V60 - Diodenlaser

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1 Theoretical Foundations

1.1 Aim

Within this experiment the working principle of a diode laser should be studied. In order to also get practical experience a diode laser is to be tuned to a wavelength of roughly 780 nm to observe absorption of the laser light within a ^{85}Rb-, ^{87}Rb-vapor by doing a frequency scan.

1.2 Working principle of general Lasers

The acronym 'Laser' stands for *light amplification by stimulated emission of radiation* and describes a light source, that emitts light of a fixed wavelength, which stays coherent over a long distances and is particulary suited for experiments due to its tunability. To achieve these properties a certain optical transition is stimulated and multiplied within an active medium.

To start off an external **pump** excites electrons within an **active medium** from a lower energy state to a higher unoccupied energy state, from which these electrons will relax and the spontaneous emission of a photon will take place. During spontaneous emission photons are emitted isotropically into all directions, but with the same energy, which corresponds to the energy difference between the higher and lower energy state $\Delta E = E_3 - E_2 = \frac{\mathrm{hc}}{\lambda}$. The active medium is located in a **resonator**, which reflects the photons travelling along a certain axis and makes them pass trough the active medium multiple times. While doing this they can interact with the active medium in two more ways pictured in figure 1. They can be absorbed and excite an electron to a higher energy state or induce the stimulated emission of a second coherent photon in connection to an electron relaxing in the same way, as the electron, that spontaneously emitted an photon by relaxing. Due to the boundary conditions within the resonator modes will develop and increase their intensity, as the photons of the mode will induce stimulated emission of coherent photons, which will then also contribute to the mode. In order to always have the possibility of stimulated emission a population inversion has to be created. This means that the electron density in the higher energy state is higher than in the lower energy state. To enable the possibility of inversion population one needs a system of at least three energy states. Given a system of four energy states the pump then excites electron from the ground state E_1 into the highest energy state E_4. These excited electrons then relax into the second highest energy state E_3 by a high possibility P_{43}. From there they relax into the second longest energy state E_2 by stimulated emission and afterwards into the ground state. To keep population inversion the transitions $4 \rightarrow 3$ and $2 \rightarrow 1$ have to be fast in comparison to the optical transition $3 \rightarrow 2$. This means the transition probabilities P_{43} and P_{21} have to be higher than P_{32}. Additionally the pump of electrons from E_1 to E_4 needs to compensate for the amount of relaxing electrons.

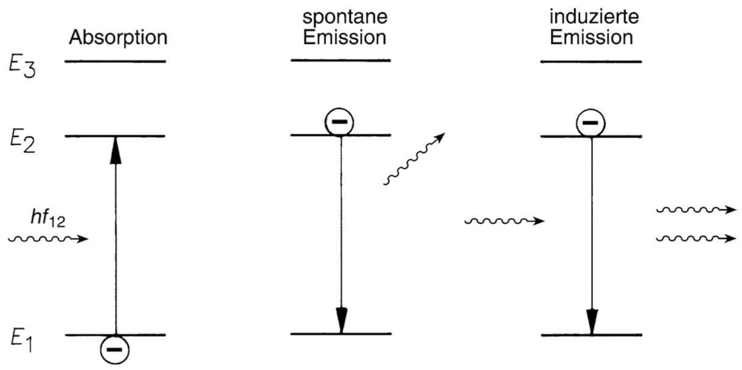


Abbildung 1: Schemes of the possible light-matter-interactions of absorption, spontaneous and stimulated (induzierte) emission. $E_{1,2,3}$ mark different atomic energy levels, h the planck contant and $f_{1,2}$ the photons frequency, which is propotional to ΔE_{12}. Taken from [1].

1.3 Diode Lasers

1.3.1 Working Principle

For diode lasers the same principles of a pump, stimulated emission within an active medium and population inversion can be applied. Additionaly some adaptions have to be done to correct for the solid state properties of the active medium, as there are now longer well defined energy states in the form of atomic orbitals. Instead the energy states now correspond to different energy bands within the solid states band structure. Every solid state body has a valence band, which is the highest occupied band below the Fermi-Energy and a conduction band, which is the lowest unoccupied energy band above the Fermi-Energy. The energy difference between these two bands is called band gap $\Delta E = E_{\mathrm{CB}} - E_{\mathrm{VB}} = \frac{\mathrm{hc}}{\lambda}$ and roughly defines the energy of a diode lasers light. In this setup a pn-junction-diode is used as the active medium. A pn-junction constists of a highly n-doted layer, which is stacked onto a highly p-doted layer. A highly n-doted layer leads to an increase of the Fermi-Energy and the insertion of electrons into the conduction band. Vice versa a highly p-doted layer leads to a lowered Fermi-Energy and the creation of holes in the valence band. These processes are depicted in figure 2.

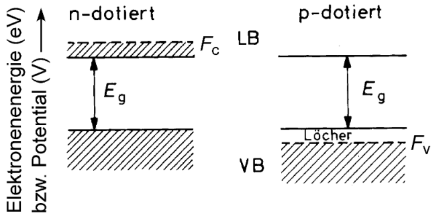


Abbildung 2: The increased Fermi-Energy within the conduction band for highly n-doted materials and the decreased Fermi-Energy within the valence band for highly p-doted materials, inserting electrons into the conduction band or creating holes in the valence band. Taken from [1].

When the two layers a brought together a pn-junction is formed, which only conducts a current into one direction, while it acts as an insulator for the other current direction. If a current is applied to the junction in the conduction direction, the holes will diffuse into the n-doted layer and the electrons into the p-doted layer. The creates the in figure 3 depicted active area of the length d, in which a population inversion is created and the electron-hole pairs recombine, emitting photons of the band-gap energy isotropically.

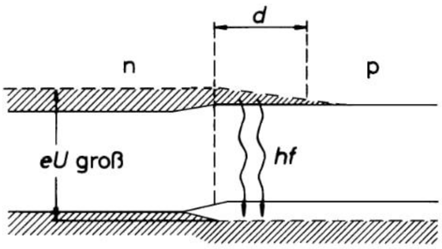


Abbildung 3: The diffusion of electrons and holes into the active layer by application of a current and the emission of photons by recombination of electron-hole-pairs. Taken from [1].

These spontaneously emitted photons are kept within the active layer as depicted in figure 4, because the refractive index of the active layer is higher than the one of the neighbouring layers and the light is thus totally reflected. The sides of the diode act as fully or partially reflecting mirrors creating an **internal resonator**, in which the reflected photons induce stimulated emission in the active layer and lay the foundation for lasing. The created light exits the diode on the partially reflecting side as a strongly diverging beam with a large bandwidth.

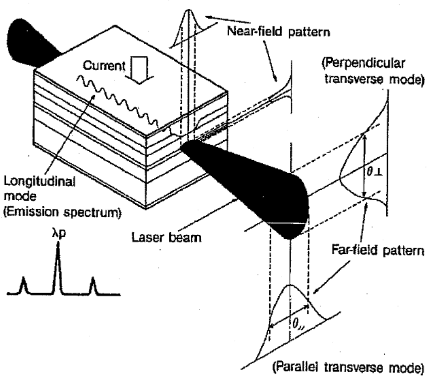


Abbildung 4: The scheme of a laser diode. The applied current enables emission of light, which is increased by stimulated emission and leads to the generation of modes. Taken from [2].

These two deficits are compensated for by the in figure 5 optical setup, that remains the laser in a so called *Littrow*-configuration and creates an additional **external resonator**. The setup constists of a lense, which collimates the light exiting the laser diode and a grating, at which the collimated beam is diffracted. This happens in a way, that the zero-order-maximum, i.e. the reflected beam, is guided out of the laser setup as the operating beam, while the first-order-maximum is diffracted back into the laser diode. Thus the new external resonator is formed between the grating and the fully reflective backend of the laser diode. The wavelength of the light diffracted back into the laser diode, has to fulfill the condition for the first-order-maximum at the given angle of the grating. The back-reflected beam helps selecting a certain wavelength in a way, that is further discussed in the section on the gain curves of a diode laser.

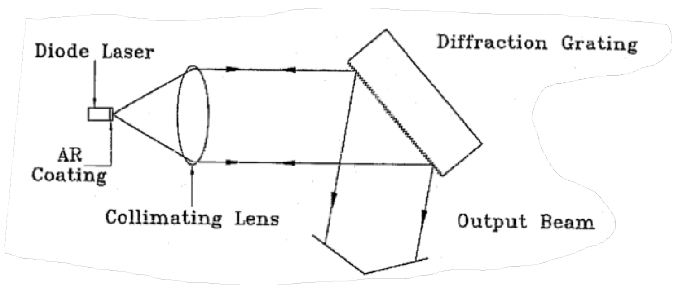


Abbildung 5: The *Littrow*-configuration constisting of a collimating lens and a diffraction grating, which enables the formation of an external resonator by reflecting the zero-order maximum out of the laser and the first-order maximum back into the laser diode. Taken from [2].

1.3.2 Gain Curves

To emit light of a well defined frequency the laser has to lase in fixed combination of a mode of the internal and one of the external resonator. Which modes will be selected, is determined by the gain curves depicted in figure 6. They show the different gains of laser intensity via different contributions against the laser wavelength. The wavelength for which the total amount of gain by all contributing factors, namely **Medium**, **Internal Cavity**, **Grating Feedback** and **External Cavity**, is the highest will be the lasing frequency and the closest internal and external modes will be the lasing modes.

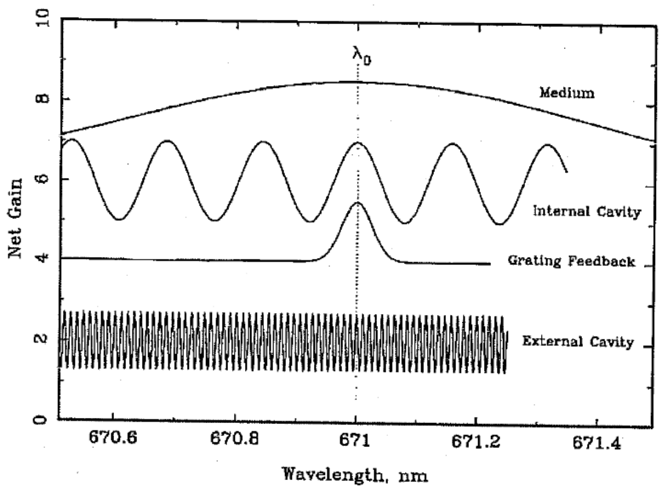


Abbildung 6: The contributing gain curves for the diode laser used in the setup. Taken from [2].

The **Medium-Gain** has a widespread peak with its maximum at the wavelength corresponding to the energy gap of the active medium. Thus the choice of the medium is the main factor governing the lasers wavelength. The position of the peak has a small dependence on the laser diodes temperatur, which is neglectible for the given experiment.

The gain of the **Internal Cavity** oscillates and has it peaks at the wavelengths of the longitudinal modes, which develop in the internal cavity. The distance between the different peaks is inversely propotional to the length of the resonator, i.e. the length of the diode, and thus rather large.

The gain of the **Grating Feedback** has a sole peak at the frequency of the first-order refracted light, that is reflected back into the diode and can thus be changed by varying the angle of the grating.

The gain of the **External Cavity** oscillates equivalently to the gain of the internal cavity but has a way smaller distance between the mode peaks, as the external resonator is way longer in comparison to the internal resonator. The position of the modes can be varied by changing the position of the grating and consequently the length of the external cavity.

1.4 Rubidium

The $5S_{\frac{1}{2}}$-electrons of the Rubidium isotopes ^{85}Rb and ^{87}Rb can be excited into the $5P_{\frac{3}{2}}$-orbitals with photons of a wavelength of roughly 780 nm. A closer look at the in figure 7 depicted fine-structure of the two isotopes shows two charateristic transitions per isotope. If you transmit a beam trough Rubidium-vapor and sligthly vary the beam wavelength around 780 nm, one will detect four dips in the transmitted intensity. Each dip is located at the wavelength equivalent to the excitation energy of the particular transition.

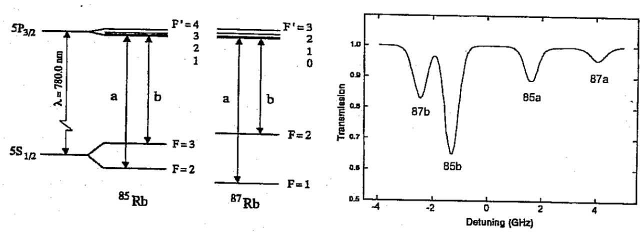


Abbildung 7: The four possible transitions from the $5S_{\frac{1}{2}}$-orbital to the $5P_{\frac{3}{2}}$-orbital for the two Rubidium isotopes and the corresponding dips in a transmission measurement. Taken from [2].

2 Experimental setup and procedure

2.1 Experimental setup

The diode laser setup consists of the diode laser itself with a permanently fixed collimator lens and a diffraction grating to complete the so-called "Littrow-setup". The horizontal orientation of the laser light and with it the length of the external cavity and the resulting wavelength can be adjusted by twisting a knob attached to the side. Furthermore there are different optical instruments available, like lenses, filters, a 50/50 beamsplitter, a detector card to make the infra-red light visible, a CCD camera and two photodiodes. The latter ones are connected to an oscilloscope and are being controlled via a power supply, where the current responsible for the laser intensity can be varied as well.

2.2 Determination of the threshold current

As a first step the laser threshold current I_{Th} is determined. I_{Th} is given as the minimal current needed for the diode laser to leave the LED-area and for lasing to take place. Therefore the detector card is placed in the beam path and the current is slowly raised at the power supply. The change to the visible pattern is observed with the CCD camera, as seen in figure 8.

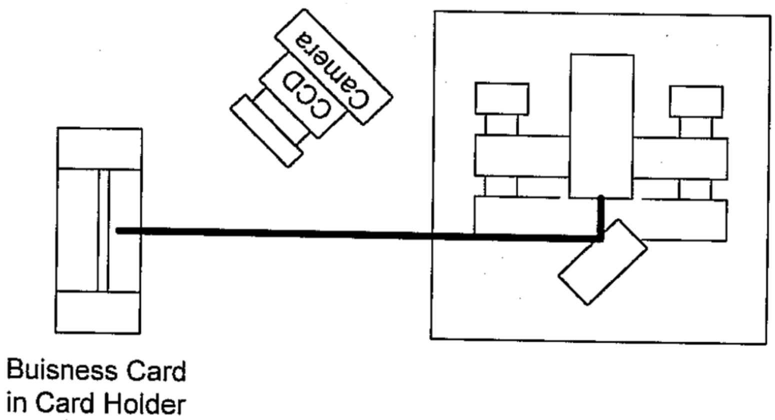


Abbildung 8: Setup for the determination of the threshold current. Taken from [2].

2.3 Recording of the rubidium fluorescence

Next, the laser light is directed onto a rubidium cell. The current is set to a value $I \gg I_{Th}$ and the CCD camera is placed orthogonal to the beam orientation with the possibility to record the interior of the cell. The described setup is represented in figure 9. The angle of the grating is adjusted precisely by a build-in piezo crystal, which allows to make the rubidium emission line permanently visible.

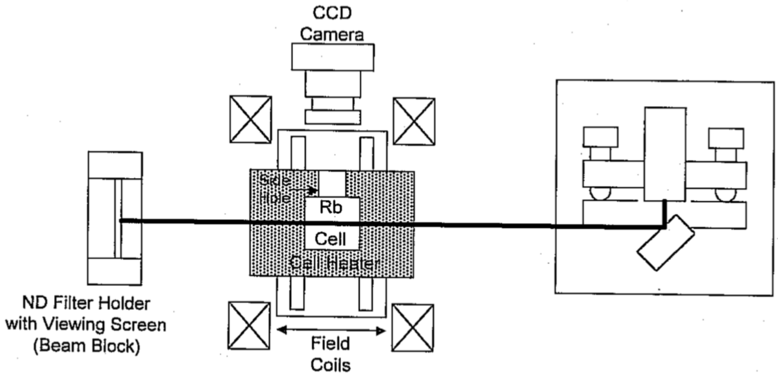


Abbildung 9: Setup for the recording of the rubidium fluorescence. Taken from [2].

2.4 Measuring the absorption spectrum of rubidium

Lastly, a beamsplitter is positioned between the laser source and the rubidium cell. At the end of each outgoing beam path a photodiode is placed (see figure 10). Both of them are connected to the oscilloscope, where their signals are subtracted from one another, so that the background is filtered out and just the voltage change due to the rubidium absorption is shown. The current and wavelength are adjusted by the piezo and control-knob that all 4 absoption peaks are visible within one mode on the oscilloscope with no mode-hops in between.

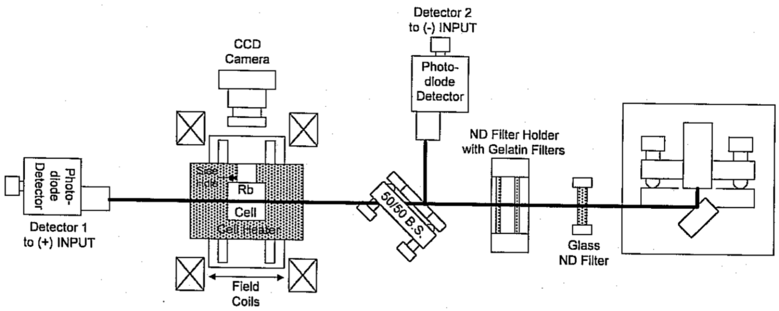
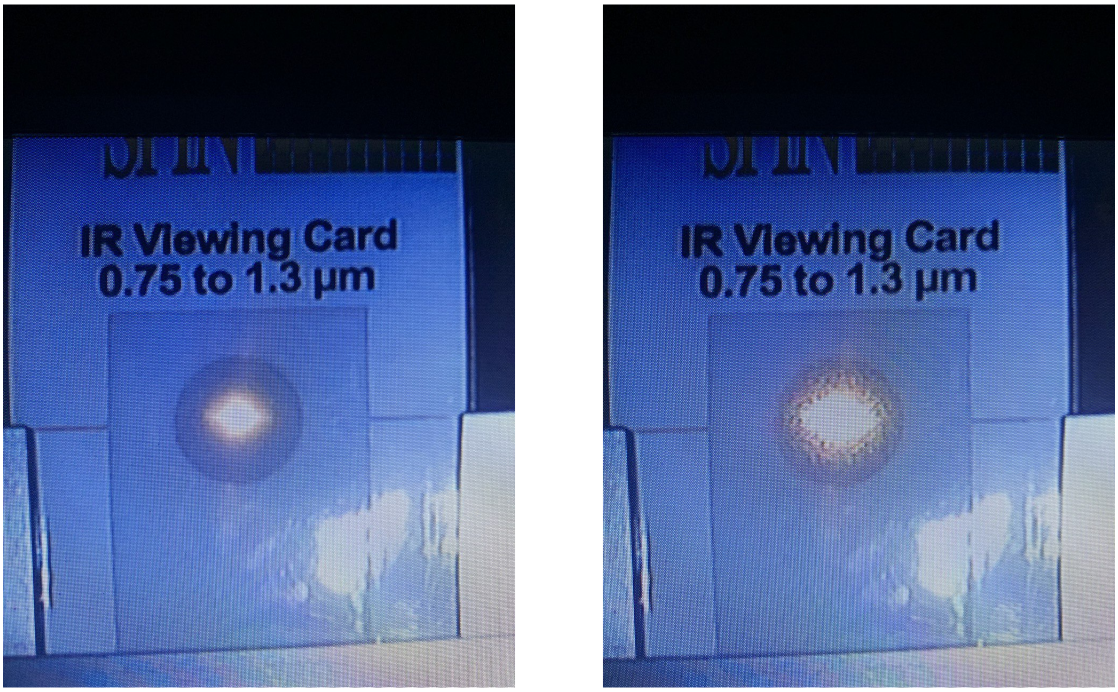


Abbildung 10: Setup for measuring the absorption spectrum of rubidium. Taken from [2].

3 Evaluation

3.1 Determination of the threshold current

The current is being read out while observing the optical pattern on the detector card through the CCD camera. At a threshold current of $I_{Th} = 34\,\text{mA}$ the laser granulation/speckle pattern emerges, indicating the transition from LED-mode to lasing-mode. The spots visible on the detector card at a current immediately before and after I_{Th} are shown in figure 11a and 11b.



(a) Optical pattern of the diode laser in LED-mode at $I < I_{Th}$.

(b) Optical pattern of the diode laser in lasing-mode at $I > I_{Th}$.

Abbildung 11: Light emission on an IR-card.

3.2 Recording of the rubidium fluorescence

The rubidium emission line, stimulated by the diode laser radiating through the cell and exciting the rubidium gas, is presented in figure 12.

Abbildung 12: Rubidium fluorescence induced by the diode laser reaching the necessary photon energy.

3.3 Measuring the absorption spectrum of rubidium

Figure 13 shows the absorption spectrum of rubidium without any mode-hops in between the individual peaks. From left to right the peaks can be assigned to the *87a*, *85a*, *85b* and *87b* optical transitions of rubidium (compare with figure 7).

Abbildung 13: Transmission spectrum of rubidium (red). The piezo-sweep is highlighted as well (blue).

4 Discussion

The experiment was successful at identifying the threshold current needed to produce coherent light in the diode laser and to use it further to excite rubidium. This allowed the measurement of the rubidium transmission spectrum and the identification of the differrent transitions in the stable rubidium isotopes.

Literatur

[1] Hans-Joachim Eichler und Jürgen Eichler. *Laser: Bauformen, Strahlführung, Anwendungen*. 8., aktualisierte und überarbeitete Auflage. Lehrbuch. Berlin Heidelberg: Springer Vieweg, 2015. 491 S. DOI: `10.1007/978-3-642-41438-1`.

[2] TU Dortmund. *Versuchsanleitung V60 - Diodenlaser*. 2022.