

Frequency locking of an external cavity diode laser

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Abstract

In this Bachelor's thesis an external cavity diode laser has been frequency locked. Saturation spectroscopy was used to resolve the sub-Doppler structure in the rubidium isotope ^{87}Rb and the laser frequency was locked against a transition between two hyperfine levels. This transition can be used for laser cooling and trapping in a Magneto-Optical Trap (MOT). This thesis is one in a series of projects with the aim of building a low cost MOT for demonstrations and laboratory exercises. The achievements in this thesis are an important step towards a working MOT.

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Chapter 1

Introduction

Lasers (Light Amplification by Stimulated Emission of Radiation) are used in a wide variety of fields. Some applications require more accuracy than a conventional laser can give. This can be overcome by active stabilization of the laser frequency. Frequency stabilized lasers are used as spectral reference [3], in some atomic clocks [5] and for high precision spectroscopy [6]. Another application is cooling and trapping atoms. The most widespread technique for cooling and trapping is in a Magneto-Optical Trap (MOT) which was awarded the Nobel prize 1997¹. In a MOT laser light is used to slow down atoms. The magnetic field is used, together with the laser light, to keep the atoms in place.

This thesis is a continuation of two previous Master's theses carried out at the division of Atomic Physics at Lund University, with the aim of building a MOT for teaching purposes. In 2004 Erik Mansten² started with a design study of a MOT [1]. The work was continued by Stefan Magnusson 2005 who constructed most of the components in the MOT but never got to see it running [2]. The main reason was that the active locking of the laser frequency was not working. Five years later this project was initialized with the aim to lock the lasers. The laser frequency is now locked against a transition between two hyperfine levels in rubidium-87 but modifications and fine tuning are necessary to operate the MOT.

This thesis is structured as follows: In chapter 2 a theoretical background to the project is given. The laser, atomic structure of rubidium, saturation spectroscopy and automatic control are explained here. Chapter three describes the experimental setup and practical aspects considering the laser and controller. Finally parts of chapter 3 and appendix B give useful information for students who will continue this series of projects finishing the MOT.

¹S. Chu, Cohen-Tannoudji and W.D. Phillips [4]

²Erik Mansten's name was Erik Gustafsson year 2004.

Chapter 2

Theory

2.1 Laser

All lasers have some properties in common. They have confined beams with coherent light emitted with a well defined wavelength¹. Most lasers consist of two main parts: a gain medium and a cavity. The gain medium acts as an amplifier. Every atom has its own structure with protons, neutrons and electrons. The forces between these basic building stones will create a unique structure for every different element giving it its own structure of energy levels. When shining light on atoms the incoming photons might be absorbed exciting electrons to higher levels. The atoms will only absorb if the energy of the photons fits the electronic transition. If the electrons already are excited, they might deexcite instead and emit photons identical to the incoming photons (see figure 2.1). If the electrons in a laser gain medium are constantly pumped to an excited level, a beam of light passing through it will get amplified. Each gain medium has its own appearance and properties such as central wavelength and bandwidth.

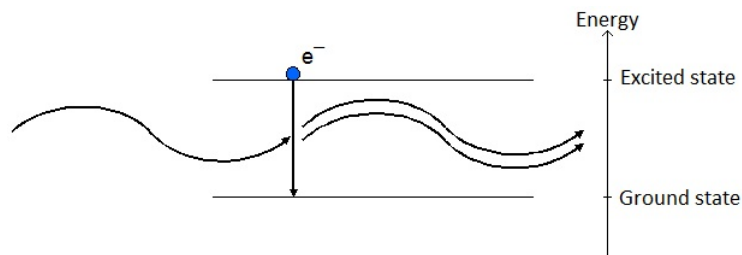


Figure 2.1: Principle of stimulated emissions.

A cavity consists of two mirrors with high reflectivity. When light travels through the gain medium it is reflected at one of the mirrors, travels back through the gain medium, gets amplified, is reflected at the other mirror and back again. Due to the wave properties of light it will interfere with itself cre-

¹This can also be a well defined wavelength region for multi-mode or pulsed lasers.

ating standing waves inside the cavity. Only light which travel a whole number of wavelengths through the cavity, at a frequency which the gain medium can amplify, will survive (see figure 2.2). Since the gain medium has a finite bandwidth, the laser will have a certain number of modes.

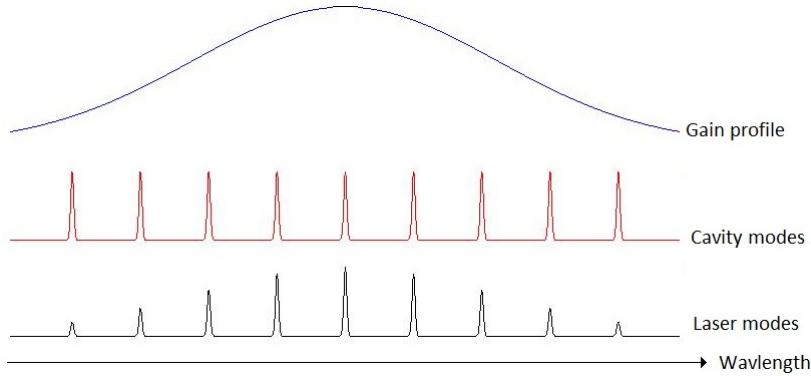


Figure 2.2: Cavity modes.

The frequency of the laser modes can be calculated with the following formula [8]

$$\nu_q = \frac{c_0}{2nL_{ext}} \cdot q \quad (2.1)$$

where ν_q is the frequency for mode q , L_{ext} is the distance between the cavity mirrors, c_0 is the velocity of light in vacuum, n is the refractive index and q is the mode number (an integer).

2.1.1 The diode laser

In a diode laser, the gain medium consists of a p-n junction and the cavity is made up by the polished surfaces of the p-n junction. A semiconductor can be doped so that it has either an excess of electrons (p-doped) or holes (lack of electrons, n-doped). If brought together, thus creating a p-n junction, a region will appear where excess electrons and holes can meet and recombine (the electrons fill the holes). If a current provides new electrons and holes (thus pumping the gain medium) the recombination can continue. When an electron-hole pair recombines, light is emitted. Stimulated emission becomes dominant over other de-excitation processes when the intensity of the incoming light reaches a certain level thus the light gets amplified. The surfaces are polished or sometimes coated making them reflect well and thereby creating a cavity. The diode becomes a laser. For more information see [9].

Other particular characteristics of a diode laser compared with other lasers are the high divergence (the laser used in this project had a divergence perpendicular $\theta_{\perp} = 17^{\circ}$ and parallel $\theta_{//} = 7^{\circ}$ to the polarization [2]), the ability to

tune with temperature and current and the small size of the cavity. The laser used in this project had an external cavity mounted in a Littrow configuration (see figure 2.3) which was built by Erik Mansten [1]. An important property of this configuration is that it is possible to tune lasing frequency with the external cavity.

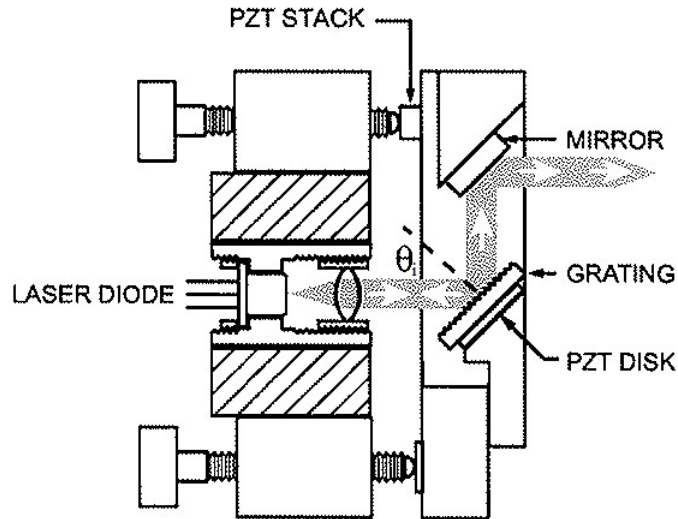


Figure 2.3: Littrow configuration for an external cavity [10].

The grating is mounted in a way that the first order of refraction (20 % of the light) is sent back into the laser due to diffraction. The grating will reflect light in a direction according to [7]:

$$\sin(\theta_q) = \sin(\theta_i) - q \cdot \frac{\lambda}{\Lambda} \quad (2.2)$$

where Λ is the distance between the grooves, λ is the wavelength, θ_i is the incident angle and θ_q is the angle of the first order of refraction. In figure 2.3 θ_1 equals θ_q i.e. the first order of diffraction is directed back into the laser. In this way an external cavity is created. Apart from the condition stated in equation 2.1 (which is true for all cavities) the wavelength must be diffracted in parallel with the incoming light. With 1800 grooves/mm, $\lambda = 780$ nm the angle θ is 44.6° . The linewidth of the feedback is 55 GHz [1].

The linewidth of the grating is significantly reduced by the external cavity since only the modes which match the wavelength conditions for both the internal and external cavities will lase (see figure 2.4). Linewidths of 370 kHz have been measured with this configuration [10], which can be compared with the linewidth 100 MHz of the diode laser without the external cavity. It is possible to read more about the construction of the external cavity in [1].

The frequency of a diode laser depends on the temperature of the laser and the current driving the laser. These two parameters are well suited for roughly

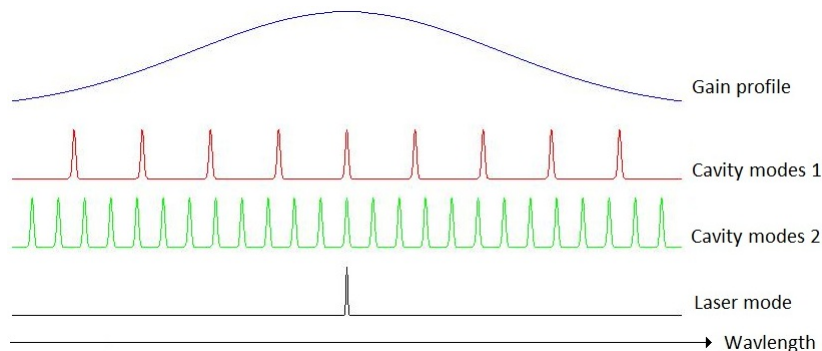


Figure 2.4: Single mode lasing can be achieved by using two cavities.

tuning the laser frequency. When the temperature changes the internal cavity length and the refractive index change which affects the optical path length inside the diode. At the same time the gain profile will move. Together these effects will change the wavelength of the laser. The gain profile will move quicker than the modes which leads to mode jumps when a new mode begins to lase. In between these modes the wavelength can be tuned continuously.

Because of the mode structure the frequency will change stepwise and not continuously.

For fine tuning the external cavity is appropriate since its length and grating angle can be changed. By increasing the size of the piezo-stack both the grating angle and the external cavity length will increase (see figure 2.5). Equation 2.1 and 2.1 and $\theta = \theta_q = \theta_i$ give us

$$\frac{\partial \nu}{\partial L_{ext}} = -\frac{c_0 q}{2nL_{ext}^2} \quad (2.3)$$

$$\frac{\partial \nu}{\partial \theta_i} = -\frac{-c_0 \cos(\theta)}{n\Lambda \sin^2(\theta)} \quad (2.4)$$

$$\frac{\partial L_{ext}}{\partial \beta} = x \cdot (1 - \tan(\beta)) \approx x \quad (2.5)$$

Here $x = 20mm$, $\theta \approx 44.6^\circ$, $L_{ext} = L_0 + x \cdot \tan(\beta) \approx 20mm$, $\Lambda = 0.56\mu m$ and $q = 2nL_{ext}/\lambda \approx 51300$. The angle β is the angle that appears between the two parts of the Littrow configuration when the piezo-stack expands (see figure 2.5). Increasing the angle β will increase the grating angle and cavity length. The grating profile and cavity modes will move in different speed but same direction, in wavelength. The piezo-disk changes only the length of the cavity while the piezo-stack changes both the length and grating angle. The tuning parameters can be seen in table 3.1.

2.2 Atomic Structure of Rubidium-87

Rubidium (^{87}Rb) is an alkali metal. Alkali metals have a number of closed electron shells shielding the nucleus and a single, loosely bound valence elec-

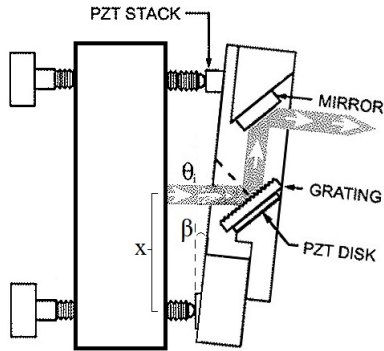


Figure 2.5: Littrow configuration for an external cavity [10]. When the piezo stack expands an angle β appears which changes both the external cavity modes and the grating angle.

tron. The transition energies for the valance electron of ^{87}Rb is accessible with standard diode lasers. This makes it suitable for a MOT. Transitions between electronic states can take place by absorbing or emitting photons². Each electron has a spin s up or down. The so called spin-orbit interaction will split the electronic states into a 'fine structure'. Together l and s will give rise to quantum number j which labels the different fine structure levels. For more information see [11].

$$|l - s| \leq j \leq l + s \quad (2.6)$$

In some atoms the nucleus will have a resulting spin I . Spin-orbit interaction of the nuclear spin I and the electron angular momentum J gives rise to a 'hyper fine structure'. The hyper fine structure levels have different angular momentum F . This is calculated in the similar way as j . Instead I and J ³ is used. For more information see [11].

In order to conserve energy, spin and momentum, selection rules for transitions appear. These are listed in table 2.1 below.

Here follows a discussion about the energy levels in ^{87}Rb . Including the spin-orbit interactions the fine structure can be obtained. These calculations only refer to the outermost electron.

For $5s$ (ground state)

$$\left. \begin{array}{l} l = 0 \\ s = 1/2 \end{array} \right\} \Rightarrow j = 1/2 \text{ and } L_j^{2s+1} \longrightarrow S_{1/2}^2$$

For $5p$ (excited state)

$$\left. \begin{array}{l} l = 1 \\ s = 1/2 \end{array} \right\} \Rightarrow j = 1/2, 3/2 \text{ and } L_j^{2s+1} \longrightarrow P_{1/2}^2, P_{3/2}^2$$

²This can also take place because of collisions, an electric current or other means.

³ J is the resultant of each valence electron's j . ^{87}Rb has one valence electron and J therefore equals j .

$\Delta J = 0, \pm 1$ (but not $J = 0$ to $J' = 0$.) $\Delta M_J = 0, \pm 1$ Parity change $\Delta l = \pm 1$ Any Δn Any $\Delta L = 0, \pm 1$ $\Delta S = 0$ $\Delta F = 0, \pm 1$ (but not $F = 0$ to $F' = 0$.) $\Delta M_F = 0, \pm 1$
--

Table 2.1: Selection rules [12].

The fine structure gives rise to the D_1 - ($j = 1/2 \rightarrow j' = 1/2$) and D_2 -lines ($j = 1/2 \rightarrow j' = 3/2$). Including the spin of the nucleus $I=3/2$ the hyperfine structure is obtained.

For $5sS_{1/2}^2$ we get

$$\left. \begin{array}{l} I = 3/2 \\ j = 1/2 \end{array} \right\} \Rightarrow F = 1, 2$$

For $5pP_{1/2}^2$ we get

$$\left. \begin{array}{l} I = 3/2 \\ j = 1/2 \end{array} \right\} \Rightarrow F' = 1, 2$$

For $5pP_{3/2}^2$ we get

$$\left. \begin{array}{l} I = 3/2 \\ j = 3/2 \end{array} \right\} \Rightarrow F' = 0, 1, 2, 3$$

Transitions between these equations are governed by the selection rules (see table 2.1) described in chapter 4.2.1 in [13]. The resulting energy level diagram can be seen in figure 2.6.

The transition that is used for cooling the rubidium atoms is $5sS_{1/2}^2 F = 2 \rightarrow 5pP_{3/2}^2 F' = 3$ and is marked with a dashed line in figure 2.6. Electrons at the $5sS_{1/2}^2 F = 2$ level might get excited to the $F'=2$ level and thereafter deexcite to $5sS_{1/2}^2 F = 1$. Even though this is unlikely to happen at each single transition the high number transitions that occurs during cooling and trapping greatly increases this probability. Atoms with electrons in this state will no longer be effected by the laser light. Therefore a re-pumping transition at $5sS_{1/2}^2 F = 1 \rightarrow 5pP_{3/2}^2 F' = 2$ is needed.

All the hyperfine transitions $5sS_{1/2}^2 \rightarrow 5pP_{1/2}^2$ are called D_1 line and all transitions $5sS_{1/2}^2 \rightarrow 5pP_{3/2}^2$ are called the D_2 line.

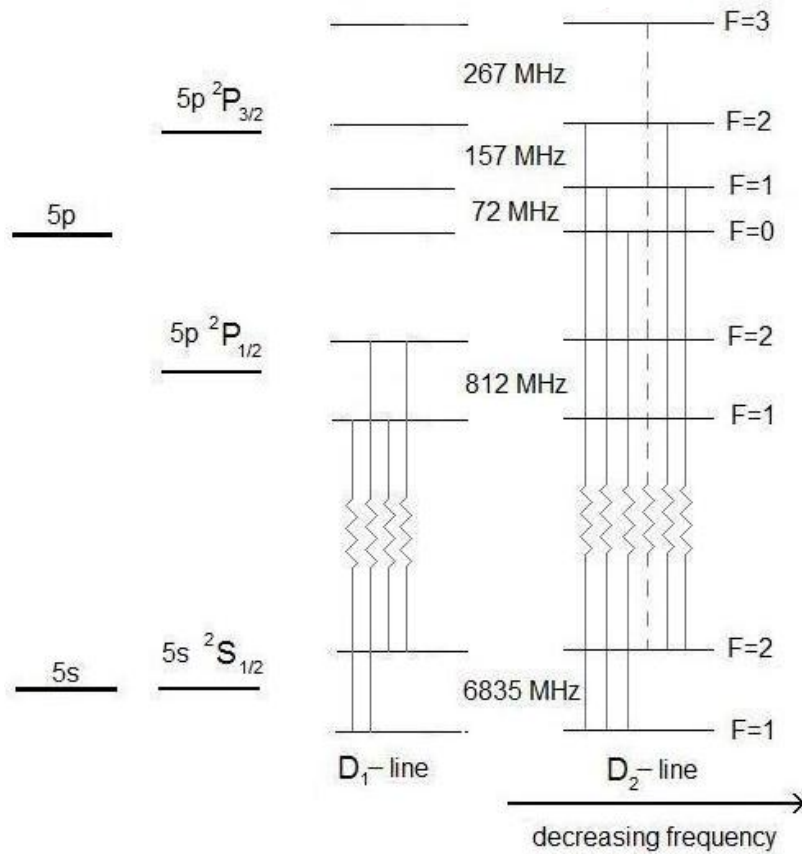


Figure 2.6: Energy level diagram of rubidium.

2.3 Saturation Spectroscopy

In this project, saturation spectroscopy was used to get a Doppler free signal and thus resolve the hyperfine structure in RB⁸⁷. As discussed in chapter 2.2, the cooling transition in the D₂ line was used as a reference for the frequency locking.

2.3.1 The Doppler effect

If a photon is emitted from an atom travelling towards an observer the frequency will be perceived as higher. This is called Doppler effect and in spectroscopy this might be a problem. In a gas, atoms travel with different speeds and directions and will thus be Doppler shifted differently. The shifts in frequency will build up a broadened spectrum. When accurate spectroscopy is needed, as in this project, one has to use Doppler free methods.

2.3.2 Principle of saturation spectroscopy

A laser beam is split into a strong pump beam and a weak probe beam. The pump beam is strong enough to saturate a transition. This is not the case for the probe beam which should leave most atoms in their ground state. Since the probe and pump beams are counter-propagating the atoms which travel with a velocity component parallel to the beams will be Doppler shifted. If they travel towards the pump beam they will perceive the pump as up-shifted and the probe as down-shifted in frequency (see figure 2.7).

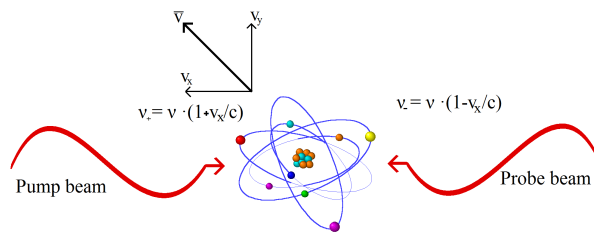


Figure 2.7: Principle of saturation spectroscopy [15].

The atom with velocity v in figure 2.7 will experience the two photons as Doppler shifted. The photon coming from the left will be up-shifted in frequency, to $\nu+$, since it travels in the opposite direction as the atom's x-component. The photon coming from the right travels in the same direction as the atom and will therefore be down-shifted, to $\nu-$. If instead the atom would travel upwards (with no x-component) in figure 2.7 neither of the photons would be shifted and be perceived as having the same frequency.

Both the probe and pump beam will excite atoms and thereby create 'holes' in the absorption distribution (see figure 2.8). If the laser frequency is slightly lower than the transition frequency the beams will only excite atoms which are up-shifted, i.e. travelling towards the beams. Since an atom cannot travel towards both beams simultaneously the beams will excite different atoms. If the laser frequency would be 200 MHz off the central absorption frequency, the pump beam will excite atoms which travel with $v_x = -156$ m/s and the probe beam atoms with $v_x = 156$ m/s.

When the laser frequency equals the transition frequency, both the pump and probe beam will excite atoms with the same velocity component $v_x = 0$. Since the pump beam has already saturated the ^{87}Rb -atoms the probe beam will experience little absorption and a higher intensity will be detected. With saturation spectroscopy the spectral linewidth decreases from the Doppler broadened profile of 500 MHz to the natural width 6 MHz.

2.3.3 Cross over resonance

If a structure with several peaks is examined a hole will be created for each peak by the pump and probe beams respectively (see figure 2.9). Absorption peaks will be detected when the pump and probe beam for peak 1 and later for peak

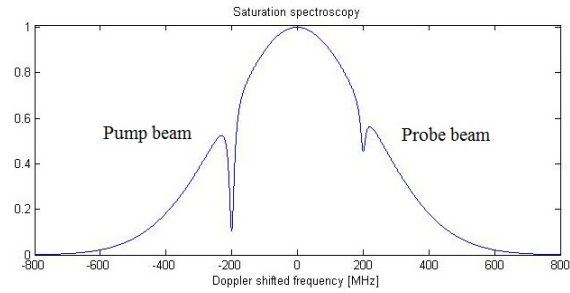


Figure 2.8: Probe and pump beam in Doppler broadened profile.

2 coincide (see figure 2.9B and D). But there is also a frequency where a cross over appear and an additional false peak is detected (see figure 2.9C). This is called a cross over resonance.

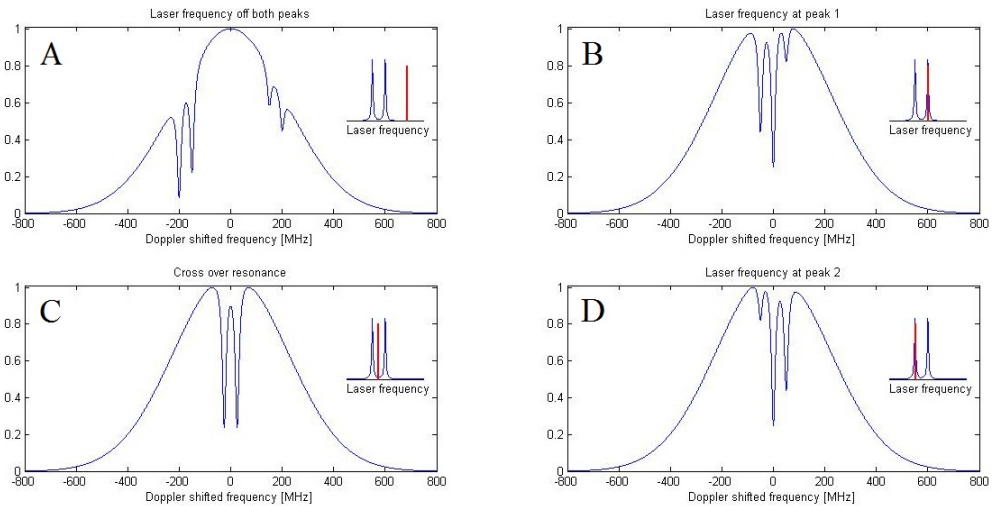


Figure 2.9: Saturation spectroscopy with two peaks. A) The laser is off both peaks and no peaks are detected. B) The first peak is detected. C) A cross over resonance is detected as a false peak. D) The second peak is detected. In each figure the laser frequency relative to the peaks is shown in the upper right corner.

If an atom travels towards the pump beam the light will be seen as up-shifted thus fitting the transition to the $F' = 3$ excitation state in figure 2.6. The same atom will will see the probe beam as down-shifted fitting the transition $F' = 2$. Since many atoms are excited to the $F' = 3$ state they will not be able to absorb the probe beam and the probe beam will therefore not be absorbed as much. A cross-over can only appear in the middle of two transitions. This is the case for the second peak from the right in figure 3.2. In this case, the ground state was the same but the excitation states were different (which is the case for all cross

overs in figure 3.2). In other cases cross overs might have same excited state but different ground states.

2.4 Lock-in detection

One technique for obtaining a correct error signal is by using lock-in. The signal is frequency modulated and then multiplied with a signal that has the same frequency as the modulation signal. When the phase is correct, the modulated signal will get amplified while noise with wrong frequency or phase will not. This is the principle of lock-in.

In saturation spectroscopy the frequency modulation will have no effect on the detector signal if the difference in absorption varies little or nothing. In a slope (at a peak) the situation is opposite and the difference in absorption is high, thus a high value is acquired (see figure 2.10A). After multiplication with the modulation the lock-in effect is created (figure 2.10B). This is proportional to the derivative of the detector signal. It is essential that there is no phase difference between the modulation and modulated detector signal. Otherwise parts of the detector signal will be amplified which do contain no information about the derivative. The derivative can be accessed by using a low-pass filter (figure 2.10C). By integrating the error signal the proportional and integrating parts of the regulation are created, which can be used to correct the laser frequency.

2.5 PID controller

A controller is often used to analyse a detector signal and produce a correction signal which tells the system how to compensate for errors. The controller used in this project was a PI-controller with a detector signal produced by saturation spectroscopy. This correction signal can consist of three different parts: a proportional to the error itself (P), a proportional to the integral of the error (I) and a proportional to the derivative of the error (D).

$$u = K \left(\underbrace{e}_P + \underbrace{\frac{1}{T_i} \int e(t) dt}_I + \underbrace{T_d \frac{de}{dt}}_D \right) \quad (2.7)$$

K decides the strength of the regulation while integration time T_i and derivative time constant T_d decide the proportions between the different parts. In this project only P and I were used. The proportional part since the error is directly coupled to how much the laser frequency must be compensated for, within small interval. The integral part will integrate the error over time and is often used for correcting a residual offset which might occur (e.g. because of drift). The derivative is often used in slowly responding systems or in systems where it is important to predict the future. This is not case in saturation spectroscopy. This is explained thoroughly in [16].

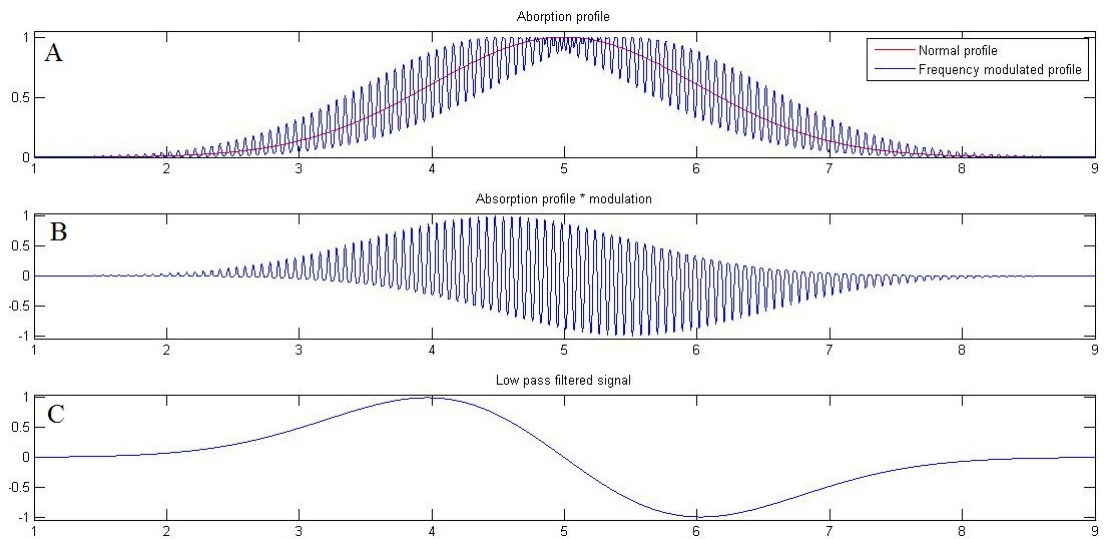


Figure 2.10: Principle of a lock-in amplifier. The signal $e^{-c_1 x^2}$ is modulated by a frequency modulation (A). By multiplying with the modulation (B) noise is attenuated and the derivative can be accessed by using a low-pass filter.

Chapter 3

Method and Results

3.1 Optical setup

As previously mentioned saturation spectroscopy is capable of sub-Doppler resolution. The setup can be seen in figure 3.1. The external cavity diode laser is set to 780.24 nm which is regulated by an external cavity mounted in a Littrow configuration. The laser beam is split up into a probe and a pump beam. Both beams are directed into an ^{87}Rb -cell, but in opposite directions. The probe is split up a second time into a wavemeter which is used for rough tuning and to monitor of the laser frequency. The detector signal is coupled to and analysed in a PI-controller and an eventual error is compensated for by regulating the length of the external cavity of the laser.

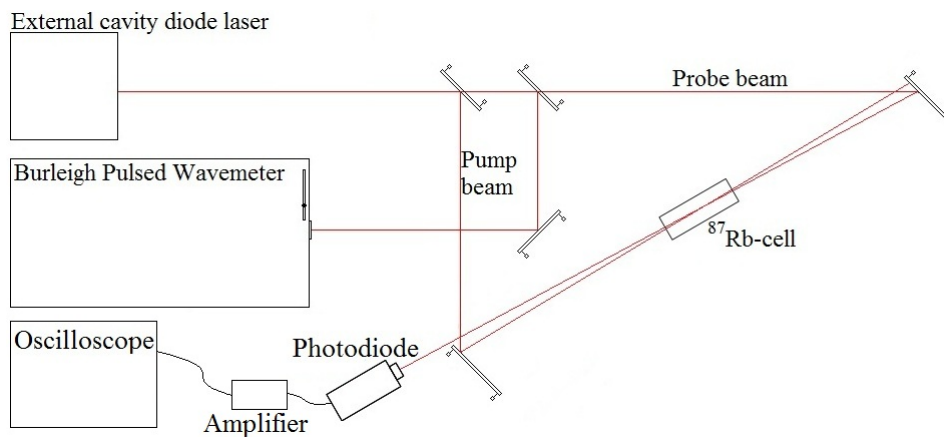


Figure 3.1: Saturation spectroscopy setup.

3.1.1 Saturation spectroscopy on ^{87}Rb

Using the optical setup shown in figure 3.1 the Doppler free spectrum of ^{87}Rb was measured, see in figure 3.2. There are three peaks corresponding to absorption lines and three cross over resonances.

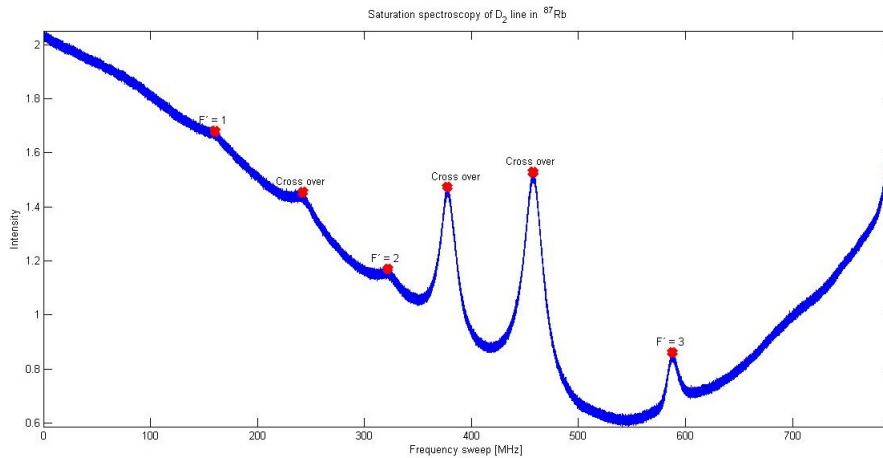


Figure 3.2: Measured saturation spectroscopy of the D_2 line in ^{87}Rb . From left to right: true peak ($F = 2 \rightarrow F' = 1$), cross over ($F = 2 \rightarrow F' = 1$ and 2), true peak ($F = 2 \rightarrow F' = 2$), cross over ($F = 2 \rightarrow F' = 1$ and 3), cross over ($F = 2 \rightarrow F' = 2$ and 3) and true peak ($F = 2 \rightarrow F' = 3$).

3.2 Regulating the laser frequency

As discussed in section 2.1.1, the laser frequency can be tuned by changing the external cavity length and angle. This can be done by using piezo disks/stacks which respond to a voltage by expanding (see figure 2.3). It would also be possible to change the laser wavelength using the temperature, if the external cavity is removed¹, though it is far too slow to regulate with. Another possibility, if the external cavity is removed, is using the drive current, though this will change the intensity of the laser. This will in turn change the amplitude of the error signal. Regulating with a piezo disk/stack has none of these effects. The piezo stack was used to regulate the laser and the piezo disk to modulate the laser frequency (to create a derivative, see chapter 5 controller). Instead of regulating, the drive current (≈ 33 mA) and the temperature ($\approx 15^\circ$) were used for roughly tuning the laser. The external cavity was used for fine tuning (see table 3.1²).

Manual actuator	75 MHz/degree
Piezo stack	40-80 MHz / V
Piezo disk	4-8 MHz / V
Temperature	70 GHz / $^\circ\text{K}$
Current	1 GHz / mA

Table 3.1: Tuning parameters of the laser. All numbers come from measurements except the current which is taken from [2].

¹The external cavity only allows a few modes to lase. Even though the gain might be more favourable for other wavelengths they will not lase.

²Between peak $F' = 2$ and 3 there is 267 MHz (see figure 3.2). The scanning parameters in table 3.1 can be measured if scanning voltage is known by using this spectrum.

3.3 Frequency controller

The controller can be divided into three different parts where each part has a role in the regulation (see figure 3.3). The first part, 'scanning', creates a scanning signal used for finding the peak for locking. In the second part, 'modulation', a signal is generated. As described in 2.4 and 2.5, the frequency modulation necessary for the lock-in part of the controller. The third part, 'Lock-in', receives the lock-in signal and the last part, 'regulation', calculates how much the laser should compensate. All parts will be explained in detail below. The letters within parenthesis refer to the circuit diagram at the end of this chapter.

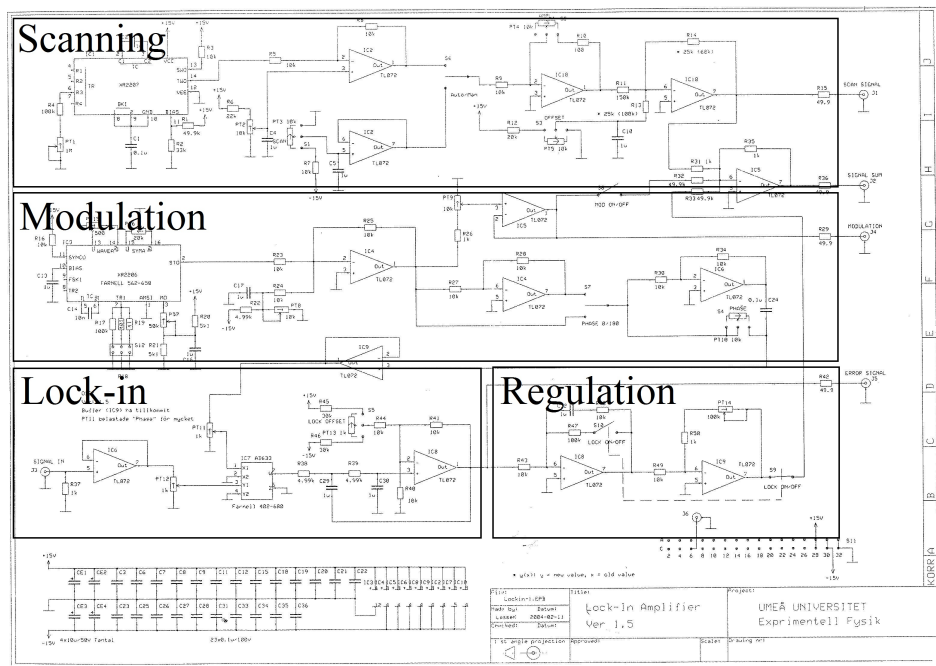


Figure 3.3: The schematics of the controller can be divided into four different parts. At the end of this chapter the circuit diagram can be found in A3 format.

3.3.1 Scanning

The first part creates a signal which can scan the wavelength of the laser either automatically or manually. The scan frequency of the automatic scan can be set to different values (A), 10 Hz is the default setting. Scanning manually can be done with a knob on the front of the controller (B). An offset (D) can be added and the amplitude of the scan signal (C) is set. These are adjusted by knobs on the front of the controller. The scanning signal can be accessed directly through output SCAN SIGNAL or through output SIGNAL SUM together with the modulation and correction signals.

3.3.2 Modulation

The modulation signal (created in E) has a sinusoidal shape with a frequency of 1 kHz. The 50 Hz electrical grid frequency is filtered out (F). The modulation signal then goes in three directions. After amplification (G) it can be accessed directly through output MODULATION³ or through output SIGNAL SUM (can be switched on/off in H) together with the scanning signal and correction signal. The modulation is an essential part of the lock-in mechanism and is therefore also connected to this part. The sign (J) and phase (K) can be adjusted to get a correct ERROR SIGNAL (see below).

3.3.3 Lock-in

To create the lock-in the detector signal, SIGNAL IN is multiplied with the modulation signal in an analogue multiplexer (N). The amplitude of each signal can be adjusted with two potentiometers (M for the detector signal and L for the modulation). The high frequency part is then filtered out (P). If this is done correctly the ERROR SIGNAL should look like a derivative of SIGNAL IN. An offset is added (P) to decide the setpoint.

3.3.4 Regulation

In this part the ERROR SIGNAL produced by the lock-in is integrated (Q) and amplified (R) to get the correction signal, which is added to SIGNAL SUM (can be switched on/off in S). The resistors preceding the amplification to the outgoing SIGNAL SUM decide how much of each part (scan, modulation and correction) that is included in the signal (I). The controller has been modified so that the resistance R33 (I) is parallel coupled with a 1 k Ω resistance and a potentiometer of 50 k Ω making the output to SIGNAL SUM adjustable (see below).

3.3.5 Modifications of the design

To the original circuit diagram was modified to obtain a stronger correction signal. In the original design, as can be seen in the circuit diagram at the end of this chapter, the correction signal could not have a higher value than ± 0.26 V which corresponds to approximately 15 MHz laser frequency change. This was not enough to lock the laser. To increase the maximum voltage of the correction signal a 50 k Ω potentiometer was added. In series with it was a 1 k Ω coupled to get a minimum level to the circuit (see figure 3.4). This way the correction signal increased to ± 3 V which improved the controller's performance notably. Note that only one of the two controllers was modified in this way.

3.3.6 Locking the laser frequency

To lock the laser frequency on a peak in the saturation spectroscopy signal, the amplitude of SCAN SIGNAL should be lowered to "zoom in" in the peak. The

³It is important that the output MODULATION is coupled to a device which can follow such a high frequency. The piezo disk can do this but not the stack.

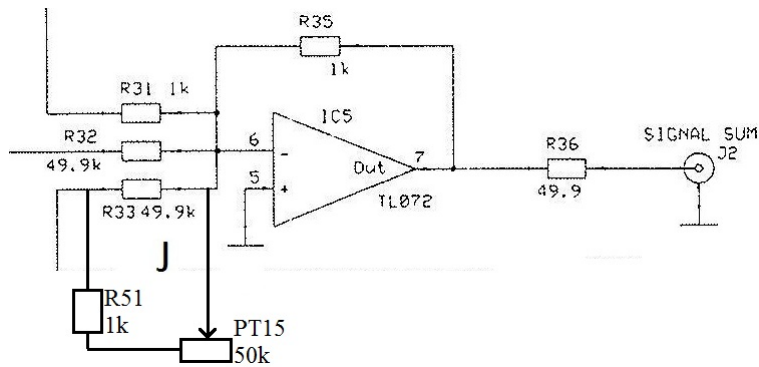


Figure 3.4: Modification of the controller. A $1\text{k}\Omega$ resistance (R51) in series with a $50\text{ k}\Omega$ potentiometer (PT15) was added put parallel to resistance R33 (J).

offset of the SCAN SIGNAL can be used to stay on the peak while zooming. The ERROR SIGNAL should look as a derivative of the detector signal (see figure 3.5). This can be done with the 'phase' knob at the front of the controller. Adjusting the potentiometers PT11 and PT12 will set the internal parameters correct (see section Regulation above). The lock offset should be set to zero at the point where one wishes to lock.

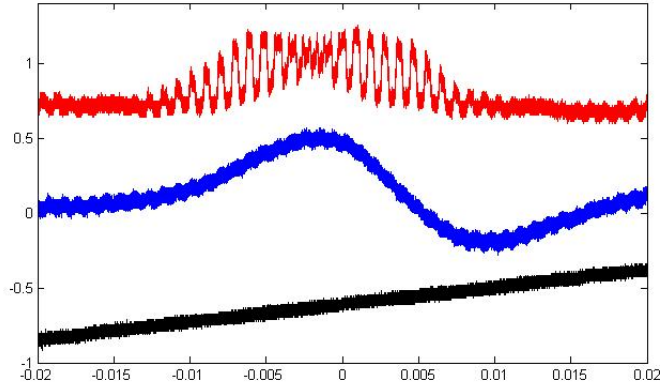


Figure 3.5: From the detector signal (above in red) the ERROR SIGNAL (middle in blue) is created during a scan sweep (below in black).

Now, the scan should be switched from automatic to manual. Setting the scan to the correct level and switching 'lock' to on the controller should now lock the laser frequency (if the sign of the feedback is correct). The potentiometer PT14 (see chapter 5.3.3 Regulation) can be used to adjust the strength of regulation. If it is set too high the error will be overcompensated and oscillation will occur.

3.4 Discussion

We managed to lock the laser at a chosen frequency. It could hold for up to a few minutes⁴. In figure 3.6 two peaks can be seen. The most stable way of locking was at the bottom between two saturation spectroscopy peaks. Locking at the top of a peak was also possible but to achieve this the phase had to be shifted 180°. Locking at the slope of one of these peaks (where the error signal is close to maximum/minimum, middle blue curve in figure 3.6) was impossible. Locking at top of the smaller peak $F' = 3$ (see figure 3.2) was more difficult than at a larger peak (since the ERROR SIGNAL has a lower amplitude at a smaller peak). A problem was that it was difficult to know where the laser frequency was locked (which of the two peaks and how high on the slope). Another problem that caused the regulation to jump from one point to another was mechanical vibrations (such as bumping into the optical table). In figure 3.7 it is shown what the display of the oscilloscope looked like while regulating.

There are several references, other than saturation spectroscopy, that can be used in laser locking such as a Fabry-Perot etalon [3] or a Michelson interferometer [14]. Using ^{87}Rb as reference was an obvious choice since the laser will be used to cool and trap ^{87}Rb atoms in a MOT.

Dew caused the diode laser to drift in frequency in an uncontrolled way. This is only a problem during the months around summer when the humidity and temperature are high. This was an unfortunate circumstance since this project was mostly done during spring and summer. This problem is more thoroughly analysed in [2].

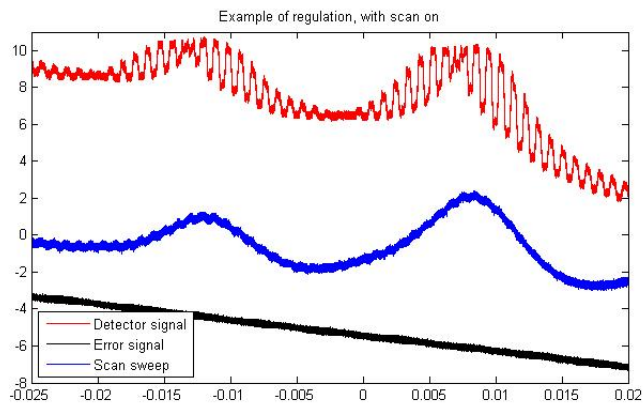


Figure 3.6: Spectrum showing two cross over resonances. The peaks seen are cross over resonances from $F' = 1$ and $F' = 3$ (left) and from $F' = 2$ and $F' = 3$ (right).

⁴This limit was caused by dew, see chapter 3.2.

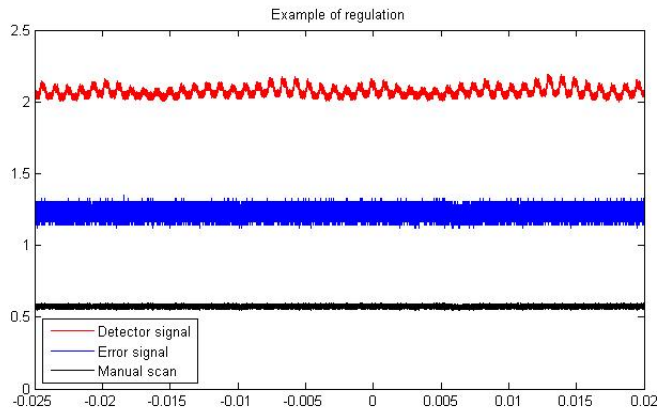
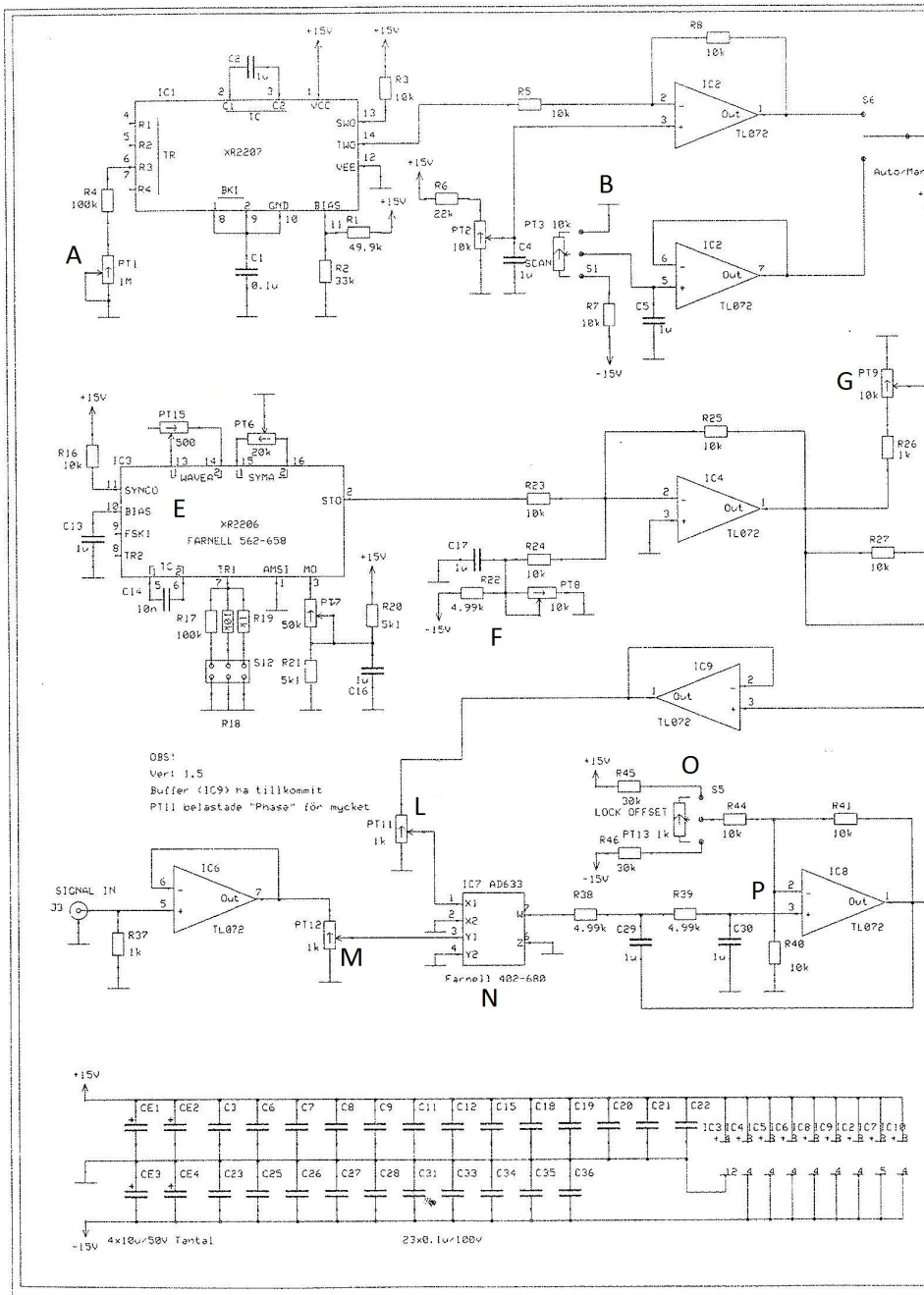
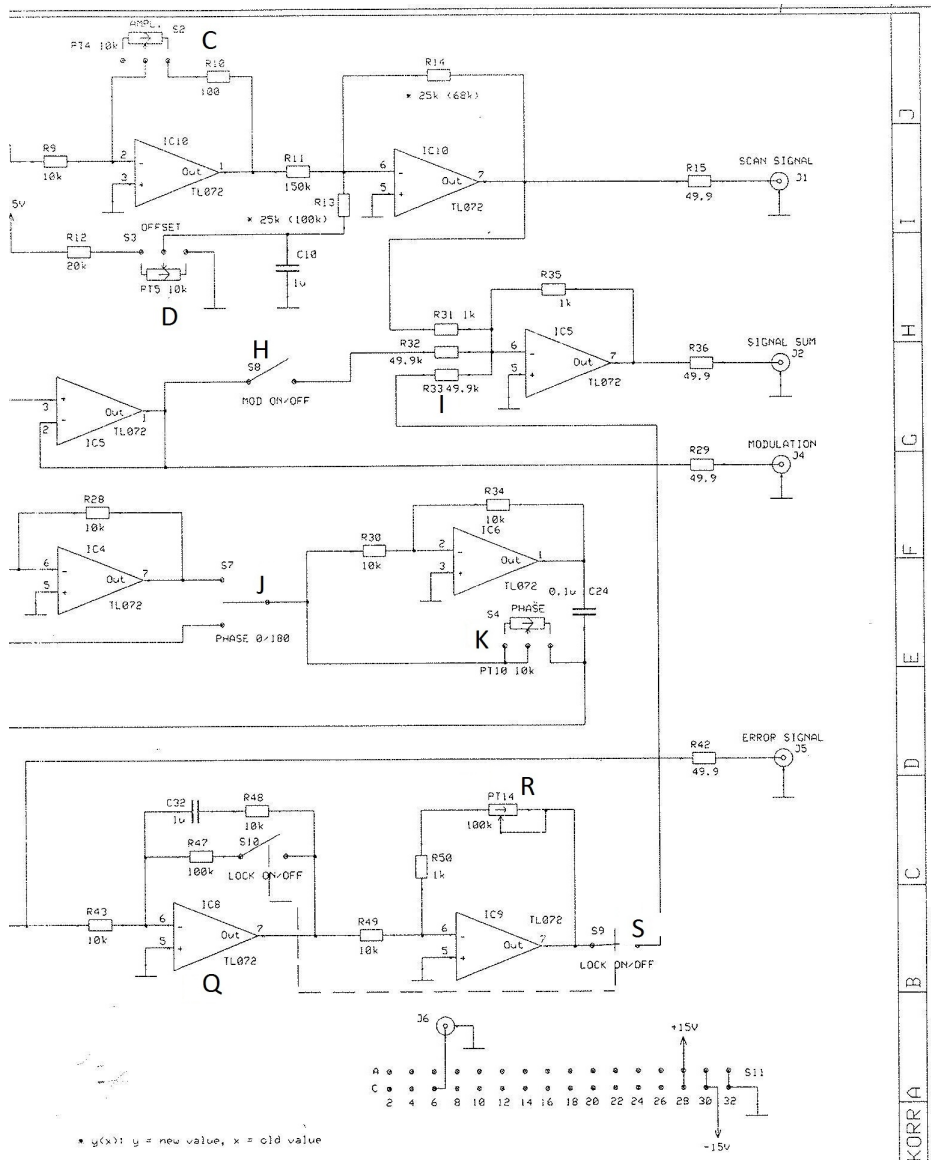


Figure 3.7: Example of regulation. In this figure the frequency is stabilized between the peaks. At top is SIGNAL in, middle is ERROR and bottom is SCAN signal

Letter	Component label	Task
A	PT1	Sets frequency of the automatic scan.
B	PT3	Manual scan. Connected to front.
C	PT4	Sets scan amplitude. Connected to front.
D	PT5	Sets scan offset. Connected to front.
E	PT6 & PT15	Changes shape of the modulation signal.
F	PT8	Filter for 50 Hz.
G	PT9	Sets amplitude of modulation signal to outputs SIGNAL SUM and MODULATION.
H	S8	On/off switch for modulation to SIGNAL SUM. Connected to front.
I	R33	Resistance deciding the strength of the correction signal. Is modified (see chapter Regulation - Modification).
	R51	Minimum resistance to amplifier input.
	PT15	Sets resistance to amplifier input.
J	S7	Switches the sign of the modulation. Connected to front.
K	PT10	Sets phase. Connected to front.
L	PT11	Sets modulation amplitude to the error signal.
M	PT12	Sets SIGNAL IN amplitude to the error signal.
N	IC7	Multiplies modulation with SIGNAL IN.
O	PT13	Sets offset to ERROR SIGNAL. Connected to front.
P	—	—
Q	—	—
R	PT14	Sets amplitude of correction signal to SIGNAL SUM.
S	S9	On/off switch for correction signal to SIGNAL SUM. Connected to front.

Table 3.2: Controller components. The labels IC# mean analog multiplexer, PT# potentiometer, R# resistance and S# switch.





File: Lockin-1.EPB	Title: Lock-In Amplifier	Project: UMEÅ UNIVERSITET Experimentell Fysik
Made by: Lassek	Date: 2004-02-11	
Checked:	Date:	
1st angle projection	Approved:	Scale: Drawing nr:

Chapter 4

Conclusion

The aim of this project was to lock the frequency of an external cavity diode laser. The laser can now be locked but not at the desired frequency. When continuing the MOT project the following points should be considered: The frequency modulation amplitude is too high for use in a magneto-optical trap, this can be solved by splitting the laser beam and using an acousto-optical modulator (instead of a piezo-disk). The remaining problems concerning the controller might be solved by finding the optimum values for PT14 and PT15 (the potentiometer added in parallel with R33). The dew-problem can be solved either by better ventilation and humidity control or by avoiding working with the lasers during the warmest months of the year. The controllers are designed for locking external cavity diode lasers but could also be used in other experimental setups. It is our hope that this report will help the next person using the controllers.

Bibliography

- [1] Erik Mansten¹, *Design study of a Magneto-Optical Trap for laser cooling of rubidium atoms*. Lund Reports on Atomic Physics LRAP-325, 2004.
- [2] Stefan Magnusson, *Design and construction of a pyramidal Magneto-Optical Trap for laser cooling of rubidium atoms* Lund Reports on Atomic Physics LRAP-339, 2005.
- [3] A. Rossi, B. Mai, V. Biancalana, L. Tomassetti *Long-term drift laser frequency stabilization using purely optical reference*. Department of Physics, University of Siena and Department of Physics, University of Ferrara, Italy, 2002.
- [4] Steven Chu, *THE MANIPULATION OF NEUTRAL PARTICLES*. Stanford University, Departments of Physics and Applied Physics, Stanford, CA 94305-4060, USA Nobel Lecture, December 8, 1997 Available from http://nobelprize.org/nobel_prizes/physics/laureates/1997/chu-lecture.pdf
- [5] M. G. Tarallo, N. Poli, M. Schioppo, G. M. Tino *A high stability semiconductor laser system for a ⁸⁸Sr-based optical lattice clock* Dipartimento di Fisica and LENS Università di Firenze, Italy, 2010.
- [6] N. Strauss, I. Ernsting, S. Schiller, A. Wicht, P. Huke, R.-H. Rinkleff *A simple scheme for precise relative frequency stabilization of lasers* Springer-Verlag 88, 21-28, 2007.
- [7] B.E.A. Saleh, M.C. Teich, *FUNDAMENTALS OF PHOTONICS* Second Edition, John Wiley & Sons, USA, 2007, chapter 2.4.
- [8] B.E.A. Saleh, M.C. Teich, *FUNDAMENTALS OF PHOTONICS* Second Edition, John Wiley & Sons, USA, 2007, chapter 10.1-6.
- [9] B.E.A. Saleh, M.C. Teich, *FUNDAMENTALS OF PHOTONICS* Second Edition, John Wiley & Sons, USA, 2007, chapter 17.3.
- [10] C. J. Hawthorn, K. P. Weber, and R. E. Scholten, *Littrow configuration tunable external cavity diode laser with fixed direction output beam*. Review of Scientific Instruments 72, 4477-4480, 2001.
- [11] Christopher J. Foot, *Atomic Physics*. Oxford University Press, Oxford, Great Britain, 2005, chapters 5, 6 and 7.

¹Erik Mansten's name was Erik Gustafsson year 2004

- [12] Christopher J. Foot, *Atomic Physics*. Oxford University Press, Oxford, Great Britain, 2005, appendix C.
- [13] Sune Svanberg, *Atomic and Molecular Spectroscopy*, Fourth Edition, Springer-Verlag, 2004.
- [14] Veronika Tsaturian, Helen S. Margolis, Giuseppe Marra, Derryck T. Reid and Patrick Gil, *Noise-insensitive self-referencing interferometer for carrier-envelope offset frequency stabilization of a Ti:sapphire laser* Laser Science to Photonic Applications, 1-2, 2010.
- [15] <http://www.oralchelation.com/technical/freerad5.htm>, accessed 9 September 2010.
- [16] Tore Hägglund, *REGLERTEKNIK AK Föreläsningar*, KFS i Lund AB, Sverige, 2006.
- [17] Bentham Instruments Ltd, *225 Lock-in Amplifier*, available at <http://www.bentham.co.uk/pdf/F225.pdf>, accessed 29 November 2010.

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M.Sc. Miguel Miranda,

M.Sc. Stefan Magnusson,

Prof. Anders Kastberg,

The Division of Atomic Physics in Lund

Appendix A

Instruments

<i>Component</i>	<i>Type</i>
Laser driver	MELLES GRIOT series 200
Temperature control	MELLES GRIOT thermoelectric cooler
Laser	NEWPORT U100-P Ultima
Detector	Burr-Brown OPA620KP, Hamamatsu S1223
Amplifier	DLPCA-200
Controller	Lock-In Amplifier built at Luleå's technical university
Oscilloscope	LeCroy waveRunner 6050A
Wave meter	Burleigh Wavemeter WA4500
Function generator	THURLBY THUNDER INSTRUMENTS TG215 2 MHz function generator

Appendix B

Saturation spectroscopy hints

B.1 Preparing the laser

The starting point in obtaining saturation spectroscopy is to prepare the laser. The laser has to be aligned and thus there should be only one laser beam coming out. If there is a weak beam besides a strong one it is poorly aligned. This means that the first order of refraction from the grating is not reflected back into the laser to get amplified. Saturation spectroscopy is thus hard to achieve. The knobs should be screwed until the highest possible power output is obtained. This is easiest done by lowering the laser power to the lasing limit. To protect the laser from outside perturbations the cover must be firmly closed. A hex key can be used to reach the knobs from outside the metal cover. Turning it will not change the direction of the laser.

B.2 Searching strategy

As mentioned above, changing temperature while searching the saturation spectroscopy signal is not recommended since it takes time to stabilize. Small changes in current might help but is inaccurate compared to using the hex key. The saturation spectroscopy can be located in the middle of a mode jump. Changing the drive current might help.

B.3 Improvement

Once the saturation spectroscopy is obtained it can be improved in a few ways. Using a low pass filter in the oscilloscope reduces noise and helps gaining a better image. Usually amplifiers (used for the lock-in signal, see figure 3.1) have filters that might help improving the image but is not very helpful if it filters away the modulation. When the saturation spectroscopy signal is found it might be good to optimize the probe and pump beam alignment until the best signal is obtained.