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Diode-Laser

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Contents

1 Theory

The aim of this experiment is to record the absorption spectrum of rubidium gas. Therefore a diode laser is adjusted and aimed towards a cell filled with rubidium gas. The following sections introduce the theory important for the understanding of the experiment.

1.1 Laser basics

A laser (Light Amplification by Stimulated Emission of radiation) emits highly intensive light with a long coherence length. First of all the interaction of a radiation field with an electron is considered within a simple energy level system. These includes absorption and spontaneous and stimulated emission of a photon, shown in figure 1. Absorption

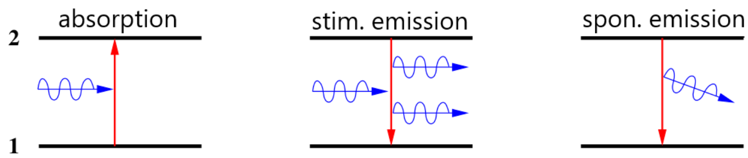


Figure 1: Absorption and both spontaneous and stimulated emission of a photon in a two energy level system. [3]

describes the process where a photon annihilates and delivers energy for the transition to a higher energy level. Spontaneous emission describes the opposite, a photon is emitted, if a transition to a lower energy level occurs spontaneously. But most important for a laser, as the name indicates, is the stimulated emission. The process of stimulated emission works as follows. If a photon with the energy same as the energy gap between the two energy levels encounters an excited state, another photon with same energy and phase is emitted and the excited state returns to the ground state. To run a laser, stimulated emission must be the most common interaction. Since the occupation of the energy levels for fermions follows the Fermi-Dirac statistics, levels above the Fermi energy are less occupied. Even if infinitely high temperatures are considered, the excited state would only be populated with the same probability as the ground state. This would not be enough in order to ensure mostly stimulated emission. Therefore a population inversion between ground state and an excited state is necessary. As to achieve this at least a three level system is of need. Transitions between the levels can be radiative as explained above as well as non radiative for example in the form of lattice vibration. Further the energy levels vary with regard to the decay rate. In figure 2 the process of pumping and stimulated emission is displayed for a three energy level system. The laser process for a three energy level system goes as follows. The transition from **E1** to **E3** is induced by absorption of energy. The level **E3** has a high decay rate from **E3** to **E2**, so a transition happens almost instantaneous through nonradiative spontaneous emission. Level **E2** compared to **E3** has a lower decay rate. So when energy is continuously pumped

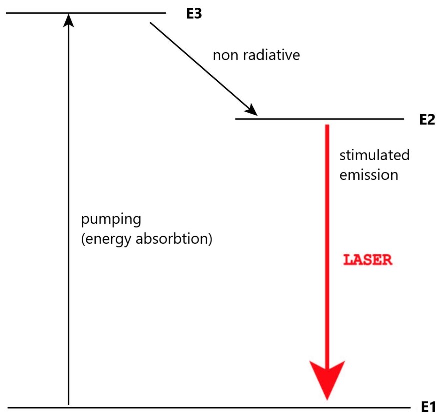


Figure 2: Three energy level system.

into level **E1**, the required population inversion between the ground state **E1** and the excited state **E2** is created. Now a photon which is emitted spontaneously through the radiative decay from **E2** to **E1** leads to stimulated emission of other photons, thus a highly intensive light with a long coherence length.

Beside the theoretical approach to accomplish laser radiation, some other criteria must also be met. First of all a gain medium with the desired energy gap is necessary, in which a population inversion is created by pumping. Pumping energy is supplied by light or electric current. In addition the gain medium is bound to a heat-sink to dissipate residual heat, which is produced by pumping. Furthermore a laser cavity, which consists of the gain medium and two mirrors, one highly reflective and the other partially transparent, the output coupler, is required. In figure 3 a schematic laser with its components is displayed. The operation of the laser cavity is as follows. Photons are emitted through

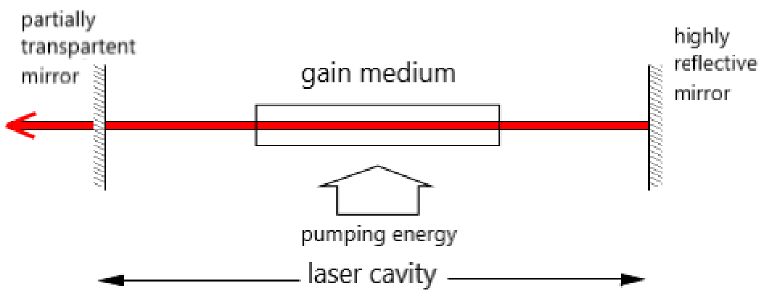


Figure 3: A schematic laser and its components. [3]

spontaneous emission in the gain medium. The two mirrors ensure that the photons stay in the laser cavity and the laser intensity increases due to stimulated emission of other photons. Depending on the cavity length L, standing waves along the cavity axis so called longitudinal modes are developed. The modes vary according to the wavelength and hence the number of knots. For the mode exists the following relation

$$L = m\,\frac{\lambda}{2} = m\,\frac{c_{\text{medium}}}{2\nu_m}\,. \tag{1}$$

Where m is a natural number and ν_m the according frequency. The spacing between frequencies of two modes in a laser cavity is given by the free spectral range (FSR)

$$\Delta\nu_{FSR} = |\nu_{m+1} - \nu_m| = \frac{c_0}{2Ln} \tag{2}$$

where c_0 is the speed of light and n is the index of refraction. A development of transversal modes in the laser cavity is also possible but is not discussed in detail. The laser ray that comes out of the output coupler contains all the frequencies of the longitudinal modes.

1.2 Semiconductor

The diode laser is a result of the research done on semiconductors. So first a deeper comprehension of semiconductor theory is needed. Hence the principle function of a simple p-n diode is described. A p-n diode exists out of two semiconductor materials one n-type and the other p-type. In the p-type semiconductor is an excess of holes and in the n-type semiconductor, an excess of electrons. An excess of holes or electrons can be accomplished by doping. When n- and p-type are merged together, electrons and holes diffuse into opposite side and recombine. This process induces an electric field between the fixed doping atoms, which counteracts the diffusion process. If equilibrium between the two forces is accomplished a charge depletion zone is created at the p-n junction. The figure 4 shows a schematic p-n Diode in equilibrium.

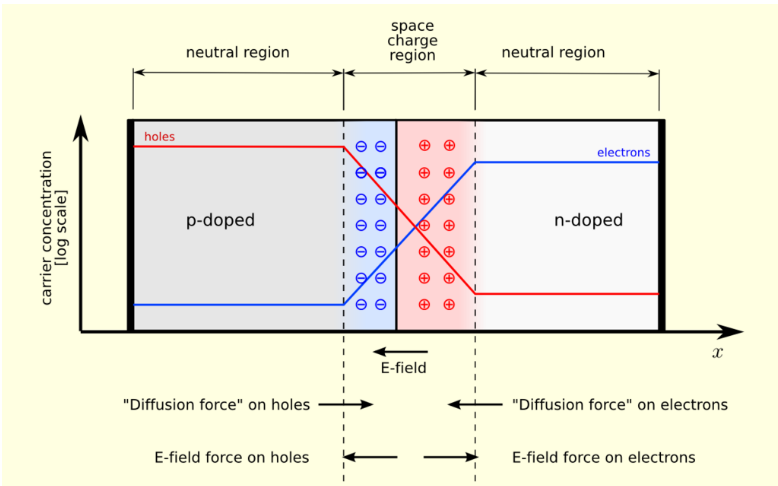


Figure 4: A schematic p-n Diode in equilibrium. [1]

There are two possible ways to apply voltage in forward bias and in reverse bias. In forward bias the diode lets the current flow but in the reverse bias the diode blocks the

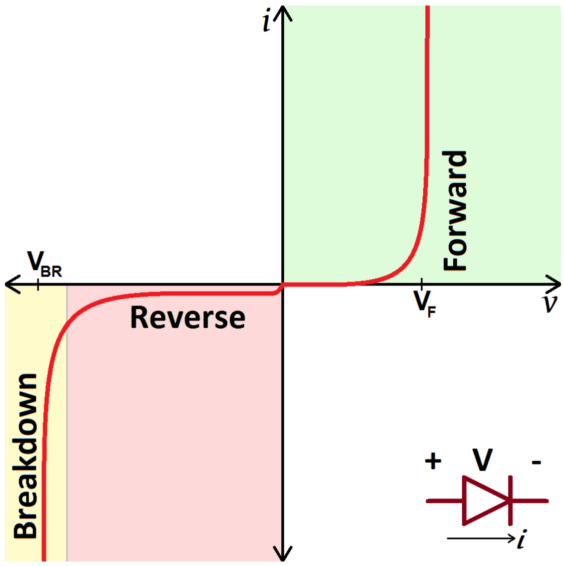


Figure 5: A characteristic of a p-n Diode. [2]

current up to the breaking point. A typical diode characteristic is shown in figure 5 For the Diode laser a light-emitting diode (LED) is necessary. A LED differs in terms of the band gap from a simple p-n diode. For a LED a direct band gap is needed, so a photon with the energy of the band gap is emitted if electrons and holes recombine.

1.3 Diode-laser

By applying the information of previous sections a diode laser can be explained. The diode laser consists of a special semiconductor chip. The chip has a certain structure shown in figure 6. The active layer of the chip has a higher refraction index than

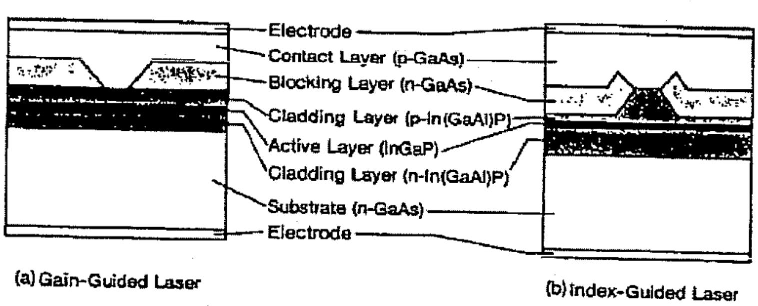


Figure 6: Two different typical structures profiles of a diode laser chip.[4]

its surroundings. Because of that light which is emitted in the active layer through recombination of electron-hole pairs is confined in the channel by total internal reflection. The cavity mirrors and output couplers arise by coating the cleaved facets at the end of the chip, to increase or decrease the facet reflectivity. So a tiny semiconductor laser cavity inside the chip with a typical linewidth $\delta\nu \approx 50\,\mathrm{MHz}$ is developed. A population inversion can be achieved by applying a current. But at low levels of current the optical losses are higher than the gain so a population inversion is not achieved and the laser diode emits a broad-band light through spontaneous emission like a LED. To obtain a coherent laser beam the current must be above a threshold current, where the gain is higher than the optical losses, so a population inversion is created. Furthermore the laser intensity increases linearly with injection current. The output beam of the chip is elliptical and strongly diverging therefore a collimating lens is necessary. There are still two problems to solve. First the diode laser is very sensitive to optical feedback. Already 10^{-6} of the output light affects the stability of the frequency when scattered back into the laser cavity. Therefore a diffraction grating is installed which is shown in figure 7.

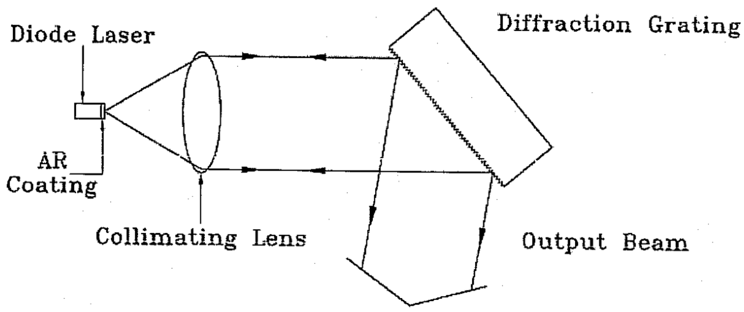


Figure 7: Schematic layout of a diode laser with collimating lens and diffraction grating.[4]

The diffraction grating ensures that a majority part of the light that is scattered back into the laser cavity is from the first order diffraction of the grating. This leads to a frequency-stabilized laser beam, because only certain wavelengths, depending on the position of the grating, scatter back in the cavity. Most part of the light scatters in the 0. order(the output beam), but 15 % scatters back into the cavity, which is enough to cause the stabilisation. Furthermore the grating and the highly reflective end of the chip form a further laser cavity, the so called external cavity. Hence the diffraction grating fortunately solves the second problem, which is the large linewidth of the bare diode laser($\Delta\nu \approx 50\,\mathrm{MHz}$) compared to the linewidth of atomic transitions (here $\Gamma \approx 5\,\mathrm{MHz}$). The external cavity reduces the linewidth namely to $\Delta\nu < 1\,\mathrm{MHz}$. All in all the diffraction grating functions as a controlled feedback for frequency stability and to reduce the linewidth of the laser.

1.4 Laser gain contributions

To observe atomic transitions, precise control of the developed frequency is necessary. In theory the laser operates at the mode with the highest net gain and other modes do not occur. However in reality it is possible, that multiple modes occur, leading to a spectrum of multiple frequencies. In the following the focus will lay on single mode operation, since this is the desired case for the experiment.

As shown in figure 8 the main contributions to the **net gain** can be reduced to the **medium**, **internal cavity**, **grating feedback** and **external cavity**. The best case scenario, in which all gain functions peak at the same wavelength, is displayed in figure 9 In the following the four contributions will be explained seperately.

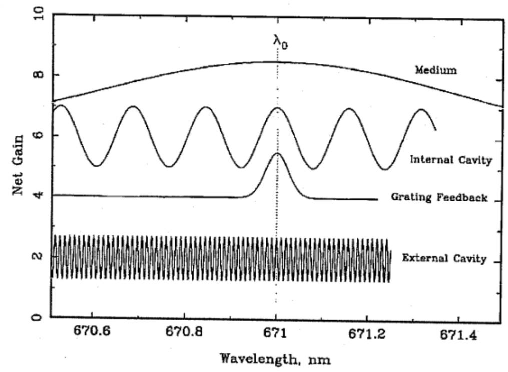


Figure 8: Overview for the contributions to the net gain as function of wavelength.[4]

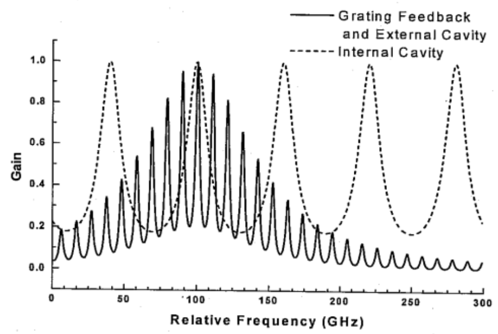


Figure 9: Overview for the contributions to the net gain as function of wavelength in the ideal case.[4]

Medium gain The medium gain as function of frequency(or wavelength) has the shape of a broad peak and is determined by the band gap of the laser's semiconductor material. The band gap depends on the temperature at which the laser is used. If the temperature is increased, the band gap decreases. Hence the temperature changes the peak's position.

The relation between output wavelength and temperature is graphically shown in figure 12 for multiple modes.

Internal cavity As described in 1.3 the diode junction itself acts as a laser cavity, that is referred to as the **internal cavity**. The associated contribution to the gain is periodically dependent on the frequency or the wavelength respectively. The **FSR** is about $\Delta\nu_{\text{FSR}} = 60\,\text{GHz}$ (or $\Delta\lambda = 0{,}122\,\text{nm}$ respectively). Since the laser's output wavelength shows a linear temperature dependency(see figure 12), the gain function for the internal cavity is moved in frequency/wavelength. A change in temperature is for example evoked by the diode current, that will increase the temperature faster($\sim 1\,\mu\text{s}$), as if the laser is heated externally($\sim 10\,\text{s}$). Besides heating the laser, the diode current changes the optical path length in the diode junction, by manipulating the concentration of charge carriers. Due to this the frequency is increased at a rate of approximately 200 MHz/mA, until it reaches its maximum at around $\sim$ (1 GHz). This effect is illustrated by figure 10.

Since the gain function of the laser medium and the gain function of the internal cavity are not moved in the same way by a change in temperature, a problem named **mode hops** can occur. This is the case, when the laser's mode changes, because the overall gain maximum switches from one peak of the internal cavity gain function (see figure 8) to another.

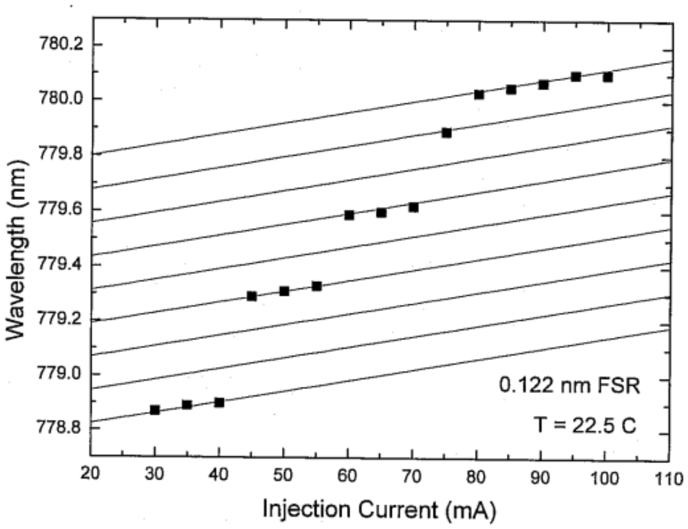


Figure 10: Relation between injection current and laser wavelength for the internal cavity.[4]

Grating feedback With the diffraction grating, light with a specific wavelength can be scattered back into the laser. This allows one to precisely influence the gain function. By modifying the left/right angle it is possible to choose which wavelengths are scattered back. Modifying the up/down angle, changes the direction of the light, that is scattered back from the grating. In this case the grating should be configured in a way, that mostly light from the first order is send back into the internal cavity. Figure 8 displays the small wavelength-band that can be chosen with the grating feedback. Hence "mode hopping" can occur, when the configuration of the grating is changed. This is illustrated in figure 11.

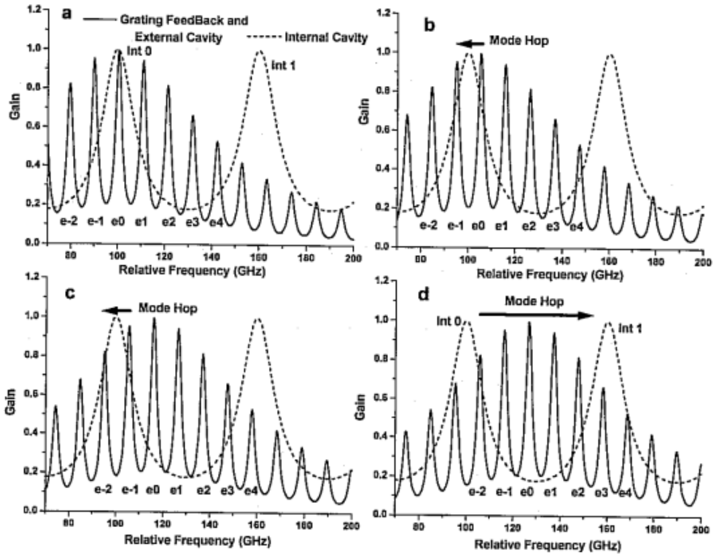


Figure 11: Illustration of mode hopping, due to change in grating feedback and external cavity.[4]

External cavity The grating and the reflective back of the diode form another cavity. It is reffered to as the **external cavity**. The external cavity posseses a by far greater length then the internal one, which results in a smaller FSR of $\sim 10\,\mathrm{GHz}$(in the case of $L = 15\,\mathrm{mm}$). If the laser itself is not moved, the gain function contribution of the external is only shifted if the grating is moved. In the experiment the grating's position is periodically changed by a **piezo element**. Another way is changing the left/right angle of the grating.

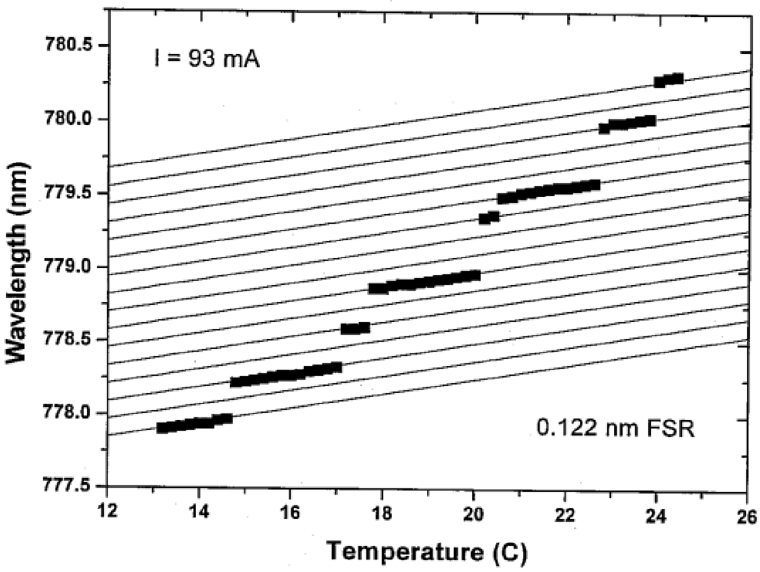


Figure 12: Relation between wavelength and diode current for different laser modes at a constant temperature.

1.5 Rubidium absorption spectrum

When light radiates through a material and is observed afterwards, specific frequencies will have a significantly lower intensity then before. This happens because certain transitions from one electron state to higher one need a certain amount of energy, which can be delivered by the absorption of light of a certain frequency. However these excited states are usually not stable and the electrons will drop to their origin states. Due to this, the before absorbed energy will be emitted, in the form of light of a certain frequency, into all directions equally. Hence those frequencies, that are associated with the energy difference between the electron states, have a reduced intensity when measured afterwards. This process leads to a characteristic absorption spectrum for every element. For example the rubidium isotopes Rb^{87} and Rb^{85}, which are examined in this experiment, lead to the spectrum shown in figure 13.

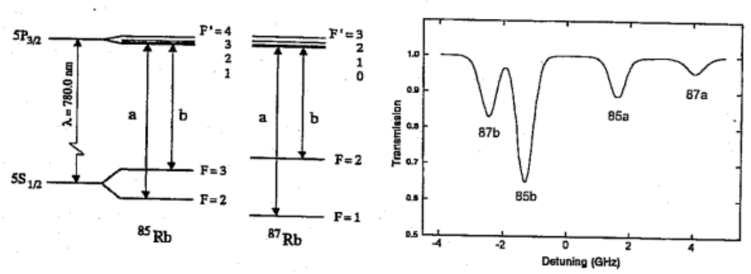


Figure 13: Expected absorption spectrum of Rb^{87} and Rb^{85}.[4]

1.6 Piezo effect

In this experiment, a so called **piezo-element** is used to move the diffraction grating, periodically with a high frequency. As indicated by the name this device utilizes the (inverse)**piezo-electrical effect**. The direct piezo-electrical effect describes the occurance of an electric potential, when a crystal(or another solid material) is deformed. The inverse piezo-electrical effect describes the reverse process. If an electrical potential is applied to a crystal, it will deform. The latter process obviously can be used to achieve the desired effect.

2 Setup and Procedure

To observe and record the rubidium absorption spectrum at the end of the experiment several premeasurements with different setups are necessary. A dark room is recommended to minimize the interfering light sources. The used diode laser has two knobs to control the alignment of grating as shown in figure 14. For the horizontal alignment the side knob is turned. The top knob changes the vertical alignment.

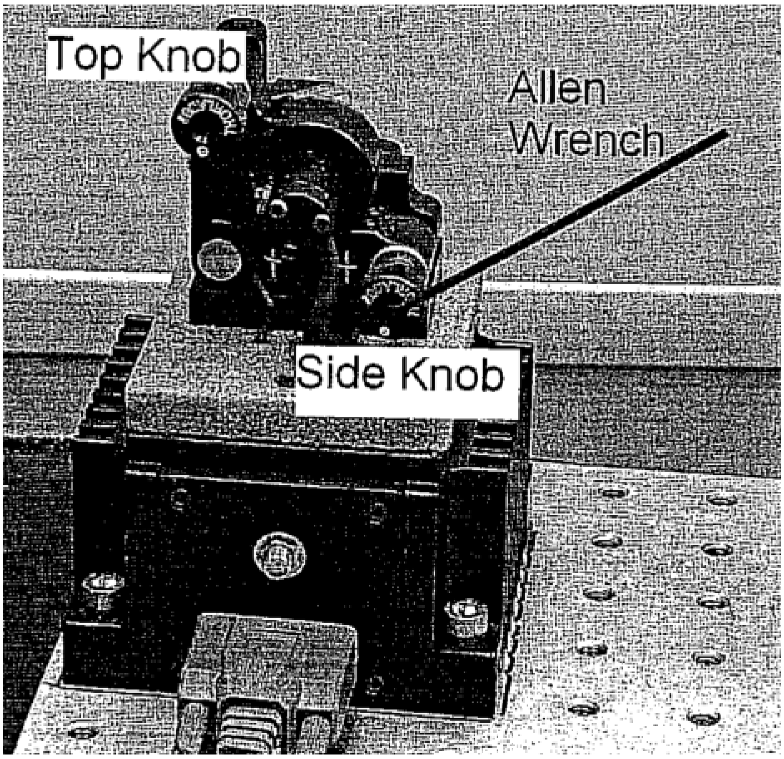


Figure 14: Top knob and side knob of the diode laser to align the grating.[4]

2.1 LED to Laser diode

The first step is to determine the threshold current of the diode laser. Therefore an index card is placed in front of the laser beam and the CCD Camera is focused on the point where the card intercepts the beam. The setup is displayed in figure 15.

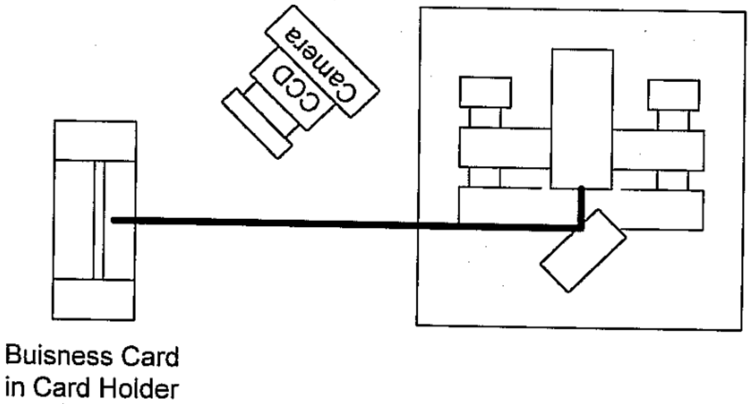


Figure 15: Schematic setup to observe the threshold current of the diode laser.[4]

By increasing the current, starting at zero, the transition from a normal LED to a laser diode is observed. The threshold current is at the transition point where the light spot becomes significantly brighter. Furthermore by adjusting the top knob the threshold current can be lowered.

2.2 Rubidium fluorescence

After the lowest possible threshold current is determined, the index card is removed and the rubidium absorption cell is placed in the laser beam instead. A schematic setup is shown in figure 16. Additionally the diode laser's ramp generator and piezo controller is wired as shown in figure 17. The camera is now focused on the absorption cell and the diode is set to operate above the threshold current.

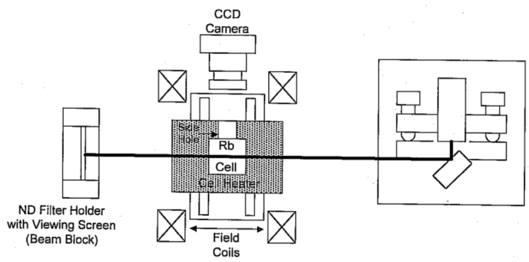


Figure 16: Schematic setup to observe the Rubidium fluorescence.[4]

By adjusting the side knob and the current, the fluorescence of Rubidium atoms in the absorption cell can be observed as a flashing along the laserbeam.

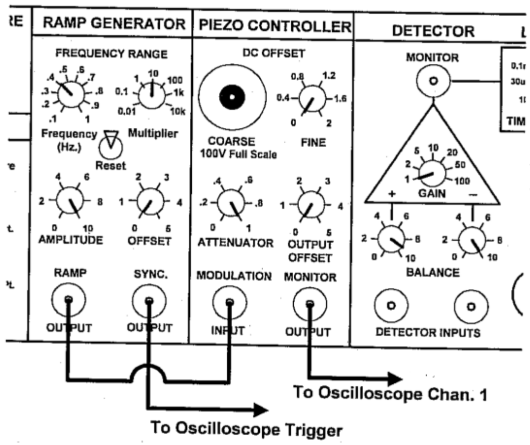


Figure 17: Wiring of the piezo controlelement to observe the Rubidium fluorescence.[4]

2.3 Rubidium absorption spectrum

Besides the observation with the camera a photodiode, which measures the intensity of the outgoing laser beam, is installed behind the absorption cell and connected to an oscilloscope to see some fraction of the rubidium absorption spectrum .

To achieve the visualization of the full rubidium spectrum simultaneous current and piezo modulation is necessary. Therefore the ramp generator output is connected also to the current modulation input. With some adjustments of the current and the side knob a full trance over the rubidium is displayed at the oscilloscope.

A second method to obtain the absorption spectrum is as follows. The setup of the other method is shown in figure 18. Additionally, to the setup before a beam splitter is added between diode laser and rubidium cell. A second photodiode is installed in the splitted laser beam of the beam splitter in order to obtain a signal without the rubidium absorption spectrum. The different signals of the two photodiodes are sent to the laser controller as shown in figure 19. Since output of the operational amplifier is the difference between the two signals, only the rubidium absorption and not the signal of the ramp generator is displayed with the oscilloscope.

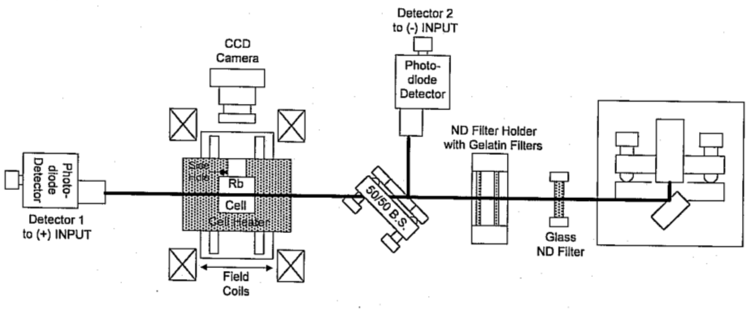


Figure 18: Another schematic setup to observe the Rubidium absorption spectrum.[4]

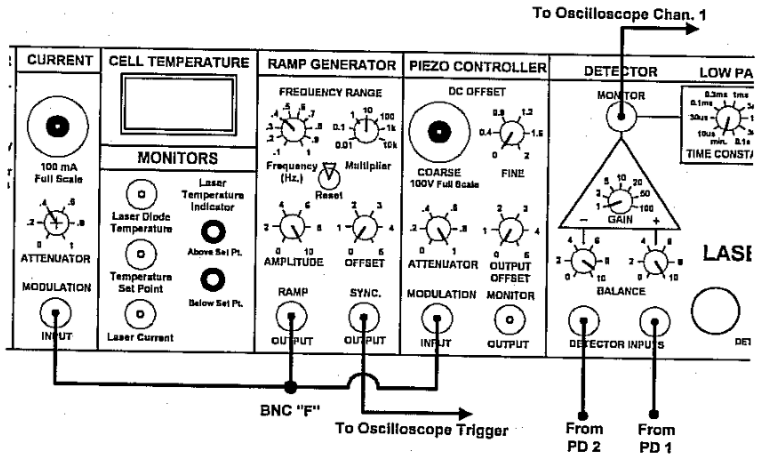


Figure 19: Wiring of the control element to observe the Rubidium fluorescence.[4]

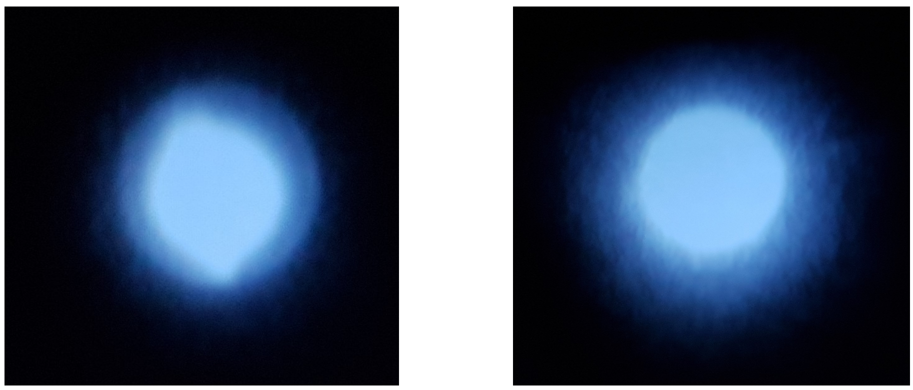
3 Analysis of the Experiment

3.1 LED to Laserdiode

First a threshold current of

$$I_{\text{threshold}} = 33{,}7\,\text{mA} \tag{3}$$

is measured. Furthermore in figure 20 the two pictures from the camera focusing on the card are shown. With the difference, that on one picture the current of the diode is below threshold 20a and on the other it is above threshold 20b. The intensity change of the



(a) LED **(b)** LASER

Figure 20: The light below 20a and above 20b the current threshold.

diode beam is clearly recognizable between the lower intensity LED radiation 20a and the higher LASER radiation20b.

3.2 Rubidium fluorescence

It follows the results for the setup 16. First with the rubidium absorption cell located in the laser beam and the current adjusted, so rubidium fluorescence is observed. The picture of the camera, which is targeted at the rubidium absorption cell, is displayed in the figure 21.

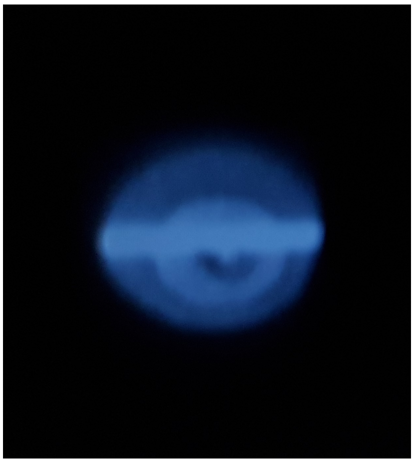


Figure 21: Observation of the rubidium fluorescence.

Rubidium fluorescence is only observed along the laser beam, therefore the brighter horizontal line in figure 21 is the track of the laser beam going through the rubidium cell and stimulating the rubidium atoms.

3.3 Rubidium absorption spectrum

Now with the active ramp generator moving the grating with the piezo stack, the signal from the photodiode behind the rubidium cell is displayed with an oscilloscope and shown in figure 22. Also the signal of the ramp generator is shown in the same figure.

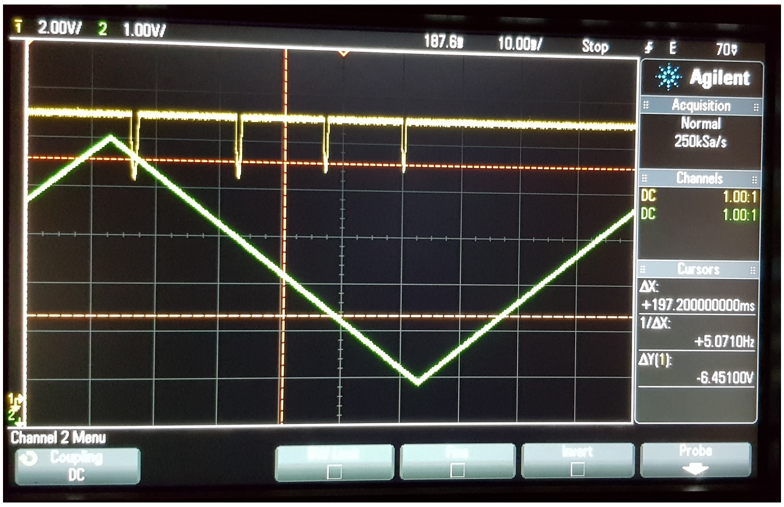


Figure 22: Signal from the photodiode and the ramp generator.

The figure 22 contains a part of the absorption spectrum as required. Due to a problem with the storage device, the pictures of the remaining measurements, where only one photodiode is used, are lost. Nevertheless an image of the hole rubidium spectrum with a simultaneous current and piezo modulation can be produced. To get an impression of the possible image, in figure 23 an example is displayed.

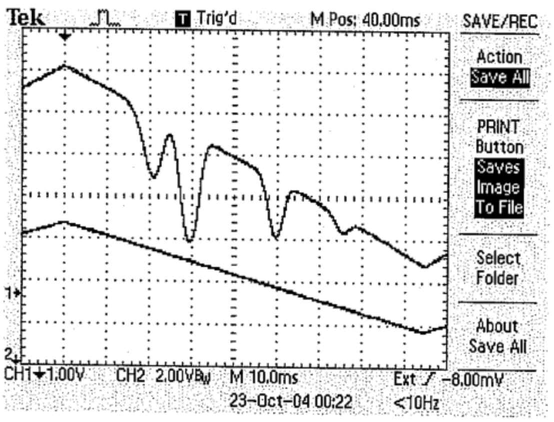


Figure 23: Signal from the photodiode and the ramp generator with simultaneous current and piezo modulation. [4]

Fortunately an oscilloscope image of the second measurement with two Photodiodes is available and displayed in figure 24.

Figure 24: Mixed signal from the two photodiodes and active ramp generator with simultaneous current and piezo modulation.

In contrast to the signal in figure 23 the signal in figure 24 the ramp generator signal is not contained in the mix signal anymore.

4 Discussion

A general difficulty is the precise adjustment of the diode laser's parameters for example grating orientation and the diode current. As described in 3.1 the transition from LED to a laser diode can be successfully observed at a threshold current of 33,7 mA. The precision of the threshold current significant dependents on experimenter subjective perception of the laser's brightness and the ability to fine tune the laser with the different knobs. Furthermore, the rubidium fluorescence can be observed as expected (see 21). Due to the unfortunate data loss, there is no evidence of the successful observation of the full rubidium absorption spectrum with the first method. On the contrary the result of the second method is recorded properly and shows a full trace over the rubidium absorption spectrum. This shows that a diode laser can be adjusted to sweep over a frequency band without mode hops by changing the current and the length of the external cavity. Hence, it is possible to observe an absorption spectrum over an extended range.

References

[1] Jan. 2019. URL: `https://en.wikipedia.org/wiki/P%E2%80%93n_junction`.

[2] Jan. 2019. URL: `https://learn.sparkfun.com/tutorials/diodes/real-diode-characteristics`.

[3] Physikalisches Praktikum - TU Dortmund. *Der HeNe-Laser*. Jan. 2019.

[4] Physikalisches Praktikum - TU Dortmund. *Diode Laser Physics*. Jan. 2019.