Nd:YAG Laser

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Contents

1 Basics

1.1 Lasers

The acronym LASER stands for Light Amplification by Stimulated Emission of Radiation. A laser is any device where stimulated emission is used to produce a beam of light with these significant properties:

- highly coherent
- well focused
- little divergence
- small spectral width
- high intensity

A laser requires a pumping process, a lasing medium, and an optical cavity. With the energy provided by the pumping the atoms in the medium are transferred to an excited state. The laser beam is then created by stimulated emission of photons from these excited atoms. The cavity, consisting of at least two mirrors, allows the photons to travel through the lasing medium multiple times and thereby to lead to more emissions. One of the mirrors is partially transmissive to allow the laser beam to leave the cavity. The working principle of a laser can be explained using a lasing medium with two different energy levels, the ground state (level 1) and an excited state (level 2).

1.2 Laser operation

Without external influences, almost all atoms in the medium are in the ground state (level 1) and only a few atoms' electrons will be in level 2. After a certain time, an excited electron (=electron in level 2) will decay back to the ground state. The energy difference between the two levels is emitted as a photon. Each of the decaying electrons will produce one such photon, but there is no correlation between the phase and direction of all these photons. This process is called spontaneous emission.
The interesting process happens, when one of these photons interacts with an electron in level 2. The electron will then drop to the level 1. The energy difference between the two levels is again emitted as a photon, but the important difference is that this new photon will match the first one's phase, wavevector and polarisation. The two photons cannot be distinguished, in other words coherent light is created. This process is called stimulated emission. The coherent photons will make up the laser beam.
The inverse process happens when the photon hits an electron in the lower level and excites it. In the lasing medium both processes happen, at rates depending on the size of the population in the lower and the higher level. The three processes are described by these equations:

$$dn_1/dt = -B_{12}n_1u_{ph}$$

n_1 ... Number of the electrons in level 1
B_{12} ... Einstein coefficient of absorption
u_{ph} ... Energy density of the external field

$$dn_2/dt = -A_{21}n_2 + B_{21}u_{ph}n_2$$

n_2 ... Number of the electrons in level 2
A_{21} ... Einstein coefficient of spontaneous emission
B_{21} ... Einstein coefficient of stimulated emission
u_{ph} ... Energy density of the external field

Since there are more atoms in the ground state than in the exited state absorption will be the predominant process. So as long as most of the atoms are in the ground state laser operation is not possible. It is necessary to have the majority of atoms in the excited state, this is called *population inversion*. Creating the population inversion requires energy. Supplying this energy is called pumping.

1.3 Pumping

There are different pumping methods, the most common are optical, electrical and chemical pumping. In our experiments, we will use a laser diode to pump the medium.

1.3.1 Laser diode pumping

A laser diode allows optical laser pumping. The light of the laser diode is directed on the medium and leads to the desired excitations. To excite a certain state the light must have a matching wavelength. If a light source with a broad spectrum is used for pumping, a lot of the power will remain unused. A laser diode emitts most of the power in small range of frequencies, therefor the degree of efficiency will be much higher. That is one of the advantages of laser diode pumping.

A laser diode consists of a semiconductor with a pn-junction. One side of the crystal is n-doped and the other side is p-doped, the junction is inbetween the two sides. On the n side, there is a surplus of electrons. On the p side there is a lack of electrons, one such missing electron is called a hole or defect electron. When then the diode is forward biased (positive voltage on the p-side), the holes will drift to the n-region and the electrons will drift into the p-region. Holes and electrons can recombine. In this process a photon is spontaneously emitted. When another recombination is stimulated by such a photon one gets stimulated emission.

The emitted wavelength depends on the current going through the diode (injection current I_{LD}) and the diode's temperature.

1.4 Cavity

As we can see from the rate equation, the amount of stimulated emission depends on the energy density of the external field. This is were the cavity comes into play. The cavity's purpose is to make the coherent photons travel through the medium multiple times. That way u_{ph} becomes large and stimulated emission dominates spontaneous emission. This is achieved with mirrors.
When the laser is operating in a steady state, there is ideally always approx. the same number of photons moving in closed paths between the mirrors through the medium. These photons form the laser beam inside the cavity. One of the mirrors is partially transmissive to allow a part of the beam to leave the cavity. The transmissivity is usually chosen small ($\approx 2\%$) to keep u_{ph} high.
There are different kinds of cavities

- **Planar parallel cavity**

  A planar parallel cavity consists of two plane mirrors set parallel to each other. The length of the cavity should be an integer number times the wavelength $\frac{\lambda}{2}$ so that standing waves can form. It is practicaly impossible to adjust the mirrors exactly parallel. Additionally the alignment becomes worse with changing temperature.

- **Spherical cavity**

  Spherical cavities are easier to adjust than planar parallel cavities but support undesired tranverse modes, which will be briefly discussed later. There are two types of spherical cavities, concentric and confocal ones. Alignments inbetween these two arrangements are also possible.

  Concentric cavities consist of two spherical mirrors with the same radius of curvature separated by a distance of two times that radius, so that the centers coincide. For confocal cavities the distance is equal to the radius so that their foci coincide. In this case, the center of curvature of one mirror lies on the surface of the other mirror.

- **Hemispherical cavity**

  A hemispherical cavity consists of a flat mirror and a spherical mirror and has the advantages of both the plan parallel and the spherical cavity, and the negative effects are much weaker than in the planar parallel or spherical cavity.

- **Ring cavity**

  A ring cavity requires multiple mirrors. The path of the optical rays is arranged in a ring configuration.

For the diode laser, the faces of the semiconductor crystal parallel to the junction serve as cavity mirrors. As in the planar parallel cavity, the distance between the mirrors is an integer number times $\frac{\lambda}{2}$ of the standing wave. This is essentially important because the crystal's length changes with temperature, so we get a temperature dependence of λ.

A larger current leads to an increase in charge density, which, in analogy to the effect of increasing gas density on the refraction index of a gas, leads to a higher refraction index. Thus λ also depends on the current through the diode, the injection current I_{LD}.

1.4.1 Modes

Reflection of the light on the mirrors means that the electromagnetic field must equal zero on the mirror surface. As explained before, certain wavelengths form a standing wave in the cavity.

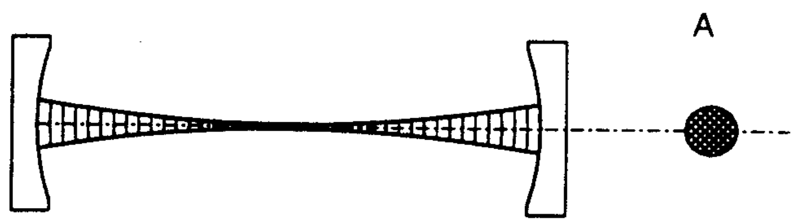

Figure 1: Longitudinal mode in a spherical cavity

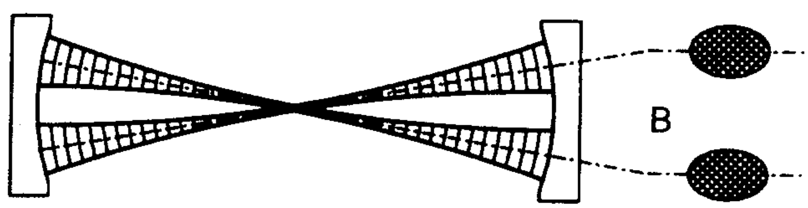

Figure 2: Transverse mode in a spherical cavity

Modes are these stationary electromagnetic waves. Both longitudinal and transverse modes occur. Transverse modes oscillate in a direction different from the longitudinal direction. When there are transverse modes, the energy distribution will no longer be axially symmetric, see fig. 2.

The modes are named by TEM_{mnq}, which stands for Transverse Electromagnetic Modes. The number m (n) represents the number of points of zero intensity on the x (y) axis. q represents the number of nodes in the longitudinal direction. This is usually a large number with no particular relevance and is usually omitted. Fig.1 shows a spherical cavity with an oscillation in TEM_{00}. Fig.2 shows a spherical cavity with an oscillation in TEM_{01}.

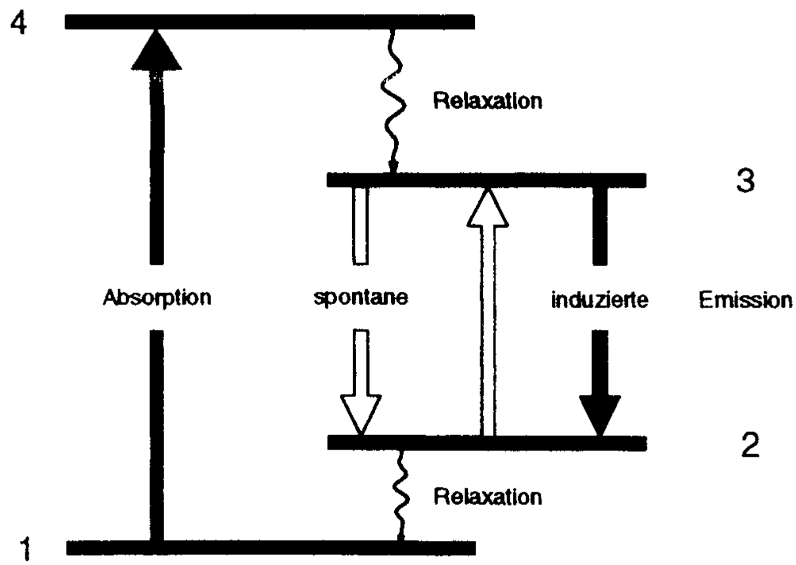

Figure 3: 4-level-Laser

1.5 The 4-level-laser

In a 2 level laser the pumping energy is the same as the laser transition energy. The problem with this is that the pumping can lead to emissions so there won't be a population inversion. For technical applications, at least three energy levels are necessary for laser operation. To achieve a better degree of efficiency, four levels are used. The Nd:YAG laser is a four level laser.
In the 4-level system (fig. 3), optical pumping from the ground state (level 1) excites the atoms to a higher state (level 4). From this level the atoms relax by a fast, radiationless transition to level 3. The lifetime of the laser transition from level 3 to level 2 is long compared to that of level 4 to level 3, a population accumulates in this level 3. Because of its long lifetime, level 3 is called a metastable state. Transitions through spontaneous and stimulated emissions lead from level 3 to level 2. However level 2 has only a short lifetime and quickly relaxes to the ground state and is therefore almost unpopulated. So there is basically a population inversion between the level 3 and 2, which is required for a laser to work. Levels 1 and 3 are called **pump levels**, levels 2 and 4 **laser levels**.

The four level system is actually a little more complex as each level is split into multiple levels as shown in figure 4.

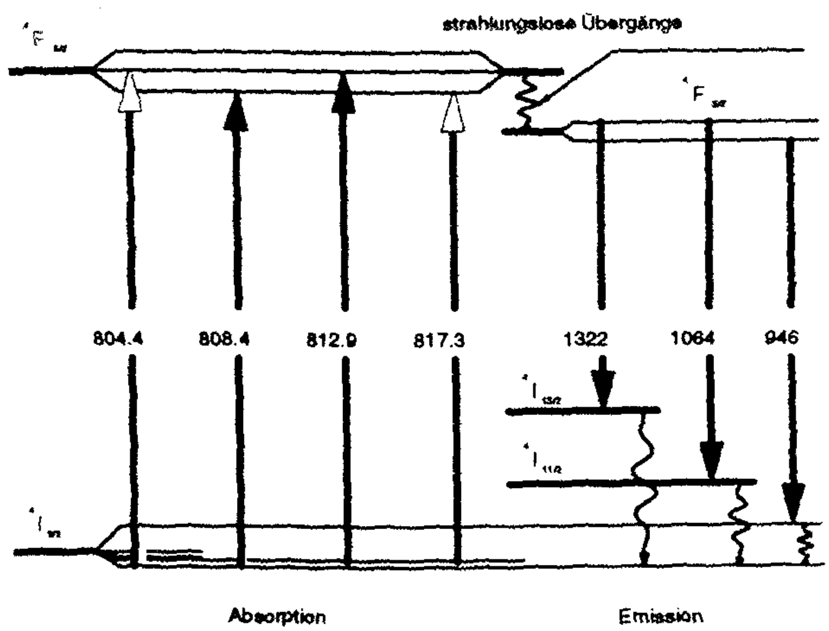

Figure 4: Precise level scheme

1.6 Frequency doubling

The propagation of light in matter is described by the refraction index n and the absorption coefficient α. In linear optics, these quantities depend only on the frequency of the light. Thus properties like refraction, reflection, absorption and velocity of light solely depend on the frequency and material properties. From Maxwell's equations on these terms follows that the frequency is constant.
As the name linear optics indicates, this is only valid for a linear dependence of the dielectric polarisation P on the electric field strength E of the light wave. The polarisation P basically describes the electric dipole moments of the atoms induced by E. In the linear case, this means that the potential felt by the electron must be quadratic, because only a quadratic potential gives a linear force. The real potential of an electron is not quadratic. A main difference between the real potential and the quadratic one is that real potential asymptotically approaches the binding energy of the electron, while the quadratic potential goes to infinity for the distance going to infinity. For small amplitudes, the real potential can be approximated by a quadratic potential and linear optics is valid.
At high field strengths, the quadratic approximation is not valid. The relation of P and E is no longer linear. One speaks of nonlinear optics.
Assuming that the nonlinear effects are still small compared to the linear effects, P can be expanded to a series in E.

$$P = \chi^{(1)}E + \chi^{(2)}E^2 + ... \tag{1}$$

χ is the susceptibility tensor. It reflects symmetry properties of the propagation medium, which is in our case a crystal. To give an example, in a lossless medium the tensor must be real and symmetric (Kleinman's symmetry).
Inversion symmetry means that the inversion of the crystal in the symmetry point does not change the lattice. Mathematically, inversion of the vector R is defined as

$$R \rightarrow -R$$

In the inverse system the series expansion becomes

$$-P = -\chi^{(1)}E + \chi^{(2)}E^2 + ... \tag{2}$$

The even powers of E don't change their sign. Thus for crystals with inversion symmetry, the terms with even powers must equal zero.
Frequency doubling is a quadratic effect. Therefore it can only happen in crystals that don't have inversion symmetry.

In general the refraction index is different for the single and the double frequency. Because of that a part of the double frequency can get lost due to destructive interference. To avoid this, the single and double frequency need to have the same refraction index.
In a birefringent crystal, the refraction index is a function of the angle to the principal axis. The phase matching condition

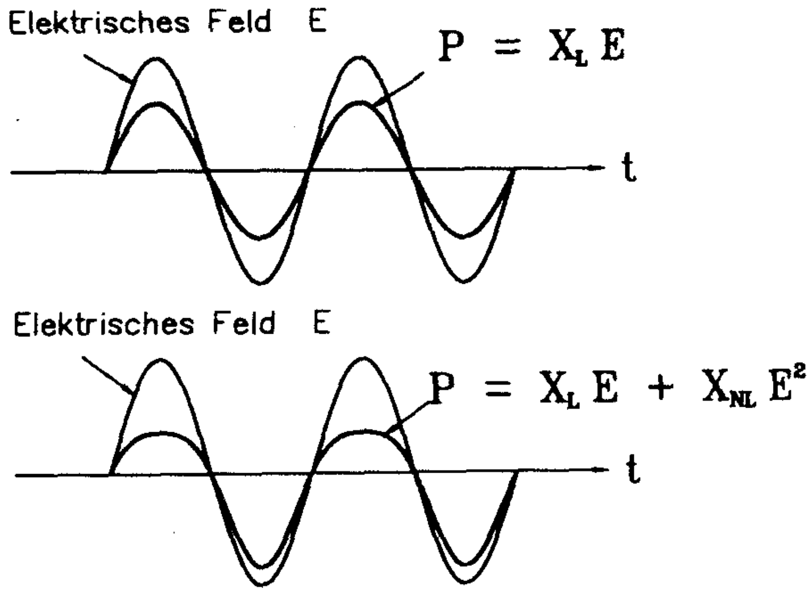

Figure 5: Linear and non-linear optics

$$\delta = k_{2\nu} - 2k_\nu = 0$$

where $k_{2\nu}$ and k_ν are the wave numbers of the single and double frequency wave, is satisfied when the refraction indices are the same. This is the case when the crystal is aligned properly. This is called angular matching.

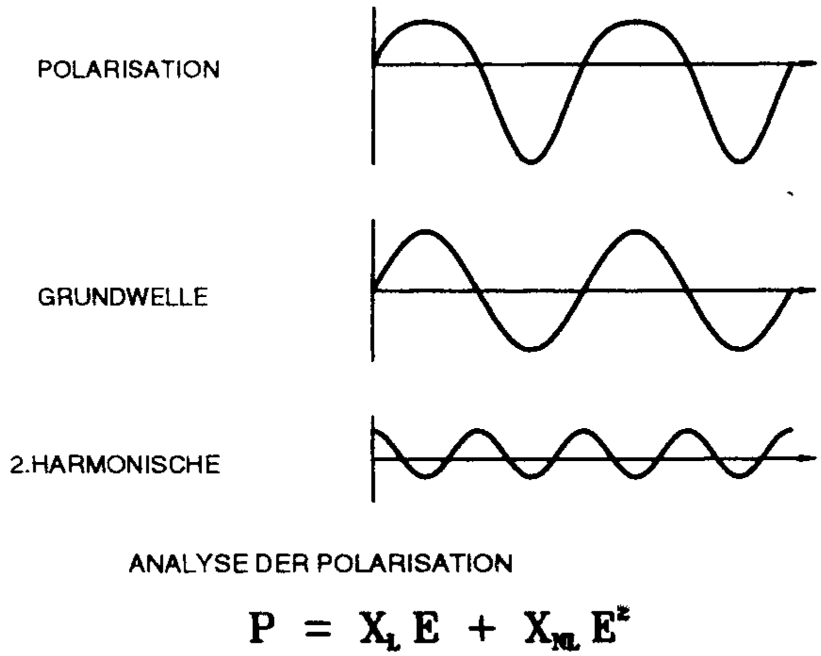

Figure 6: Frequency doubling

2 Tasks

- Setup of the laser diode and focusing of the beam
- Measurement of the absorption spectrum of the Nd:YAG crystal to calibrate the diode laser wavelength
- Measurement of the calibration curve I(T) at a given wavelength
- Measurement of the pump power as a function of the injection current
- Measurement of the lifetime of the metastable state
- Insertion of the output coupler mirrer and cavity adjustment for laser operation
- Measurement of the laser power as function of the pump power
- Measurement of the laser power at various wavelengths
- Frequency doubling with a KTP crystal (potassium- titanyl-phosphate), visualization of laser modes
- Measurement of the power of the second harmonic as function of the power of first harmonic

3 Equipment

- Collimating optics
- Focusing lens
- Laser diode
- Nd:YAG rod with built-in high reflector
- Intensity measuring instrument (Photo diode with Amplifier)
- Oscilloscope
- Output coupler mirror (partially transmissive)
- KTP crystal
- Low pass filter for $\lambda \tilde{<} 1000$nm
- Band pass filter for $\lambda \simeq 532$nm

4 Experiments

The photo diode gives a current which is proportional to the number of photons impinching on the diode per second. Because of the unknown proportionality factor and device specific losses we cannot give absolute values for the power. The photo diode current I_{PD} was measured with the oscilloscope as a voltage at a resistance of 50Ω (input resistance of the amplifier). For plot purposes we use this current. Parenthesis indicate that a data point has not been used for fits. This concerns values that were measured at low intensities.

4.1 Setup of the laser diode

The beam of the laser diode had to be focused using two lenses (fig.7). The lense B is used to get parallel light which is focused on the Nd:YAG crystal by lense C. This way a better efficiency is achieved than with just one lense. A photo diode, linked to an oscilloscope, was then used to measure the intensity of the light that reaches the photo diode.

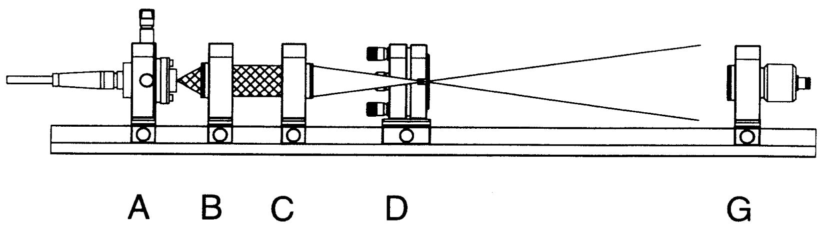

Figure 7: **Setup for the Laser diode**

A	... Laser diode
B, C	... Lenses
D	... Nd:YAG crystal and mirror
G	... Photo diode

4.2 Measurement of the absorption spectrum

The Nd:YAG crystal absorbs light from the laser diode. The intensity of the transmitted light depends on the wavelength, because the Nd:YAG crystal absorption varies with the excitation energy of its transitions.

The temperature dependence of the diode's wavelength allows the measurement of the transmission spectrum by measuring the temperature and the intensity at a constant injection current. The absorption spectrum is calculated from the transmission spectrum. We are only interested in the temperature of maximum absorption, not in the absorbed power, so we simply multiplied the transmission data (table 4.2) with -1 to get the absorption spectrum. A transmission minimum becomes an absorption maximum so we can read the temperatures of the absorption peaks from the spectrum.

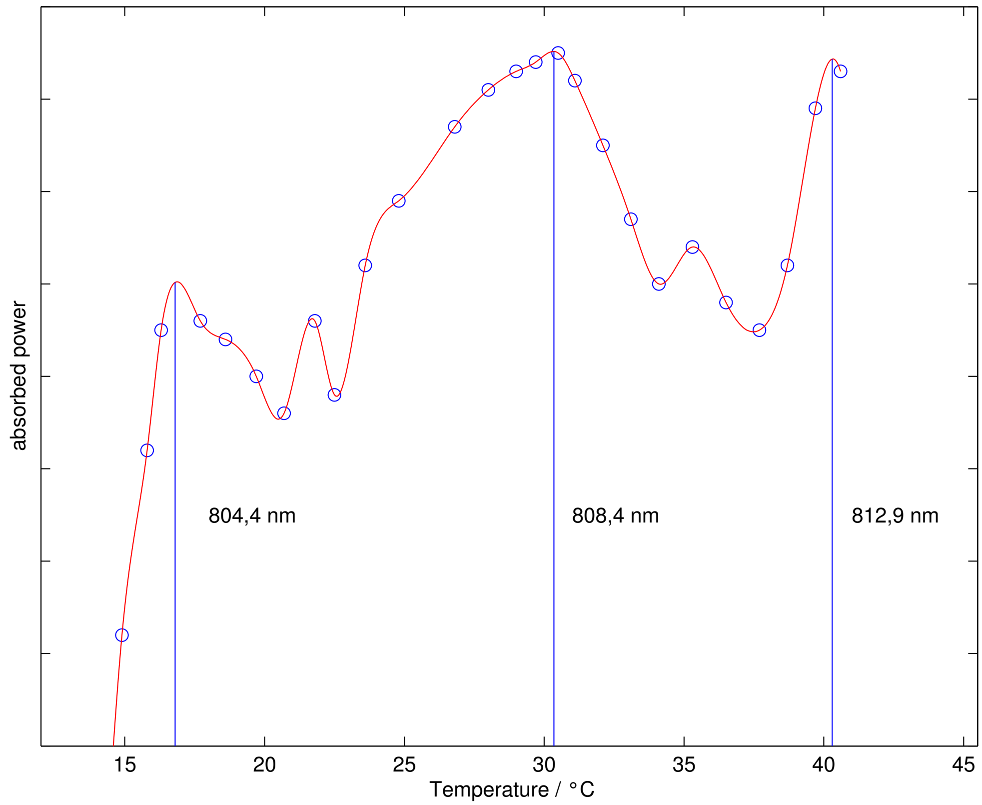

Figure 8: Absorption spectrum of the Nd:YAG crystal.

All further measurement are done at the maximum absorption to get high intensities. The measured absorption spectrum is shown in fig. 8. The absorption spectrum of Nd:YAG is well known, so the wavelengths of the maxima can be determined.

Table 4.2: **Measurement of the absorption spectrum of the Nd:YAG crystal**
T: Temperature of the laser diode
D: Number of divisions on the oscilloscope
Scale: Scale for the divisions on the oscilloscope
U: Voltage on the oscilloscope

T / °C	D / div	Scale / V/div	U / mV
8,9	3,3	0,050	165,0
10,2	2,9	0,050	145,0
11,4	5,1	0,020	102,0
12,1	4,6	0,020	92,0
13,1	3,2	0,020	64,0
14,0	2,6	0,020	52,0
14,9	3,4	0,010	34,0
15,8	2,4	0,010	24,0
16,3	3,5	0,005	17,5
17,7	3,4	0,005	17,0
18,6	3,6	0,005	18,0
19,7	4,0	0,005	20,0
20,7	4,4	0,005	22,0
21,8	3,4	0,005	17,0
22,5	4,2	0,005	21,0
23,6	2,8	0,005	14,0
24,8	2,1	0,005	10,5
26,8	1,3	0,005	6,5
28,0	0,9	0,005	4,5
29,0	0,7	0,005	3,5
29,7	0,6	0,005	3,0
30,5	0,5	0,005	2,5
31,1	0,8	0,005	4,0
32,1	1,5	0,005	7,5
33,1	2,3	0,005	11,5
34,1	3,0	0,005	15,0
35,3	2,6	0,005	13,0
36,5	3,2	0,005	16,0
37,7	3,5	0,005	17,5
38,7	2,8	0,005	14,0
39,7	1,1	0,005	5,5
40,6	0,7	0,005	3,5

4.3 Measurement of the calibration curve for a given wavelength

Using the current dependence of the diode's wavelength one can measure the calibration curve at a given wavelength. The current and the temperature are adjusted in a way that leaves the transmission at the minimum. The calibration curve is assumed to be linear. The curve is shown in fig. 9. With the calibration curve we know what temperature is necessary at a certain injection current to keep the wavelength constant.

Table 4.3: **Measurement of the calibration curve at a given wavelength**
I: Current through the laser diode
T: Temperature of the laser diode

I / mA	T / °C
200	31,8
210	31,5
220	31,1
230	30,8
240	30,4
260	29,6
270	29,2
280	28,7
290	28,2
300	27,7
310	27,4
320	27,4
330	27,1
340	26,7
350	26,5
360	26,1
370	25,7
380	25,1
390	24,7
400	24,3
410	24,1
420	23,9
430	23,5
440	23,1
450	22,7

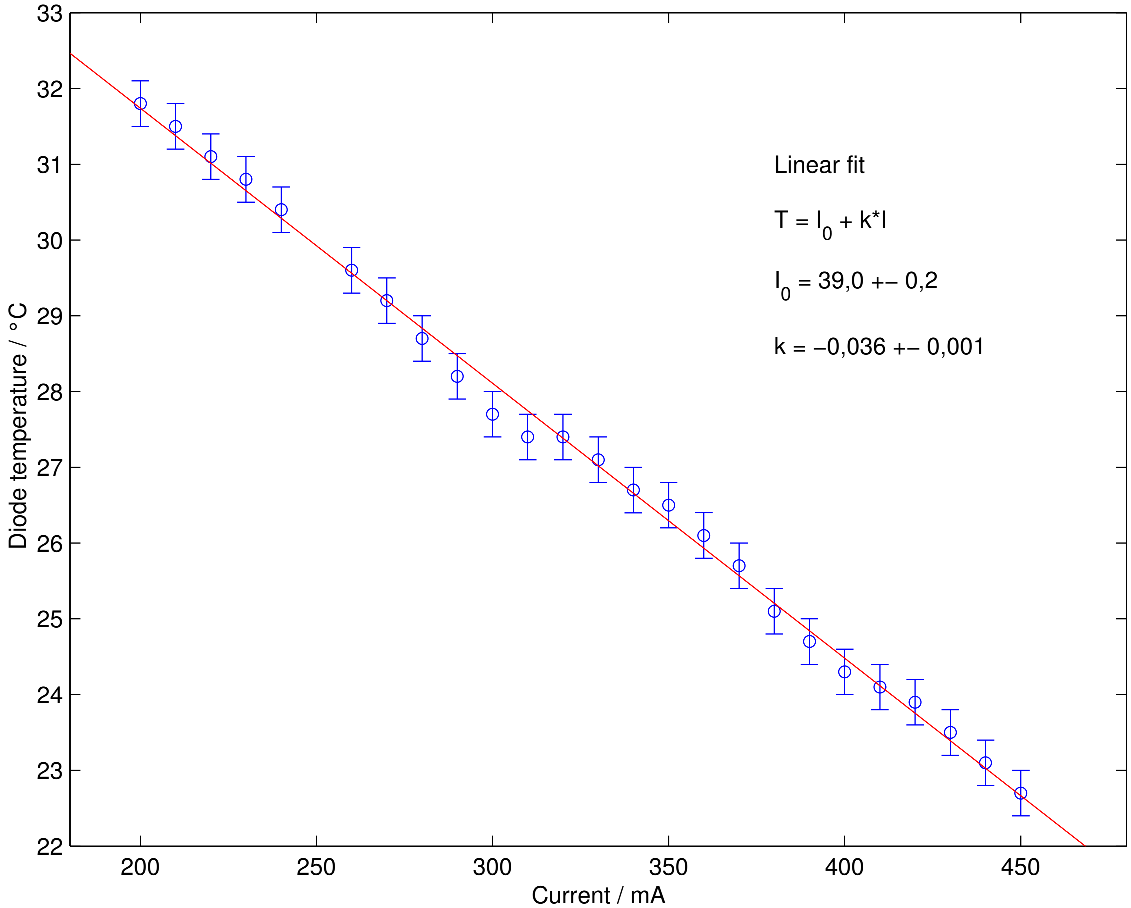

Figure 9: Calibration curve at a given wavelength.

4.4 Lifetime of the metastable state

A low pass filter was inserted before the photo diode in order to filter all wavelengths smaller than 1000nm. This was done to eliminate the intensity from the pump diode. The intensity shows an exponential decrease with time. The liftetime is defined as the time it takes for the intensity to drop to 1/e of its initial value. The exponential fit $y = y_0\, e^{a\,\tau}$ used to calculate the lifetime is shown in fig. 10.

Table 4.4: **Measurement of the lifetime of the metastable state**
Y: Position on the Y-grid of the oscilloscope
t: Time (X-Grid of the oscilloscope)

t / μs	Y / div
0	8,0
15	7,0
45	6,0
85	5,0
130	4,0
200	3,0
300	2,0
350	1,5
400	1,2
450	1,0
500	0,7

The exponential fit gives a lifetime of $(211 \pm 18)\mu$s.

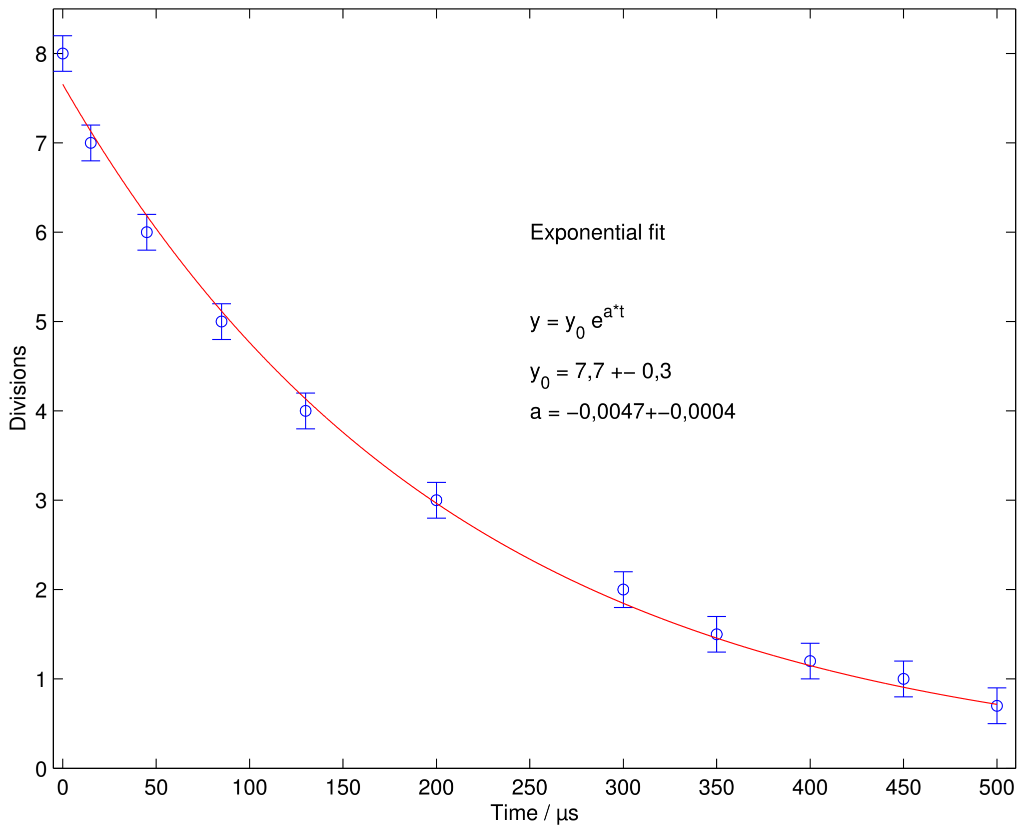

Figure 10: Lifetime of the metastable state.

4.5 Measurement of the pump power

We performed a linear fit to get the calibration curve of the diode in order to get the appropriate temperature for the maximum absorption wavelength. The diode was operated at various currents and temperatures given by the calibration curve to keep the wavelength constant. The pump power was then measured using a photo diode, which gives a current proportional to the pump power. The linear relation between the currents is shown in fig. 11.

Table 4.5: **Measurement of the pump power**
T: Temperature of the laser diode
I_{LD}: Current through the laser diode
D: Number of divisions on the oscilloscope
Scale: Scale for the divisions on the oscilloscope
U: Voltage on the oscilloscope
I_{PD}: Photo diode current
Δ I_{PD}: Error on the photo diode current

T / °C	I_{LD} / mA	D / div	Scale / V/div	U / mV	I_{PD} / mA	Δ I_{PD}
22,7	450	6,5	0,100	650	13,0	0,4
23,0	440	6,3	0,100	630	12,6	0,4
23,4	430	6,0	0,100	600	12,0	0,4
23,8	420	5,8	0,100	580	11,6	0,4
24,1	410	5,6	0,100	560	11,2	0,4
24,5	400	5,4	0,100	540	10,8	0,4
24,8	390	5,2	0,100	520	10,4	0,4
25,2	380	4,9	0,100	490	9,8	0,4
25,6	370	4,7	0,100	470	9,4	0,4
25,9	360	4,4	0,100	440	8,8	0,4
26,3	350	4,1	0,100	410	8,2	0,4
26,7	340	3,8	0,100	380	7,6	0,4
27,0	330	3,6	0,100	360	7,2	0,4
27,4	320	3,3	0,100	330	6,6	0,4
27,7	310	3,0	0,100	300	6,0	0,4
28,1	300	2,7	0,100	270	5,4	0,4
28,5	290	2,3	0,100	230	4,6	0,4
28,8	280	2,0	0,100	200	4,0	0,4
29,2	270	1,6	0,100	160	3,2	0,4
29,6	260	1,2	0,100	120	2,4	0,4
29,9	250	4,0	0,020	80	(1,6)	-
30,3	240	1,9	0,020	38	(0,76)	-
30,6	230	1,4	0,005	7	(0,14)	-
31,0	220	0,7	0,005	3,5	(0,07)	-

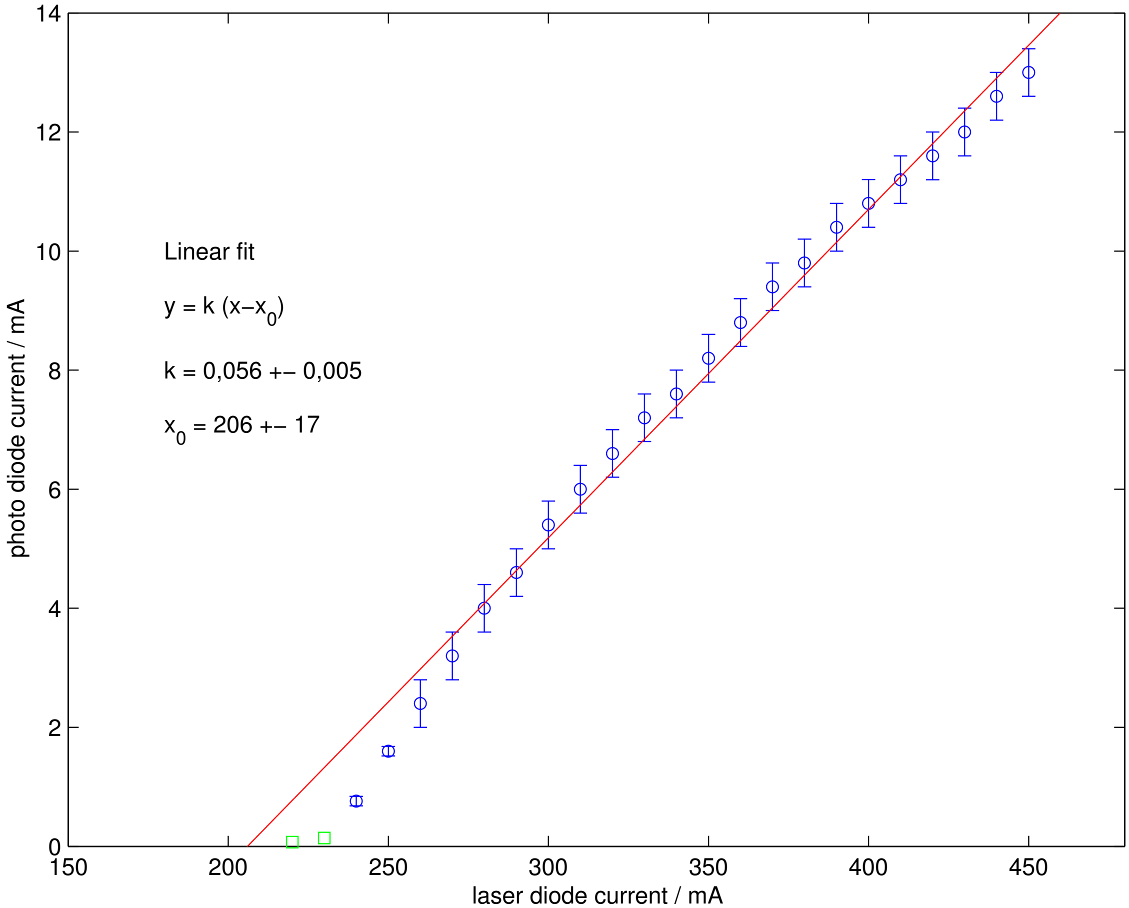

Figure 11: Pump power as function of the laser diode current.

4.6 Adjusting the laser

The cavity was set up and needed to be adjusted until an increase in intensity was detectable on the oscilloscope. This increase comes from the beginning of lasing. A finer adjustment is then done to get the best possible efficiency. The beam itself has a wavelength of $1064nm$ and is not visible to the eye.

4.7 Measurement of the laser power as function of the pump power

This measurement was performed in the same way as the measurement of the pump power. A filter for the pump light was used so that the pump light does not disturb the measurement. The linear relation between the injection current and the photo diode current is shown in fig. 12.

Table 4.7: **Measurement of the laser power**
T: Temperature of the laser diode
I_{LD}: Current through the laser diode
D: Number of divisions on the oscilloscope
Scale: Scale for the divisions on the oscilloscope
U: Voltage on the oscilloscope
I_{PD}: Photo diode current
Δ I_{PD}: Error on the photo diode current

T / °C	I_{LD} / mA	D / div	Scale / V/div	U / mV	I_{PD} / mA	Δ I_{PD}
22,7	450	4,9	0,50	2450	49,0	2,0
23,0	440	4,6	0,50	2300	46,0	2,0
23,4	430	4,4	0,50	2200	44,0	2,0
23,8	420	4,1	0,50	2050	41,0	2,0
24,1	410	3,9	0,50	1950	39,0	2,0
24,5	400	3,7	0,50	1850	37,0	2,0
24,8	390	3,4	0,50	1700	34,0	2,0
25,2	380	3,1	0,50	1550	31,0	2,0
25,6	370	2,9	0,50	1450	29,0	2,0
25,9	360	2,7	0,50	1350	27,0	2,0
26,3	350	6,0	0,20	1200	24,0	0,8
26,7	340	5,4	0,20	1080	21,6	0,8
27,0	330	4,7	0,20	940	18,8	0,8
27,4	320	4,1	0,20	820	16,4	0,8
27,7	310	3,6	0,20	720	14,4	0,8
28,1	300	3,0	0,20	600	12,0	0,8
28,5	290	2,5	0,20	500	10,0	0,8
28,8	280	3,8	0,10	380	7,6	0,4
29,2	270	2,7	0,10	270	5,4	0,4
29,6	260	4,1	0,05	205	(4,1)	-

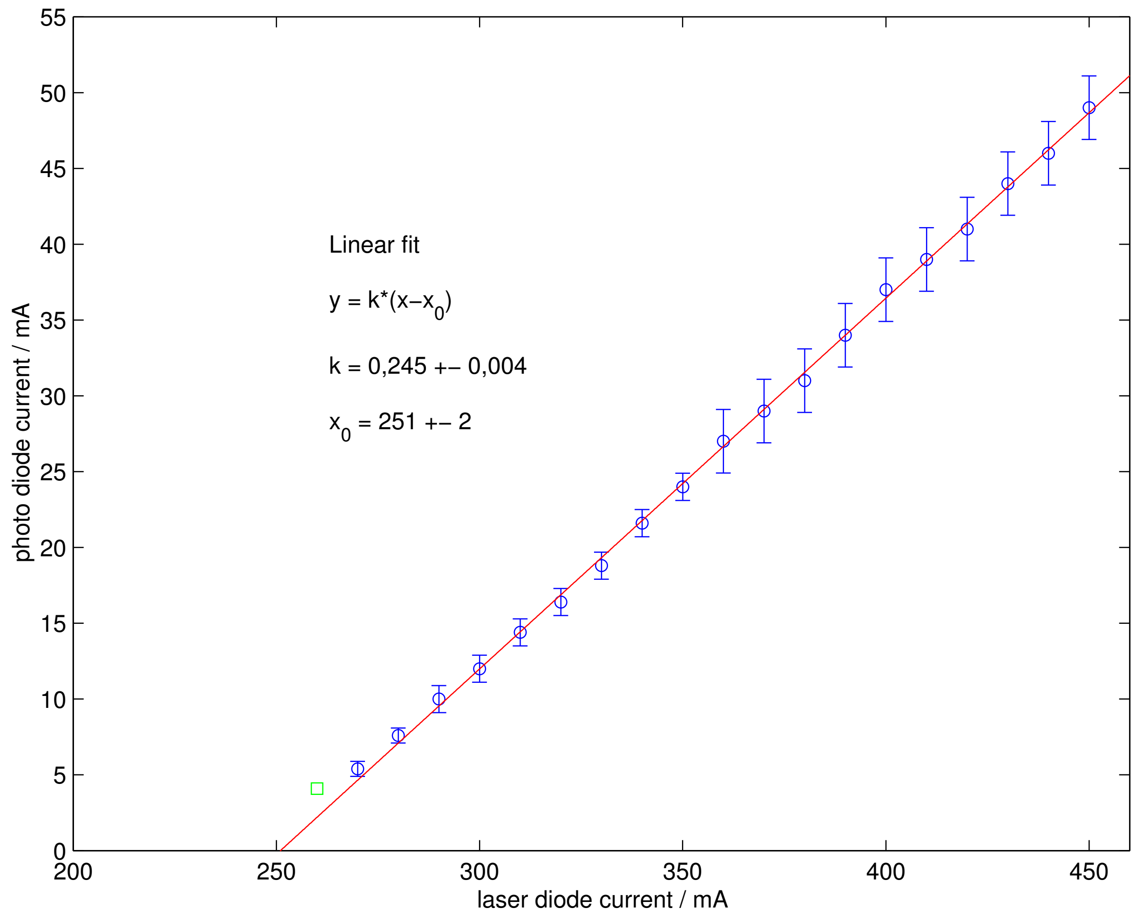

Figure 12: Laser power over pump power.

4.8 Measurement of the laser power at various wavelengths

The current through the diode was kept constant while the temperature was varied over the available temperature range. The laser power was again measured using the photo diode. The laser power will have a maximum when the wavelength is one with a maximum absorption. The wavelength dependence of the laser power will show a behaviour similiar to the absorption curve for the Nd:YAG crytal. The peak temperatures do not coincide with the temperatures in fig.8 because we measured at a different $\mathrm{I}_L D$.

I_{PD} at various wavelengths is shown in fig 13.

Table 4.8: **Measurement of the laser power at various wavelengths**
T: Temperature of the laser diode
D: Number of divisions on the oscilloscope
Scale: Scale for the divisions on the oscilloscope
U: Voltage on the oscilloscope
I_{PD}: Photo diode current
ΔI_{PD}: Error on the photo diode current

T / °C	D / div	Scale / V/div	U / mV	I_{PD} / mA	ΔI_{PD}
8,9	3,4	0,2	680	13,6	0,8
9,8	4,2	0,2	840	16,8	0,8
10,7	5,0	0,2	1000	20,0	0,8
12,0	6,2	0,2	1240	24,8	0,8
13,0	6,5	0,2	1300	26,0	0,8
14,0	6,6	0,2	1320	26,4	0,8
15,1	6,2	0,2	1240	24,8	0,8
16,3	6,0	0,2	1200	24,0	0,8
17,5	5,7	0,2	1140	22,8	0,8
18,2	5,7	0,2	1140	22,8	0,8
19,3	5,8	0,2	1160	23,2	0,8
20,5	5,9	0,2	1180	23,6	0,8
21,5	6,0	0,2	1200	24,0	0,8
22,5	6,1	0,2	1220	24,4	0,8
23,6	6,1	0,2	1220	24,4	0,8
24,9	6,2	0,2	1240	24,8	0,8
26,5	5,8	0,2	1160	23,2	0,8
27,3	5,4	0,2	1080	21,6	0,8
28,5	4,6	0,2	920	18,4	0,8
29,7	3,6	0,2	720	14,4	0,8
30,9	3,0	0,2	600	12,0	0,8
32,2	2,4	0,2	480	9,6	0,8
33,0	2,3	0,2	460	9,2	0,8
34,2	4,3	0,1	430	8,6	0,4
35,3	4,6	0,1	460	9,2	0,4
36,3	5,1	0,1	510	10,2	0,4
37,2	5,5	0,1	550	11,0	0,4
38,3	6,1	0,1	610	12,2	0,4
39,1	6,6	0,1	660	13,2	0,4
40,2	7,0	0,1	700	14,0	0,4
41,4	7,0	0,1	700	14,0	0,4

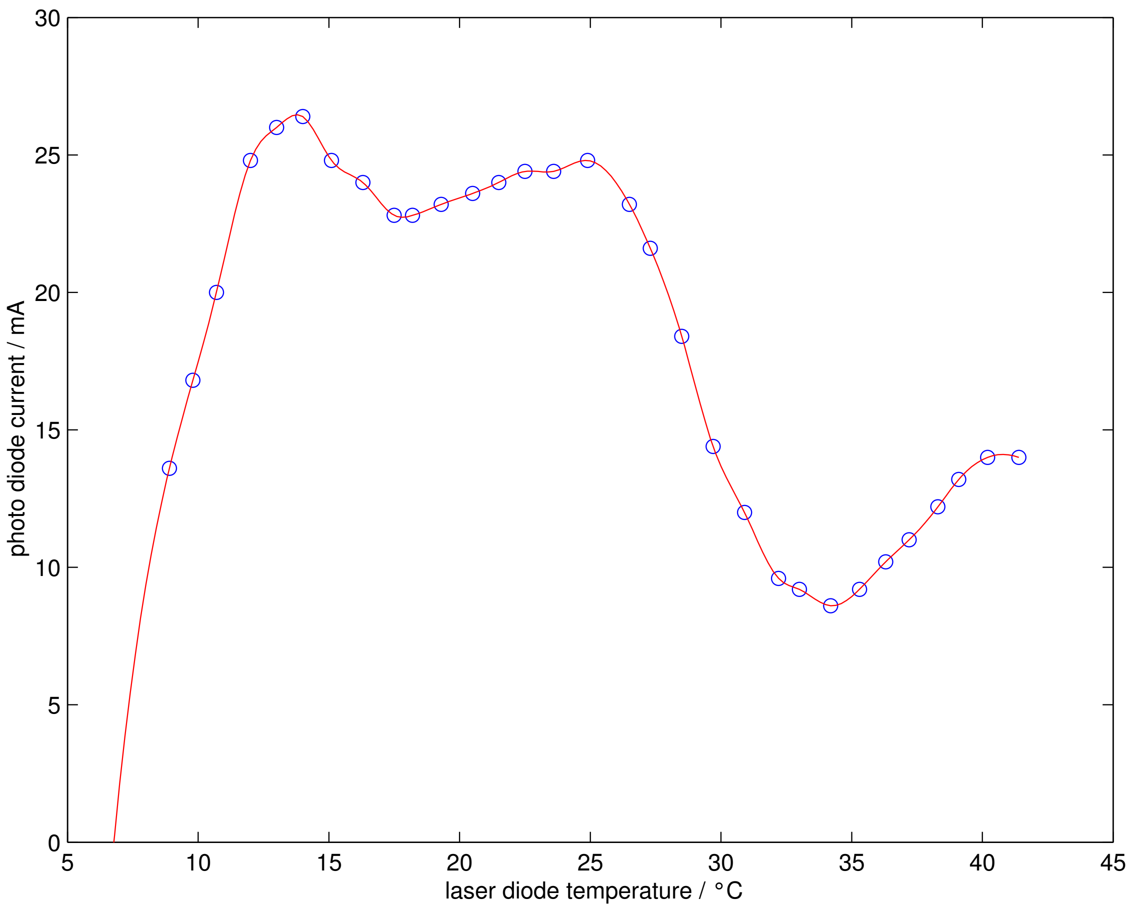

Figure 13: Laser power at various wavelengths.

4.9 Frequency doubling with a KTP crystal

After doubling the frequency, the laser beam becomes visible. The KTP crystal needs to be arranged to gain the maximum intensity, which is obtained by fulfilling the angular matching condition. The doubled beam will have a wavelength of 532nm. It is visible for the eye as a green beam.

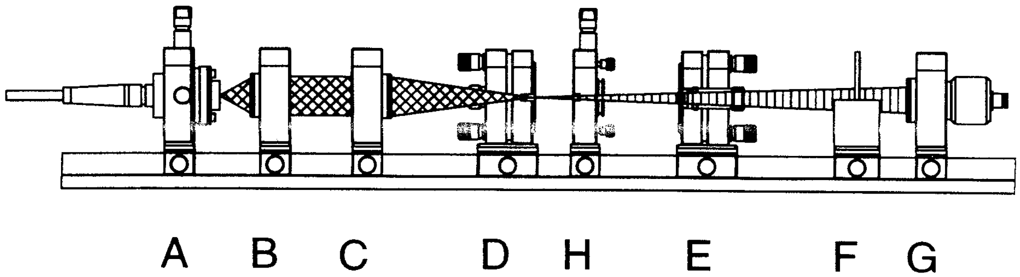

Figure 14: **Setup for the laser diode**

A	... Laser diode
B, C	... Lenses
D	... Nd:YAG crystal and mirror
E	... 2^{nd} mirror
F	... RG 1000 filter
G	... Photo diode
H	... KTP crystal

4.10 Measurement of the power of the second harmonic as function of the power of first harmonic

The laser power was varied to measure the power of the green beam as function of the laser power.

Because of the low intensity of the green beam, we used a resistance of 1MΩ instead of 50Ω (Signal directly on the oscilloscope instead of the amplifier). We avoided this before because the RC circuit created by the oscilloscope input resistance and the capacity of the photo diode has a large time constant ($\tau = RC$). It was necessary to do it for this measurement because the photo diode current is very small. The quadratic increase of the power of the second harmonic is shown in fig. 15. A straight line was added in the figure to show the deviation from a linear increase.

Table 4.10: **Power of the second harmonic**
T: Temperature of the laser diode
I_LD: Current through the laser diode
D: Number of divisions on the oscilloscope
Scale: Scale for the divisions on the oscilloscope
U: Voltage on the oscilloscope
I_{PD}: Photo diode current
Δ I_{PD}: Error on the photo diode current

T / °C	I_{LD} / mA	D / div	Scale / V/div	U / mV	I_{PD} / mA	Δ I_{PD}
22,7	450	6,0	0,050	300	$3,00 \cdot 10^{-4}$	$0,1 \cdot 10^{-4}$
23,0	440	5,8	0,050	290	$2,90 \cdot 10^{-4}$	$0,1 \cdot 10^{-4}$
23,4	430	5,3	0,050	265	$2,65 \cdot 10^{-4}$	$0,1 \cdot 10^{-4}$
23,8	420	4,7	0,050	235	$2,35 \cdot 10^{-4}$	$0,1 \cdot 10^{-4}$
24,1	410	4,2	0,050	210	$2,10 \cdot 10^{-4}$	$0,1 \cdot 10^{-4}$
24,5	400	3,9	0,050	195	$1,95 \cdot 10^{-4}$	$0,1 \cdot 10^{-4}$
24,8	390	3,5	0,050	175	$1,75 \cdot 10^{-4}$	$0,1 \cdot 10^{-4}$
25,2	380	2,6	0,050	130	$1,30 \cdot 10^{-4}$	$0,1 \cdot 10^{-4}$
25,6	370	3,3	0,020	66	$(0,66 \cdot 10^{-4})$	-
25,9	360	2,4	0,010	24	$(0,24 \cdot 10^{-4})$	-
26,3	350	0,0	0,005	0	$(0,00 \cdot 10^{-4})$	-

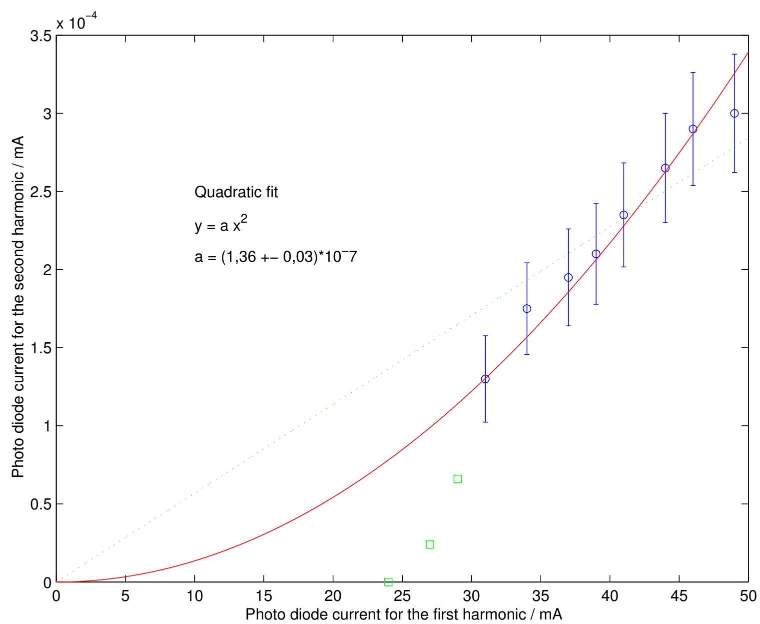

Figure 15: Quadratic relation between the power of the first and second harmonic.

5 Error analysis

5.1 Calibration curve for constant wavelengths

We assumed an error of $\pm 0,3°C$ on the temperature to account for the error of reading when searching the minimum transmission on the oscilloscope.

5.2 Pump power and lifetime measurement

We assumed an error of reading of 0,2 divisions.
This gives an error of 0,4mA on the photo diode current. From the exponential fit for the lifetime we get an error of 18μs on the lifetime.

$$|\frac{\Delta\tau}{\tau}| = |\frac{\Delta a}{a}|$$

5.3 Laser power measurements

In previous measurements, we neglected the error on the abscissa, because we assumed negligible error on the current. For the plot of the laser power over the pump power, the abscissa error is given by the error of reading for the pump power measurement. Accordingly, for the power of the second harmonic over the power of the first harmonic, the abscissa error is given by the error on the laser power. Abscissa errors Δx can be transformed to ordinate errors Δy using the formula

$$y = f(x) \qquad \Delta y = |\frac{\partial f(x)}{\partial x}|\Delta x$$

This has been done for the power measurements of the single and double frequency beam.

5.3.1 Error for the single frequency power measurement

The error Δx on the pump power was transformed using the formula

$$\Delta y = k\,\Delta x = 0,238\,\Delta x$$

Scale: Scale for the divisions on the oscilloscope
ΔI_L: Error on the laser power
ΔI_P: Transformed error on the pump power
ΔI: Total error

Scale / V/div	ΔI_L / mA	ΔI_P / mA	ΔI / mA
0,50	2,0	0,1	2,1
0,20	0,8	0,1	0,9
0,10	0,4	0,1	0,5

5.3.2 Error for the double frequency power measurement

The error Δx on the pump power was transformed using the formula

$$\Delta y = 2ax\,\Delta x = 2 * 1,36 \cdot 10^{-7}\,x\,\Delta x$$

I_{PD}: Photo diode current
ΔI_D: Error on the double frequency power
ΔI_S: Transformed error on the single frequency power
ΔI: Total error

I_{PD} / mA	ΔI_D / mA	ΔI_S / mA	ΔI / mA
450	$0,1 \cdot 10^{-4}$	$0,28 \cdot 10^{-4}$	$0,38 \cdot 10^{-4}$
440	$0,1 \cdot 10^{-4}$	$0,26 \cdot 10^{-4}$	$0,36 \cdot 10^{-4}$
430	$0,1 \cdot 10^{-4}$	$0,25 \cdot 10^{-4}$	$0,35 \cdot 10^{-4}$
420	$0,1 \cdot 10^{-4}$	$0,23 \cdot 10^{-4}$	$0,33 \cdot 10^{-4}$
410	$0,1 \cdot 10^{-4}$	$0,22 \cdot 10^{-4}$	$0,32 \cdot 10^{-4}$
400	$0,1 \cdot 10^{-4}$	$0,21 \cdot 10^{-4}$	$0,31 \cdot 10^{-4}$
390	$0,1 \cdot 10^{-4}$	$0,19 \cdot 10^{-4}$	$0,29 \cdot 10^{-4}$
380	$0,1 \cdot 10^{-4}$	$0,18 \cdot 10^{-4}$	$0,28 \cdot 10^{-4}$

6 Summary

6.1 Measurement of the absorption spectrum of the Nd:YAG crystal

The absorption maxima was found at ≈30,5°C and assigned to a wavelength of 808,4nm.

6.2 Measurement of the calibration curve for constant wavelengths

A linear dependence between the temperature T and the current I was found. A linear fit gives

$$\frac{T}{[°C]} = (39 \pm 0,2) - (0,036 \pm 0,001) \cdot \frac{I}{[mA]}$$

6.3 Measurement of the pump power

The linear relation between laser diode current I_{LD} and photo diode I_{PD} current was found to be

$$\frac{I_{PD}}{[mA]} = (0,056 \pm 0,005) \cdot \frac{((206 \pm 17) - I_{LD})}{[mA]}$$

6.4 Measurement of the lifetime of the metastable state

From the exponential fit we get a lifetime of $(211 \pm 18)\mu$s. The literature value is 230μs.

6.5 Measurement of the laser power as function of the pump power

Again there is a linear dependence between the laser diode current I_{LD} and the photo diode current I_{PD}.

$$\frac{I_{PD}}{[mA]} = (0,245 \pm 0,004) \cdot \frac{((251 \pm 2) - I_{LD})}{[mA]}$$

6.6 Measurement of the laser power at various wavelengths

The laser power at various wavelengths is shown in fig.13.

6.7 Measurement of the power of the second harmonic as function of the power of first harmonic

The relation between the powers is quadratic, a quadratic fit gave

$$\frac{I_{PD}}{[mA]} = (1,36 \pm 0,03) * 10^{-7} \cdot \frac{I_{LD}^2}{[mA^2]}$$