radiation. With its front face reflectivity of about 10% it serves also as an external cavity mirror to study the effect of a coupled optical cavity. The pump laser diode is connected to a controller with adjustable injection current and modulation. This allows to study the amplified spontaneous emission (ASE) below and above the laser threshold. By using the modulation of the injection current the lifetime of the excited state as well as impressive laser spiking is displayed and measured on an oscilloscope

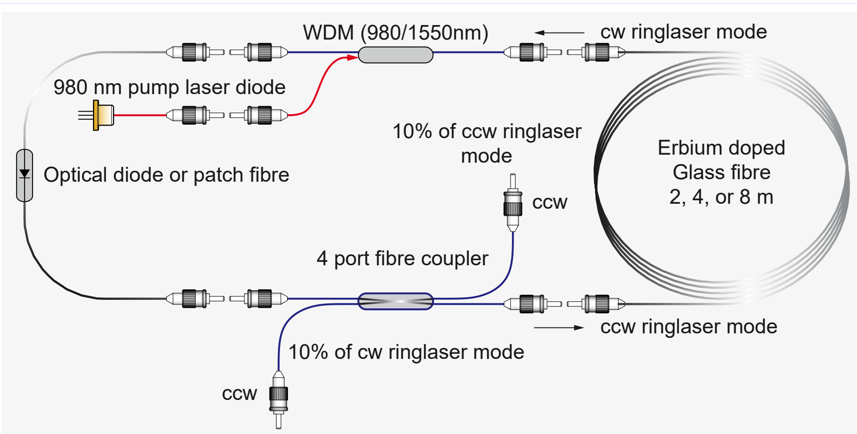


Fig. 2.100: Fibre ring laser

The pump radiation is injected by a wavelength division multiplexer (WDM) into the ring structure which consists out of the EDF, a 4 port fibre coupler and an optical diode or just a fibre patch cable. The optical diode is used to force the ring laser either to the clockwise (cw) or counter clockwise (CCW) operation. Exchanging the optical diode against a fibre the ring laser oscillates in both directions. The 4 port fibre coupler is used to extract about 10% of the internal power of the cw and ccw ring laser mode for measurement purposes. Including the optical diode into the ring structures only cw or ccw oscillation occurs. By using an electronic spectrum analyser the beat frequency of the longitudinal ring resonator modes is measured and set into relation to the resonator length for the 2, 4 or 8 m long EDF.

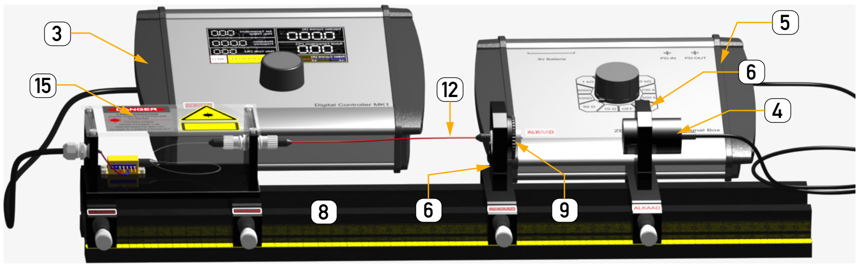


Fig. 2.101: Characterization of the pump laser

In this experiment the pump laser (15) is characterized. The diode laser of (15) is built into a butterfly housing which contains a Peltier cooler and the necessary temperature sensor. The controller (3) provides the injection current as well as the temperature controller. The output power of the diode laser is 300 mW measured at the single mode fibre pigtail which is connected via a single mode patch cable (11) to the fibre connector of (9). The InGaAs photodiode (4) and the junction box (5) is used to measure the output power in relative units.

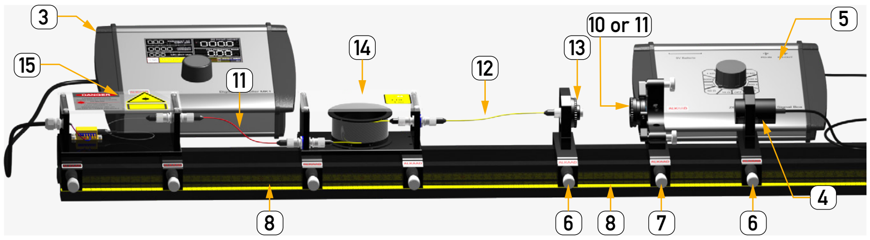


Fig. 2.102: Measurements with Erbium doped fibre (EDF)

The EDF (14) is added to the optical bench and connected via the fibre patch cable to the pump laser diode and to the fibre jacket (13). The emitted radiation passes either the 980 nm laser line filter (10) to measure the absorption of the pump radiation or the 1550 nm laser line filter (11) to measure only the spontaneous and stimulated emission. Using the modulation of the pump laser diode (15), the dynamic behaviour of the fluorescence and laser action is studied.

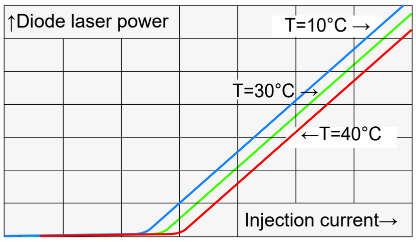


Fig. 2.103: Pump laser power versus injection current and temperature

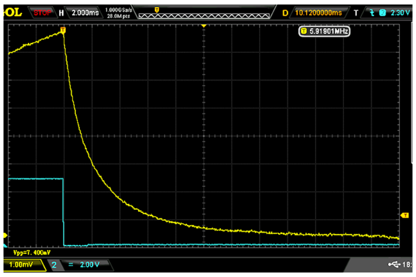


Fig. 2.104: Lifetime of the excited state

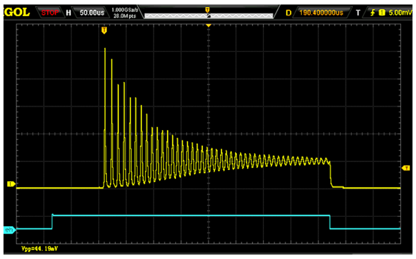


Fig. 2.105: Spiking of the Erbium laser

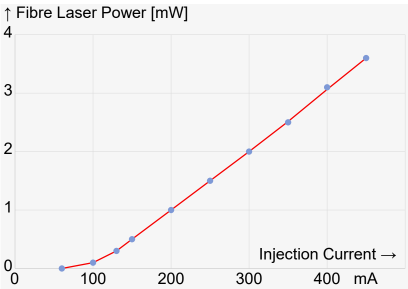


Fig. 2.106: Output power versus injection current

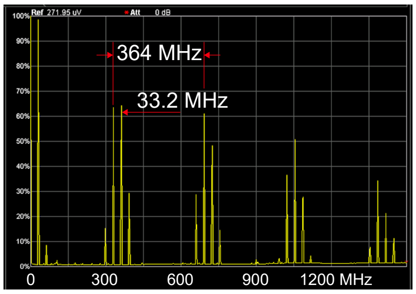


Fig. 2.107: Mode beat frequencies on the spectrum analyser

The photodetector (4) is connected to the signal box (5) and the output to the optional spectrum analyser (18). The screen shot of Fig. 2.107 has been recorded for a fibre length of 8 metre. In the range from 0 - 1,500 MHz 4 groups with a spectral distance of 364 MHz to each other appears. Each group consists of 4 peaks with a spectral distance of 33 MHz. From this value the free spectral range of the fibre cavity can be determined as well as the number of oscillating modes. The measurements are also carried for the 2 and 4 metre long Erbium doped fibre. A great task to identify the modes only by combinational analysis.

LE-1200 Erbium doped Fibre Laser consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	CA-0070	1	NIR Laser viewing card 980 nm and 1.5µm	64 (11)
2	CA-0450	1	BNC connection cable 1 m	67 (28)
3	DC-0040	1	Diode laser controller MK1	58 (4)
4	DC-0160	1	InGaAs Photodetector with connection leads	60 (18)
5	DC-0380	1	Photodetector Junction Box ZB1	62 (31)
6	MM-0020	2	Mounting plate C25 on carrier MG20	30 (9)
7	MM-0440	1	Kinematic mount ø25.4 mm on MG20	33 (26)
8	MP-0150	2	Optical Bench MG-65, 500 mm	30 (8)
9	OC-0430	1	Fibre jacket in C25 mount	37 (21)
10	OC-0758	1	Laser line filter 980 nm in C25 mount	39 (41)
11	OC-0760	1	Laser line filter 1550 nm in C25 mount	40 (42)
12	OC-2010	2	ST/ST SM Fibre patch cable, length 0.25 m	44 (84)
13	OC-2100	1	SM Fibre collimator	45 (88)
14	OC-2200	1	Erbium doped fibre unit, ST terminated 1.5 m	45 (90)
15	OM-0540	1	Diode laser module 980 nm, ST fibre connector	50 (23)
16	UM-LE12	1	Manual Fibre Laser	
	Option (order separately)			
17	CA-0200	1	Oscilloscope 100 MHz digital, two channel	66 (19)
18	CA-0210	1	Spectrum Analyzer 100 kHz - 500 MHz	66 (20)
19	LE-1240	1	Fibre Ring Laser Extension	page 35
20	OC-2210	1	Erbium doped fibre unit, ST terminated 4.0 m	45 (91)
21	OC-2220	1	Erbium doped fibre unit, ST terminated, length 8 m	45 (92)
22	OC-2230	1	Erbium doped fibre unit, ST terminated, length 16 m	45 (93)

Highlights

Basic, advanced, and top level ★ experiments

Outstanding features for an all fibre coupled linear and ring fibre laser:

- ★★★ Two photon excitation
- ★★★ High gain, easy alignment
- ★★★ Visible 544 nm emission
- ★★★ Real time mode spectra analysis

Intended institutions and users:

Physics Laboratory
Telecommunication
Engineering department
Electronic department
Biophotonics department
Chemistry department

LE-1240 Fibre Ring Laser Extension

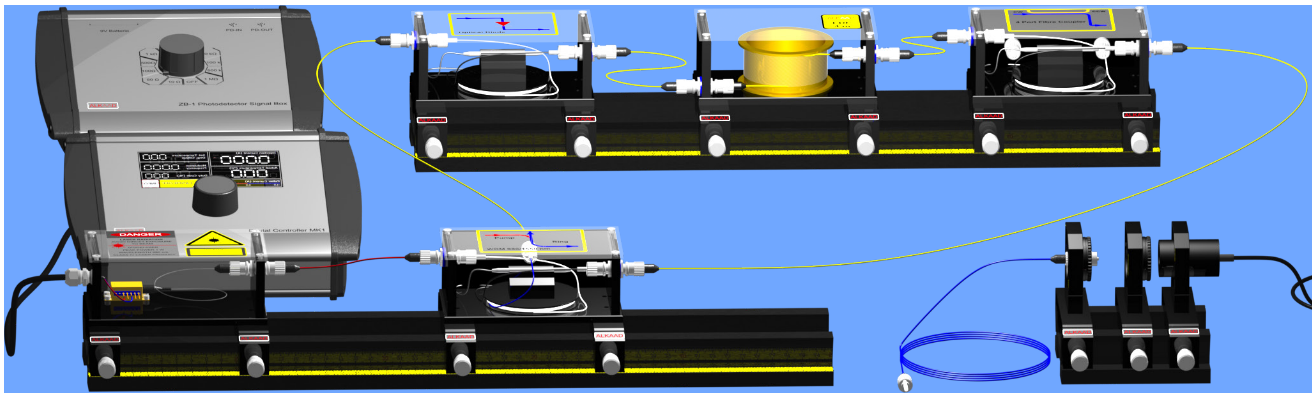


Fig. 2.108: Setup as combination of the LE-1200 Fibre Laser with the Fibre Ring Laser Extension

The fibre laser (LE-1200) is converted to a ring laser by adding the "Fibre Ring Laser Extension (LE-1240). The extension consists mainly out of the WDM coupler (6) which is used to inject the pump radiation of 980 nm into the ring structure and the 4 port fibre coupler (7). This coupler provides access to the ring laser emission by two output ports through which 10% of the cw and ccw direction is transmitted. Thus the device can be considered also as output coupler with a transmission of 10%. This ports are connected via a 1 m long patch cable (4) used to measure the relative output power with the fast InGaAs photodetector. The length of the ring structure is the length of the used Erbium doped fibre plus the length of the patch cable ($2 \cdot 1$ m + $2 \cdot 0.25$ m = 2.5 m) resulting for the 8 m long EDF in a spectral mode spacing of 19.7 MHz expecting an index of refraction of 1.45 for the core of the fibre. By using the optical diode (5) unidirectional ring laser oscillation in either the cw or ccw direction is forced. An extra mounting plate (2) and a short carrier (2) are used to form the detection block.

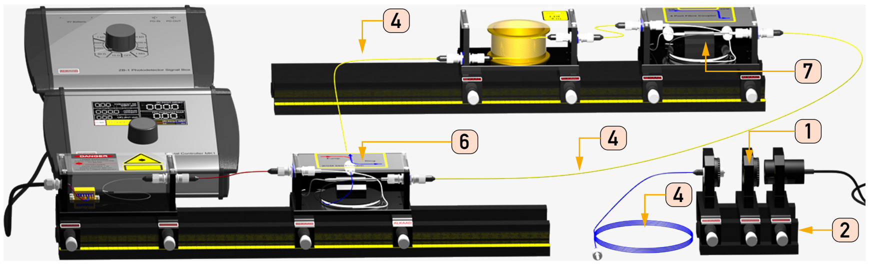


Fig. 2.109: Ring laser setup for two directional (cw and ccw) operation

This setup demonstrates the fibre ring laser without optical diode, which means the ring laser oscillates in cw and ccw direction simultaneously. The output power of the cw and ccw mode is measured as function of the 980 nm pump power. From these measurements the ring laser threshold and slope efficiency are determined. For this purpose the patch cable (4) of the detection block is connected either to the cw or ccw output of the 4 port coupler. To measure the beat frequency of the modes an oscilloscope or spectrum analyser is required. Compared to the linear fibre laser the beat frequency should be 2 times larger. The demonstration of spiking and amplified spontaneous emission (ASE) and the measurement of the lifetime of the excited state can be done as well and the compared to the results of the linear fibre laser and differences discussed, if any. By opening the ring (removal of the patch cable from the 4 port coupler to the WDM) results in a linear fibre laser.

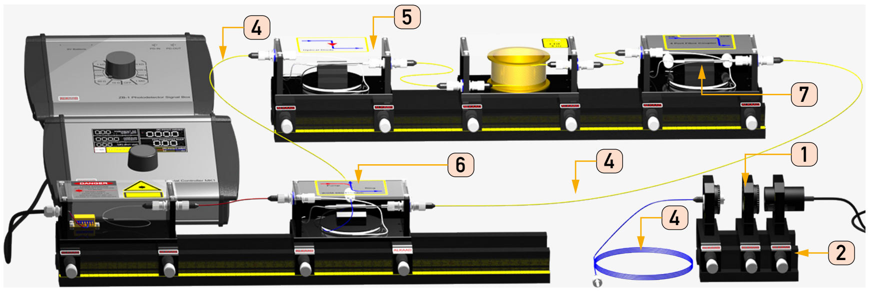


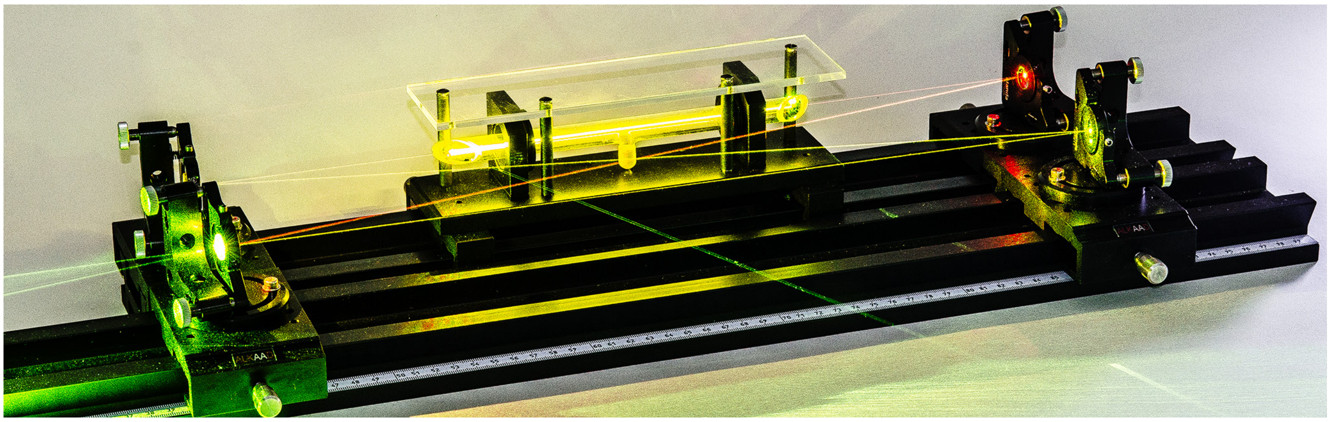
Fig. 2.110: Ring laser setup for unidirectional (cw or ccw) operation

Within this experiment the optical diode (5) is used, which allows the transmission in only one direction. In optics there exists only one optical device which works like a diode in electronics, it is based on the Faraday rotator effect. All required components are integrated into a small sleeve terminated with single mode pig tail fibres. Operating the ring laser with the optical diode only one directional ring laser mode oscillates. By measuring the output power at the two output ports of the 4 port coupler will tell us what oscillation direction is currently running.

LE-1240 Fibre Ring Laser Extension consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	MM-0020	1	Mounting plate C25 on carrier MG20	30 (1)
2	MP-0120	1	Optical bench MG-65, 200 mm	29 (6)
3	OC-2010	2	ST/ST SM Fibre patch cable, length 0.25 m	44 (84)
4	OC-2020	3	ST/ST SM Fibre patch cable, length 1 m	44 (85)
5	OC-2110	1	SM Fibre optical isolator, 980 nm, ST terminated	45 (89)
6	OC-2300	1	SM-WDM coupler 980/1550 nm unit ST terminated	45 (94)
7	OC-2350	1	SM Four port fibre coupler unit	46 (95)

LE-1300 Iodine Raman Laser



Keywords

Molecular Spectroscopy
Dunham Coefficients
Optical stability range
Multiline Laser
Hyper Fine Structure
Laser pointer like excitation
Franck Condon Principle
Raman Gain
Single Line Laser
Molecular energy level
Unidirectional Ring Laser Operation
Density Matrix Formalism
Single Mode Ring Laser

Introduction

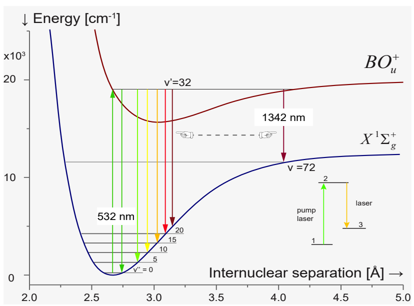


Fig. 2.111: Energy level diagram of the Iodine molecule

Within the experiment "PE-1600 Iodine Molecular Spectroscopy" on page 89 we already studied the spectral property of the Iodine molecule when excited with the 532 nm line of a pump laser. The Iodine Raman laser belongs to the class of molecular laser. However, the laser transition starts from the same level (2) as the pump laser forming a so called Λ system.

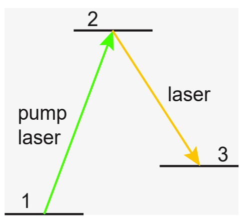
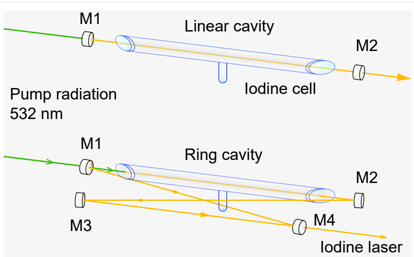


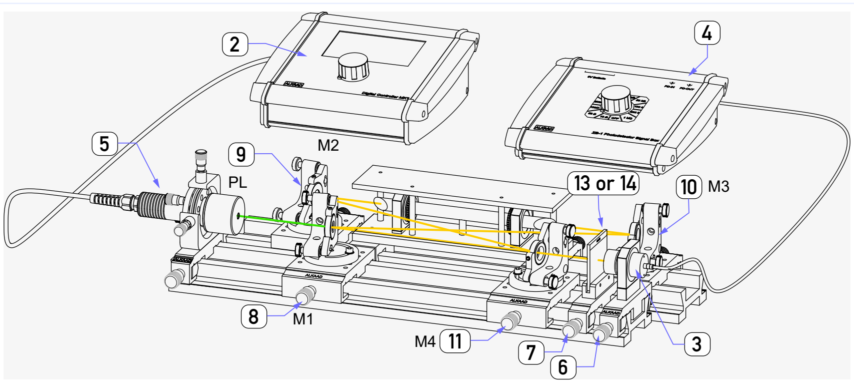
Fig. 2.112: Three level laser

Due to this coupling a variety of coherent phenomena occur. One of it is the Raman gain which leads to an asymmetrical gain distribution favouring the direction of the pump laser. This effect causes spontaneous unidirectional propagation inside a ring laser and has been firstly observed and explained by Wellegehausen et. al. in 1979. So far, known experiments have been carried out with expensive pump laser. The invention of inexpensive laser pointer like DPSSL emitting laser radiation at 532 nm is ideal to excite the iodine molecule allowing new affordable exciting new experiments for education. However, the underlying generation of the green radiation is based on the frequency doubling of a diode pumped $Nd:VO_4$ laser. Such a laser has a gain bandwidth of about 1 nm. Due to thermal drift of the cavity, the frequency doubled radiation also drifts in a range of 0.5 nm. The absorption width of the Iodine molecule is much smaller compared to the thermal drift of the excitation laser. Therefore the cavity of the "green laser" must be thermally stabilised by controlling the temperature of the pump laser with an accuracy of 0.01°C and the injection current of 0.1 mA. In such a way it is possible to tune the pump laser to the resonance of the transition indicated by the appearance of strong fluorescence light of the excited Iodine.

How it works



The Iodine Raman laser can be operated in a linear cavity consisting of two mirrors (M1) and (M2). A four mirror ring cavity has two main advantages. Firstly, in such a ring structure there are no back reflexes into the pump laser. This is very important since the pump laser is operating in a single mode. All back reflections into the cavity of the pump laser destabilises the emission and causes unwanted chaotic mode hopping. Secondly, a major feature of the Raman effect is that the gain in forward direction with respect to the pump direction is much higher than in the backward direction. This leads to the unidirectional operation in a ring cavity. The pump radiation enters the ring cavity via the mirror M1 which has a high transmission (HT) for the pump and a high reflectivity (HR) for the Iodine Raman laser. The flat mirror M2 has a high reflectivity for the pump as well as for the Iodine Raman Laser radiation and deflects the pump radiation to the mirror curved M3. The radius of curvature of M3 is chosen in such that the pump radiation is focused into the middle of the Iodine cell. M4 has the same properties as M3.



Of course all spectroscopic measurements can be carried out as described in "PE-1600 Iodine Molecular Spectroscopy" on page 45. Two 500 mm long optical rails are placed side by side to each other and form the base for the ring laser setup.

The pump laser (5) contains a temperature controlled DPSSL emitting 40 mW at a wavelength of 532 nm. The 4 adjustment screws of (5) are for the alignment of the laser beam with respect to the mechanical axis of the rail. The injection current as well as the temperature of the DPSSL is controlled and monitored by the laser controller (2). The cavity mirrors are mounted into individual adjustment holders. Each adjustment holder's angle orientation is set by the attachment block to the carrier. The Filter (14) blocks the pump radiation so that only the laser wavelength is passed to the photo detector (3). Instead of the filter (14) the grating (13) can be inserted into the plate holder to visualise the different wavelengths. By means of the photodetector (3) the relative output power of the pump laser (5) as well as of the Raman laser is measured.

Line selection with Birefringent Tuner

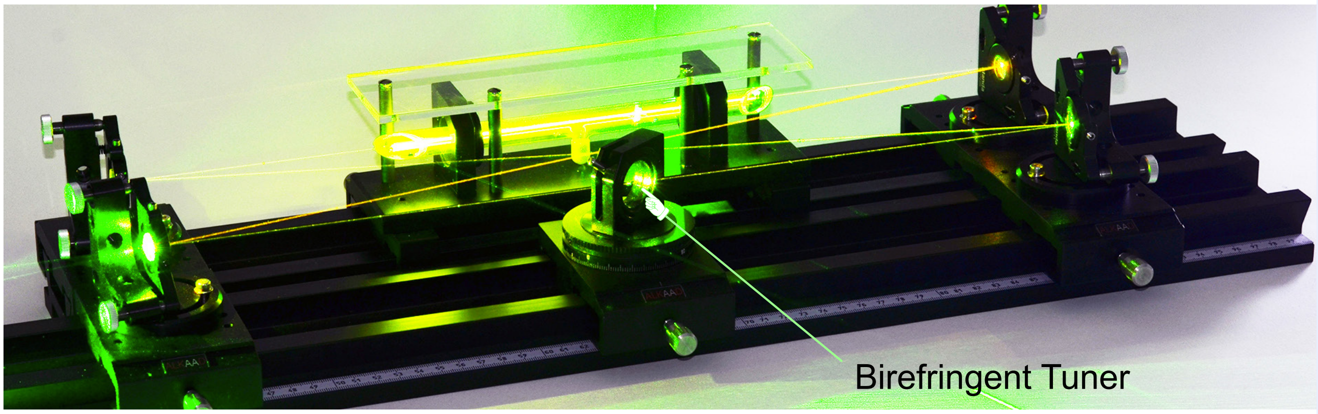


Fig. 2.113: Iodine ring laser with BFT

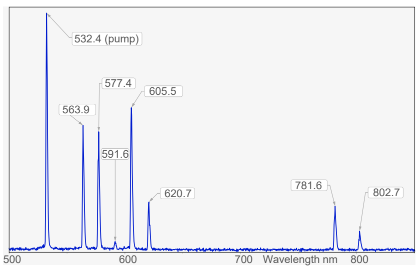


Fig. 2.114: Multiline Oscillation

During the operation with the ring laser it will be noticed that the laser's wavelength spontaneously changes. Sometimes it is yellow, orange or red or even mixed wavelength. To force the laser to emit on a selected line only a so called birefringent tuner (BFT) is placed inside the cavity. By tilting the lever the birefringent quartz plate rotates and individual lines can be selected. The spectrum shown in Fig. 2.114 shows the multitude of simultaneous laser lines without such a BFT. The table below summarizes all lines which can be obtained.

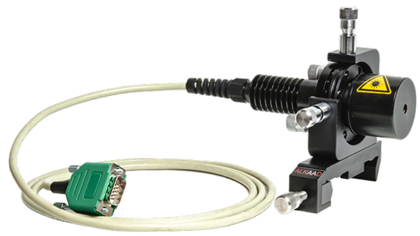


Fig. 2.115: Green (532 nm) stabilized Laser

Wavelength [nm]	Frequency [cm^{-1}]	v''↔v'	J''→J'
Pump: 532.25	18,788.33	0 → 32	R57
Laser lines:			
557.29	17,944.01	4 ← 32	R56
557.55	17,935.54	4 ← 32	R58
563.82	17,736.04	5 ← 32	R56
564.09	17,727.60	5 ← 32	R58
570.47	17,529.33	6 ← 32	R56
570.75	17,520.92	6 ← 32	R58
577.24	17,323.90	7 ← 32	R56
577.52	17,315.51	7 ← 32	R58
591.13	16,916.88	9 ← 32	R56
591.42	16,908.54	9 ← 32	R58
605.51	16,515.05	11 ← 32	R56
605.81	16,506.78	11 ← 32	R58
620.40	16,118.50	13 ← 32	R56
620.72	16,110.28	13 ← 32	R58

Wavelength [nm]	Frequency [cm^{-1}]	v''↔v'	J''→J'
635.84	15,727.32	15 ← 32	R56
636.17	15,719.16	15 ← 32	R58
643.76	15,533.77	16 ← 32	R56
644.10	15,525.64	16 ← 32	R58
660.03	15,150.81	18 ← 32	R56
660.38	15,142.73	18 ← 32	R58
694.36	14,401.82	22 ← 32	R56
694.74	14,393.87	22 ← 32	R58
712.45	14,036.03	24 ← 32	R56
712.85	14,028.14	24 ← 32	R58
760.58	13,147.94	29 ← 32	R56
761.02	13,140.22	29 ← 32	R58
781.03	12,803.65	31 ← 32	R56
781.49	12,795.99	31 ← 32	R58
802.19	12,465.84	33 ← 32	R56
802.68	12,458.26	33 ← 32	R58

Table 2.1: Obtained laser lines (the wavelength is given as vacuum wavelength)

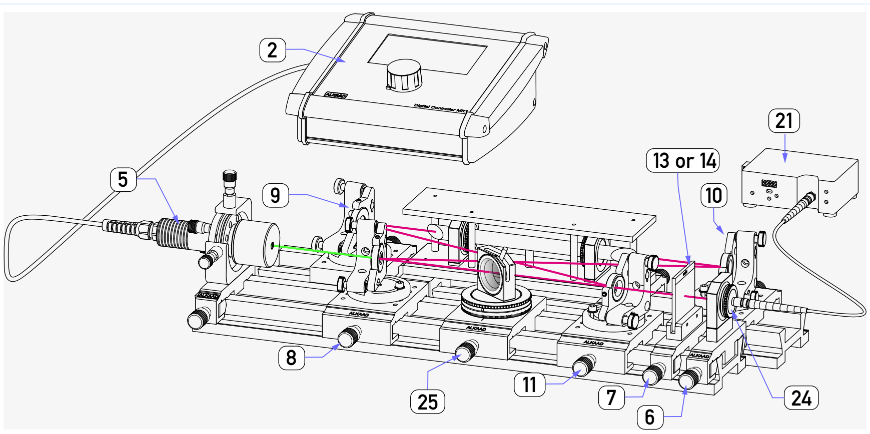


Fig. 2.116: Iodine Raman Laser with birefringent tuner

The setup of Fig. 2.116 shows the location of the birefringent tuner (BFT) inside the cavity. The Filter (14 - GG495) blocks the residual, not absorbed green pump radiation. The fibre of the spectrometer (21) is connected to the fibre jacket of the C25 mount (24). By rotating the birefringent quartz plate different lines will be observed. To obtain the weaker lines, the ring laser must be aligned carefully and the quartz plate thoroughly cleaned. The spectral distance of the doublets R56/58 is in the range of about 0.4 nm and cannot be separated by the birefringent tuner. The line spectrum of the Fig. 2.114 is recorded by the optional provided spectrometer (21) and does not resolve the doublets. For this purpose a spectrometer with higher resolution is required.

Oscillation on Hyper Fine Structure Lines

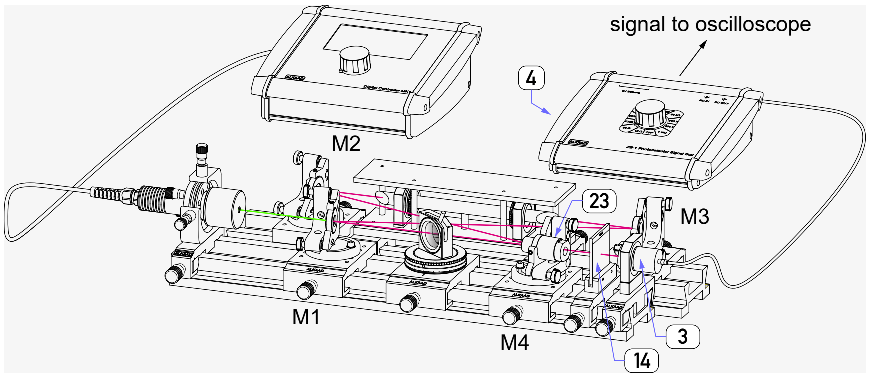


Fig. 2.118: Setup with piezo transducer

The mirror M4 is exchanged against a mirror which is mounted to the piezo transducer (PZT, 23). The PZT controller (22) provides the periodic triangle voltage as well an DC offset to drive the PZT periodically forth and back. The PZT contains a mirror with same properties as used before. The output of the modulated ring laser passes the GG495 Filter (14) to suppress undesired residual pump radiation and is detected by the photodetector (3). The signal is further conditioned with the photodetector junction box (4) and finally connected to an oscilloscope (the Fig. 2.117 shows such a signal). As reference for the translation of the PZT the driving voltage is used.

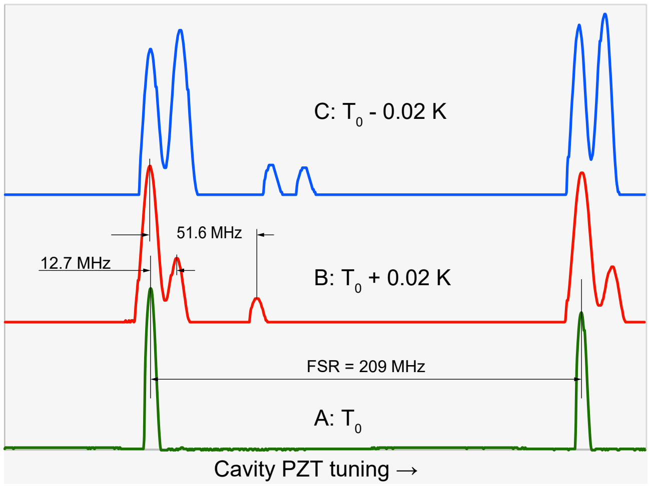


Fig. 2.117: Iodine laser power profiles for different fine tuned pump wavelengths.

The BFT is tuned to operate the 591.42 nm (32-9(R58)) line only, at a temperature T_0 of 30.09 °C. The cavity length was set to 1418 mm, resulting in a FSR of 209 MHz. The temperature change of 0.02 K corresponds to a detuning of the DPSSL of about 90 MHz. The curves show lasing on 1, 3 and 4 hyperfine components.

The absorption profile of molecular iodine is broadened by overlapping hyperfine components. Therefore, depending on the exact setting of the pump wavelength (temperature of the DPSSL), the pump laser will excite more or less hyperfine components, which then will contribute to the fluorescence and laser emission. While in fluorescence these components can not be resolved, it should be possible to see them in laser emission due to the narrow power profiles of the laser. For this, the laser is operated on a single strong line by careful adjustment of the birefringent tuner and the pinhole to achieve TEM_{00} emission. To scan the power profile of the laser emission, a ramp voltage is applied to the PZT to periodically change the cavity length. The results are given in Fig. 2.117 for the 32-9(R58) line at 591.42 nm (see also Table 1). The curves of Fig. 2.117 show power profiles for different fine tuned pump wavelengths, achieved by small changes of ±0.02 K of the temperature of the DPSSL around an initial temperature T_0. The temperature change of 0.02 K corresponds to a frequency change of about 90 MHz. The curves show lasing on 1, 3 and 4 hyperfine components. The separation of the hyperfine components agrees with the well-known molecular data and demonstrates the power and the possibilities of this laser system.

LE-1300 Iodine Raman Laser consisting of:

Item	*Code*	*Qty.*	*Description*	*Details page*
1	CA-0450	2	BNC connection cable 1 m	67 (28)
2	DC-0040	1	Diode laser controller MK1	58 (4)
3	DC-0120	1	Si-PIN Photodetector, BPX61 with connection leads	60 (15)
4	DC-0380	1	Photodetector Junction Box ZB1	62 (31)
5	LQ-0040	1	Green (532 nm) stabilized Laser, 40 mW	56 (3)
6	MM-0020	1	Mounting plate C25 on carrier MG20	30 (1)
7	MM-0060	1	Filter plate holder on MG20	31 (7)
8	MM-0160	1	Ring laser mirror mount M1 on MG65	32 (14)
9	MM-0162	1	Ring laser mirror mount M2 on MG65	32 (15)
10	MM-0163	1	Ring laser mirror mount M3 on MG65	32 (16)
11	MM-0164	1	Ring laser mirror mount M4 on MG65	32 (17)
12	MP-0150	2	Optical Bench MG-65, 500 mm	30 (8)
13	OC-0460	1	Transmission grating 600 l/mm	37 (22)
14	OC-0970	1	Filter GG495, 50 x 50 x 3 mm	41 (55)
15	OC-1110	1	Laser mirror 1/2" in 1" mount, ROC flat, HR 550-800 nm	43 (72)
16	OC-1114	1	Laser mirror 1/2", ROC flat, HT 532, HR 540-700 nm	43 (73)
17	OC-1116	2	Laser mirror 1/2, ROC 250 nm, HR 520-700 nm	43 (74)
18	OM-3010	1	Iodine cell on carrier	55 (53)
19	UM-LE13	1	Manual Iodine Raman Laser	
	Option (order separately)			
20	CA-0200	1	Oscilloscope 100 MHz digital, two channel	66 (19)
21	CA-0270	1	Fibre coupled spectrometer 200 - 1200 nm, USB	67 (26)
22	DC-0070	1	Piezo controller 0-150V	59 (10)
23	MM-0504	1	Piezo transducer 10µ/150V with 24 mm collar	34 (37)
24	OC-0430	1	Fibre jacket in C25 mount	37 (21)
25	OM-0580	1	Birefringent Tuner	51 (27)

Highlights

Basic, advanced, and top level ★★★ experiments

Outstanding features for an Iodine molecular experimental Laser:

- ★★★ Scanned Laser Cavity
- ★★★ Power Profile
- ★★★ Hyperfine Laser Lines
- ★★★ Unidirectional Ring Laser

Intended institutions and users:

- Physics Laboratory
- Engineering department
- Electronic department
- Biophotonics department