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Diode Laser Spectroscopy

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Contents

1 Objective

In this experiment, the functioning of a diode laser is considered in order to use it to record different resonance and fluorescence lines of rubidium.

2 Theory [1]

The following section explains the theoretical principles of a diode laser.

2.1 Historical Background

Before semiconductor lasers were invented, physicists used tunable 'dye' lasers. This worked by the use of a chemical dye as the active medium, i.e the material which produces the laser emission. A fixed-frequency 'pump'-laser is used to create a population inversion. Each individual dye will lase over a limited wavelenght range. This means with different dyes it is possible to generate tunable lasers at basically all near-infrared wavelenghts. Dye Lasers have some disadvantages. They are very large, with high costs of purchase and operation.

The situation has changed due to the development of the diode laser. These lasers are inexpensive, easy to operate and produce high power.

2.2 Diode Laser

The basics of how a diode laser works are explained below.

2.2.1 Structure and Mode of Operation

A diode laser is a laser whose light is generated with a laser diode, i.e. with semiconductor materials. An important component is the diode chip which can be seen in Figure 1.

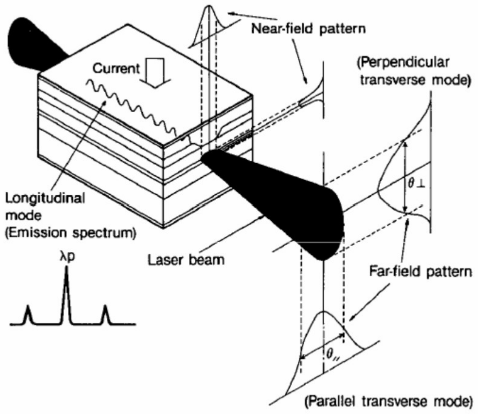


Figure 1: Schematic view of a laser diode chip. [1]

The chip consists of a p-doped and a n-doped layer. The p-n junction between the layers is the active medium. An excitation current can be connected to the upper and lower ends of the diode to create electron-hole pairs which recombine in the active layer and emit light in the process. The current serves as a pump source for the population inversion which occurs in the laser medium. For population inversion more than two states in the system are needed otherwise the member will immediately drop down. The wavelength of the emitted light is approximately that of the band gab of the semiconductor material. To create a cavity the claved facets of the chip act as a partially reflecting mirrors. On this side the light comes out. Standing waves are formed inside the cavity. The leaving light beam is elliptical and strongly divergent due to the rectangular shape of the exit apperature.

The light beam has two unwanted properties which are to be adjusted by an external resonator. On one hand the light beam has a large linewidth thereby being unuseable to examine atomic structures. On the other hand the frequency stability ist very sensitive to scattering of emitted light back into the diode. A Littrow configuration is used in this experiment which is shown in Figure 2.

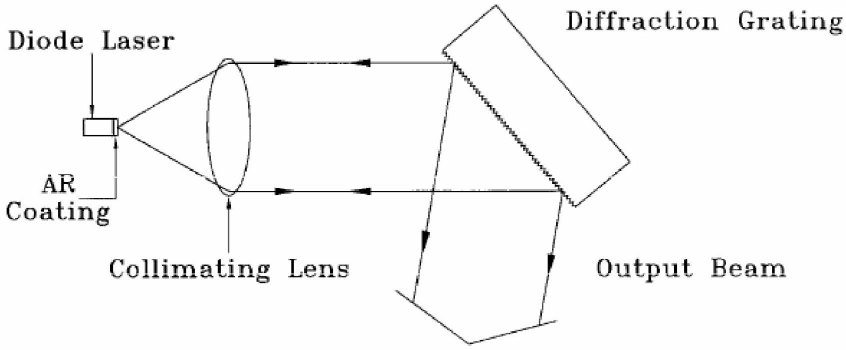


Figure 2: Schematic configuration of the diode laser system. [1]

The external cavity is realized with a lens and a diffraction grating. After leaving the inner cavity the light beam hits a lens which collimates the beam. Afterwards the light beam encounters the diffraction grating. Most of the light is directly reflected by the grating ($m = 0$ grating order). About 15% reflect back into the laser ($m = 1$ grating order). The grating forms the external cavity. This results in a small loss of power, but a much more stable laser beam and a reduced linewidth of $\Delta\nu \approx 1\,\mathrm{MHz}$.

2.2.2 Laser Tuning

To set up the wavelenght of the light emitted by the laser various components must be considered. Therefore the laser output depends for example on modulation of the current, the temperature of the diode and the postion of the grating. To understand each component it is important to understand that the laser will tend to lase at the mode frequency with the greatest net gain. As soon as the laser starts lasing in this mode it results in a single-mode output beam. Under real conditions the laser will sometimes lase in two or more modes at the same time. This experiment will concentrate to find a place in the parameter space where the laser operates in a single mode.

In Figure 3 the wavelength is plotted as a function of the individual amplification modes. The curves are diplaced relative to one another.

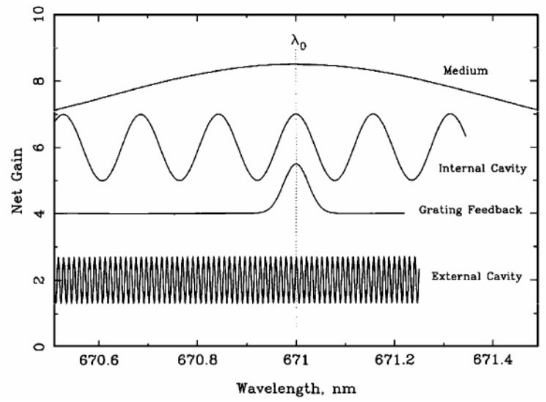


Figure 3: Schematic of the different constributions to the net gain. [1]

The active medium has a bandgap which depends on the material of the medium. This results in a broad peak in the wavelenght distribution of the amplification. The peak depends on the temperature of the material. In the case of rubidium for the resonance the temperature should be set so that the laser operates near 780 nm. The dependence is shown in Figure 4.

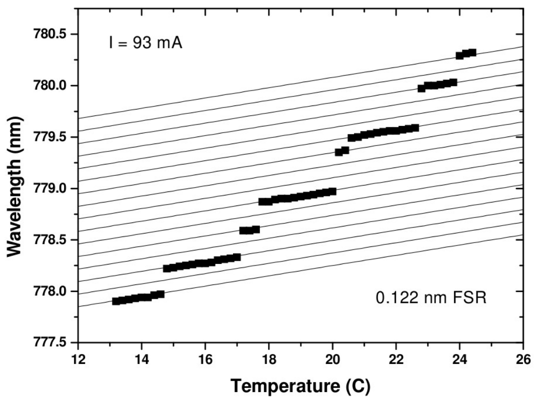


Figure 4: Dependence of the wavelength on the temperature of the diode. [1]

It can be seen that the wavelength correlates with the temperature of the diode. That means the rising temperature impacts the Bandgap, which shrinks. Once the medium gain curve is adjusted the curve is so broad that it is unimportant for net gain.

The internal cavity forms a small Fabry-Pérot étalon thus an optical cavity with a normal mode structure. As shown in Figure 3 the gain function is periodic in frequency, whereby the period is called free spectral range given by

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

In this equation c is the speed of light, n is the index of refraction and L is the cavity length. For the internal cavity the wavelength of the light depends on the current which is represented in Figure 5. The current affects the diode in two ways. First, the diode is heated by the applied current. Second, the current changes the carrier concentration in the active medium.

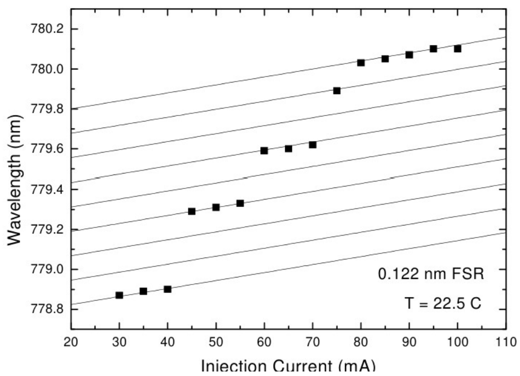


Figure 5: Dependence of the wavelength on the injection current at a fixed temperature. [1]

With a external cavity it is possible that the laser can be made to operate at any wavelength within a reasonably broad range. Since only light from a narrow wavelength band $(m = 1$ grating order$)$ will be fed back into the laser for a fixed grating, which can be found by

$$\lambda = 2d \sin \theta. \tag{2}$$

The size d indicates the line spacing of the grating and θ is the grating angle. The external cavity ist limited on the one side by the grating and on the other side by the reflective back facet of the diode. The length of the external cavity is much larger which results in denser peaks in Figure 3. To shift the curve from the external cavity the position of the grating has to be moved with either the L/R knob on the laser or with the piezo-electric transducer. The laser should lase in a single mode operation at a given wavelength λ_0. Each gain component is supposed to peak at λ_0 as shown in Figure 3.

Figure 6 diplays how the individual components overlap. It shows a " best guess " picture of the shape of the various modes in the laser.

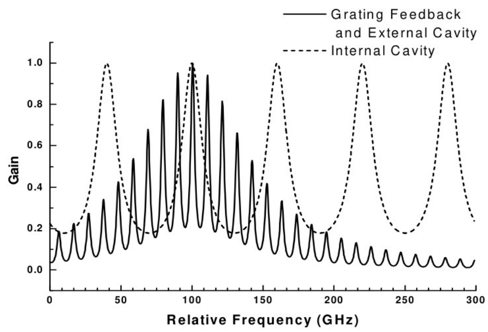


Figure 6: Internal cavity, grating feedback and external cavity modes. [1]

Mode hops are a phenomenon which is important in the context of a single mode laser. In this case mode hops are the result of increasing the temperature which has an impact on the maximum gain of the medium and the internal cavity modes. These will shift to longer wavelengths but not shift at the same rate. The outcome of this are the laser mode hopsto different peaks of the cavity gain function. Adjusting the angle of the grating results in mode hops. By changing the current of the laser it is possible to change the position of the internal modes. Figure 7 shows the imapct of decreasing the grating angle on the external and internal modes.

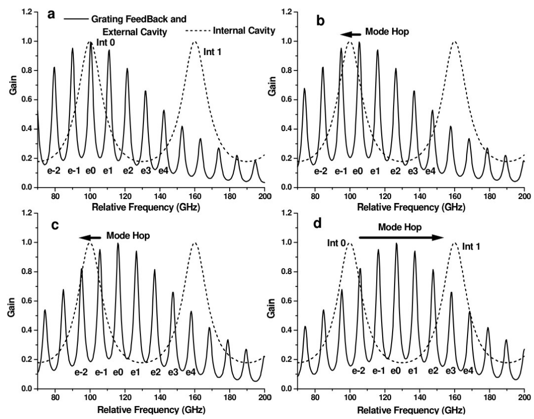


Figure 7: Series of pictures of the external and internal cavity modes as the grating angle decreased. [1]

For tuning the wavelength of the laser correctly the right grating angle and laser current must be found.

2.3 Rubidium Absorption Spectrum

Figure 8 shows the expected Rubidium spectrum and the Energy level diagrams of Rb-85 and Rb-87.

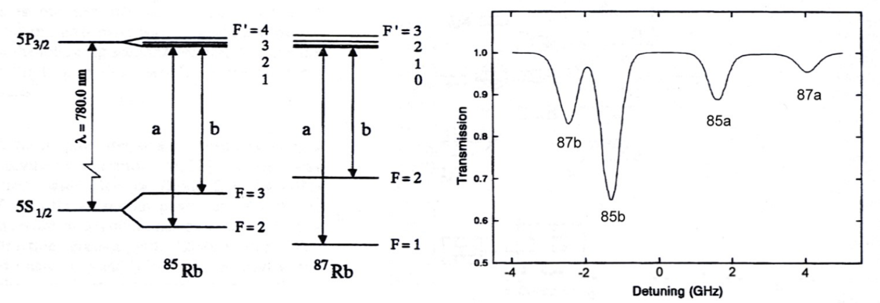


Figure 8: Energy level diagrams and the spectrum of rubidium. [1]

3 Setup

The set-up consists of a laser diode which has both a controllable temperature and an adjustable current. The position of the external resonator is set via a piezo stack. Around the diode is a plexiglass cover which protects the diode from air currents and unwanted contact of the knobs. The apparatus is equipped with two photodiodes, one of which detects the light in front and the other detects the light behind the sample. Before the light hits the detector, it falls on a 50/50 beam splitter. To audit the functions of the diode laser it has an Laser Diode Controller which is shown in Figure 9.

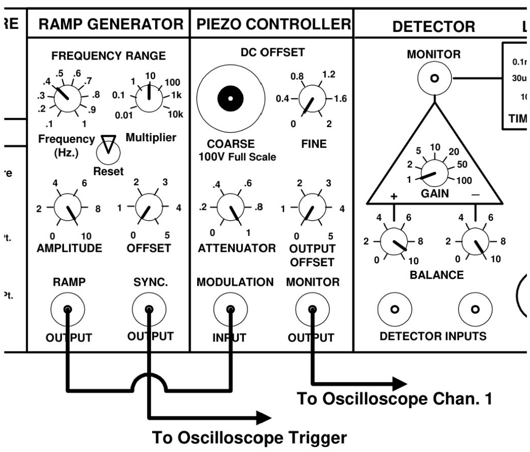


Figure 9: Exemplary combination from measuring and processing instruments. [1]

To record different resonance and fluorescence lines of rubidium an oscilloscope is connected. A camera connected to a TV is available to take pictures of the fluorescence and the light from the laser.

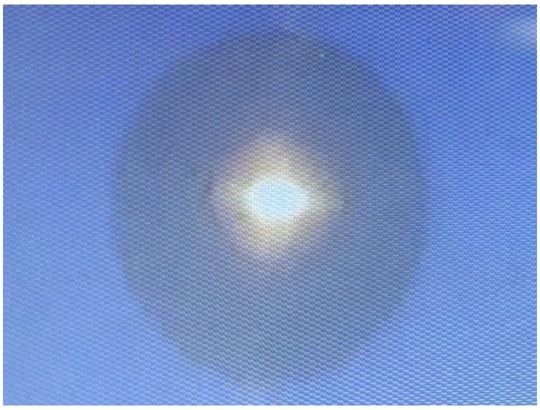
4 Procedure

Initially, the individual components need to be positioned and fastened on the breadboard. This process includes the vertical and horizontal alignment of the laser grating, the CCD camera as well as the photodiodes. Due to the laser beam being invisible to the human eye, the provided IR sensitive viewing card is used to check for centered and maximally orthogonal incidence. After completing this first part, the lasing threshhold is evaluated by slowly adjusting the current and checking for a change in the light pattern. Once this has been observed and the corresponding value has been noted down, the resonant configuration for the rubidium fluorescence is searched for by iteratively changing both the grating angle and the laser current until a flashing line becomes visible on the display. Finally, while ensuring no further changes to the setup, the main focus of the measuring process is proceeded with. To perform saturated absorption spectroscopy, the contributing gain components from the internal cavity as well as from the external cavity with grating feedback need to be modulated in a way such that no mode hops occur during the scanning process over all rubidium lines of interest. To achieve this, the piezo stack and the laser cavity are adressed simultaneously with a ramp current, changing the diffraction angle via piezoelectric expansion or contraction and shifting the internal mode maximum. By tuning current and DC offset parameters, this method allows for comparably large continuous sweeping intervals. Lastly, to remove the sloping background from the obtained signal, the photocurrent from the split beam is used with some manually set coefficient to subtract from the waves altered due to passing through the rubidium cell.

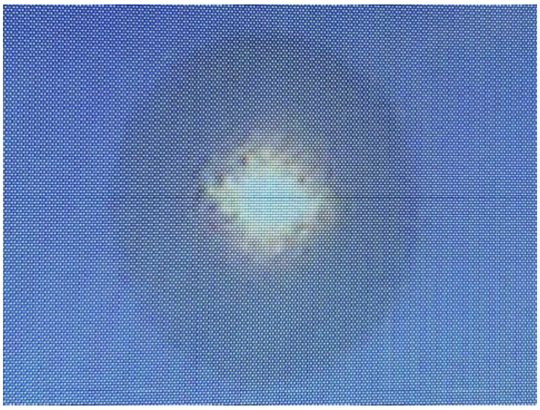
5 Results

Determining the value for the threshold current requires careful adjustment of the unattenuated laser power. For the LED regime, in which spontaneous emission dominates the light production, stable interference patterns cannot exist. This means that the light on the IR viewing card appears diffuse and symmetrical. As soon as stimulated emission begins to dominate, the diode operates in the LASER regime. The now coherent wave interacts with the texture of the card surface and creates a stable asymmetrical image. The observed type of diffraction occurs due to the various bumps and grooves roughly matching the wavelength in size, resulting in random granulation as predicted by Huygens principle.

While lasing, the intensity also increases much more rapidly due to the strictly linear dependence on charge carrier flow.



(a) LED regime at $I = 34.4\,\mathrm{mA}$.



(b) LASER regime at $I = 34.6\,\mathrm{mA}$.

Figure 10: Comparison of light pattern slightly below and above the chosen threshold current $I = 34.5\,\mathrm{mA}$. Note the diffuse reflection on the left versus the coarse granulation on the right. These distinct appearances are the results from random diffraction of incoherent or coherent waves respectively.

The described patterns can be viewed in Figure 10 for values slightly above and below the threshold. For the given apparatus, visual examination yields $I = 34.5\,\mathrm{mA}$ as the minimum lasing current, though there is some ambiguity as will be discussed later.

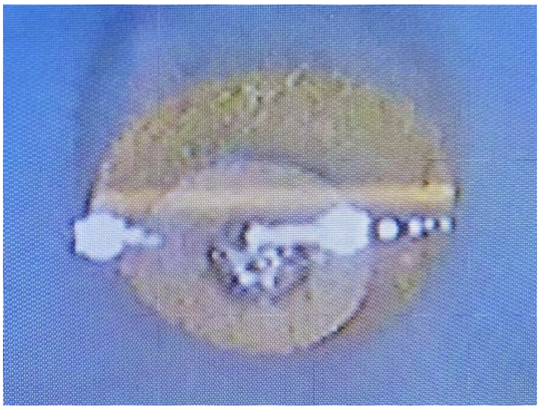


Figure 11: Rubidium fluorescence line along the laser beam as seen through the observation window in the vapor cell.

To find the approximate resonance of the rubidium fluorescence, laser current and grating angle are adjusted until a bright flashing line along the path of the light beam manifests inside the vapor cell. To confirm this setting, Figure 11 displays the observed excitation.

Following the previous steps, the hyperfine structure absorption spectrum of rubidium can be analysed. After iteratively tuning current and DC offset values for the piezo stack, we arrive at Figure 12 without any mode hops.

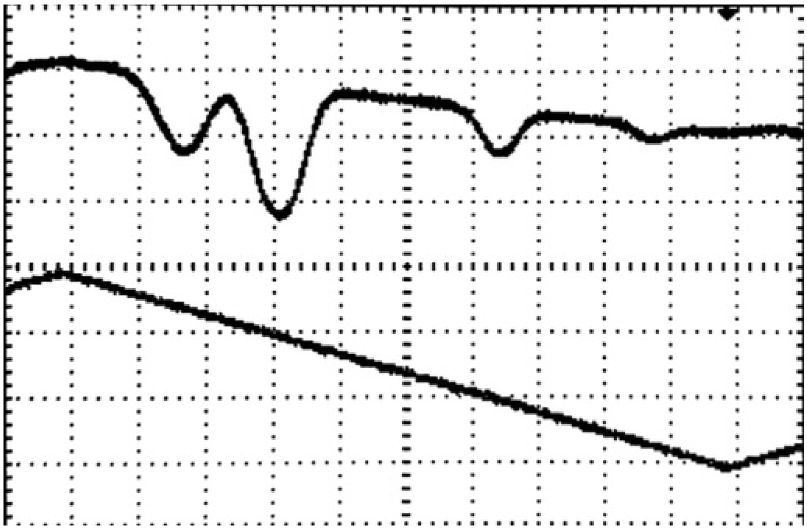


Figure 12: Modulated signal without correction (top). Triggered ramp output for laser and piezo stack (bottom). As previously described, the expected linear proportionality between the two currents is clearly visible outside the absorption dips.

From this result, we finally obtain the corrected spectrum. Figure 13 shows the signal shape after trying to achieve a constant background outside of the peaks. The success of this technique is evaluated in the next section.

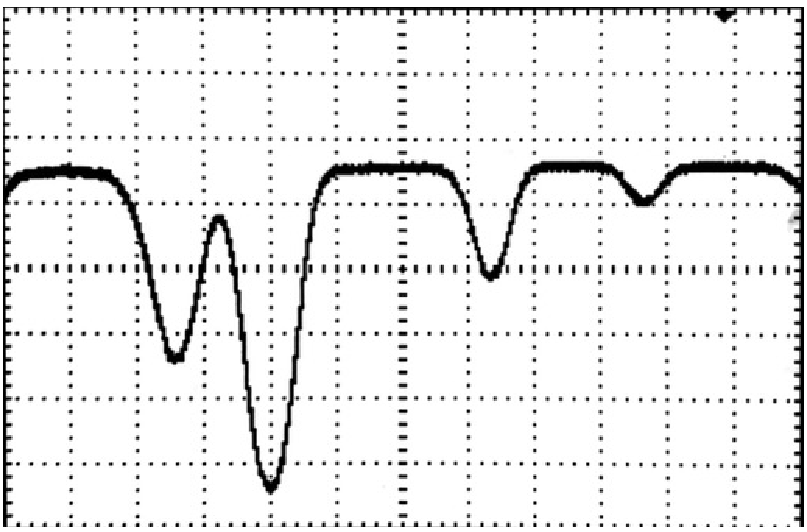


Figure 13: Spectrum after manual compensation via background subtraction for the scanning current contribution.

6 Discussion

Overall, the results are in good agreement with theoretical predictions. The transition from LED to LASER operation produces clearly different light patterns. The only notable caveat for this part of the procedure is that the patch does not abruptly change from diffuse to granular appearance. Instead, there exists a narrow current interval of about 1 mA in which the pattern type is not easily distinguishable. This should however not pose any problems down the line, as the resonant current for rubidium is significantly higher than the threshold. After tuning the rubidium fluorescence and correcting for the scanning slope, the final spectrum in Figure 13 qualitatively matches the expectation presented in Figure 8, though a slight positive slope is now visible. This points to a small overcorrection but does not detract from the interpretability of the concluding result.

References

[1] *Manual for Experiment 60, Diode Laser Spectroscopy.* TU Dortmund, Department of Physics. 2024.