V 60

The Diode Laser

Timo Gräßer
timo.graesser@udo.edu

Jasper Karl Lammering
jasper.lammering@udo.edu

Execution: 17.10.18

Delivery: 26.10.18

TU Dortmund – Fakultät Physik

Contents

1. Theory

1.1. introduction

Within this experiment we try to view the absorption spectrum of Rubidium with a diode laser. Therefor the functionality of lasers, diodes and the combination of both are presented in this theory. One technique to obtain a continuous spectrum is to use a piezo crystall with an alternating current, which will also be discussed in the following. Furthermore we will shortly present the procedure and the setup of this experiment. At the end of this report we provide our results and discuss them.

1.2. Functionality of a laser

The scientific abbreviation **LASER** means "**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation". With the schematic functionality of a laser, presented in the following, a laser is able to emit very monochromatic and highly coherent light. To realize a laser, four components are needed: a laser medium, a pump, a cooling system and a resonator. However, the laser medium has to be a material, where a so called population inversion can be archieved by external excitation. therefor it is usefull, to consider a system with three energy levels like shown in illustration 1. The ground state is the most filled state

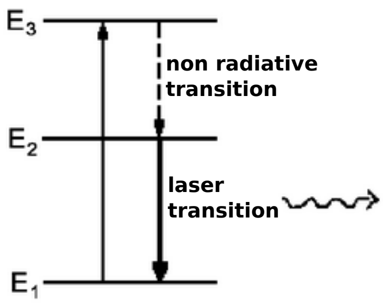


Figure 1: Schematic plot of the three level system used in a laser medium [1] *edited*.

at finite temperatur, like one can comprehend, when regarding the Boltzmann statistics. With an external pumping the electrons from the ground state are excited to the instable third level and they immediatly transit to the second state without emitting photons. The electrons from the second, more stable state fall back to the ground state at a smaller rate by spontaneous or stimulated emission. With this configuration and a strong pumping an inversion population can be reached in contrast to a two level system, where the maximum reached population in the second state is 50 %.
There are several different possibilities, to excite the laser medium external, for instance thermal pumping, electrical pumping, which is used in this experiment, or even chemical pumping. In every case it is important, to cool the system well, because not the full energy, which is pumped into the system, is converted to radiation. A non negligible part of the energy is transfered to phonons, so resulting in heat. The cooling system will

guarantee for a constant temperature of the laser medium, so that the thermal radiation stays constant and the laser doesn't overheat.
However, the last but not least component of the laser is the resonator, see figure 2. The emitted photons of the laser medium radiate to the front and the backside of the laser can, where they are reflected. Of course the front side mirror has to be partly reflecting, because there has to be an output beam. The reflected photons radiate back into the laser medium and induce other radiation transitions with the same energy as the inducing photons. We emphasize, that this so called stimulated emission is of great importance for the functionality of a laser, including the emission of monochromatic light. Beside this, another effect occurs: Because of the mirrors on both sides the laser can forms a resonator for the beam. Only light modes with certain frequencies enjoy constructive interference in the resonator and therefor their intensities are increased. The difference between the frequencies of two next neighbour modes is called free spectral range and given by

$$\varDelta\nu_{\mathrm{FSR}} = \frac{\mathrm{c}}{2Ln}, \tag{1}$$

where c is the speed of light, L is the length of the resonator and n is the refraction index of the laser medium.

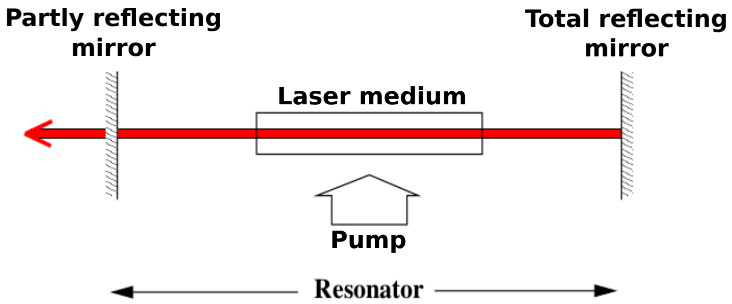


Figure 2: Setup of a laser in principle [2] *edited.*

With all the mentioned components of the laser setup one obtains an almost monochromatic and coherent laser beam. To improve the laser with regard to its frequency width it is e.g. possible to build an external cavity with a diffraction grating. We will treat this later both in theory and in experiment.
The main property of a diode laser is, that it contains a semiconductor medium and an electrical current pump, forming a diode. Thus we present a short description of semiconductors, doping of them and the funcionality of a diode in the following sections.

1.3. Semiconductors and doping

A semiconductor is a material with two main properties: it conducts weaker than a metall, but stronger than an insulator and its conductivity rises with the temperature. The illustrative reason for the enumerated things is, that the Fermi energy of those materials is located inside a narrow band gap of the band structure. That means, that

at zero temperature the valence band of a semiconductor is filled, while the conducting band is empty, so no current can occur. At higher temperatures thermal excitations let the electrons overcome the band gap, so that the conductivity increases.
Doping a semiconductor means placing impurities into it to change its conductivity substantial. One distinguishes between doping with donor materials and doping with acceptor materials. In the first case the impurity provides an additional electron, which is energetically by far closer to the conductive band than the valence band. The consequence is, that the conductivity increases, because the additional electrons only need to overcome a smaller band gap. In the second case the impurity provides a hole, which lies energetically near to the valence band. This hole can be occupied by an electron with much less energy than in the non doped case, so that the conductivity again rises. Both concepts are illustrated in figures 3 and 4.

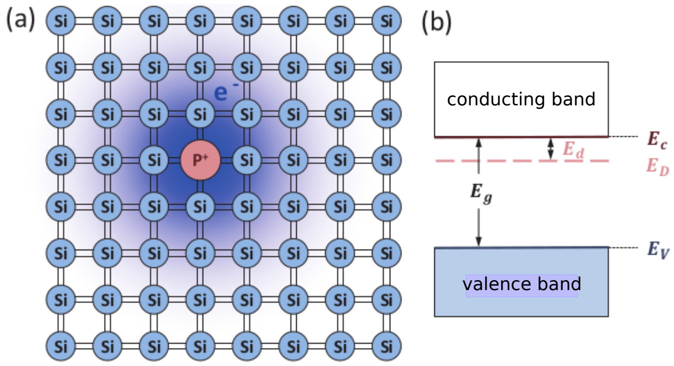


Figure 3: (a) Illustration of the grid of n-doped silicon. The phosphor impurity serves as an electron donor. (b) Schematic depiction of the band structure of a n-doped semiconductor [4] *edited*.

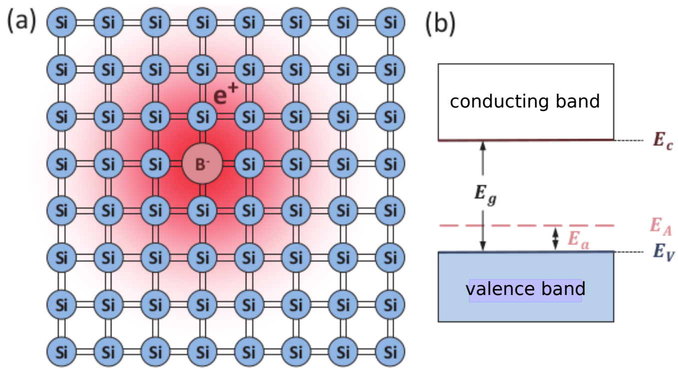


Figure 4: (a) Illustration of the grid of p-doped silicon. The boron impurity serves as an electron acceptor. (b) Schematic depiction of the band structure of a p-doped semiconductor [4] *edited*.

1.4. Funcionality of a diode

Basically a diode consists of a semiconductor material, which is p-doped on one side and n-doped on the other side. Without any external influences some of the almost not bounded electrons from the n-doped side will recombine, among emission of a photon, with some holes from the p-doped side, caused by diffusion. The result is firstly a transition zone between the two doped sides, where no free charge carriers remain, and secondly an electric field, which acts against the progress of recombination, because it accelerates electrons from the p-doped side to the n-doped side. After a short time the system arrives at an equilibrium state, where the diffusion current and the counter field current vanish. The width of the so called depletion zone at this point depends on the doping densities and the diffusion potential.
However, if one attaches a power supply to the presented configuration, meaning to the diode, there are two relevant cases to consider: In the first case the plus terminal is connected to the n-doped side, while the minus terminal is connected to the p-doped side. The consequence is, that the doped semiconductor loses its conductivity, because the depletion layer width increases as the remaining free charge carriers are pulled out by the power supply. One calls this configuration of the diode the reverse or blocking direction. The second case includes connecting the poles the other way round, so that of course the depletion layer width decreases and the conductivity rises. This setting is called the forward or passing direction of the diode. As a conclusion of this section the current-voltage characteristic of the diode is presented in figure 5

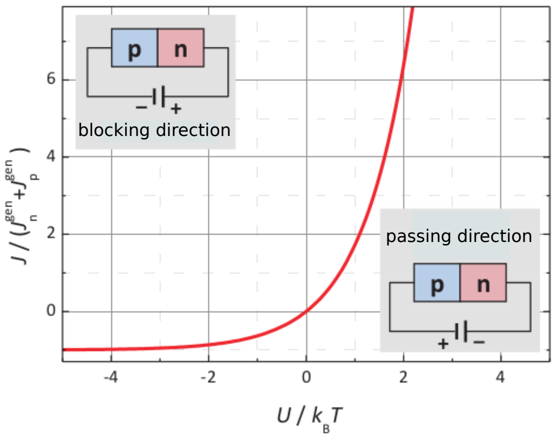


Figure 5: Current-voltage characteristic of the diode [4] *edited.*

1.5. Functionality of a diode laser

To realize a diode laser, one has to operate with the diode in forward direction. Electrons from the narrow depletion zone are pulled to the plus terminal, while holes are pulled to the minus terminal. Because of diffusion, electrons and holes from the doped sides recombine again in the depletion zone, while emitting a photon. Due to this, the depletion

zone is also called active layer. Its width stays constant within the permanent repetition of the enumerated processes. So as a result of the pn-transition and the external electrical pumping one has a diode with a light emitting active layer.
Because the active layer has a larger index of refraction than the surrounding layers, the emitted light is confined and expands only within a tiny channel. To realize the resonator mentioned in section 1.2 the front and back facets of the semiconductor are cleaved to act as cavity mirrors. If the pump current lies under a certain threshold, the stimulated gain is lower than the optical losses and the output of the diode laser is comparable to that of a LED. Above this threshold the stimulated emission causes a population inversion and therefor a strong light amplification. The intensity of the resulting coherent laser beam increases linearly with the current.
However, this is not the full necessary theoretical part of this experiment, because two problems occur: The linewidth of the output beam is around $\Delta\nu \approx 50\,\mathrm{MHz}$, so larger than the atomic transitions of rubidium $\Delta\nu_{\mathrm{Rub}} \approx 5\,\mathrm{MHz}$ and the diode laser is very sensitive to optical feedback. In the next section an optical instrument, which solves those problems, is presented.

1.6. Optimizing the laser beam

A possible solution for the enumerated problems in the last section is presented in figure 6. After the output beam is collimated by a lens it hits a diffraction grating. With this optical tool, the optical feedback is not deactivated, but controlled. Most of the light, however, is reflected by the diffraction grating, but around 15 % strays back into the diode. So the grating and the back facet of the diode form an external cavity for the laser beam. The consequences of this are explained later.

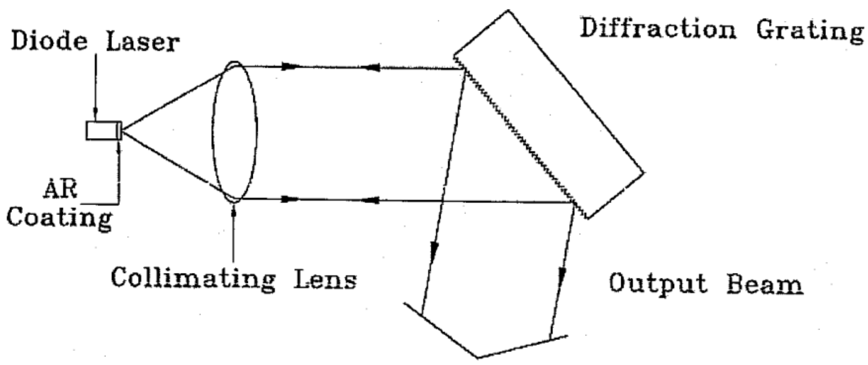


Figure 6: Setup of the diode laser with an external diffraction grating [3] *edited.*

Considering the total construction one has four different contributions to the optical gain of the laser: the medium gain, the internal cavity, the grating feedback and the external cavity. In figure 7 this is illustrated. Theoretically the laser will lase in the mode with the highest net gain, because this mode amplifies itself the most via stimulated emission. In practice more modes can occur at once and the output frequency can vary chaotically.

One task in this experiment is to estimate parameter configurations to get a single mode output through adjusting.

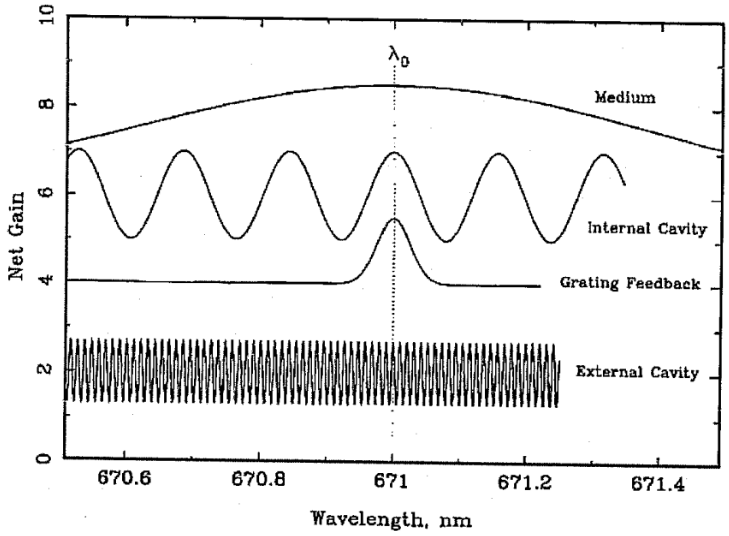


Figure 7: Schematic trend of the net gain for the four contributions [3].

The position of the maximum of the broad medium gain peak depends on the temperature of the laser. After adjusting the temperature and therefor the wavelength to the required value, the medium gain can be neglected, because of its broad peak.
Like mentioned before, the diode can forms an internal resonator or optical cavity, where frequently, as shown in equation (1), certain wavelengths are amplified. The laser will tend to lase in those modes, because the net gain is at the maximum. One can affect the wavelength by directly increasing the temperature of the laser head, which is impractical, because it requires some time. However, the wavelength can also be manipulated, while raising the pump current. The latter increases firstly the temperature almost instantaneously and secondly the carrier concentration inside the active layer, and hence the optical path length. At this point we emphasize, that even though the temperature and therefor the wavelength can be varied, not every required wavelength can be reached with adjusting the bare laser. Because of the oscillating internal cavity gain the wavelength shifts at certain temperature or current positions and so called mode hops occur. This adds up to the two problems counted in section 1.5 and can be solved by the same optical tool: a diffraction grating.
The first presented contribution to the net gain by the diffraction grating is the grating feedback. The incoming light is dispersed by the grating and a wavelength band with narrow width is emitted back into the laser. So the net gain function consists of only one peak like one can view in figure 7. Its position is determined by the horizontal grating angle, and the grating itself, especially the space d between the grating lines. The width of this peak depends on the expansion of the laser beam and the amount of grating lines.
The second and last contribution to the net gain by the diffraction grating is the external cavity. One can recognize in figure 7, that the resulting net gain function has a higher

frequency than the net gain function of the internal cavity. This is constituted by the depending of the free spectral range, see equation (1), on the reciprocal length of the resonator. To comprehend the interaction of the contributions of the grating feedback, the internal and the external cavity one may have a look at the so called best guess picture in figure 8. In the illustrated optimal case the laser will lase in the mode, where the cavity and feedback contributions are at maximum, but this is of course not the general case.

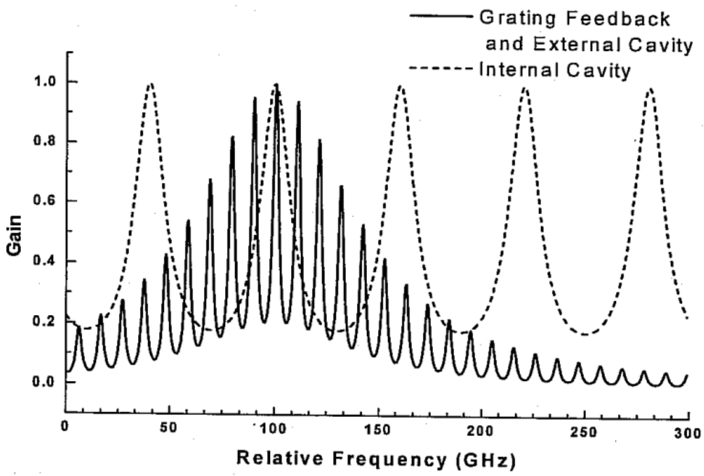


Figure 8: Best guess picture of the internal, external and grating feedback contibutions to the net gain [3].

In general it results, that the broad band internal cavity modes dominate at the long scale, while the narrow band external cavity modes dominate at the short scale. An instance for this is presented in illustration 9. The net gain function of the grating feedback and the external cavity can be shifted continuously, when varying the horizontal grating angle. As shown in the subfigures **b** and **c** of figure 9 the small changing of the grating angle causes firstly a continuous shifting of the frequency and secondly, when a threshold is reached, short scale mode hops between the external cavity modes. When a long scale threshold is reached by adjusting the laser, a broad mode hop occurs between the internal cavity modes, like shown in subfigure **d** of figure 9. As explained above the narrow band external cavity modes dominate at short scale, so if one only adjusts the grating angle, only a narrow frequency band around the internal modes can be reached. This can also be noticed, when viewing figure 9. The discussed thing seems to be a problem, but we remind the reader, that the internal modes can also be varied by changing the current. Together the full frequency spectrum is covered continuously.

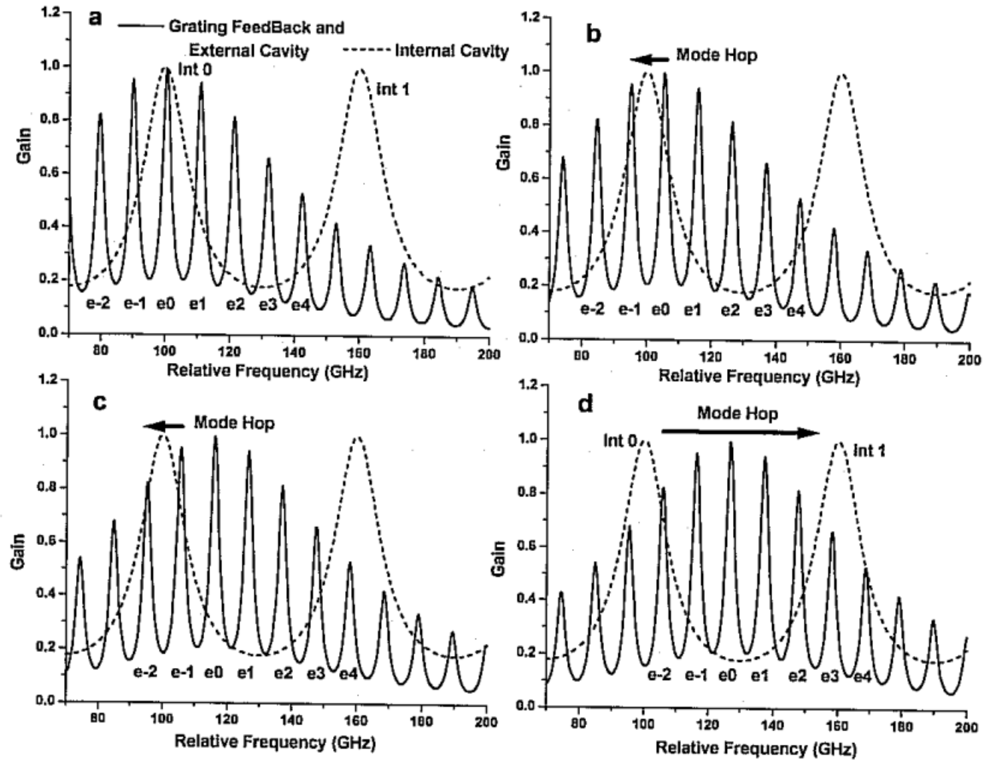


Figure 9: An Instance to comprehend the short and long scale mode hops, that occur, when adjusting the grating angle. Subfigure **a** shows the starting position, **b** and **c** show external cavity mode hops and in the last subfigure **d** one can see an internal cavity mode hop [3].

1.7. Absorption spectrum of Rubidium

The analysed Rubidium probe in this experiment consists of the isotopes ^{85}Rb and ^{87}Rb. In figure 10 one can view the relevant atomic hyperfine transitions, that can be induced with the output wavelength of the diode laser. When the right wavelength is adjusted, the Rubidium cell absorbs a big part of the light and emitts it in any direction, so that the intensity of the beam decreases in the direction of expansion. This lack of intensity can be detected with a diode behind the Rubidium cell. Even though the transition energies are very precise, even when regarding the energy unsharpness, one obtains a relatively broad laser peak, because of the Doppler widening. The Rubidium atoms can move almost freely inside the cell and therefor the wavelength obtained from their inertial system is in general not equal to the one obtained in the labour system. As a result the absorption peak gets more broad, because atoms moving towards the laser beam are excited by higher wavelengths, while atoms moving in the other direction are excited by lower wavelengths. The Doppler broaden spectrum is also presented in figure 10. How this can be monitored within this experiment is shortly described in the procedure section.

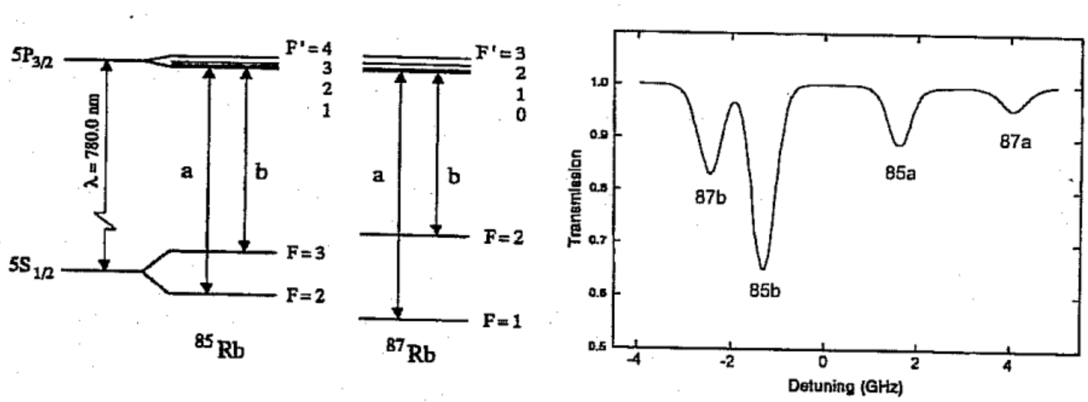


Figure 10: Left subfigure: Term scheme and relevant transitions. Right subfigure: Doppler broaden spectrum [3].

1.8. Piezo crystall

The piezoelectrical effect comprises the mutual interaction between an external deformation and an electrical potential inside a piezo crystal. It is used in this experiment, to vary the grating angle continuously, so that the required wavelengths to induce the rubidium transitions are runned through. Therefor a piezo crystal is placed below the diffraction grating and connected to an alternating current. Together with some other techniques presented in the following section one is able to obtain a Doppler broaden spectrum like the one in figure 10.

2. Procedure

The used diode laser in this experiment provides a beam with an output power of up to 70 mW and a wavelength around 785 nm, almost ideal for examining rubidium transitions.

2.1. Experimental setup

The schematic experimental setup is illustrated in figure 11. On the right side one can view the diode laser with the diffraction grating producing the laser beam. The diffraction grating has two adjustable angles, the horizontal one to vary the highest gain wavelength and the vertical one to vary the external cavity length. The beam is splitted at the 50/50 beam splitter so that one part proceeds directly to a photo diode, where its intensity is estimated, and the other part hits the Rubidium cell. A CCD infrared camera is mounted next to the cell to view the fluorescence, when the right beam wavelength is adjusted. The remaining intensity of the laser beam after passing the cell is again detected by a photo diode.

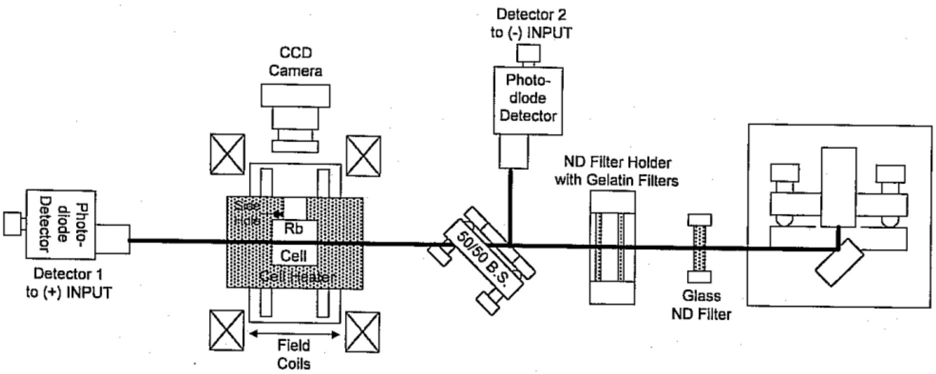


Figure 11: Schematic experimental setup to monitor the Rubidium spectrum [3].

2.2. Adjusting steps

The full experimental procedure deals with the adjusting the laser. The step by step manual can be viewed in source [3]. To start with the experiment the laser temperature is adjusted to 50 °C and the wiring between diode laser and laser controller is checked. The first important step is the estimation of the threshold current. Therefor the output beam is absorbed by an infrared screen and monitored by the camera. One varies the current, so that a typical speckle pattern only just can be viewed. After that one varies the current and the angles of the diffraction grating alternating to estimate the threshold current as exact as possible.
The second step is the adjusting of the laser to observe the Rubidium fluorescence. Therefor the camera is mounted like shown in figure 11 and the ramp generator and the piezo module are connected to the setup. The angles of the diffraction grating are again varied until one sees the fluorescence on the monitor.

For the last step the entire setup presented in figure 11 is needed. By using the detector electronics the two signals detected by the photodiodes are substracted. To get succesfull results one may has to modify the altitude and the position of the photodiodes. With the help of the piezo module one can view a continuous Doppler broaden spectrum on the oscilloscope screen.

3. Results

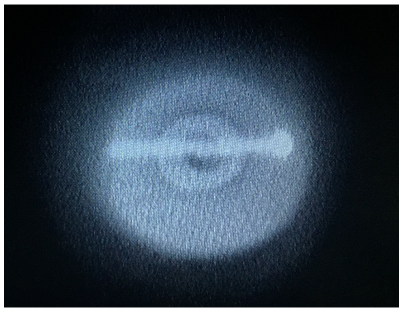
3.1. Laser Mode

As the first step we determine the current treshold from which on the diode is in laser mode. To get a visual indication of the transition from LED to laser diode a IR viewing card is placed in front of the laser. This card emitts light in the optical spectrum if infrared light hits it. We observe this light with the video of the camera on a screen. For the wide spectrum of the LED mode it shows a rather clean circle. When the diode enters laser mode a speckle pattern is seen. Then we lower the current slightly under this laser treshold and optimize the positioning of the gatter in terms of the vertical orientation. This increases the amplification by the aforementioned external cavity. When the speckle pattern is seen again we lower again the current a bit. After a few iterations of these two steps the laser is in an optimal condition for the next step. The voltage of the treshold is $U_\mathrm{t} = (3.42 \pm 0.01)\,\mathrm{V}$ and because of the inner resistance of $R_\mathrm{i} = (100 \pm 1)\,\Omega$ the current is $I_\mathrm{t} = (34.2 \pm 0.4)\,\mathrm{mA}$.

3.2. Fluorescence

In the next step we try to reach the wavelength which fits the energygap in the absorption spectrum of the rubidium gas. To change the wavelength of the laser we change the current which is applied to it. This changes the temperature of the semiconductor and therefore its bandgap. In addition the reflectionindex changes. These effects result in a different overall wavelength and a different ”free spectral range” because of formel (1). The pictures in figure 12 show the difference it makes when the laser hits the right wavelength. Then a clear beam of florescence is seen. The right one was achieved with a voltage of $U_\mathrm{f} = (5.33 \pm 0.01)\,\mathrm{V}$ and this means a current of $I_\mathrm{f} = (53.3 \pm 0.5)\,\mathrm{mA}$ with the same resistance as above.

(a) Cell hit by a wavelength outside of the absorption spectrum.



(b) Cell hit by a wavelength inside of the absorption spectrum.

Figure 12: Pictures of the rubidiumcell enlightened by different wavelengths.

3.3. The Absorption Spectrum of Rubidium

Now that we obtained a laser with a fitting intensity and a wavelength near to the absorption spectrum the next step is to loop over a few different wavelengths to record the whole spectrum. To achieve this we connect a ramp generator to the piezo controller. This enlargens the piezoelectric stack which moves the gatter therefore vary the length of the external cavity and results in a periodically changing wavelength. In figure 13 the voltage applied to the piezo monitor and the signal of one photodiode after the cell is shown. The signal of the photodiode may be a bit wrong because at this part of the experiment the laser did not hit the diode completely.

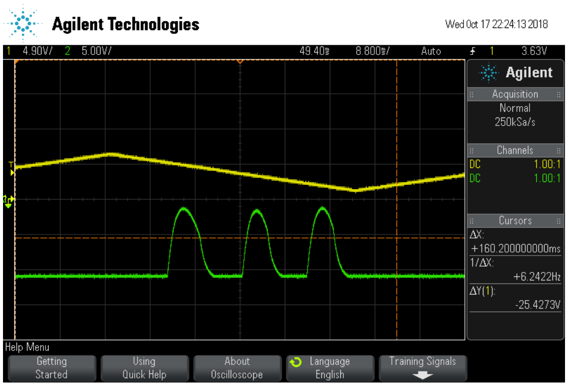


Figure 13: Voltage on the piezoelectric stack and some absorption dips from one photodiode.

Now we connect the ramp generator besides its connection to the piezo controller also to the laser current. This allows a larger scan area without mode hops. With the right settings figure 14 is shown on the oscilloscope screen. To surpress the effect of the changing laser intensity we place a beam splitter in front of the cell which reflects one half of the laser beam to another photodiode. After this we can substract the signal of the laser which went through rubidium, from the laser signal which went directly into the

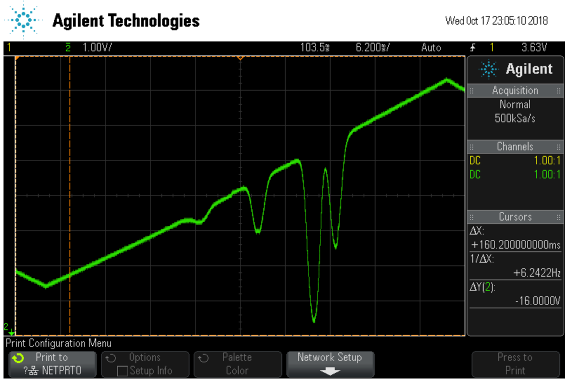


Figure 14: Signal of one photodiode with synchronized current and piezo controller.

second photodiode. By balancing the two signals with the controls on the subtraction controller a nice picture of the absorption spectrum can be achieved and is shown in figure 15.

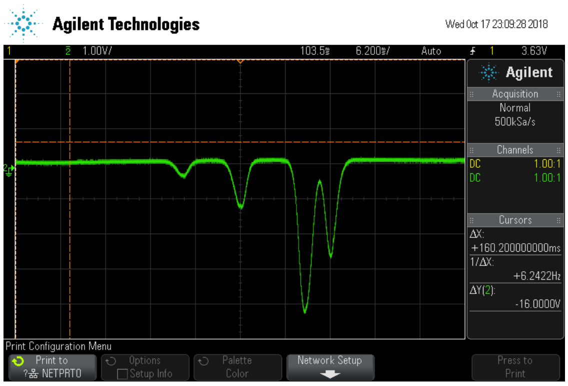


Figure 15: The recorded absorption spectrum of the two rubidium isotopes.

4. Discussion

The goal of this experiment was to learn about the handling of a diode laser and with its help to observe the absorption spectrum of rubidium-85 and rubidium-87. By manipulating the laser current we change the values of the internal cavity and by varying the positioning of the gatter we change the behaviour of the external cavity as described in section 1.6. Through this the right wavelength of $\lambda \approx 780\,\mathrm{nm}$ is obtained. This fits the needed energy for observing the absortion spectrum of the two rubidium isotopes. By using the piezoelectric stack and the subtraction technique described above, a nice picture of the spectrum is achieved as shown in 15. There we can recognise the four absorption dips 87b, 85b, 85a and 87a like in 10 only in a mirrored order. The order origins in the phase in which the piezo controller is in. It depends if its in an enlarging motion or in a shrinking motion because this changes the direction from which the wavelength are run through.

References

[1] TU Braunschweig. *Laser*. 2018. URL: http://www.pci.tu-bs.de/aggericke/PC4/Kap_III/Laser.htm.

[2] TU Dortmund. *Der HeNe Laser*. 2018. URL: 129.217.224.2/HOMEPAGE/PHYSIKER/MASTER/SKRIPT/V61.pdf.

[3] TU Dortmund. *Diode Laser Physics*. 2018. URL: 129.217.224.2/HOMEPAGE/PHYSIKER/MASTER/SKRIPT/Diodenl.pdf.

[4] Rudolph Gross and Achim Marx. *Festkörperphysik*. 2018. URL: https://www.degruyter.com/viewbooktoc/product/495417.

A. Copy of the Original Data

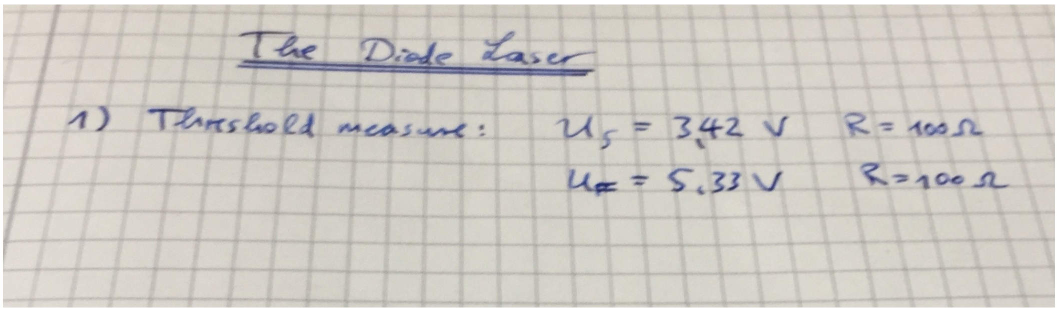


Figure 16: The recorded data for the treshold and the florescence.