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Diode Laser

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Correction

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Contents

The aim of this experiment is understanding and getting used to the handling of diode lasers by assembling a suitable experimental setup to observe the absorption lines of rubidium gas.
The following outline is closely related to the lab instructions of the experiment (see [1]).

1 Introduction to diode lasers

Laser is a shortcut of light amplification by stimulated emission of radiation. Its technical invention leads back to 1960 when Theodor Maiman developed a ruby laser [2]. Since that time lasers and related techniques have been constantly improved and still are subject of state-of-the-art research as recently acknowledged by with Nobel Prize in Physics 2018 awarded for groundbreaking inventions in the field of laser physics [3].
In the following, we discuss the crucial properties of laser light, the essential components of a laser, the basic functionality of a diode, and the diode laser as a specific example.

1.1 Laser

This section treats the operating principle of a laser. More specifically, the underlying atomic processes, the defining property coherence, as well as the essential components.

1.1.1 Relaxation proocesses

Different processes occur when an excited system returns into its ground stated. Here, a pumping process excites the electrons into an energy state above the ground state. By relaxing back to the ground state, the electrons release energy emitting either a phonon (heat) or a photon (light).The radiative relaxation can either be spontaneous or stimulated. Stimulated emissions requires photons with energy roughly equivalent to the energy difference E_{AB}between the electron's excited state A and any energy state below B (not necessarily the ground state). The photon can cause the electron to relax into state B and emit a second photon with energy E_{AB}. The result are two photons of roughly the same wavelength and the same phase or, in other words, coherent light.
Condensed, stimulated emission produces the characteristic coherent light of a laser. The following section defines coherence more precisely.

1.1.2 Coherence

We distinguish two types of coherence:
First order coherence requires well defined wavelength and phase. For this kind of light, interference can be observed and used as an indicator for the quality of the coherence. Stimulated emission, as described above, results in first order coherent light. However, first order coherence can be achieved by filtering any light if high losses due to the filtering process are acceptable [4].

Second order coherence means that the emission of photons happens independently of time and regardless of whether another photon has just been emitted or not. This property is described by the correlation function $g^{(2)}(\tau)$. Light emitted by a laser is coherent in terms of second order coherence and $g^{(2)}(\tau) = 1$ [4].

1.1.3 Essential components

Any laser consists of four essential components: A pump source, an active medium, one or several cavities, and a chiller.

The **pump source** forces the active medium to be excited.
Without pumping, the electron population in the ground state is described by the Fermi-Dirac distribution

$$f(E) = \frac{1}{\mathrm{e}^{(E-\mu)/k_B T} + 1}$$

with the energy of the electron E, the temperature T, the chemical potential μ, and the Boltzmann-constant k_B. In the high energy limit, this becomes $1/2$ resulting in equally populated ground and excited state. But to promote stimulated emissions, population inversion is necessary. However due to thermodynamic reasons, population inversion can never be achieved in a two level system.
Figure 1 shows a three level system with pump source. Electrons are excited to level 3 by the pump source. They quickly relax into level 2 and 1 but slowly from 2 to 1. As the pump source constantly "empties" level 1, there is going to be a population inversion between level 1 and 2.

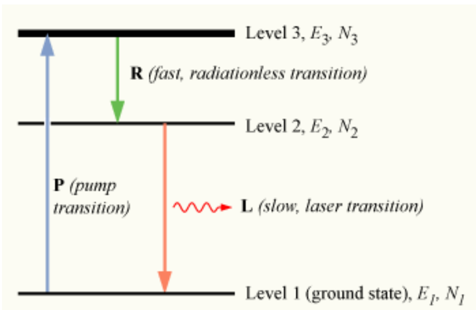


Figure 1: Population inversion between level 1 and 2 in a three level system with pump source.

Population inversion can also be achieved in systems with more energy levels or by using different techniques. Pump sources may be electrical currents, light sources like other lasers, or even chemical reactions.

The **active medium** is a medium with a well defined energy gap between ground state and excited state. This energy gap determines the wavelength of the emitted light. However, transitions with different energies are possible (if different transitions occur in the active medium and due to statistical variations of the bad gap) and may be selected by the cavity.

The **cavity** amplifies light of certain wavelengths. It consists of two mirrors facing each other and enclosing the active medium creating standing waves of the photons emitted in the medium. The distance L between the mirrors defines the amplified wavelength λ or frequency ν in a medium with a refraction index n:

$$\lambda = \frac{2Ln}{m} \quad \text{and} \quad \nu = \frac{cm}{2Ln} \ , \quad m \in \mathbb{N} \ , \quad c: \ \text{speed of light} \ .$$

The amplified frequencies are equally spaced with a distance

$$\Delta\nu = \frac{c}{2Ln} \ . \tag{1}$$

For $\nu >> \Delta\nu$, the relative frequency is proportional to the relative wavelength

$$\Delta\lambda = \lambda_2 - \lambda_1 = c\left(\frac{1}{\nu_1} - \frac{1}{\nu_2}\right) \approx \frac{c}{\nu^2}\Delta\nu \ . \tag{2}$$

One of the mirrors must be partially transparent allowing the laser beam to leave the active medium.

The gain due to stimulated emission must prevail the losses due to leaving light and non-light-emitting relaxation processes that produce heat. To keep the temperature of the active medium constant regardless to the produced heat a **chiller** is needed.

1.2 Diode

Diodes are semiconductor devices with a characteristic nonlinear current-voltage relation. Even though there are numerous types of diodes, we shall only refer to bipolar diodes in the following.
Bipolar diodes contain two differently doped materials. The transition between them determines the current-voltage-characteristic and is called pn-junction.

1.2.1 pn-junction

In general, semiconductors describe materials with completely filled valence band and empty conduction band. In contrast to isolators the energy gap between conduction and valence band is sufficiently small to allow transitions at finite temperature. Semiconductor materials have four valence electrons. They can be doped which means that additional atoms with another number of valence electrons are injected into the material. N-doped materials contain donors with additional electrons and p-doped materials acceptors with additional holes. In a bipolar diode a n-doped material is in contact with a p-doted one. This contact is called pn-junction.

In the surrounding of the pn-junction, electrons and holes recombine resulting in a diffusion current of electrons coming from the n-side and holes coming from the p-side. Due to the recombination positively charged ionized ions N_D^+ remain in the n-side whereas negatively charged ionized ions N_A^- remain in the p-side causing an electric force opposing the force of diffusion. An equilibrium between the resultant electric force and the force of diffusion is established. At the equilibrium the Fermi energy is constant. This and other effects are exemplarily illustrated in figure 2 for silicon. Subfigure (a) displays the spacial distribution of the p-, N_A^--, N_D^+-, and n-side. Recombination takes place in the area shaded in grey, also called **depletion layer**. Subfigure (b) emphasizes the **potential difference** V_{bi} between p- and n-side caused by different energy levels of valence and conduction band in the differently doped materials shown in (c). Subfigure (d) illustrates the strength of the electrical field within the depletion layer. Finally, subfigures (e) and (f) focus on the charge carrier concentration in the different regions. Right in the middle of the depletion layer, there are just as many electrons as holes (e) but the sum of free-carrier densities drops significantly (f). This is an important feature since it influences the current-voltage-characteristic.

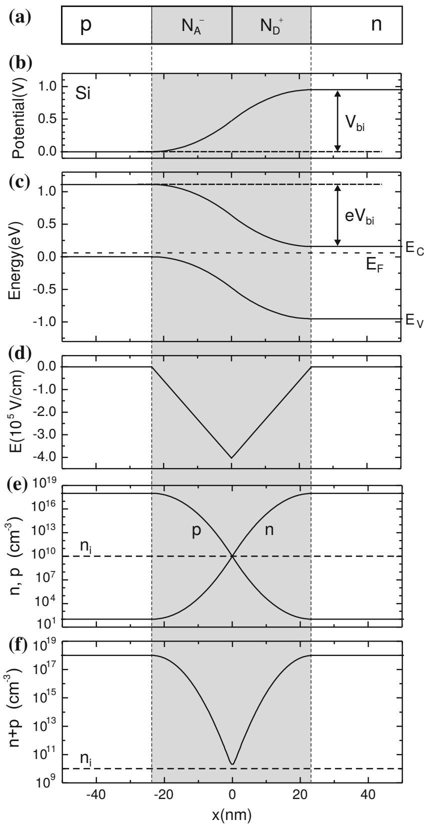


Figure 2: Properties at the pn-junction in doped silicon with zero bias. [5]

An external voltage as well as the temperature change the equilibrium behaviour. An external voltage can either inject holes in the p-type material and electrons in the n-type material (**forward bias**, $V > 0$) or act the other way around (**reverse bias**, $V < 0$). The width of the depletion layer w shrinks for forward bias voltage and enlarges for increasing temperature T [5]

$$w \sim \sqrt{1 - \frac{V}{V_{\text{bi}} - 2\frac{k_B T}{e}}}$$

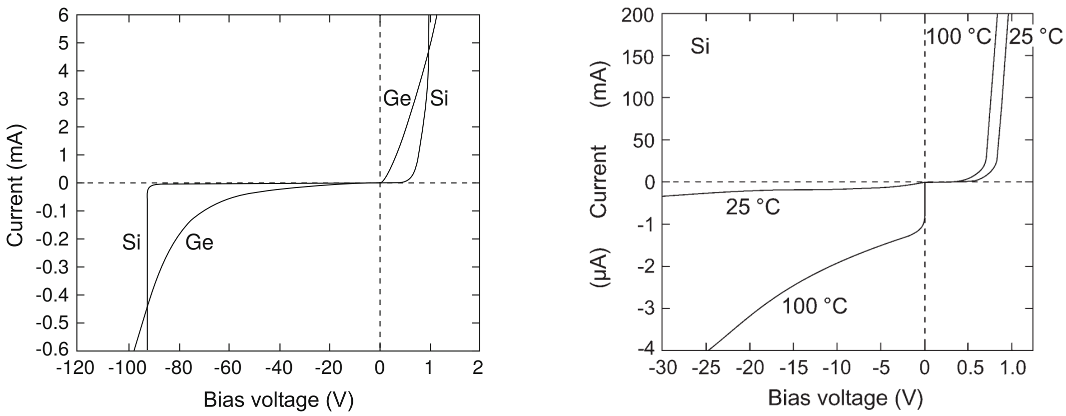
with the build-in potential V_{bi} in the depletion layer and the Boltzmann constant k_B. The the radiative recombination current, which is important for the usage as light emitter, behaves contradictory. It grows with forward bias voltage and shrinks at higher temperatures [5]

$$j_{\text{rad}} \sim \left(\exp\left(V \frac{e}{k_B T} \right) - 1 \right) .$$

The influence of the external voltage on the current is described in the following section.

1.2.2 Current-voltage-characteristic

The current-voltage-characteristic of bipolar diodes varies dependent on the material and temperature of the diode as shown in figure 3.



(a) Material dependence **(b)** Temperature dependence

Figure 3: Current-voltage-characteristic of a bipolar diode. [5]

However, there are some similarities. For a forward bias external voltage, the current increases exponentially. For a reverse bias voltage, only a small and constant leakage current exists until the voltage gets high enough for a breakdown. In general, the current is determined by the minority carriers which are holes in the n-side and electrons in the p-side.
For **forward bias** voltage, electrons are injected into the n-side. A field parallel to the electric field in the depletion layer arises and the depletion layer narrows. The energy step between the band edges is lowered. A diffusion current of holes from the p-side to the n-side and for electrons vice-versa takes place.
For **reverse bias** voltage, additional holes are injected into the n-side and the electrical field in the depletion layer is weekend by the external field. The depletion layer broadens and the region with less free-carriers dominates the pn-junction. Due to the lack of free-cariers an electrical current through the pn-junction gets impossible, except a low current caused by thermal fluctuations.
A diode laser consists of a bipolar diode with forward bias voltage and uses radiative recombination of electrons and holes as transition from excited state to ground state.

1.3 Diode laser

Diode lasers in general consist of the essential components discussed in section 1.1.3.

The active medium is a semiconductor heterostructure containing pn-junctions. The wavelength of the laser is determined by the band gap between the recombining electrons and holes.

The pump source is an electrical current which induces electrons and holes and leads to a population inversion of holes and electrons as shown in figure 4.

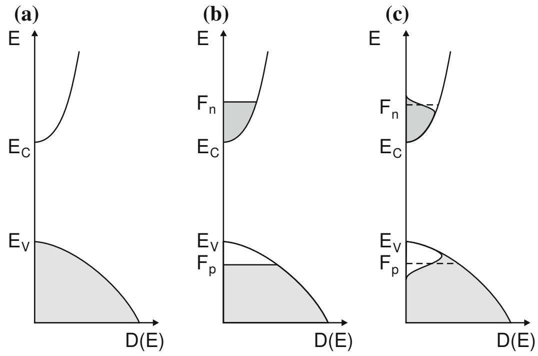


Figure 4: Electron population of the valence and conduction band for zero current and zero temperature (a), current above threshold with zero temperature (b) and finite temperature (c). [6]

The semiconductor heterostructure itself forms a cavity and additionally serves as an optical waveguide due to its reflective index as illustrated in figure 5.The emitted beam leaves the chip on two opposite sites and is elliptically shaped.One of the beams is the laser beam itself and the other can be used to measure the beam's intensity. An additional external cavity is used to stabilize the frequency as explained in section 2.1.

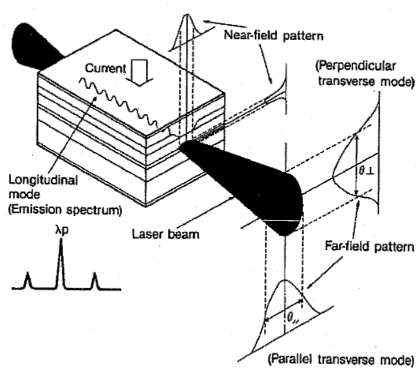


Figure 5: Schematic picture of the semiconductor heterostructure and the emitted beam shape.[1]

For low currents the overall losses in the medium and at the mirrors are too large to generate a coherent beam. Also, spontaneous emissions dominate the radiative recombination and broad-band light is emitted. The diode is now a light emitting diode, usually referred to as LED and commonly used in every day life. Above the threshold current I_T, spontaneous emissions dominate meaning the laser is lasing. When passing the threshold current from lower to higher, a drastic increase in emitted power is visible as documented in figure 6.

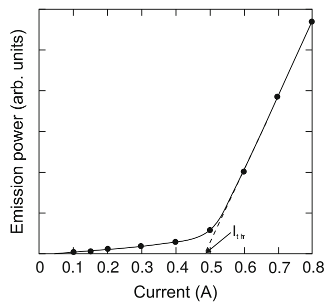


Figure 6: Emission power below and above the current threshold of a diode laser. [6]

Generally, diode lasers offer several advantages: they are tunable with narrow-bandwidth, inexpensive, efficient, and easy to operate. However, the bandwidth and the sensitivity to optical feedback must be improved for example by an external cavity and controlled optical feedback as described in the following chapter.

2 TeachSpin diode laser

The TheachSpin diode laser (Sanyo DL-2140-201S) operates at a wavelength around $\lambda \approx 785\,\text{nm}$ with a maximum output power of $70\,\text{mW}$.

2.1 Operating wavelength

The wavelength of the emitted light depends on the interplay of several components: the active medium, the internal cavity, the grating feedback, and the external cavity as shown in figure 7. All components are described in detail in the following. In general, the laser favours the wavelength with the largest overall optical net gain.

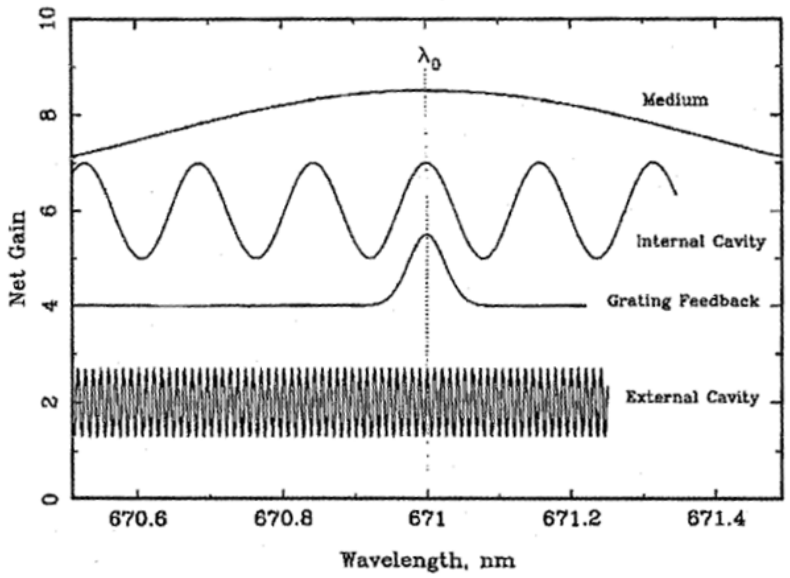
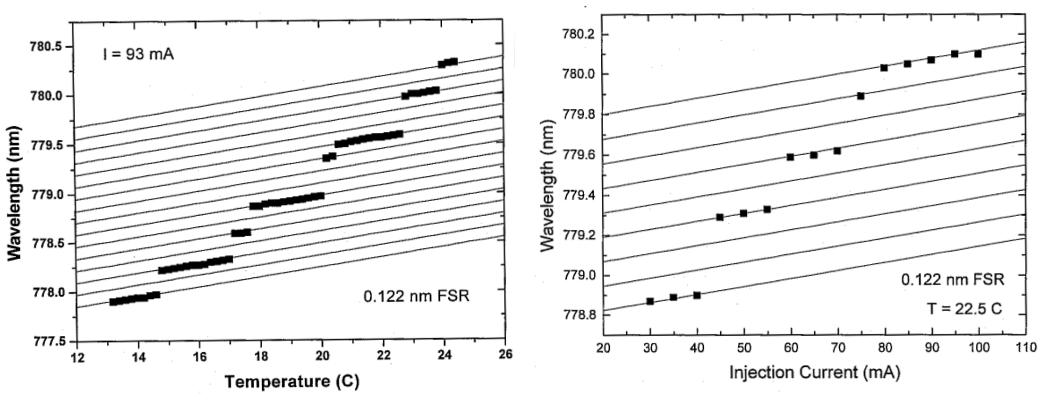


Figure 7: Optical net gain of the separate contributing components.[1]

The contribution of the active **medium** is quite broad and depends strongly on the temperature of the active medium. Through heating of the diode laser the wavelength of maximum gain in the active medium λ_0 can be shifted as shown in figure 8a. At higher temperatures the band gap shrinks for many semiconductors. Thus, the wavelength enlarges as described by the Varshni formula [7]. Furthermore, a modification of the laser current changes λ_0 due to heating by $2\,\text{GHz/mA}$ and due to changes in carrier concentration by $200\,\text{MHz/mA}$ as shown in figure 8b. The discrete lines in both figures refer to wavelengths supported by the internal cavity.

The **internal cavity** has a fixed length ($L \approx 700\,\mu\text{m}$) and refraction index ($n \approx 3.6$). Therefore, the difference between two supported wavelengths is approximately $\Delta\lambda \approx 0.122\,\text{nm}$ which corresponds to $\Delta\nu \approx 60\,\text{GHz}$ according to equation (1) and (2).

Grating feedback is reflection of the emitted light at a diffraction grating as shown in figure 9. The diffraction grating reflects about $15\,\%$ of the incoming light directly



(a) Temperature dependence **(b)** Current dependence

Figure 8: Supported wavelength λ_0 of the medium and the internal cavity.[1]

back into the laser. The angle of the grating is chosen in a way that the first order maximum of the interference pattern is reflected. This suppresses other optical feedback such as stray light and thus makes the laser less sensitive to undesired optical feedback. The width of the first order maximum is given by the incoming frequency and the number of slits covered by light: $\Delta\nu = \nu/N \approx 70\,\mathrm{GHz}$. The more slits are covered by light, the narrower the maximum is.

The length of the **external cavity** is varied by a piezo-electric transducer attached to the diffraction grating. According to (1) the relative frequency $\Delta\nu$ for $L \approx 15\,\mathrm{mm}$ and $n \approx 1$ is $10\,\mathrm{GHz}$.

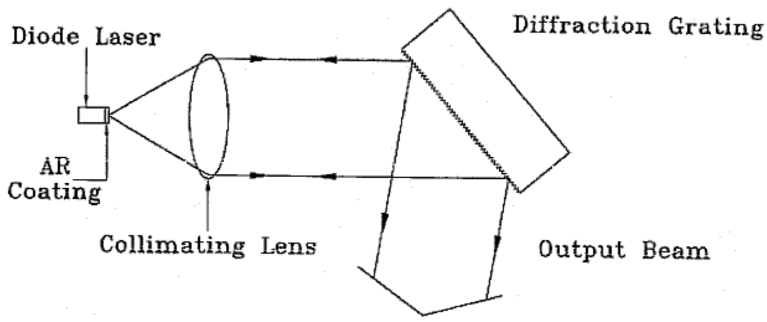


Figure 9: External cavity and diffraction grating of the diode laser.[1]

2.2 Mode hopping

The operating wavelength is determined by all factors discussed in section 2.1. Figure 10 shows the gain in the internal cavity (dashed line) and the sum of the gains due to grating feedback and external cavitiy (solid line). The gain of the medium is omitted as the width of its maximum is broad compared to the other contributions. The maxima of the internal cavity are called Int0 and Int1 and the maxima of the external cavity e0, e1, and e3.
In figure **a** Int0 and e0 are at the same frequency. This is the favoured frequency since the gains of internal and external cavity and feedback respectively are added.
Varying the length of the external cavity with the piezo-electrical transducer moves the maxima of the external cavity (solid line). Therefore, the maxima Int0 is between e0 and e-1 in **b**. No single frequency is clearly favoured anymore because adding both lines results in two similarly high peaks.
Varying the length a little more moves e-1 to the frequency of Int0 making this the favoured frequency (between figures **b** and **c**). The change in favoured modes, from e0 to e-1, is called mode hop.
By varying the length of the external cavity even further, the maxima of the external cavity (solid line) will eventually be closer to Int1. Now, the favoured frequencies are determined by the position of Int1. This is also called mode hopping.
Changing the current and the length of the external cavity simultaneously avoids mode hopping because thereby the position of the maxima of the gain in the internal cavity move at the same time as the maxima of the gain due to the external cavity.

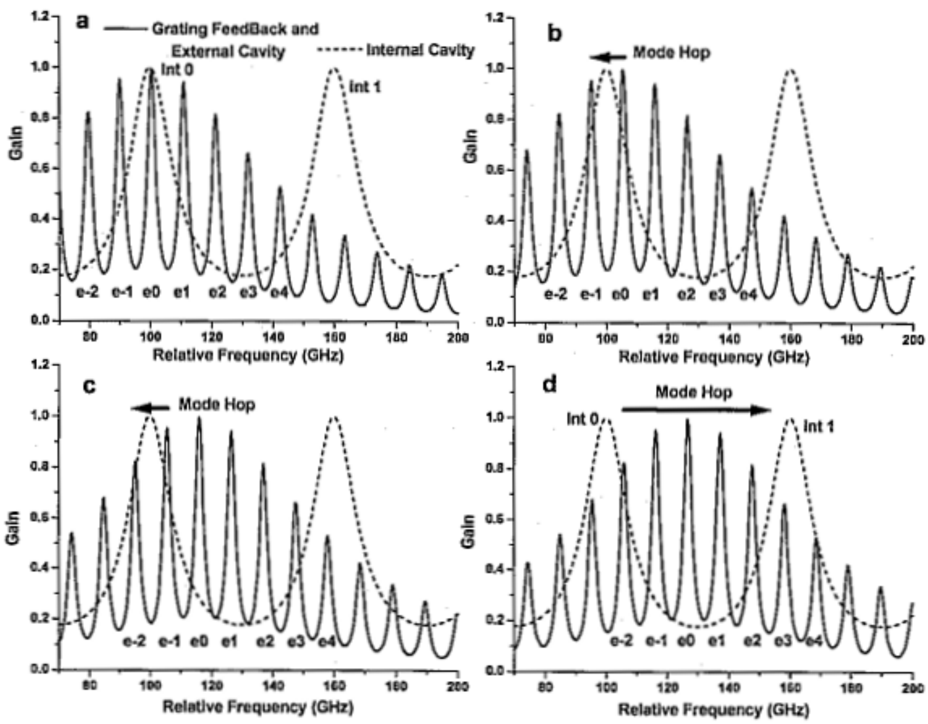


Figure 10: Illustration of mode hopping.[1]

2.3 Rubidium fluorescence

The aim of this experiment is observing the absorption lines of rubidium using fluorescence.
By exposing atoms to light, an electron on its ground energy state A can be excited to an energy state B above the ground state. Any electron from an energy level higher than the ground state A relaxes with a certain probability (relaxation time) into the now empty place on A and thereby emits a photon. If the exciting photon is in the ultraviolet regime and the emitted photon is in the visible range, this process is called fluorescence.[8]
The rubidium cell in this experiment contains the isotopes rubidium-85 and rubidium-87. Like any atom, the energy levels of both isotopes are split to the so-called hyperfine structure. Figure 11 (left) shows the split ground state $5S_{1/2}$ and a split energy state above ($5P_{3/2}$) for both isotopes. The energy difference between these two states without considering the splitting due to spin (hyperfine structure) is 0.384 GHz. As the splitting of the upper state is roughly one order of magnitude smaller than the splitting of the ground state, we only expect to see the splitting of the ground state. The absorption spectrum should therefore show four peaks (or dips resp.): 85a, 85b, 87a, 87b. Since the splitting of the rubidium-87 ground state is approximately twice as big as the the splitting of the rubidium-85 ground state, one peak of rubidium-87 should be at a lower frequency and the other one at a higher frequency than the rubidium-85 peaks (see figure 11 right).[9]

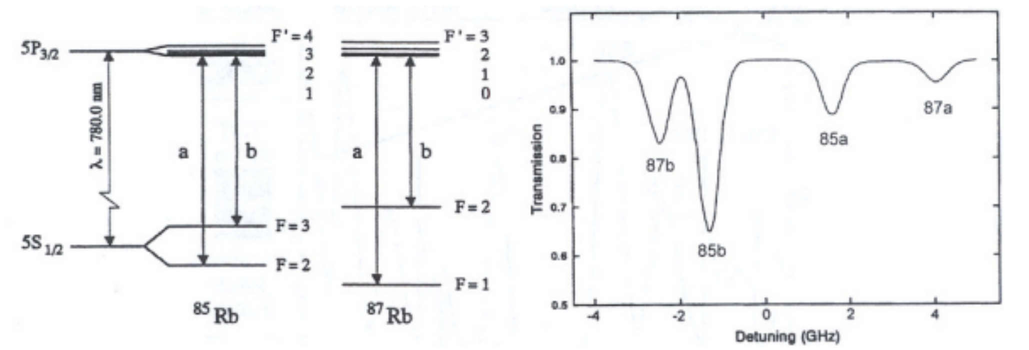


Figure 11: Rubidium levels with hyperfine structure splitting (left) and resulting absorption spectrum (right). [1]

3 Assembly of the Setup and Observations

This section explains every step during the assembly of the setup thoroughly. We choose to structure the outline into three parts: first, examine the laser properties and find the threshold current; second, make the observe the rubidium luminescence; and third, obtain a nice spectrum of the absorption lines of rubidium on the oscilloscope.

3.1 Finding the Threshold Current

As described in the theory section, the laser emits light even with very low currents. This is not laser light but non-coherent broad-band light from spontaneous emission. With the help of an IR camera, we can observe the resulting light spot on an IR card. Actually the light spot is visible by eye but the camera is much more sensitive to this wavelength region. When raising the current, the spot first only grows constantly, then suddenly brightens a lot, and afterwards grows constantly again. The sudden brightening marks the transition from purely spontaneous emission (LED) to mostly stimulated emission (laser). We measure the corresponding laser current with a multimeter. By adjusting outer cavity (top and side knob), we minimize this current.

More precisely, the favoured frequencies of the internal cavity are given by its length and refraction index. The length of the external cavity has to be adjusted to favour the same frequency. The tuning of the grating angle stabilises the lasers by reflecting said favoured frequency back into the internal cavity. Rotational adjustment of cavity length, grating angle, and laser current leads to the lowest achievable current, the threshold current, of

$$I \approx (32.85 \pm 0.25)\,\mathrm{mA}\ .$$

This value is obtained by measuring the voltage output of the photodiode just below the threshold $U_{\text{below}} = 3.26\,\mathrm{V}$ and just above $U_{\text{above}} = 3.26\,\mathrm{V}$ using a multi-meter. Knowing the resistance is $100\,\Omega$, the threshold current is calculated as mean of the value just above and below threshold. The stated uncertainty is set to cover exactly the range between I_{below} and I_{above} making sure the true value is included.
See two pictures of the camera screen at current just below the threshold and just above in figure 12. The left picture (below the threshold) shows a clearly confined spot characteristic to the spontaneous emission. The right picture (above the threshold) shows a more diffuse border due to more stray light and corresponds to laser light.

3.2 Observing the Rubidium Luminescence

To see a nice and well visible luminescence, it is necessary to turn up the laser current for a more powerful laser. We want to observe the absorption lines described in section 2.3. So, we need to adjust the laser to aproximately 780 nm by again changing the length of the external cavity and match the grating. The observed luminescence is shown in figure 13.
The rubidium gas can be saturated resulting in a less visible luminescence. Therefore an attenuator is placed between the laser and the rubidium cell.

Figure 12: Picture on the camera screen just below the threshold current (left) and just above (right).

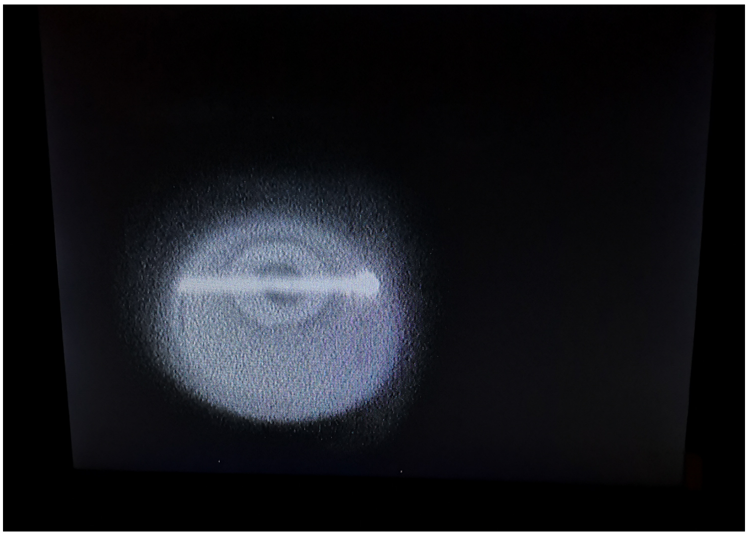


Figure 13: Laser inducing luminescence in the rubidium filled chamber. (Note: This image looks different to the ones in figure 12 because it was taken without flash. However, the same camera and display were used.)

3.3 Measuring the Spectrum on the Oscilloscope

As we want to see *all four* rubidium absorption lines described in section 2.3. Therefore, **we need different wavelengths**. This can be achieved using a piezo cristal attached to the external cavity of the laser. The volume of a piezo cristal is proportional to the voltage applied to it. Thus, by applying a varying voltage to the piezo with a ramp generator, we can change the external cavity length continuously obtaining a laser with changing wavelength. The luminescence observed by the camera and shown on the screen is now flickering because only certain wavelengths of all the ones in the tried match the rubidium absorption lines.

A photodiode is place behind the rubidium filled cell to measure the transmitted light. Giving its signal to the oscilloscope, we observe the green line in figure 14. The yellow line is the voltage applied to the piezo cristal and therefore serves as **reference to the position in the laser wavelength range**. In other words: one edge of the

yellow line represents the *expansion* of the piezo cristal leading to a *decrease* in length of the external cavity over time resulting in a *decrease* of laser wavelengths over time; the other edge represents the *shrinkage* of the piezo cristal leading to an *increase* in length of the external cavity over time resulting in an *increase* of laser wavelength over time.
During one run through the wavelengths (so, either increasing or decreasing edge of the reference signal), there are three oddly shaped peaks. Mode-hopping as described in section 2.2 (sudden change in wavelength) is the reason why the peaks are cut off in some places.

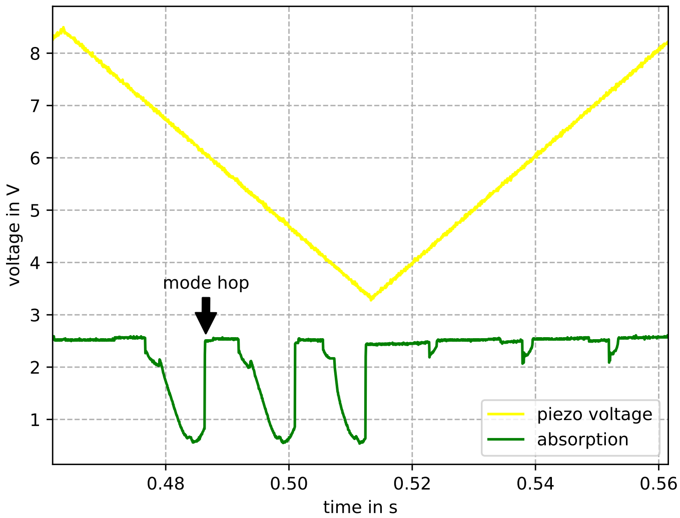


Figure 14: Absorption lines of rubidium before tuning (green) and voltage applied to the piezo (yellow).

By connecting the ramp generator not only to the piezo but also to the laser current, we simultaneously adjust the length of the external cavity (piezo) and internal cavity (laser current) and thereby avoid seeing mode hops within a broader wavelength range. The now tuned signal is shown in figure 15. We can clearly determine four peaks in each run through the wavelengths.
The group of peaks is not centered but moved to one end of the covered spectrum. This could have been adjusted by changing the range of the voltage applied to the piezo. This is a merely optical and not qualitative flaw, so we do not bother with it. Also, the "baseline" decreases and increases parallelly to the voltage applied to the piezo and the current. That is because raising the laser current raises the laser intensity.

The final step in obtaining a nice absorption spectrum on the oscilloscope is getting rid of the baseline slope. As the instructions mention this could be done by recording the absorption spectrum with and without the rubidium cell. And later digitally divide the signal with cell by the signal without the cell to lose the impact of the

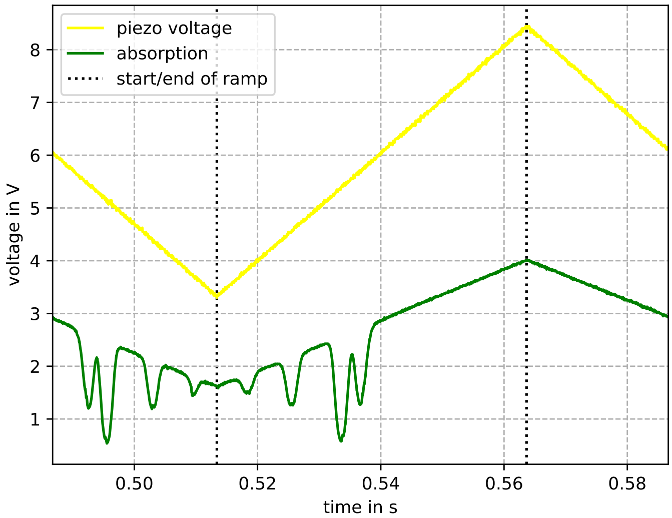


Figure 15: Absorption lines of rubidium after tuning and with simultaneous adjustment of laser current and piezo modulation (green) and voltage applied to the piezo (yellow).

change in laser intensity.
But since there are two photodiodes available we choose to use the set-up in figure 16 to do the job. Now, the laser beam is split before propagating through the rubidium cell. Thereby, we can measure the "clean" signal from the laser (Detector 2, newly inserted) and the absorption spectrum (Detector 1, same as before). By dividing the absorption spectrum by the "clean" signal, we remove the effect of the laser intensity from the absorption spectrum.

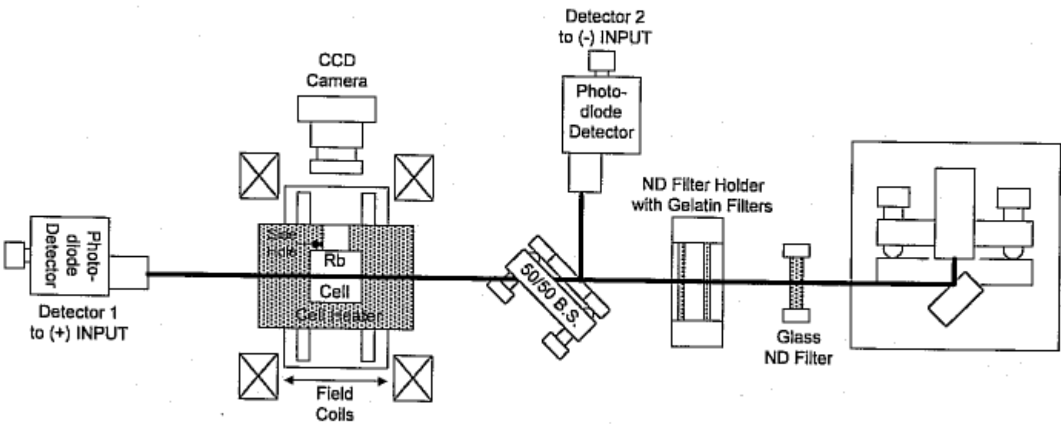


Figure 16: Altered set-up to remove the increase of laser intensity (baseline slope) in the absorption spectrum. [1]

The "division" of the signals is done measuring the difference in voltage. Figure 17 might help understanding the following explanation. PD2 is the diode detecting the "clean" signal. PD1 is the diode detecting the absorption spectrum. Both signals can be suppressed individually by the tunable knobs called *Balance*. The triangle represents the division the result thereof can be amplified using the *Gain* knob. Adjusting the *Balance* knobs, we can observe the absorption spectrum 18 as the *to oscilloscope* output. From left to right, we can identify the absorption lines 87b, 85b, 85a, and 87a. Curiously, the "baseline" is still increasing but only within the spectrum: to the left of peak 87b and right of peak 87a the baseline is constant but between the peaks it is raising.

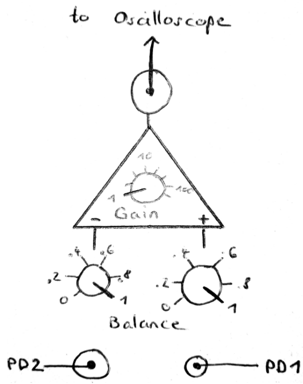


Figure 17: Division of the signals to remove the impact of the increasing laser intensity. (Self-made, inspired by [1].)

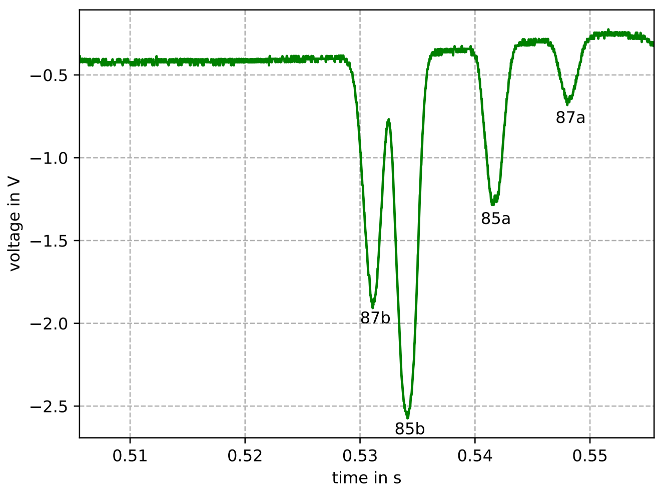


Figure 18: Final (tuned and baseline corrected) absorption spectrum of the rubidium cell.

4 Discussion

We were able to observe a nice rubidium fluorescence spectrum as shown in 18. Assembling the experimental setup, we could observe a variety of aspects crucial to lasers and diode lasers in particular.
We examined the behaviour of the laser above and below its lasing threshold which we determined to be

$$I \approx (32.85 \pm 0.25)\,\mathrm{mA}\ .$$

Adjusting the laser to the correct wavelengths, we examined the range of possible configurations of external cavity length and grating feedback. By changing the internal cavity, we observed mode hops which were eliminated by simultaneous adjustment of internal and external cavity.
Finally, we obtained the aforementioned nice spectrum by dividing the spectrum by its baseline increase.

List of Figures

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