DIODE LASER SPECTROSCOPY (160309)

Introduction

The purpose of this laboratory exercise is to illustrate how we may investigate tiny energy splittings in an atomic system using laser spectroscopy. As an example we are going to measure the ground state hyperfine splitting in Rubidium (^{87}Rb and/or ^{85}Rb), arising from the interaction of the magnetic field created by the orbiting electrons and the magnetic moment due to the nuclear spin. Other examples of small energy effects that could be measured in a similar way are isotope shifts (see figure 2 below) and Zeeman splittings in external magnetic fields. A central concept in the investigation of small energy splittings is that of line width, and its influence on the experimental resolution. A very simple type of laser, still capable of (limited) wavelength scanning, is the diode laser, which we are going to use. You will also find that it is possible to accurately measure gas concentrations using laser techniques. This is useful in many practical applications, e.g. measuring the concentration of oxygen in a respiratory tube in an operating room or air pollutants in the atmosphere across a city.

During the laboratory exercise you will also practice your ability to align optical components, use a Fabry-Pérot interferometer and a digital oscilloscope.

Preparation

Hyperfine interactions and isotope effects are discussed in Spectrophysics 3.8 and the different line broadening mechanisms in 8.1 – 8.4 and 14.3. These subjects are also treated by Foot in 6.1 – 6.2 and 8.1 – 8.3, respectively. The Fabry-Pérot etalon, used here to obtain an accurate frequency scale, is discussed in the instructions to the Zeeman lab.

Safety.

The diode laser emits intense and invisible light (780 nm). Hence you must wear protective goggles at all times when a laser is active.

Preparatory exercises

1. *Line widths*. The wavelength of the D_2-line (5s $^2S_{1/2}$ - 5p $^2P_{3/2}$) in Rubidium is 780.2 nm.
    a) What is the frequency of the transition?
    b) What is the natural frequency line width of this transition if the upper level has a lifetime of 26.0 ns?
    c) What is the Doppler frequency line width at 20 and 120 °C, respectively?
    d) What is the line widths calculated above expressed in nm at 780 nm?

2. Figure 2 shows fluorescence spectrum of the D_2-linje in Rubidium recorded using a diode laser that excites a <u>collimated beam</u> of Rb-atoms, i.e. an almost Doppler free measurement.
    a) Derive the frequency differences between the ^{87}Rb peaks. Use the known free spectral range in the Fabry-Pérot recording done simultaneously to

obtain your frequency scale. Are your results consistent with the data given in Figure 1?

b) Determine the line width (FWHM) of the largest peak and compare with the results above.

c) Assume now, that instead of a collimated beam experiment, we make the measurements directly in a gas cell at room temperature. Can you then resolve the hyperfine structure in the ground state (5s) and in the excited (5p) state?

3. The distance between the mirrored surfaces in a typical Fabry- Pérot etalon is 10.90 cm and the refractive index of the material is $n = 1{,}511$. What is the free spectral rage of the etalon?

4. At room temperature (20 °C) the vapor pressure of rubidium is $2 \cdot 10^{-5}$ Pa. How many atoms per m^3 are there then in a cell with rubidium?

Hyperfine structure in Rubidium

In Rubidium the resonance lines have the following wavelengths:

$5s\ ^2S_{1/2}$ - $5p\ ^2P_{1/2}$ 794,7 nm (historically called the D_1-line)

$5s\ ^2S_{1/2}$ - $5p\ ^2P_{3/2}$ 780,2 nm (historically called the D_2-line)

The designations D_1 and D_2 are frequently used for the resonance lines in alkali metals, but have no meaning what so ever. Naturally occurring Rubidium have 2 isotopes ^{85}Rb (73%) and ^{87}Rb (27%), but we are going to use cells that contain either pure 85 or 87 Rubidium.

Figure 1 shows the hyperfine structure in the 2 levels in ^{87}Rb, where the nuclear spin is $I = 3/2$. The energy differences due to the hyperfine interaction are given in frequency units ($\Delta E/h$). The selection rule for transitions between hyperfine levels is: $\Delta F = 0, \pm 1$ ($F = 0$ to $F = 0$ forbidden), where F is the quantum number describing the total angular momentum $\mathbf{F} = \mathbf{I} + \mathbf{J}$.
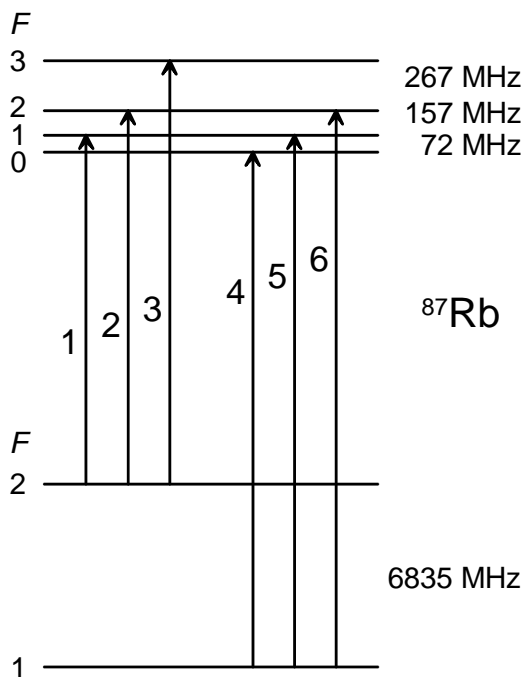

Figure 1. Hyperfine structure in the ground state $5s\ ^2S_{1/2}$ and in the excited state $5p\ ^2P_{3/2}$ in ^{87}Rb. The figure is not to scale. The six transitions are numbered according to increasing frequency, and an experimental spectrum is shown in Figure 2.
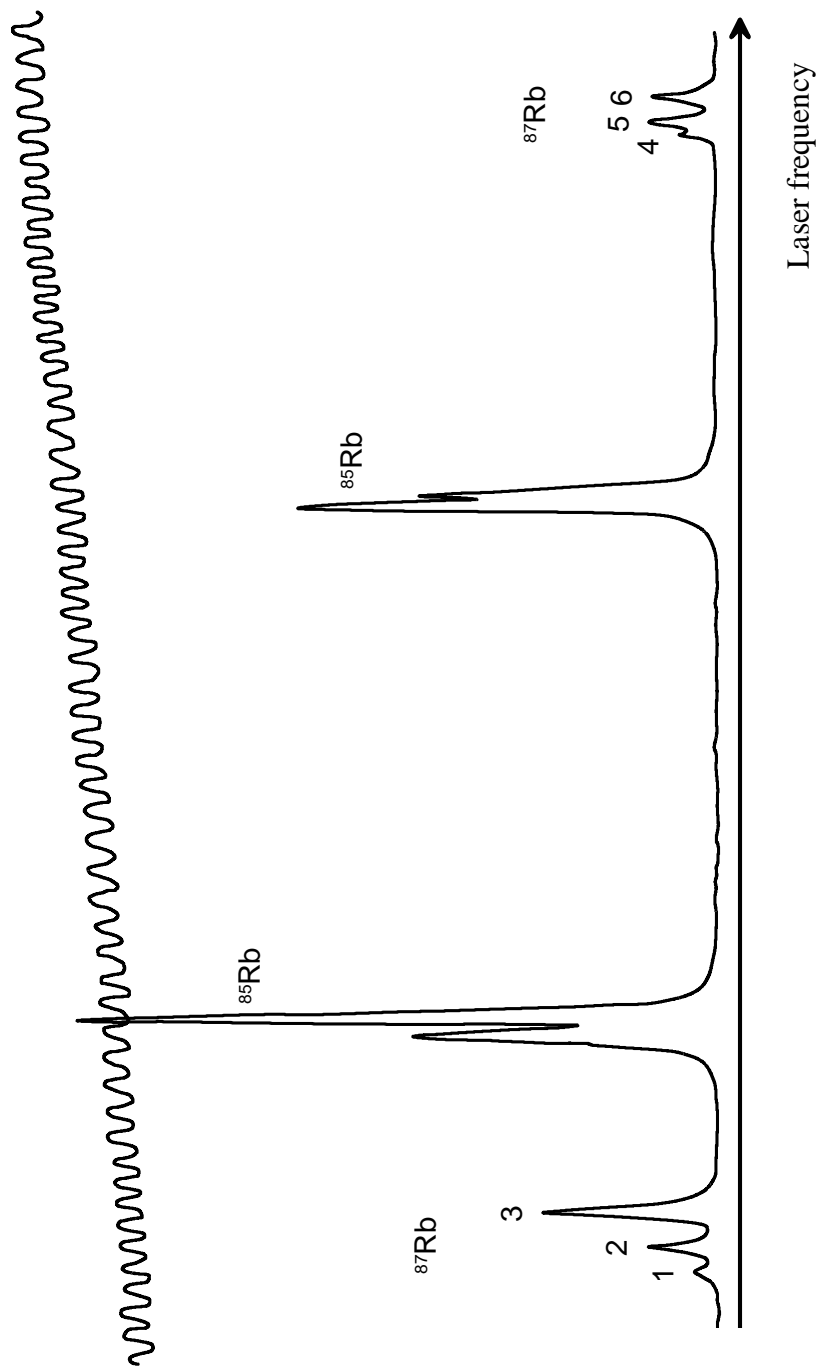
Figure 2. A fluorescence spectrum of the D_2-linje in naturally occurring Rubidium (^{85}Rb and ^{87}Rb), recorded using a narrow band laser that excites a collimated beam of Rb-atoms. The numbers on the ^{87}Rb peaks refer to the transitions in Figure 1. As the laser scans, part of the light is simultaneously sent through a Fabry- Pérot etalon with a free spectral range of 141 MHz, and the interference fringes are also recorded.

The Diode laser - Distributed Feedback Lasers

A laser diode is a laser where the active medium is a semiconductor doped with materials from group III (Al, Ga, In) or group V (N, P, As, Sb). The most common type of laser diode is formed from a p-n junction and powered by injected electric current.

A p-n junction consists of two doped semiconductors, one n-doped and the other p-doped, that are put in close contact with each other. The band gap structure of a p-n junction is shown in the left part of Figure 3. The Fermi levels of the two doped materials lie at the same level. If a forward voltage is applied over the p-n junction, a potential difference is established between the Fermi levels of the p-and-n side, which is shown in the right part of Figure 3. In this case, there will be population inversion in the so-called depletion region between the p-and-n side, with electrons in the conduction band and holes in the valence band. This means it is possible to get stimulated emission in this region.
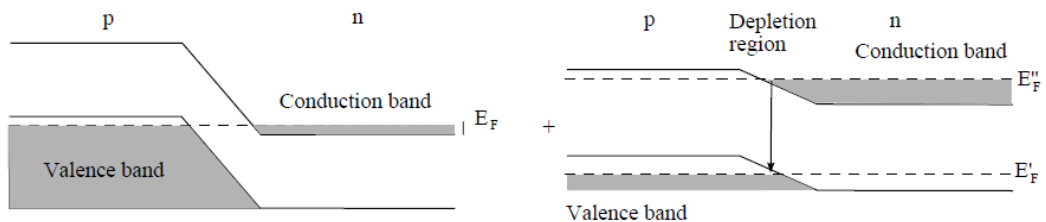

Figure 3: Left: The energy level diagram of a p-n junction. The Fermi energy is at the same level for the p and n side. Right: The energy level diagram of a forward-biased p-n junction. Population inversion is achieved in the depletion region between the p and n side, and this makes stimulated emission possible.

Diode lasers are good light sources for absorption spectroscopy due to their stable and smooth wavelength tunability as well as being easy to handle and control. Changing the current and/or the temperature of the diode results in an altered output wavelength because of changes in the band gap, the refractive index and the laser gain-curve. To study the hyperfine structure in Rb we will use a diode laser that emits light in a narrow band around 780 nm. The laser is shown in Figure 4 and is made of GaAs.

Figure 4. The diode laser is inside a sealed capsule.

In our experiments we are going to use an advanced form of diode laser, called a Distributed Feedback Laser (DFB). To stabilize the lasing wavelength, a diffraction grating is etched close to the p-n junction of the diode. This grating acts like an optical filter, causing a single wavelength to be fed back to the gain region and laze. For a DFB temperature tuning results in a wavelength shift of 0.1 nm/K or -25 GHz/K whereas current tuning gives a shift of $1 - 10$ GHz/mA. Practically this

means that the temperature is used for coarse tuning and the injection current for fine tuning of the output wavelength

The output power of the laser depends strongly on the current over the p-n junction, see Figure 5. For low currents the component works like an LED, and only for currents above a threshold value do we get laser action.
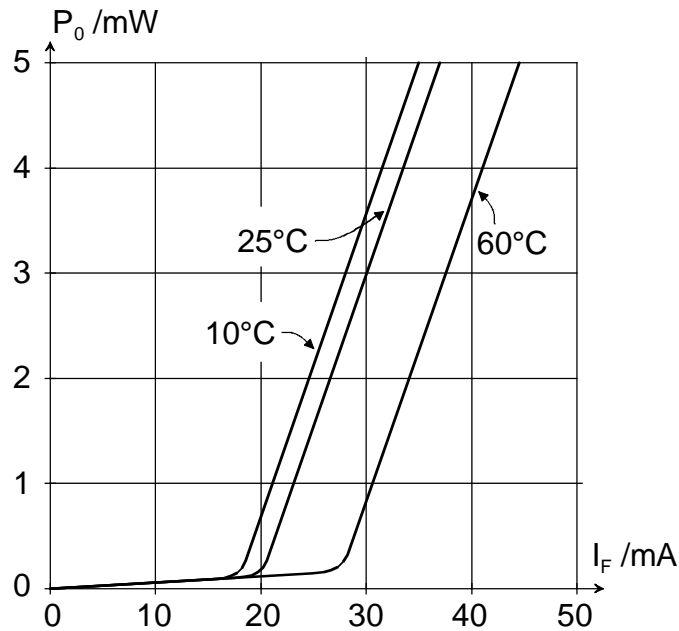

Figure 5. The output power P_0 of the laser as a function of current I_F.

Our DFB lasers have a maximum output of 100 mW, which is very dangerous to the eyes, particularly since the blinking reflex is not present with invisible light. **Hence you must wear protective goggles at all times when a laser is active. Note, not only yours but any laser in the room**

To achieve a smooth and continuous wavelength scan in our experiments we will use the following technique. A function generator produces triangular wave shaped <u>voltage pulses</u> which are fed to the laser driver unit where they are converted to <u>current ramps</u> around a set current value which, finally, produces a smooth <u>wavelength scan</u> around a set wavelength. By monitoring the laser intensity after passing through a gas cell with Rubidium as a function of time on an oscilloscope we may thus see an atomic absorption spectrum in real time.

Beer-Lambert law

A gas containing a certain type of atoms will absorb light at different wavelengths according to its energy levels diagram and the transition rules between different levels. If light of a resonance wavelength for a certain atom is sent through a gas containing these atoms, the light will be absorbed. The intensity of the light will then decrease as it passes through the gas. The decrease is governed by the Beer-Lambert law

$$I = I_0 e^{-\mu x}$$

Where I_0 is the intensity before passing through the gas, I is the intensity after the gas, x is the distance that the light passes through the gas and μ is the linear absorption coefficient. The Beer-Lambert law also works for the absorption of light in liquids and solids.

The linear absorption coefficient μ is a measure of how much light is absorbed over a certain distance in the absorbing gas. μ depends on the transition probabilities of the transition in the absorbing atom or molecule, and also depends on the concentration of the absorbing species. For an absorption line with a large μ, more light will be absorbed over the same distance x than for an absorption line with a smaller μ.

Tunable diode laser absorption spectroscopy

A common way to perform absorption spectroscopy is to shine laser light through a gas and then sweep the wavelength of the laser over the absorption line of the gas. Then the decrease in transmitted intensity through the gas when the laser is tuned to the absorption wavelength is measured. Diode lasers are ideal for this task since it is easy to alter the wavelength by changing the driving current to the laser. The use of diode lasers for absorption spectroscopy has been given the name "Tunable diode laser absorption spectroscopy" (TDLAS).

As stated above, the output wavelength of a laser diode can be tuned over a certain range of wavelengths by changing the temperature and/or the driving current to the diode. The temperature is mostly used to set the laser to roughly the correct wavelength, while the current is used to sweep the wavelength repeatedly over the absorption line to be studied. In this laboratory exercise, this will be achieved by modulating the driving current with a triangular wave modulation, i.e. the driving current will change linearly over time, sweeping back and forth between two set values. This way, the wavelength of the laser will also change linearly back and forth between two set values. The output power of the diode laser also changes when the driving current is modulated. Therefore, the laser power (or laser intensity) from a diode laser will also follow a triangular curve, where different points in the sweep correspond to different wavelengths as well as different intensities. When the light passes the resonance wavelength, the intensity of the transmitted light decreases; see Figure 6.
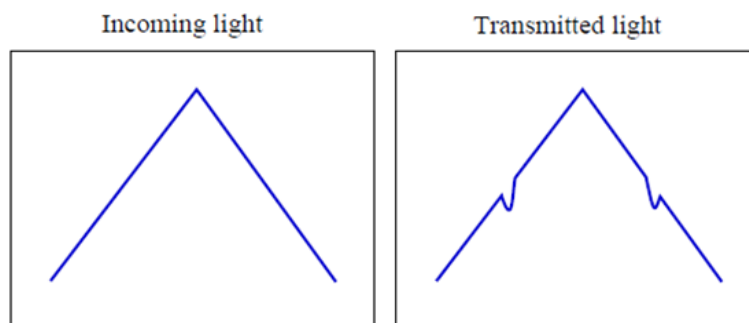

Figure 6: The principles of analyzing an absorption signal with TDLAS. *Left:* The laser output power as a function of time during one sweep of the driving current. Each point on the slope corresponds to a different frequency of the laser light. *Right:* The light intensity transmitted through the sample decreases every time the laser scans over the resonance frequency.

The transmitted light at an absorption peak is related to the incoming light by the Beer-Lambert law, $I = I_0 e^{-\mu x}$. Figure 7 illustrates how I_0 and I can be measured from an absorption spectrum. I_0 is the intensity of the light without any absorbing atoms, which may be estimated from extrapolating the laser intensity curve over the absorption line. The linear absorption coefficient μ of the absorption line can be calculated from I_0 and I using the Beer-Lambert law if we know the distance x the laser passes through the absorbing gas.
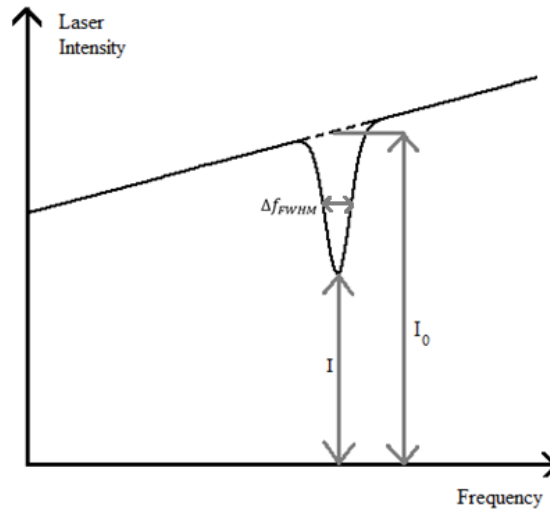
Figure 7: A typical absorption spectrum from a diode laser. The laser frequency is tuned by changing the driving current of the laser. The laser intensity increases as the driving current increases (as illustrated in Figure 6). The absorption is seen as a decrease in the transmitted laser intensity at a certain frequency of the laser light. The transmitted light (I) and the light before absorption (I_0) are marked in the figure. The line width Δf_{FWHM} of the absorption line is also marked in the figure.

As stated before, the linear absorption coefficient μ depends on the concentration of the absorbing gas. It is possible to relate gas concentration n in the gas cell to μ using the following approximate relation:

$$ n = \frac{8\pi \cdot \tau \cdot \mu \cdot \Delta f_{FWHM}}{\lambda^2} \cdot \frac{G_1}{G_2} $$

where τ is the lifetime of the excited state, Δf_{FWHM} is the linewidth of the absorption line, λ is the wavelength of the laser and G_1 and G_2 are the statistical weights for the excited and ground states for the transition.

The advantages with TDLAS are many compared with other types of absorption spectroscopy. Diode lasers are small and compact and relatively inexpensive, compared with other tunable laser light sources. They can be made to have single-mode operation and narrow linewidths. It is easy to sweep the wavelength of the laser by applying a ramped current. The disadvantages of TDLAS are mainly that there is a limited choice of wavelength range, and that the tuning range is relatively small. A laser diode can normally only be tuned a few nm, which is troublesome if many absorption lines are to be studied quasi-simultaneously. There are still no diode lasers in the UV-region (ultra-violet), and diodes in the mid-IR-and-IR regions normally need powerful cooling to work.

Fabry–Pérot etalon

A Fabry-Pérot etalon is a useful tool for frequency calibration in TDLAS. It normally consists of a glass cylinder with two parallel, highly reflective surfaces. Because of this, light that passes through the etalon will undergo multiple reflections, and the light will pass many times through the etalon. This is illustrated in Figure 8. The light is both transmitted and reflected in each surface. The reflected beams are drawn beside the transmitted beams to show the effect more clearly (in reality, all beams pass on top of each other). After the etalon, the light that passed straight through the etalon will interfere with the light that was transmitted after a number of reflections.
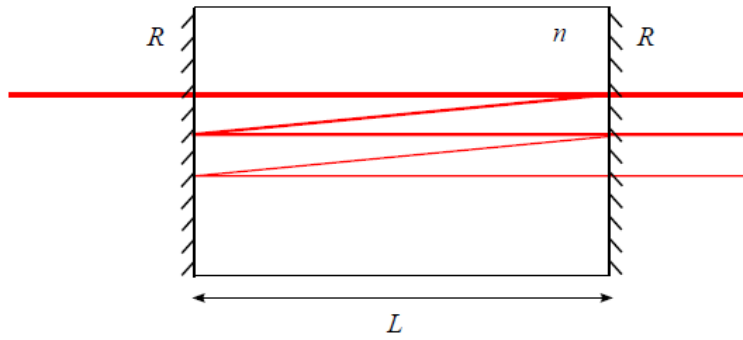
Figure 8: An illustration of how a Fabry-Pérot-interferometer works. The light is transmitted and reflected at each surface (here the reflected beams are drawn beside the original ones, to better illustrate the effect). Multiple interference gives strong transmission for some wavelengths and weak for others

If the light that is transmitted through the etalon is in phase, the transmission of light will be high due to constructive interference. This will happen for waves that can fit an integer number of half wavelengths in the etalon length *L*. Thus, the transmittance of light through the etalon will vary periodically if the frequency of the laser light is scanned over a frequency interval. The frequency difference between two adjacent wavelengths that have high transmittance is called the free spectral range, Δf_{FSR}, of the etalon and is calculated according

$$\Delta f_{FSR} = \frac{c}{2nL}$$

where c is the speed of light and *n* is the refractive index of the material in the etalon. Figure 9 (and Figure 2) shows a typical transmission spectrum from a Fabry-Pérot etalon when the frequency is changed. The free spectral range is marked in the figure.
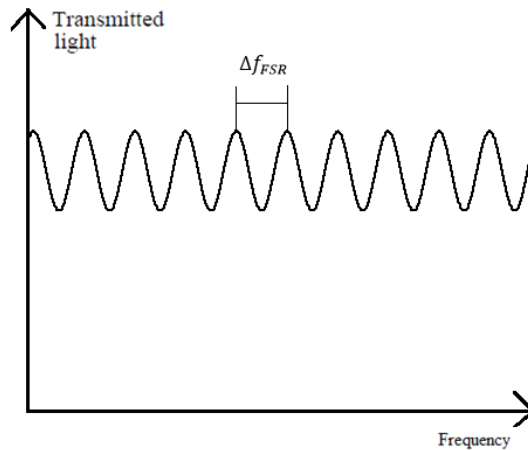

Figure 9: A transmission spectrum from a Fabry-Pérot etalon as a function of frequency. Δf_{FSR} is the difference in frequency between two adjacent peaks.
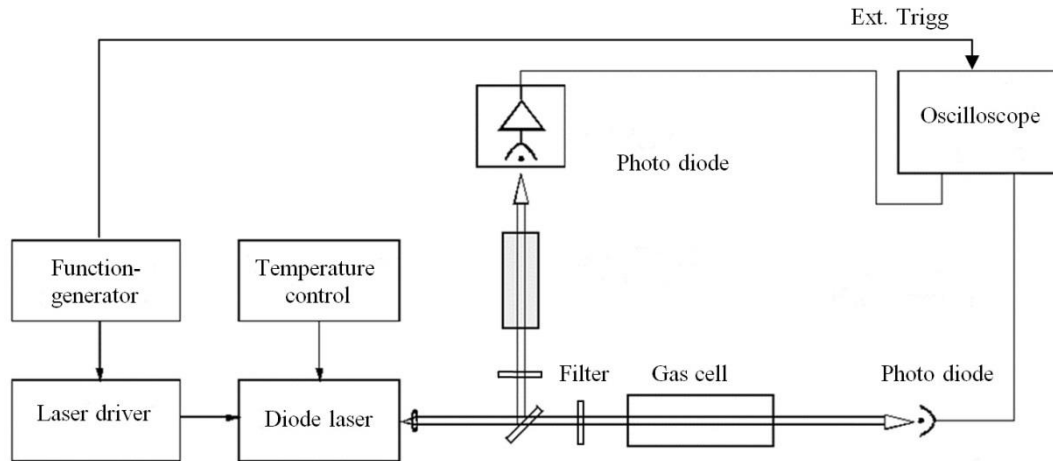
Experiments

Figure 10. Set-up for laser absorption spectroscopy.

1. Set the temperature for your unit to the value given by the instructor. While you wait for it to stabilize familiarize yourself with the rest of the components and practice using the different menus on the oscilloscope: "Vertical menu", "Trigger menu", "Cursor" and "Acquire" (if you are not already an expert!).

2. Calculate the free spectral range on your Fabry-Pérot etalon. Use a plastic ruler to measure its length and that the refractive index data is 1,51118 (for etalons marked BK7) and 1,51075 (for etalons marked K8), respectively at 780 nm.

3. Connect the function generator main output to one of the channels on the oscilloscope and study the signal. Set the function generator to generate a triangular wave with about 100 Hz and 200 mV peak-to-peak amplitude. To get a stable signal on the oscilloscope screen, connect the trigger output from the function generator (SYNC OUT or AUX OUT) to the external trigger input in the oscilloscope (use "Trigger menu" to set the oscilloscope to "Ext" trigger).

4. When you have a triangular wave with the right frequency and amplitude, connect the function generator main output to the laser driver (MOD IN)

5. Set the driving current on the laser driver to the value given by the instructor. Warn everybody that you're going to switch on the laser. When everybody in the room has their laser goggles on you may start the laser. Warning! Diode lasers are very sensitive to transients, do not turn off power to the function generator or disconnect any cables while the diode laser is on.

6. Align the optics according to Figure 10.

   a. Place the filter marked ND 2 in the beam path before the gas cell to reduce its intensity by a factor 100

   b. Place the Rb-cell in the beam path. Manually scan the driving   current slowly around the recommended value (you can scan ± 5 mA), until you find the absorption lines. (If the oscilloscope image looks "upside down", the photo detector may be connected so it gives a negative output voltage, which makes the absorption peaks look like emission peaks! To make it

more pedagogical you can use "invert on" on the "vertical menu" in the oscilloscope.)

    c.   Use a 45 degree beam splitter (Figure 10) to send some laser light to the second photo diode, which you connect to channel 2 on the oscilloscope.

    d.   Put in the Fabry- Pérot etalon and adjust it to obtain the interference fringes on the oscilloscope. Place a ND 1 filter between the beam splitter and lens to avoid feedback reflections from the Fabry-Pérot into the diode laser. *Hint: the laser beam must be incident on the Fabry Pérot with a 90° angle*

7.   Hyperfine splitting and line width. Use the cursor function on the oscilloscope to determine the hyperfine splitting (the distance between the absorption peaks) and the line width (FWHM) of the absorption peaks.

8.   Gas concentration. The concentration of Rb-atoms in the cell will influence the depth of the absorption peaks (higher concentration $\Rightarrow$ more light will be absorbed). This means that we can use the absorption spectrum to calculate the concentration of Rb-atoms in the cell

    a.   To calculate the gas concentration from our absorption spectrum, it is absolutely necessary that the detector is working in a linear range, and that you eliminate as much background light as possible.

        •   Switch the oscilloscope "vertical menu" from "AC" to "DC" coupling and adjust the vertical scale until you can see the signal again.

        •   Put in more filters in the laser beam path until you are certain that there are no saturation effects, i.e. that the detector is working in a linear range. Use the 0.3 filter (dampening factor $10^{0.3} \approx 2$) to check the linearity

    b.   Calculate the linear absorption coefficient μ using the Beer-Lambert law.

    c.   Calculate the atomic density in the cell, and compare with the value calculated in preparatory exercise 4. Use the equation on page 7.

        •   For this transition in ^{87}Rb $\lambda = 780.2$ nm and $\tau = 26$ ns.

        •   When calculating the statistical weights (G) we use $G_2 = 2F + 1$ for the resolved hyperfine states in 5s ^{2}S$_{1/2}$ and $G_1 = 2J + 1$ for the unresolved hyperfine structure in 5p ^{2}P$_{3/2}$. This gives us $G_1/G_2 = 4/5$ for the stronger absorption peak and $G_1/G_2 = 4/3$ for the weaker absorption peak.

9.   Modify the set-up so that you can observe laser-induced fluorescence from the cell instead of absorption. Hint: fluorescence is another word for the spontaneous emission of light when an atom deexcites from a higher level