

# A246 - High Resolution Laser Spectroscopy

Course description

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# 1 Outline of the course

In this lab course you will use a diode laser emitting radiation at 794 nm to study the characteristics of laser diodes and Fabry-Pérot interferometers, and to perform optical spectroscopy experiments on rubidium vapor. You will first apply a linear spectroscopic technique to study Doppler-broadened transitions. In a second step you will use non-linear spectroscopy in order to increase the spectral resolution by eliminating the Doppler effect.

In the first part, the characteristic properties of a single-mode extended-cavity diode laser will be studied. The frequency scale in the spectroscopy experiments will be calibrated by monitoring the transmission of a part of the laser beam through a Fabry-Pérot interferometer. You should get familiar with the properties of the interferometer and its practical use.

Atomic and molecular spectroscopy is one of the major applications of lasers in science. Laser spectroscopic techniques are mainly used for ultra-high resolution studies of the properties of atoms and molecules. They also play an important role in tests of advanced physical theories, such as quantum electrodynamics, or to define standards in metrology, such as the realization of primary and secondary frequency standards.

In the second part of the course you will set up a linear spectroscopy experiment to study the  $D_1$  transition of the isotopes  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$ . You will measure fundamental atomic parameters such as the Doppler width of the transition, hyperfine coupling constants and the isotope shift.

In the third part of the course you will build up a spectroscopic experiment that uses a nonlinear technique. This will allow you to observe spectral lines without Doppler broadening, thus revealing spectral structures (such as the hyperfine structure of atomic states) hidden by the Doppler effect in linear spectroscopy. It will further allow the more accurate determination of the parameters determined with the linear technique.

This description is designed to give you a guideline to follow in order to successfully conduct this experimental lab course. Your tutors are there to help you to have a good experience in learning new physical concepts and how to perform lab work. So do not hesitate to contact them; before, during or after the lab work! On the first day of the on-site work, there will be an oral examination about the physical and technical details of high resolution laser spectroscopy. You should show that you are well prepared and can be trusted to safely work on the experimental setup.

## 2 Safety precautions

In this lab course you will use a diode laser emitting radiation at 794 nm. The laser is of class 3 and emits strong radiation in the near-infrared spectral range. Special care has to be taken while operating it. Please stick strictly to the following rules:

- Never look into the laser beam or reflections of it, your eyes will close too slowly to prevent damage to your retina. There will be safety goggles which you must wear at all times when doing alignment work on the setup.
- Before starting adjustments remove all reflecting objects (such as watches, rings or metal buttons) from your hands and wrists.
- Keep the laser beams at table height and your eyes well above the table.
- No laser beam should leave the table. There will be black anodized aluminum plates to block stray reflections.
- You will use expensive, fragile optical equipment. See Section 6.2 for a look into the room and equipment. Do not touch any of the optical surfaces with your bare fingers. In case this happens accidentally, tell your tutors and ask them to clean the components for you. Do not attempt to clean the components yourself, the coatings might get damaged.
- Never let the optical components rest face down on the table or on any other hard surface. Put the components back into their mounts and fix them when they are not used. Be careful when handling them, do not drop them!
- Do not turn the alignment screws too tightly, the threads will wear out, especially the ones of the mirror mounts.
- The laser diode is extremely sensitive to even tiny electrical shocks, which can destroy your laser within fractions of a second. It takes months and about 20.000 Euros to replace it! To prevent unnecessary laser death do not disconnect the laser from its control unit. Do not touch any settings on the controller, unless the supervisor has given the OK.
- Although some people can see light of 794 nm directly, an infrared sensor card and a surveillance camera will be available. They should be used to trace out the paths of the laser beams. Do not loose the cards and always place them in an easy-to-see spot.
- A mechanical beam blocker (red slider) directly at the laser output port can be used to block the laser light independently of the control unit. Make use of it to feel more comfortable moving optics while no laser beam on table.
- Please do not touch/move the two mirrors directly behind the laser. They are used to put the beam onto the correct height to fit all the optical elements used in this lab course. They are not meant for you to align the beam.

- It is good practice to have the laser beam always at a fixed height and follow holes for easy track of beam path. During conducting this experiment, you will be required to deviate from the holes.

## 3 Equipment

- The heart of the experiment is a commercial diode laser system (Model DLC DL Pro from Toptica). It is an extended-cavity laser with feedback from an external grating mounted in Littrow configuration. More details can be found in Part III of the manual available in the lab. The laser diode operates nominally at  $\lambda = 794\text{ nm}$  and delivers an output power of about 7 mW, which can be dangerous to the eyes.

CAUTION: Before turning on the Electronic Control Unit (ECU) make sure that all cables between the ECU and the laser are connected. Connecting these cables after the unit is turned on may instantly kill the laser! Replacing the laser is costly, tedious, and might take weeks.

- Control Unit of the diode laser. It features:
  - **In general** To turn on the power supply, turn the key *after* you have checked that the controls for the scan are switched off. The temperature stabilization should be activated (this should be checked by the supervisor). The monitors for current and temperature will tell you the actual values.
  - **Temperature Control** After turning on the power supply, switch on the temperature control first and set it to the appropriate value, which the supervisor will tell you. If you feel you must change this value check with your supervisor first. It should only be changed in the presence of the supervisor. Do not change the other settings, the stabilization might fail and the laser might be destroyed.
  - **Current Control.** It is turned on with the small switch on the middle right side of the unit. The laser current is adjusted using a big knob. By pressing it, the decimal position can be changed. Rotating it changes the value. The maximum value of the laser current is set to 100 mA. If you try to exceed it a light will flash and a sound will tell you not to do it again. Do not touch any other settings than the current control knob.
  - **Scan Control** Next check the Scan Control, which can be activated pressing the touch screen in the corresponding line. The laser frequency is scanned by tilting the grating with a piezo-electric ceramic (PZT). The Scan Control Unit allows to apply a ramped voltage to the PZT. You will need to set the amplitude and offset of the scanning voltage (i.e. grating angle) by turning the appropriate knobs. Connect the TRIGGER output to the EXT TRIGGER input of the oscilloscope to allow recordings of spectra synchronized with the scan ramp. To switch off the scan set the switch CONT./ EXT.TRIG. to the EXT.TRIG. The unit will then wait for an external trigger signal and stop scanning.
  - **Feed Foward** In order to extend the mode-hop free scanning range, enable the feed forward control by pressing the touch screen in the corresponding line.
- 8 mirrors with mounts (the 2 after the laser should not be moved!!),
- 1 glass wedge,

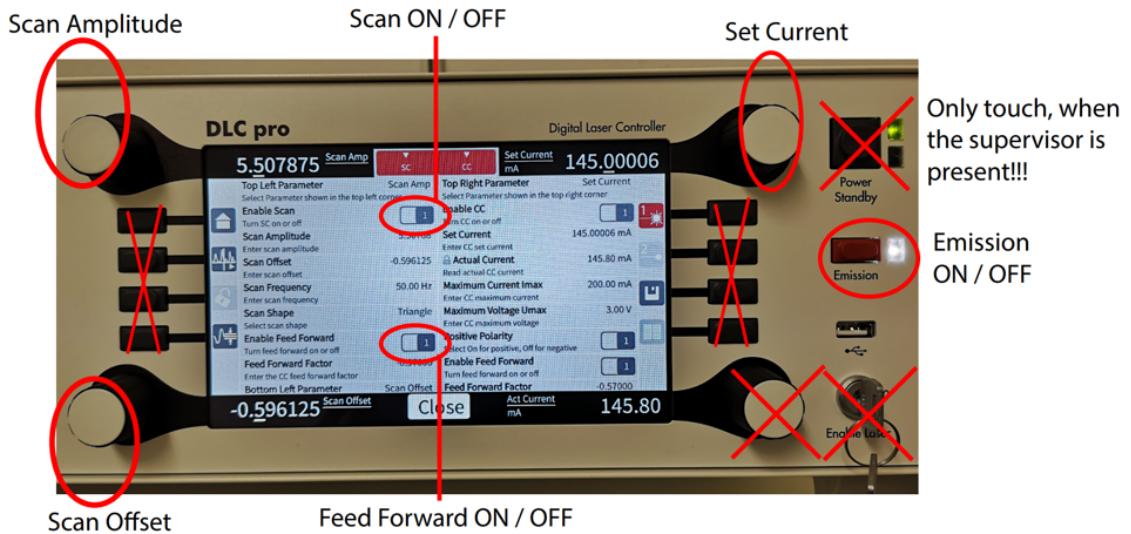


Figure 1: Laser controller.

- 6 lenses  $f = 50 \text{ mm}$  (3x),  $f = 100 \text{ mm}$  (2x),  $f = 200 \text{ mm}$  (1x),
- $\pm 15 \text{ V}$  power supply with 5 ports for power meter, camera and photodiodes,
- one power meter,
- 3 photodiodes with a reverse bias of  $-15 \text{ V}$ , one photodiode is calibrated ( $10 \text{ k}\Omega$  current-to-voltage converting resistor) to give a direct reading of the power on the power meter in  $\mu\text{W}$ . Two of the photodiodes have  $100 \text{ k}\Omega$  resistors.
- 4 optical attenuators (neutral density filters),
- one confocal Fabry-Pérot interferometer (mirror separation of 50 cm, mirror reflectivities of 85 %),
- one two-channel digital storage oscilloscope ISO-TECH IDS 8062,
- 2 vapor cells (length 2 cm and 5 cm) with a natural mixture of both rubidium isotopes,
- (at least) two infrared-sensitive viewing cards (charge with room light),
- one infrared-sensitive camera with monitor.

## 4 Theoretical background

This section covers all the topics relevant to conduct the experiment. You will be examined on these topics at the beginnig of the first day of the lab course.

### 4.1 Diode laser characteristics

In 1962 laser operation in suitable semiconductor devices was achieved for the first time. Driven by demands for efficiency, reliability, and ease of use tremendous efforts have been made since then to develop the first laboratory prototypes of diode lasers into commercially interesting devices. Today diode lasers constitute an indispensable ingredient of modern communication infrastructure (light sources for fiber optic communication links) and various consumer devices (Audio-CD, CD-ROM). Hundreds of millions of laser diodes are produced every year for these markets.

Beginning in the 1980ies diode lasers were sufficiently advanced to be interesting also for applications in spectroscopy. They are now a widely used source of narrow-band and frequency-tunable radiation. Because of the very qualities that make them interesting for commercial applications they have also caused a small revolution in the study and manipulation of atoms, ions, molecules, and clusters. Many modern experiments in physics rely on the complex interplay of several laser sources and are possible only because of the simplicity and reliability of diode lasers.

The basic principle of operation of a semiconductor laser can be explained with the help of a simple p-n junction (a diode) in a direct band gap semiconductor crystal. When the diode is biased in the forward direction electrons from the n-side of the junction and holes from the p-side meet and recombine in the vicinity of the junction under emission of light with a wavelength corresponding to the gap energy of the semiconductor material. The semiconductor crystal is cleaved along two lattice planes perpendicular to the junction plane. These crystal faces form the two end mirrors of a Fabry-Pérot laser cavity. For GaAs with an index of refraction of 3.5 the Fresnel reflection from the crystal faces is about 31%, enough to overcome the optical losses and lead to laser oscillation when the current  $I$  injected into the p-n diode is higher than the threshold current  $I_{\text{thr}}$ . For  $I < I_{\text{thr}}$  the laser diode behaves similarly to a light-emitting diode (LED) whereas for  $I > I_{\text{thr}}$  a coherent output beam is emitted. Ideally the output power increases linearly with  $I - I_{\text{thr}}$  until at some point the optical intensity at the output facets becomes so high that the facets are damaged and the diode is irreversibly destroyed.

Modern designs are much more complicated than just a simple p-n junction. A typical diode laser consists of tens or even hundreds of layers of different semiconductor materials of well-defined thickness, designed in such a way as to confine both the charge carriers and the generated light to a narrow region, the so-called active zone. This zone is typically 100–300 nm high in the direction perpendicular to the junction plane, 5 μm wide at the output facets, and 0.3 mm long. This asymmetry in the cross section of the active zone is one of the reasons for the strongly elliptical profile of the output beam. The smallness further means that the laser beam is highly divergent (typically more than 20° opening angle) so that a high-quality lens system is required close to the diode output facet in order to collect and collimate the output beam. In the best designs (multiple quantum well lasers) the conversion of electrical into optical power has an efficiency of more than

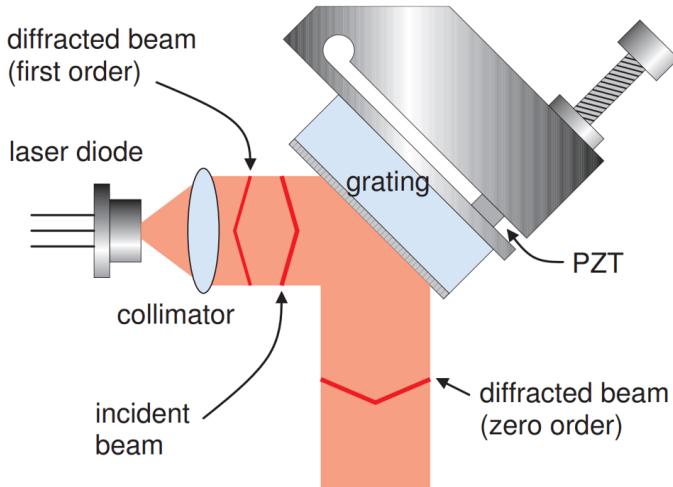


Figure 2: Diode laser with extended-cavity using diffraction from a grating in Littrow configuration. PZT: piezo-electric transducer.

50 percent, making diode lasers the most efficient of all laser types.

Solitary laser diodes have linewidths of typically  $\Delta\nu \approx 20$  MHz. This width can be reduced greatly by optical feedback from a frequency-selective optical element.

The arrangement chosen here (Fig. 2) has become a standard for high-precision laser spectroscopy [7]. The laser beam is incident on a diffraction grating (1800 lines/mm) at such an angle that the minus first diffraction order is sent back into the laser (Littrow configuration). In our setup the diffraction efficiency is about 20% so that most of the output power is available in the zeroth diffraction order. It should be noted, however, that the narrowing of the emission linewidth is not due to the frequency selectivity of the grating itself but mainly to a combination of two effects. The more obvious one is the improvement in the quality of the diode laser resonator because its optical length is now a few cm instead of  $0.3\text{ mm} \times 3.5 \approx 1\text{ mm}$ . Another reason is the complicated dynamics inside the laser gain material itself when part of the output light is fed back into it with a phase delay. The overall effect of the properly aligned grating is a line narrowing to approximately 1 MHz. For a detailed description see [7, 8, 9].

Another beneficial effect of the grating is a reduction in the sensitivity of the laser to uncontrolled optical feedback. When only  $10^{-6}$  of the emitted light is scattered back into the laser (for instance by lens surfaces or cell windows) this would already be enough to affect the frequency stability of a solitary laser diode. While for the most demanding applications expensive precautions against unwanted optical feedback have to be taken this is not necessary in the setup used here.

For spectroscopic purposes it is essential that the output wavelength can be chosen and tuned reliably. The laser wavelength is primarily determined by the semiconductor material itself: it corresponds roughly to the band gap energy but can be adjusted to some degree by proper design of the sequence of layers within and surrounding the active layer. In the manufacturing process the desired wavelength is usually reproduced to within a few nanometers. Around this center wavelength there is a broad gain profile where laser emission is possible in principle on a number of modes of the Fabry-Pérot resonator formed by the laser diode facets. It is essential to be able to tune the resonance frequency of one

of these modes to exactly the desired value and then to make the laser oscillate on this one mode only.

There are various means of tuning the laser output wavelength/frequency to the desired atomic transition.

- **Laser temperature**

With all other parameters fixed the output frequency of a GaAs laser decreases for increasing temperature. This temperature dependence is a combination of two effects, one of them an overall shift of the gain profile of the diode laser material. The second effect is a change of the diode length due to thermal expansion. This causes the pattern of Fabry-Pérot modes to move across the gain profile, thus making different output wavelengths possible. In the experiment an electronic servo loop stabilizes the diode temperature to the value required to move the overall gain profile to the 794 nm absorption line of rubidium. This temperature can drift slightly due to ageing of the diode; the current value can be obtained from the supervisor or the lab notebook.

**Warning:** Because of the thermal inertia of the setup it can take some time until the laser has stabilized to a new temperature value. The diode temperature is therefore unsuitable for the rapid scanning of the laser output frequency. If you feel you must change the temperature to make the laser operate at the desired frequency, check with your supervisor first!

- **Laser current**

Changing the injection current causes small changes in the refractive index of the gain medium because of the changing carrier density. The main effect is, however, a change in ohmic heating of the laser junction due to the finite quantum efficiency of the device. Since this heating mostly occurs within the small active layer it is not subject to the same delays as a change of the total laser diode temperature. This internal heating effect therefore allows to scan or to modulate the laser at rates of up to a few MHz. For even faster current modulation the thermal effect is too slow again, and only the smaller carrier concentration effect remains. Adjusting the current is the most sensitive way to tune the laser.

- **Grating angle**

For fixed diode temperature and injection current optical feedback from the external diffraction grating is only possible within a narrow range of angles, determined by the spectral dispersion of the grating. Within this range a change in grating angle causes a change in the output wavelength of the combined laser–grating system due to the complicated interplay of gain medium dynamics and optical feedback. In particular, the positions and the losses of the individual Fabry-Pérot modes are modified such that under optimum conditions it is possible to reach laser oscillation for only a single one out of the many modes. This single-mode operation is essential for the laser spectroscopy experiments to be performed here. Under the single-mode condition one can tune the laser by slightly changing the grating angle via the PZT.

Because there are so many effects that influence the laser output frequency, special care has to be taken to make all these effects compatible with each other over a wide tuning

range. For instance, for both temperature and current tuning the gain profile of the laser medium and the positions of the Fabry-Pérot modes do not necessarily shift at the same rate. This will eventually cause mode hops: the laser output frequency jumps to a different Fabry-Pérot mode. There are also instability regions where no single-mode operation is possible and the laser repeatedly jumps between different modes or even operates on several modes simultaneously. Mode hops or multi-mode operation can also occur when the grating angle is changed because this, too, alters the losses for the individual modes.

In the experiment the tuning is performed by tilting the grating periodically with the help of a piezo element. If this scan range is too wide mode hops will occur. It is possible to extend the single-mode scanning range by using a so-called “feed forward” technique: a copy of the grating piezo voltage is suitably attenuated and added to the diode injection current. This synchronization of grating angle and injection current allows to tune the specific mode of interest over a much wider output frequency range before another mode becomes more favorable for the laser system and a mode hop occurs.

## 4.2 Fabry-Pérot interferometer

In the experiments a confocal Fabry-Pérot interferometer (FPI) will be used to produce a frequency reference for the atomic spectra. The FPI consists of a resonator formed by two spherical mirrors (radius of curvature of 500 mm; reflectivity of  $R = 0.85$  at 794 nm) separated by a distance of  $L = 500$  mm in air. The mirror separation is defined by a quartz tube and stainless steel mounting rings in such a way that the thermal expansion of both materials compensate each other. The brass tube surrounding the interferometer is used as a thermal mass to ensure that the quartz and the steel are at the same temperature.

Details on the properties of FPI’s can be found in standard textbooks on optics (see e.g, [5, 6]). The characteristic feature of the FPI is a periodic resonant transmission of the laser beam given by

$$T_{\text{FPI}} = \frac{1}{1 + F \sin^2 \frac{\varphi}{2}}, \quad (1)$$

with

$$F = \frac{4R}{(1 - R)^2} \quad (2)$$

where  $R$  is the mirror reflectivity. The phase  $\varphi$  accumulated in one round-trip is given by

$$\frac{\varphi}{2} = nk_0 L = \frac{2\pi nL}{\lambda_0} = \frac{n\omega L}{c}. \quad (3)$$

The transmission peaks are equally spaced in frequency with a separation (called free spectral range, FSR) of

$$\Delta\nu_{\text{FSR}} = \frac{c}{2nL}, \quad (4)$$

where  $n$  is the index of refraction of the medium between the mirrors (here air, i.e.  $n = 1$ ) and  $c$  the speed of light.

In the case of highly reflecting mirrors (i.e.  $F \gg 1$ ) the FWHM of the transmission peaks is given by

$$\delta\nu_{\text{FWHM}} = \frac{\Delta\nu_{\text{FSR}}}{\mathcal{F}}, \quad (5)$$

where

$$\mathcal{F} = \frac{\pi\sqrt{R}}{1-R} \quad (6)$$

is called the finesse of the interferometer.

The resonator modes discussed so far are called longitudinal modes. The laser may also excite a large number of transverse modes which in general have different resonance frequencies. For a confocal mirror arrangement, when the radius of curvature of the mirrors is equal to the cavity length, as in the present case, all even-symmetry transverse modes ( $\text{TEM}_{00}$ ,  $\text{TEM}_{11}$ ,  $\text{TEM}_{02}$ ,  $\text{TEM}_{20}, \dots$ ) are degenerate at the longitudinal mode frequencies and all odd-symmetry modes ( $\text{TEM}_{01}$ ,  $\text{TEM}_{10}$ ,  $\text{TEM}_{12}$ ,  $\text{TEM}_{21}, \dots$ ) are degenerate at the frequencies midway between them [6]. Then the total spectrum of the cavity will exhibit a mode spacing of

$$\Delta\nu_{\text{mode}} = \frac{\Delta\nu_{\text{FSR}}}{2} = \frac{c}{4nL}. \quad (7)$$

The mode spacing of the FPI was calibrated at the Institut für Angewandte Physik:

$$\Delta\nu_{\text{mode}} = 149.9348(2) \text{ MHz}. \quad (8)$$

### 4.3 Linear absorption spectroscopy of rubidium

Natural rubidium consists of the two isotopes  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$ . Some of the atomic properties of these isotopes are summarized in the table in chapter 6.1. Rb was chosen for this course because the resonance absorption lines of alkali atoms are very strong and have a simple structure. Moreover, Rb (and also Cs) have a relatively high vapor pressure so that the experiments do not require the use of heated samples. The Rb atoms are present as saturated vapor in evacuated Pyrex cells (of length 20 and 50 mm) containing a droplet of the metal. The vapor pressure, i.e. the atomic number density, is determined by the temperature of the metal-vapor interface.

In the experiments the  $D_1$  resonance line corresponding to the transition from the ground state  $5^2S_{1/2}$  to the lowest-lying excited state  $5^2P_{1/2}$  will be investigated. The resonance wavelength of this transition is around 794 nm.

All alkali atoms have a  $^2S_{1/2}$  ground state which splits into two levels by the hyperfine interaction between the valence electron and the nucleus. The same interaction also splits the excited state into two distinct levels. A schematic representation of the level structure of the two Rb isotopes is shown in Fig. 3.

The selection rules for electric dipole transitions are  $\Delta F = 0, \pm 1$  so that the absorption spectrum of each isotope consists of 4 isolated lines, some of which may be masked in the experimental spectrum because of the finite linewidth of the individual spectral lines. A typical spectrum is shown in Fig. 4.

**Spectral resolution** The spectral resolution of an optical frequency spectroscopy setup quantifies how well atomic resonances can be resolved. It is defined by the ratio  $\Delta\nu/\nu$ , with  $\Delta\nu$  the spectral width of an optical transition line at a frequency of  $\nu$ .

**Hyperfine interaction** The hyperfine interaction results from the interaction of the nuclear magnetic moment with the magnetic moment of the valence electron. For  $S_{1/2}$  states

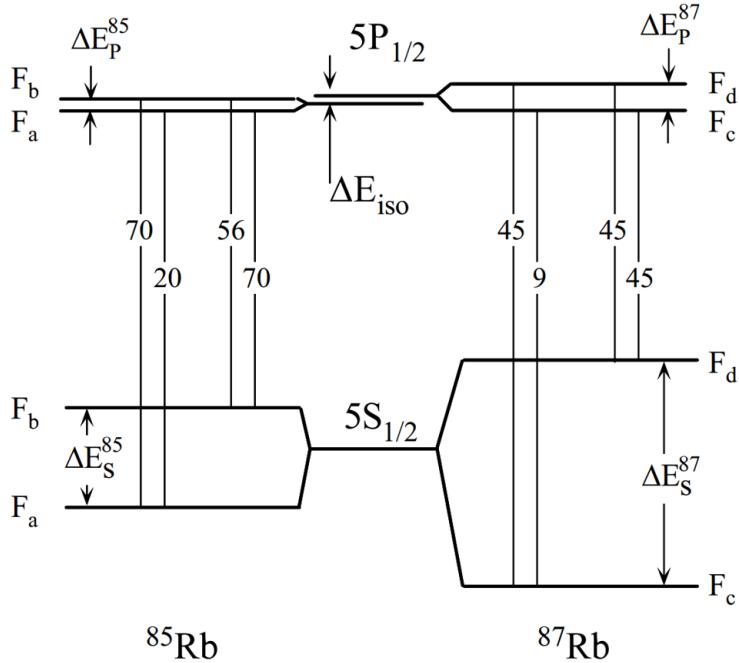


Figure 3: Term diagram of the two lowest energy levels of  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  including hyperfine structure.  $\Delta E_{\text{iso}}$  is the isotope shift. The numbers on the vertical lines give the relative transition probabilities for each isotope.

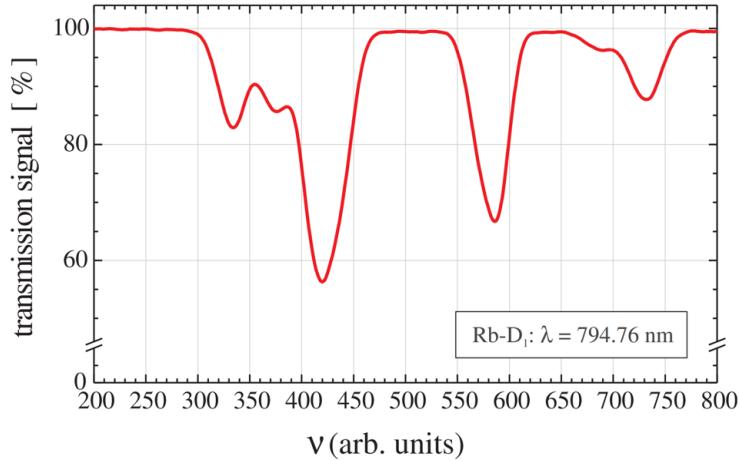


Figure 4: Hyperfine structure of the  $D_1$  absorption spectrum recorded with a 20 cm vapor cell containing a natural mixture of  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  vapor at room temperature

the h.f. interaction is determined by the Fermi contact interaction, a purely quantum-mechanical effect, while for  $P_{1/2}$  states it is determined by the dipole-dipole interaction. For states with  $J = 1/2$  there is no contribution from the electric quadrupole interaction. The Hamiltonian of both the contact and the dipole-dipole interaction can be parametrized by

$$\hat{\mathcal{H}}_{\text{hfs}} = A_{\text{hfs}}(nL_J) \vec{I} \cdot \vec{J}, \quad (9)$$

where  $\vec{I}$  and  $\vec{J}$  are the nuclear and electronic angular momenta.  $A_{\text{hfs}}(nL_J)$  is called

the hyperfine coupling constant.

#### 4.4 Doppler-broadened linear absorption spectroscopy

The transmission of a plane wave of frequency  $\nu$  through a medium of two level atoms (column length  $L$ ) is given by

$$T(\nu) = e^{-\kappa(\nu)L}, \quad (10)$$

which reduces to

$$T(\nu) = 1 - \kappa(\nu)L \quad (11)$$

when the medium is optically thin, i.e. when  $\kappa(\nu)L \ll 1$ . The absorption coefficient  $\kappa(\nu)$  for a linear medium of atoms at rest is given by

$$\kappa(\nu) = \kappa_0 \frac{(\Delta\nu/2)^2}{(\nu - \nu_0)^2 + (\Delta\nu/2)^2} \quad (12)$$

where  $\nu_0$  is the resonance frequency of the two level system and  $\kappa_0$  the absorption coefficient on resonance.  $\Delta\nu$  is the homogeneous or natural width of the transition (FWHM). It is related to the lifetime of the excited state by

$$\tau = \frac{1}{\gamma} = \frac{1}{2\pi\Delta\nu}. \quad (13)$$

If the atoms are in motion they will see the frequency of the light beam shifted by the amount  $\Delta\nu = kv$  due to the Doppler effect. Here  $k = 2\pi/\lambda$  is the wave vector of the light and  $v$  the velocity component of the atom along the  $k$ -vector. In this case the spectral profile has to be calculated by a convolution of the velocity distribution of the atoms  $N(v)$  and the absorption coefficient (Eq. 12)

$$\kappa_V(\nu) = \int N(v) \kappa(\nu - kv) dv. \quad (14)$$

This line shape is referred to as Voigt profile. For a Maxwellian thermal velocity distribution

$$N(v) = N_0 \exp \left[ -\left( \frac{v}{v_0} \right)^2 \right], \quad (15)$$

where  $v_0 = \sqrt{2kT/m_{\text{Atom}}}$  is the average thermal velocity of the atoms, the Voigt profile (Eq. 14) reduces to the Doppler profile

$$\kappa_D(\nu) = \kappa_D(0) \exp \left[ -\frac{(\nu - \nu_0)^2}{2\Delta\nu_D^2} \right] \quad (16)$$

when  $kv_0 \gg 2\pi\Delta\nu$  (Doppler limit).

$$\Delta\nu_D = \nu_0 \sqrt{\frac{kT}{m_{\text{Atom}}c^2}} \quad (17)$$

is the Doppler width of the transition. Note that  $\Delta\nu_D$  is not the same as the full width at half maximum (FWHM) of the absorption line. The broadening of spectral lines by the Doppler effect is an example of an *inhomogeneous* line broadening.

## 4.5 Non-linear spectroscopy of rubidium

When the optical excitation rate from the ground state to the excited state is much smaller than the (natural) decay rate of the excited state most of the atoms remain in the ground state and no appreciable fraction of atoms is found in the excited state. The spectroscopy in this case is referred to as linear absorption spectroscopy. Most experiments using spectral lamps as light sources are therefore in the domain of *linear spectroscopy*. The advent of the laser with its very high spectral brightness has opened the field of *non-linear spectroscopy*. As laser radiation is highly monochromatic (temporal coherence) and as it may be focused into small spatial regions (spatial coherence) it allows to achieve much higher optical transition rates than can be obtained with conventional light sources. One of the most widely used non-linear spectroscopic techniques is saturated absorption spectroscopy. One speaks of saturation when the excitation is so strong that in steady state an appreciable fraction of the atoms is in the excited state. As the absorption coefficient of a medium is proportional to the difference of the populations in the excited and ground state, a saturated medium is characterized by a smaller absorption. In the extreme case where the light intensity is strong enough to equalize the populations in the coupled states the medium will become completely transparent. It is the velocity dependent bleaching of the absorption properties which is at the basis of Doppler-free saturated absorption spectroscopy, a technique which allows to observe narrow spectral lines (e.g. Lorentzian shaped) inside the Doppler profile (Gaussian shape). Different variants of saturated absorption spectroscopy are discussed in many textbooks, as e.g. in [1, 3].

## 4.6 Saturation of optical transitions

A saturating light beam will affect the linear absorption coefficient of the medium given by Eq. 12. For atoms at rest the nonlinear absorption coefficient can be calculated explicitly and yields

$$\kappa(\nu) = \kappa_0 \frac{(\Delta\nu/2)^2}{(\nu - \nu_0)^2 + (\Delta\nu/2)^2(1 + S)}, \quad (18)$$

where the light intensity dependence is contained in the (dimensionless) optical saturation parameter  $S$ . It is proportional to the intensity  $I$  ([ $I$ ]=power/unit area) of the light field and is commonly parametrized as

$$S = \frac{I}{I_{\text{sat}}} = \frac{P}{P_{\text{sat}}}, \quad (19)$$

where  $I_{\text{sat}}$  and  $P_{\text{sat}}$  are the saturation intensity and saturation power of the beam. For a two-level system the saturation intensity may be expressed in terms of the decay rate  $\Gamma$  of the excited state as

$$I_{\text{sat}} = \frac{2\pi^2 hc\Gamma}{3\lambda^3}. \quad (20)$$

Note that the saturation parameter may also be written as

$$S = \frac{\gamma_p}{\gamma}, \quad (21)$$

where  $\gamma_p$  is the optical pump or optical absorption rate, i.e. the number of photons absorbed per second by each atom. Eq. 18 reduces to the the linear absorption coefficient

when  $S = 0$ .  $\kappa_0$  is therefore the linear absorption coefficient on resonance. When atomic motion is considered Eq. 18 has to be convoluted with the Maxwellian distribution as discussed in the case of the linear absorption coefficient.

The resonant nonlinear absorption coefficient of atoms at rest is given by

$$\kappa(\nu = \nu_0) = \kappa_0(\nu = \nu_0) \frac{1}{1 + S} \quad (22)$$

and goes to 0 as  $S \rightarrow \infty$ . Note that the absorbed power  $\Delta P$  which is proportional to

$$\Delta P \propto \kappa P \propto \kappa S \propto \frac{S}{1 + S} \quad (23)$$

saturates at a constant asymptotic value. One can show that for a Doppler broadened medium the peak absorption coefficient and the absorbed power have the following dependencies on the saturation parameter

$$\kappa_D(\nu = \nu_0) = \kappa_{D0}(\nu = \nu_0) \frac{1}{\sqrt{1 + S}} \quad (24)$$

and

$$\Delta P \propto \frac{S}{\sqrt{1 + S}}. \quad (25)$$

This interesting feature — that the absorbed power in this case does not saturate, but rather keeps growing as  $S \rightarrow \infty$  — is due to the fact that the Doppler profile can be seen as a superposition of an infinite number of narrow homogeneous lines, one for each velocity class. While the absorption for the resonant velocity class saturates rapidly according to Eq. 22 the neighbouring velocity classes are only affected via the wings of their Lorentzian absorption coefficients and therefore saturate in a much slower way. Eq. 18 may also be interpreted as a Lorentzian with a power (intensity) dependent width  $\Delta\nu$

$$\Delta\nu(S) = \Delta\nu\sqrt{1 + S}. \quad (26)$$

This effect is called optical power broadening.

## 4.7 Saturated absorption spectroscopy

The experimental implementation of saturated absorption spectroscopy generally uses two counter-propagating laser beams of the same frequency: a strong pump beam and a weak probe beam.

Let us first consider the effect of the pump beam. In Fig. 5a we show the linear absorption coefficient, whose shape reflects the Maxwellian velocity distribution of atoms in the ground state. When a saturating laser beam (pump beam) traverses the medium it will transfer a certain number of atoms into the excited state. However, only a small subgroup of atoms, namely those whose velocity is in the range  $v \pm \Delta v/2$ , where  $v$  fulfills  $kv = \omega - \omega_0$  and  $k\Delta v = \gamma$  will be affected by this transfer. In frequency space this means that the saturating laser "burns" a hole of width  $\Delta\omega_B = \gamma$  into the spectral profile of the absorption coefficient  $\kappa(\omega)$ . This structure is called Bennett hole. This is shown in Fig. 5b. If both the (counter-propagating) probe and the pump beam traverse the cell, a given atom with a non-zero longitudinal velocity component will see one of the beams blue-shifted, while the other beam will appear red-shifted. The two laser beams will therefore interact with different classes of atoms and the probe beam will not be sensitive to the hole burned by the pump beam. This changes dramatically when both beams are tuned into resonance. In this case both beams will interact with the same (zero-velocity) class of atoms and the probe beam will feel the modified absorption (Fig. 5c). The absorption coefficient of the probe beam will therefore be the usual Doppler-broadened profile with a narrow structure with decreased absorption at the center of the line. This spectral profile, described by a Lorentzian function, is called "Lamb dip".

Let us extend the discussion to atoms with one ground state and two excited states,

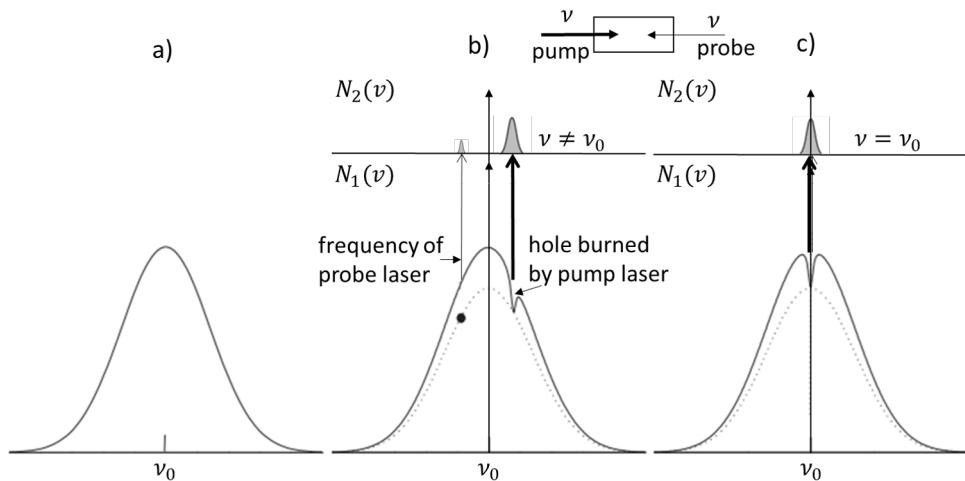


Figure 5: Origin of Lamb dips. a) Linear Doppler-broadened absorption profile. b) Bennett hole burnt by off-resonant pump laser. The hole is can be understand as atoms being pumped out of the ground state population  $N_1(v)$  and into the excited state  $N_2(v)$ . In the configuration of pump and probe addressing different atom classes, the hole is not seen by the probe laser. c) Bennett hole burnt by resonant pump laser. The hole is seen by the probe laser and is called a Lamb dip.

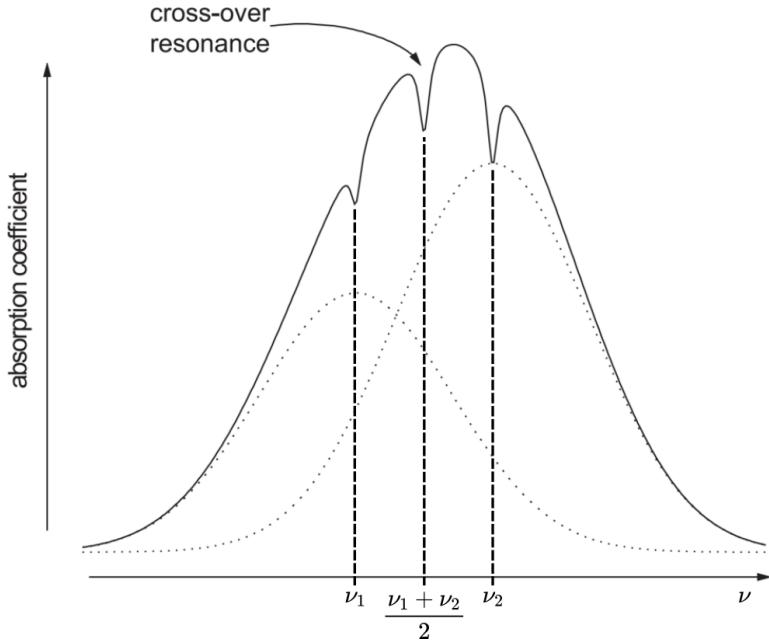


Figure 6: Lamb dips and a cross-over resonance inside the contour of an unresolved Doppler-broadened line. The unresolved individual resonances at  $\nu_1$  and  $\nu_2$  are shown as dotted curves with their respective Gaussian lineshape. In between the two lines, a crossover resonance, with a Lorentzian shape, is created.

whose spectral separation is less than the Doppler width. In linear spectroscopy, one can not resolve the resonances corresponding to the two transitions  $\nu_1$  and  $\nu_2$  (dotted curves in Fig. 6). In a saturated absorption spectrum one would naively expect two narrow Lamb dips inside of the Doppler contour. In the experiment, however, one will observe an additional narrow resonance centered exactly at the average frequency of the two Lamb dips. This structure is called a "cross-over" resonance (Fig. 6). It results from atoms moving at a velocity such that the pump beam is at resonance with one transition and the probe beam at resonance with the other one. In this case the hole burned by the pump laser into the ground state velocity distribution is also seen by the probe laser.

## 5 Things to do

### 5.1 General experimental hints

- **Digital storage oscilloscope:** For data acquisition and storage there is a digital oscilloscope. You can choose different resolutions for one scan: 500 or 12500 (25000) points. Always use the high resolution. This is especially important for measuring the lamp dips. Press “Acquire” and select the right “Memory length”.

Regarding the vertical scale, also try to zoom into the signal as much as possible to achieve also a good vertical resolution and not suffer from digitization losses.

Before storing the data, you can use averaging to improve the signal-to-noise ratio when the signal is sufficiently stable (no horizontal drifts): press “Acquire” and select “Average”.

The data you take is stored on an USB-stick. Press “Save/Recall”, then select “Save Waveform”. Always use the “Save All” function to make sure that you store all comma separated raw data and not only a screenshot. If possible, check the data you store for validity.

- **Photodiodes:** For recording the atomic spectra and the FPI transmission spectra, there are two non-calibrated photodiodes with a high sensitivity. Their (inverted) output is linear in the range 0 ... – 10 V. If possible, try to maximize the signal but stay in the linear range.

### 5.2 Diode laser characteristics

- Measure the dependence of laser output power as a function of injection current and plot the results. Determine the threshold current and the slope efficiency  $\partial P_{\text{out}} / \partial I$  above threshold, as well as the quantum efficiency of the laser, i.e. number of photons emitted per injected electron.

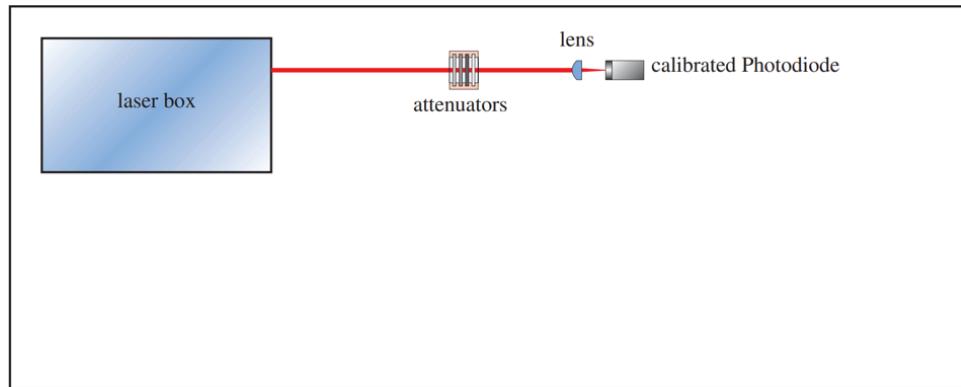


Figure 7: Experimental setup for the measurement of laser output power vs. injection current.

**Hints for experiments** Before switching on the laser (using the button), check that scan controls are *switched off*. In order to align and tune the laser to the desired resonance frequency, you should first set the temperature to the latest value given in the lab book or told by your supervisor. This temperature setting is mostly already done by the tutor. This value will change when the diode is aging. Wait for the temperature to stabilize (approx. five minutes). Next switch on the current control and increase the current until you see emission of infrared light from the laser on the sensor card. The laser characteristics should be measured with a fixed laser frequency. Therefore switch on the scan unit, but set its trigger mode to EXT.TRIG. In this mode the Scan Unit will wait for a trigger signal and will not scan the laser frequency as desired, here (until a trigger signal would be detected). The output power can be measured by focusing the output beam with a lens onto the calibrated photodiode. The Si-photodiode needs a -15 V power supply and will yield a direct reading in  $\mu\text{W}$  of the laser power on the powermeter. Make sure that the photodiode does not saturate, i.e. that its output voltage is below 1.4 mW. In case of saturation reduce the light power by putting an attenuator in front of the photodiode (as shown in Fig. 7).

### 5.3 Use of the Fabry-Pérot interferometer

- Verify Eqs. 5 and 6 which relate the fringe width to the FSR of the FPI. What is the expected finesse of the FPI by assuming that it is only determined by the finite mirror reflectivity ( $R=0.85$ )?
- Couple the laser into the FPI and display the FPI mode structure on the oscilloscope. Measure the finesse of the FPI using the value for the FSR (Eq. 8) given above. Compare to your theoretical value.
- Evaluate the fringe spacings to get a calibration curve. Use it for the subsequent spectroscopic measurements to gauge the time axis in a relative frequency scale. If the fringe spacing distant is not constant, what could be the cause? What are the consequences for calibrating the frequency axis?

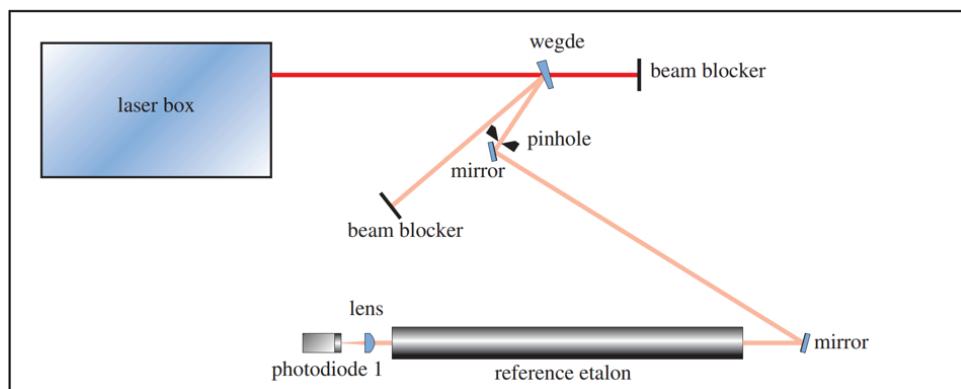


Figure 8: Experimental setup for the measurement of the finesse of the Fabry-Pérot etalon.

**Hints for experiments:** In order to use the FPI you have to align the laser beam very carefully. A suggestion for the setup is shown in Fig. 8.

Use the viewing cards to visualize the path of the infrared beam. The glass wedge should be used to generate two weak auxiliary beams, one of which should be coupled into the FPI. Make sure you position it correctly to implement the setups used e.g. for the non-linear part, see Fig. 10. Make sure to block the unused beams. The beam directed to the FPI should pass through the pinhole in order to prevent reflections from the FPI into the laser. Two adjustable mirror mounts will provide the necessary degrees of freedom to couple the beam from behind the pinhole into the FPI. Observing the reflected light from the FPI using a piece of paper with a hole can help to align the beam perpendicular to the incoupling mirror. The transmitted laser beam should be focused onto a photodiode with a lens. In order to record the transmission spectrum of the FPI you should display the transmitted infrared power on the oscilloscope while scanning the laser frequency.

## 5.4 Linear spectroscopy of the $D_1$ transition of Rb

- Knowing that the total angular momentum  $\vec{F}$  of an atomic state is given by  $\vec{F} = \vec{J} + \vec{I}$  and that the nuclear spins  $I$  of  $^{85}\text{Rb}$  and  $^{87}\text{Rb}$  are  $5/2$  and  $3/2$  respectively, show that the levels  $S_{1/2}$  and  $P_{1/2}$  split into two hyperfine levels due to the hyperfine interaction. Assign numerical values to all the  $F$  quantum numbers of Fig. 3. Express the hyperfine splitting  $\Delta E$  of each state  $nL_J$  in terms of the hyperfine coupling constants  $A(nL_J)$  given by Eq. 9.
- Using the level scheme of Fig. 3 make separate sketches of the expected absorption spectra of the  $D_1$  lines for both isotopes. Superpose the spectra and shift them relative to one another to account for the isotope shift. Try to identify the lines by comparing your theoretical spectra with the experimental spectrum of Fig. 4.
- Build up an experimental arrangement (Fig. 9) to measure the linear absorption spectrum of Rb. Record simultaneously the Rb absorption spectrum and the transmission spectrum of the FPI. Identify the lines in the spectrum and determine the hyperfine coupling constant of the ground state of both isotopes. Determine the spectral resolution  $\Delta\nu/\nu$  of this linear spectroscopy by using an isolated line in your recorded spectrum? What can you say about the excited state hyperfine splittings?
- Determine the isotope shift (optional).
- Identify an isolated line in the spectrum and determine its FWHM. Check in your sketched expected absorption spectrum for an isolated line. Derive the relation between the theoretical Doppler-FWHM and  $\Delta\nu_D$  (Eq. 17), and compare the experimental FWHM with the theoretical FWHM at room temperature.
- Compare the absorption spectra of the two cells and verify the Lambert-Beer absorption law. Consider again an isolated line and record the transmission around that line for the three cell arrangements  $2\text{ cm}$ ,  $5\text{ cm}$  and  $2 + 5\text{ cm}$ .

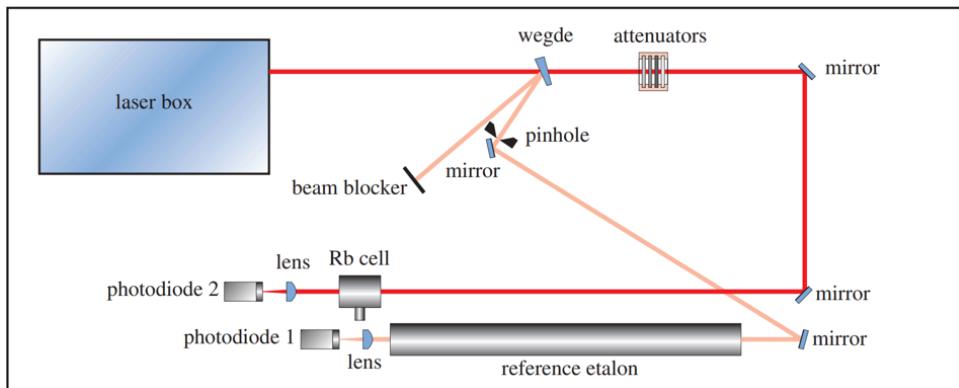


Figure 9: Experimental setup for linear absorption spectroscopy.

**Hints for experiments:** Use the longer cell and attenuate the laser power entering the cell to a level of  $20 \mu\text{W}$ . Tune the laser frequency to the vicinity of the resonance lines by using the injection current. Using the CCD camera from the side you will identify the correct wavelength setting by the appearance of fluorescence. Check the output of the FPI to make sure that the laser runs single mode, i.e. nice symmetric peaks with regular spacing, no sub-structure. Try to adjust the control parameters of the scan so that the whole spectrum is displayed on the oscilloscope without mode-hops. Use a second oscilloscope channel to display the power transmitted through the FPI in order to calibrate the time axis in frequency units. In order to get the best signal and the photodiode, you can use the two mirrors before the Rb cell and adjust the beam pointing for the cleanest Rb spectrum on the oscilloscope.

## 5.5 Non-linear spectroscopy of the $D_1$ transition of Rb

- Set up a pump-probe configuration to measure the saturated absorption spectrum of Rb. Identify the sub-Doppler resonance lines and the cross-over lines in the spectrum. Measure the hyperfine splittings in the ground and excited states of both isotopes and determine the corresponding hyperfine coupling constants. What is the resolution  $\Delta\nu/\nu$  that can be achieved with this non-linear spectroscopic technique?
- Identify the  $5S_{1/2}(F=2) \rightarrow 5P_{1/2}(F'=1)$  hyperfine component of  $^{87}\text{Rb}$ . Measure the amplitude  $A$  and the width  $\Delta\nu$  of the Lamb dip of this line as a function of pump laser power. From the plots  $A$  vs  $P_{\text{pump}}$  and  $(\Delta\nu)^2$  vs  $P_{\text{pump}}$  determine the saturation power  $P_{\text{sat}}$ . Estimate the beam diameter and determine the saturation intensity  $I_{\text{sat}}$ .

**Hints for experiments:** Follow the outline of Fig. 10 to set up the non-linear spectroscopy using a strong pump beam and a weak probe beam counter-propagating through the absorption cell. Use the beam transmitted through the wedge as pump beam and a reflected beam from the wedge as probe beam. Focus the probe beam onto a photodiode. Scan the laser frequency and display the transmitted probe beam intensity as well as the FPI transmission on two oscilloscope traces.

The camera and the viewing cards will help you to align both beams and to make sure that they have a maximum overlap inside the cell. In order to realize this the path

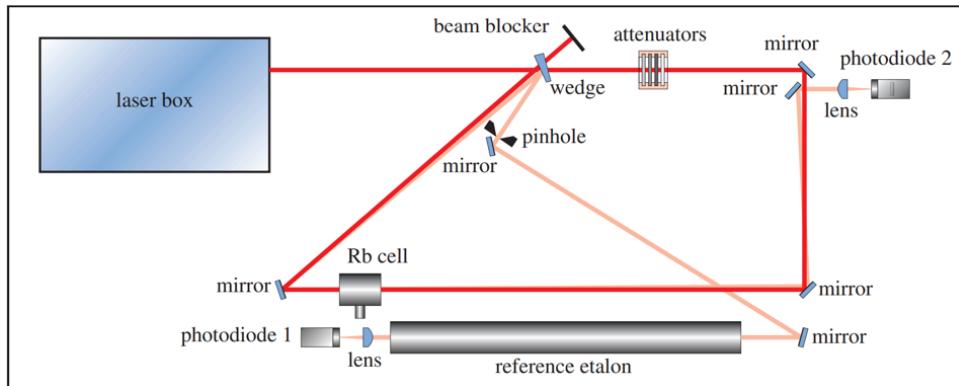


Figure 10: Experimental setup for a non-linear saturated absorption spectroscopy

of the pump beam between the beam splitting wedge and the cell should be as long as possible. Once you see saturation dips in your spectra, maximize the depths of the dips by making fine-adjustments of the overlap using the first mirror the pump beam hits after passing through the wedge. Make sure to block the pump beam behind the cell and all its reflections, so that no beams walk off the table. Use different combinations of the neutral density filters to vary the intensity of the pump beam.

The depth and the width of the dips can be measured using cursors on the oscilloscope or better by plotting and fitting a function on a computer using e.g. python. For the first part, try to fit the whole spectrum at once considering a sum of multiple Gaussian and Lorentzian functions (with different sign). For the width and depth analysis, you can only record the asked transition on the oscilloscope.

# 6 Appendix

## 6.1 Atomic constants

	$^{85}_{37}\text{Rb}$	$^{87}_{37}\text{Rb}$
natural abundance	72.17%	27.83%
nuclear spin	5/2	3/2
atomic mass	84.9118 u	86.9092 u
$\tau(5P_{1/2})$	28.5 ns	28.5 ns

## 6.2 Optical setup

If this is the first time you are working with optical components, following the safety precautions should be your first priority and knowing how the lab room and the optical components look like might be helpful. If you have specific questions regarding the setup, do not hesitate to contact your tutor in advance to the lab course experiment. Fig. 11 shows the room where the experiment is carried out. On the left you can see the laser controller, the oscilloscope, and the monitor of the infrared-sensitive camera. To the right there is an optical table with various components arranged in an optical setup.

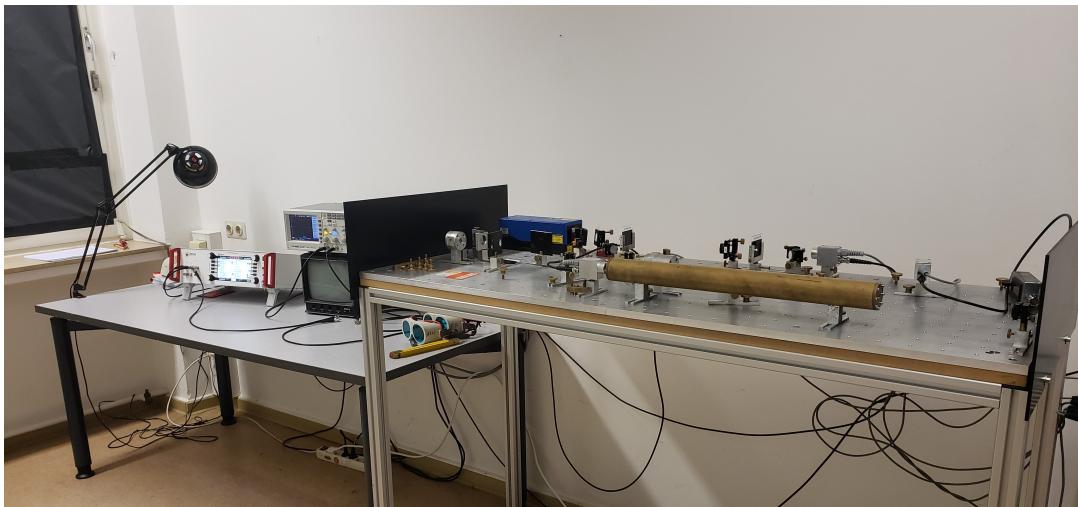


Figure 11: High resolution laser spectroscopy laboratory room.

Fig. 12 shows several of the components necessary for the execution of the experiment. Be careful to follow the safety precautions stated in section 1 and not to touch the two mirrors in front of the laser. They are used to bring the laser onto the correct height to be used during all the experiment parts to be conducted.

As a final comment, in Fig. 13 a) the glass wedge is shown in its optical mount with a representation of the incident, transmitted, and reflected beams. Fig. 13 b) shows the vertical and horizontal knobs that allow adjusting the propagation direction of the reflected beams. It is important to maintain all beams parallel to the optical table and to block all stray reflections.

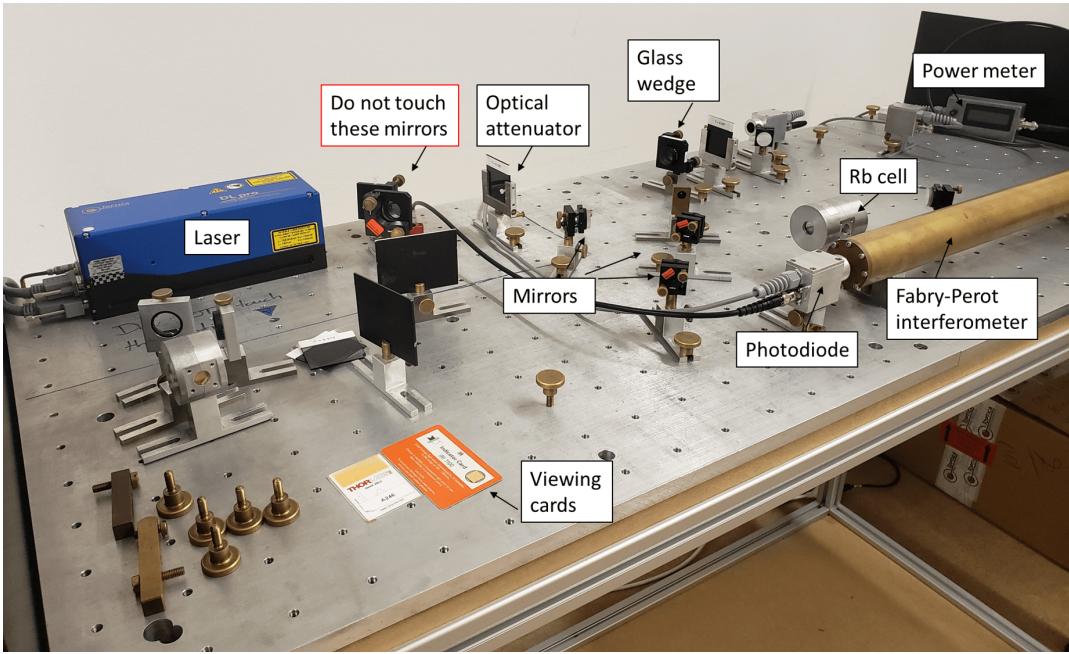


Figure 12: Optical setup. All the optical elements need to be screwed onto the optical breadboard. The most important components are labeled.

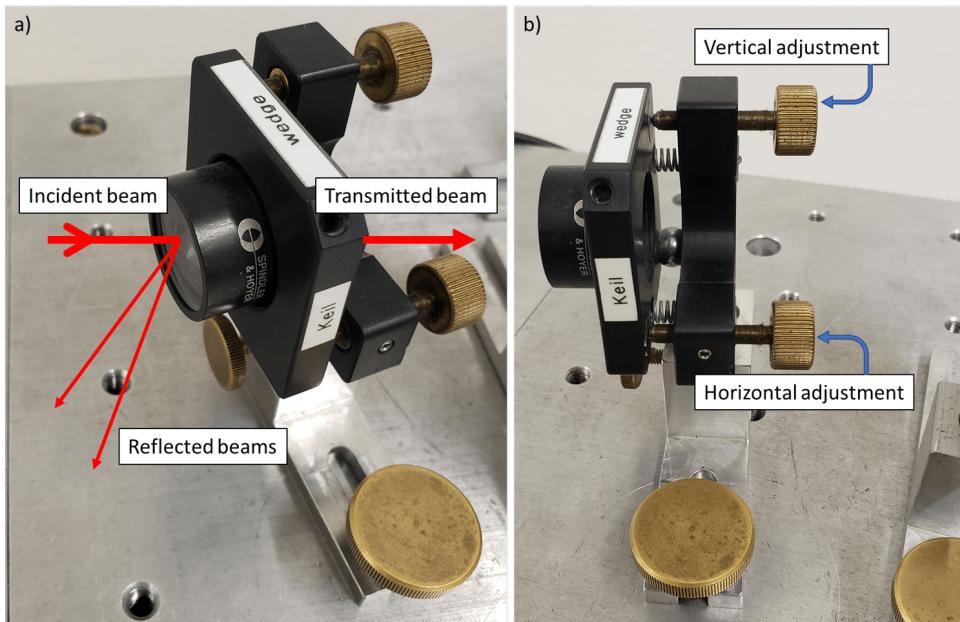


Figure 13: Glass wedge on its optical mount: a) Representation of the incident, transmitted, and reflected beams on the same plane. b) Vertical and horizontal adjustment knobs.

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