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Frequency Modulation Saturation Spectroscopy Laser Lock of An Interference-Filter-Stabilized External-Cavity Diode Laser

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Abstract

This document gives a short theoretical introduction to Frequency Modulation Saturation Laser Lock. Moreover, the experimental realization of a lock for an external-cavity diode laser is described and characterized and a short manual of how to start the laser lock setup and to optimize the error signal is given. It continues the work of Matthias Scholl which is described in [1].

Contents

1. Motivation (Summary)

Many labs all over the world are working with Ultra Cold Atoms to study the quantum behaviour of atoms and molecules and to test or improve theoretical models that are important to understand popular and interesting phenomena like high temperature superconductivity or how to build a quantum computer that could have a great impact on how we live in the future. In the Ultra Cold Atoms lab at University of Toronto atoms are loaded into a lattice potential with tunable interactions between the atoms to simulate atoms in condensed matter system and to test and study the Hubbard model that exactly describes this system but is not solvable analytically.

One major step of bringing the atoms to these very low temperatures is laser cooling, that was simultaneously proposed by Wineland and Dehmelt [2] as well as Hänsch and Schawlow [3], which is still used widely to cool the atoms to temperatures about $100\,\mu K$. To reach temperatures that are needed to create BECs or degenerate Fermi gases and that are about two magnitudes of order lower evaporative cooling is used.

The lasers that are used in laser cooling need high frequency stability and small linewidth ($< 1\,MHz$). Several techniques are established to stabilize lasers to fulfill these requirements. This report describes the realization and characterization of a Frequency Modulation Spectroscopy laser lock. It concentrates on the creation and the optimization of the error signal and doesn't talk about the control servo needed to create the signal that is fed back to the laser. At the time when this report was written the laser were only locked with slow piezo feedback. However, the performance has already been sufficient to be used in the experiment but will be further improved by using fast current feeback.

2. Theory

2.1. Saturation Absorption Spectroscopy

One of the major applications of lasers is the investigation of the energy structure of atoms and molecules with laser spectroscopy. With a single laser it is possible to reach resolutions that are only limited by the Doppler-width of the atomic transitions as long as the laser linewidth is smaller than the Doppler-width. Our laser has a free running linewidth of $\Delta\nu_{free} \approx 1\,MHz$ which is much smaller than the $\Delta\nu_{doppler} \approx 1,25GHz$ Doppler-width of the Potassium D2-line at $766,7\,nm$ [4] that is used as an atomic reference in our setup.

However, it is possible to resolve energy levels within the Doppler-broadening if the atomic vapor is saturated by a so called pump laser as it is the case in saturation absorption spectroscopy (1).

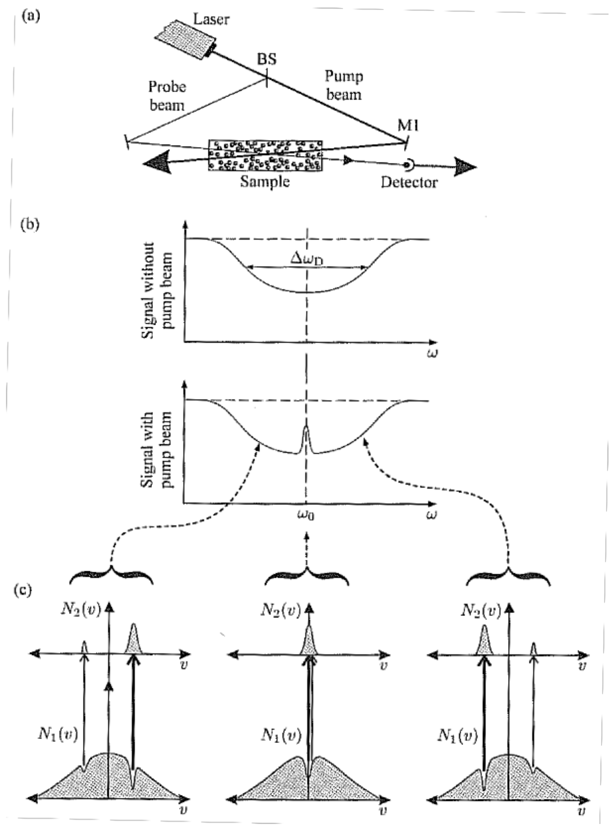

Figure 1: A saturated absorption spectroscopy (SAS) experiment [5]. a) Basic SAS setup. b) Shape of photo diode signal without and with pump beam. c) Velocity (only component in beam direction) distribution of atoms in a two level system with increasing beam frequencies from left to right hitting the resonance on the picture in the center. Positive velocities are defined in probe beam direction. The thick arrows are pointing out the higher intensity of the pump beam.

The picture on the bottom of figure 1 shows the velocity distribution of the atoms in the ground and the excited state. If the beam with frequency f is for example red-detuned from resonance at f_0 to lower frequencies by $\delta = f - f_0$, atoms have to counterpropagate the beam with a velocity $v = \frac{\delta}{f_0} \cdot c$ to get a doppler-shift that brings them back to resonance. Only atoms with a velocity in a narrow interval around this velocity will be excited.

Therefore, atoms that are resonant with the probe beam (thin arrow) have negative velocities (because positive velocities are defined in probe beam direction). Since probe and pump have the exact same frequency, atoms that are resonant with the pump beam must have the same value but opposite sign of velocity. Both, pump and probe beam excite resonant atoms from the ground into the excited state leaving "'holes"' in the velocity distribution of the ground state.

When the laser beam is in resonance with the atomic transition $\delta = 0$, both, pump and probe beam get resonant with atoms that have velocity components in beam direction that are close to zero. The deep hole "'burned"' by the pump beam reduces the number of atoms available for excitation through the probe beam and therefore reduces the absorption of the latter. This results in the sub-doppler resolution peak at resonance shown in inset b). So far, we only looked at simple two level systems. In systems with more energy levels additional peaks (crossover peak) appear exactly halfways between the resonance of two transitions in the SAS signal due to hole burning and optical pumping [6], [7].

Figure 2 shows the ^{39}K D2-line signal with $F = 1$, $F = 2$ and crossover peak (see potassium energy level structure showing the D1 and D2-line in figure 3).

2.2. Laser Lock

As mentioned before, our homebuilt ECDLaser system has to work at a very stable frequency ($\pm 1\, MHz$) with a narrow frequency distribution. There are several techniques to "'lock"' (stabilize) a laser to a certain frequency that ensure this. Single beam methods like dichroic atomic vapour laser lock (DAVLL) have doppler-broadened features which results in large recapture ranges of several hundred MHz. However, the sub-doppler resolution of saturation spectroscopy methods like frequency modulation saturation spectroscopy (FMS), which is applied in this project, leads to steeper gradients of the error signal ensuring higher stability. Moreover, the atomic vapor that is used in FMS gives an absolute frequency reference.

Error Signal

The underlying principle of all lock-in methods is to create a so called **error signal** that is proportional to the difference between the actual, possibly perturbed frequency of the laser and the reference frequency that is often obtained by using an atomic transition (see fig. 4, more details in the follow-

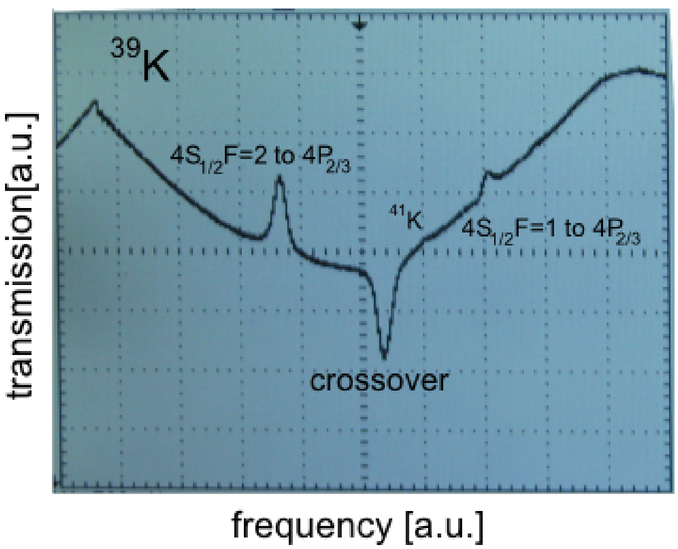

Figure 2: Saturation absorption spectroscopy signal of our setup. $F = 1$, $F = 2$ and crossover peaks of the ^{39}K D2-line are labeled (see potassium energy levels D1 and D2-line in figure 3. ^{41}K isotope peaks are barely visible. We dont substract the single beam doppler peak because it doesn't contribute significantly to the error signal (see section 2.2.) (which is proportional to the first derivative of the saturation signal).

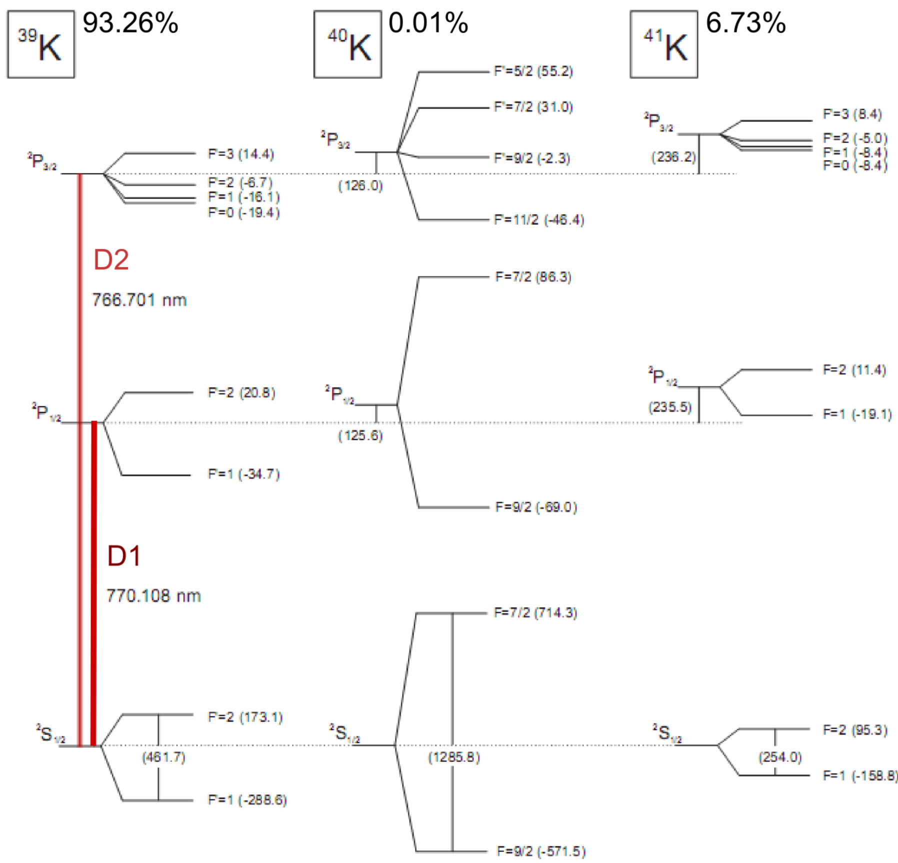

Figure 3: Energy level structure showing the D1- and D2-line of the potassium isotopes ^{39}K, ^{40}K and ^{41}K from [4].

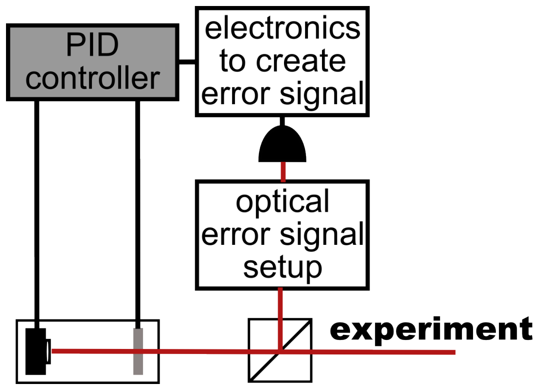

Figure 4: Principle of a laser lock setup. A small part of the laser intensity is used to create an optical frequency dependend signal that is detected and manipulated electronically to create a linear frequency depend error signal that is fed back to the laser to correct for the frequency aberration.

ing sections). This signal is fed back to the laser to correct the aberration for example by changing the voltage of a piezo crystal that changes the length of the laser cavity or by controlling the current of the laser diode.

Frequency Modulation Spectroscopy (FMS)

As in SAS a strong pump beam is used to saturate the excitation of atoms in a vapor cell. The transmission of the weak counterpropagating probe beam is detected. In FMS however, the probe beam frequency is modulated before passing the vapor cell. The error signal is extracted from the magnitude of the frequency component of the signal that oszillates with the modulation frequency. This is described in the following section.

An Electro-Optical Modulator (EOM) is used to modulate the phase of the probe beam. The phase shift of light Φ on the output of the EOM crystal is proportional to the electric field E_a applied inside the birefringent crystal (see also Pockels-effect, e.g. [8]):

$$\Phi = \frac{\beta\omega_0}{c} E_a l, \tag{1}$$

where l is the length of the crystal in beam direction, β is the Pockels coefficient and ω_0 is the frequency of the beam.

The polarization of light travelling through the crystal stays linear if the light is polarized parallel or perpendicular to the optical axis. A periodically varied voltage $V = V_0 \sin(\omega_m t)$ is applied over the height d of the crystal with modulation frequency ω_m creating a maximal phase shift of $\Phi_{max} = M = \frac{\beta\omega_0}{c}\frac{l}{d}V_0$. The modulated light can than be written as

$$E(t) = E_0 \exp[i(\omega_0 t + M \sin w_m t)] \tag{2}$$

$$= E_0 \exp(i\omega_0 t) \sum_{n=-\infty}^{+\infty} J_n(M) \exp(in\omega_m t). \tag{3}$$

The phase modulated light may also be written as the Fourier sum of equally spaced fixed frequencies with amplitudes that are given by the nth order Bessel functions J_n as in 3. The first three order Bessel functions are shown in figure 5.

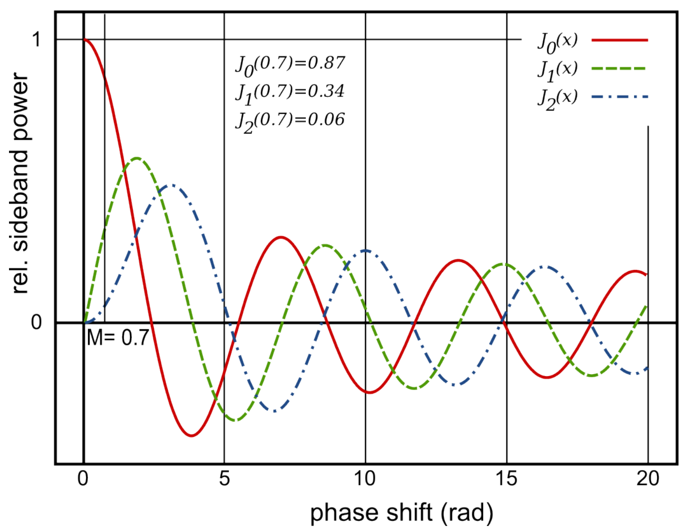

Figure 5: First three order Bessel functions. Vertical line shows modulation depth in our setup at $M \approx 0.7(rad)$.

The following mathematical derivation is taken from Hall's and North's review (2000) [9]. The effect of a sample of length L with an absorption coefficient $\alpha(\omega)$ and index of refraction $\eta(\omega)$ can be written in terms of a complex, frequency-dependent transmission function, $T(\omega) = \exp(-\delta - i\psi)$, with amplitude attenuation δ and phase shift ψ, where $\delta(\omega) = \alpha(\omega)L/2$ and $\psi(\omega) = \eta(\omega)L\omega/c$. The frequency dependence of δ is the absorption line shape, and the frequency dependence of ϕ is the dispersion line shape. The electric field transmitted through a sample then depends on the absorption and dispersion at the carrier frequency and all the sidebands according to

$$E(t) = E_0 \exp(i\omega_0 t) \sum_{n=-\infty}^{+\infty} T(\omega_n) J_n(M) \exp(in\omega_m t). \tag{4}$$

The even and odd order sidebands are, respectively, in and out of phase, as the Bessel functions of negative integer order have the symmetry property $J_{-n}(M) = (-1)J_n(M)$. Therefore the amplitude modulations caused by two symmetric sidebands are out of phase and exactly cancel out leaving pure frequency modulation. Because of the frequency dependence of the attenuation, however, the sidebands have different amplitudes after the transmission through the probe leading to amplitude modulation at the modulation frequency ω_m that is linear in the difference of the attenuation of the two first order sidebands (figure 6).

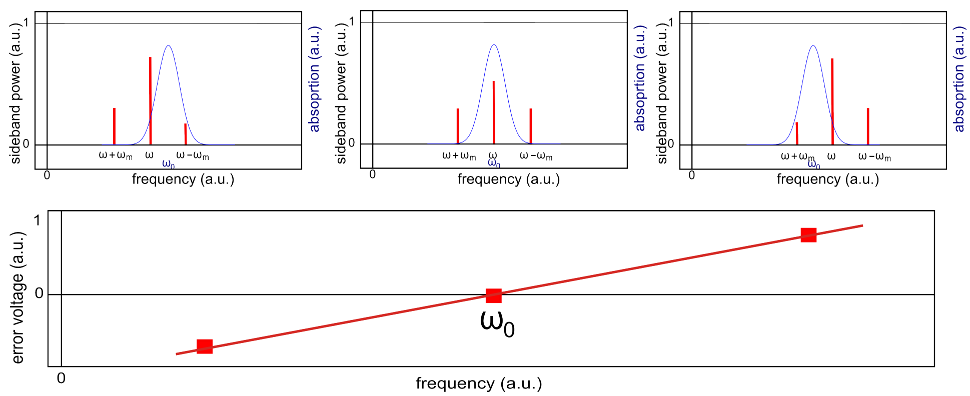

Figure 6: The three upper graphs show the sideband attenuation for different frequencies of the main peak with the corresponding DC-error-signal underneath.

A DC error-signal that is proportional to the amplitude modulation depth may be extracted by mixing the detected signal with the modulation signal. This signal has to be low pass filtered below the modulation frequency because it contains contributions of integer multiples of the modulation frequency. In the limit of weak modulation $M < 1$ only the first order sidebands contribute to this signal leading to an intensity

$$I_{FM} = E_0 \exp(-2\delta_0)[M(\delta_{-1} - \delta_{+1}) \cos\theta + M(\psi_{-1} + \psi_{+1} - 2\psi_0) \sin\theta], \tag{5}$$

where δ_i and ψ_i are the attenuation and the dispersion of the ith order sidebands and θ is the phase shift between the modulation signal and the saturation signal in the mixer. The dispersion term can usually be neglected.

Especially for a symmetric dispersion profile around the resonance frequency. Equation 5 shows that we have to match the phase θ, improve the absorption signal or increase the modualtion amplitude M to get a strong error signal.

The treatment using fixed frequencies only makes sense when the frequency is modulated fast in the timescale of absorption $\omega_m \gtrsim \Gamma$, where Γ is the linewidth of the transition. For slow modulation the time-dependent transmitted intensity just follows the absorption spectrum at the instantaneous frequency, without a phase lag. The natural linewidth of the ^{39}K D2-line is about $6\,MHz$ which is broadened in the saturation spectroscopy signal because of insufficient resolution to resolve transitions to different hyperfine states in the excited $^2P_{3/2}$-level and because of power broadening. For very high modulation frequencies the sidebands showed in figure 6 lie far away from the absorption peak and the difference between them and hence the error signal stay small. The optimal modulation frequencies for our setup therefore lie between $10\,MHz$ and $35\,MHz$.

3. Experiment, Setup

Figure 7 shows our realization of the Frequency Modulation Saturation Spectroscopy Laser Lock. In the following paragraphs it will be explained how to start the laser setup in practice and how to get the optimized error signal.

3.1. Optical Isolator

The alignment of the optical isolator should be done as described in the user's manual.

3.2. Electro-optical Modulator (EOM)

We have chosen a commercial broadband electro-optic phase modulator EO-PM-NR-C1 from Thorlabs to be able to tune the modulation frequency to optimize the phase between the photo diode signal and the modulation signal in the mixer. Resonant mode modulators have the advantage of higher modulation depth M when used with a tank circuit. The modulation signal for the broadband EOM in our setup, however, has to be amplified by a $2\,W$ amplifier (minicircuits, ZHL-1-2W). Because of the poor impedance matching most of the power is reflected back from the crystal into the amplifier which has to be cooled by an additional fan over the pre-mounted heat sink. We also considered attenuating the amplified signal before the EOM because the reflected power would be attenuated another time before reaching the

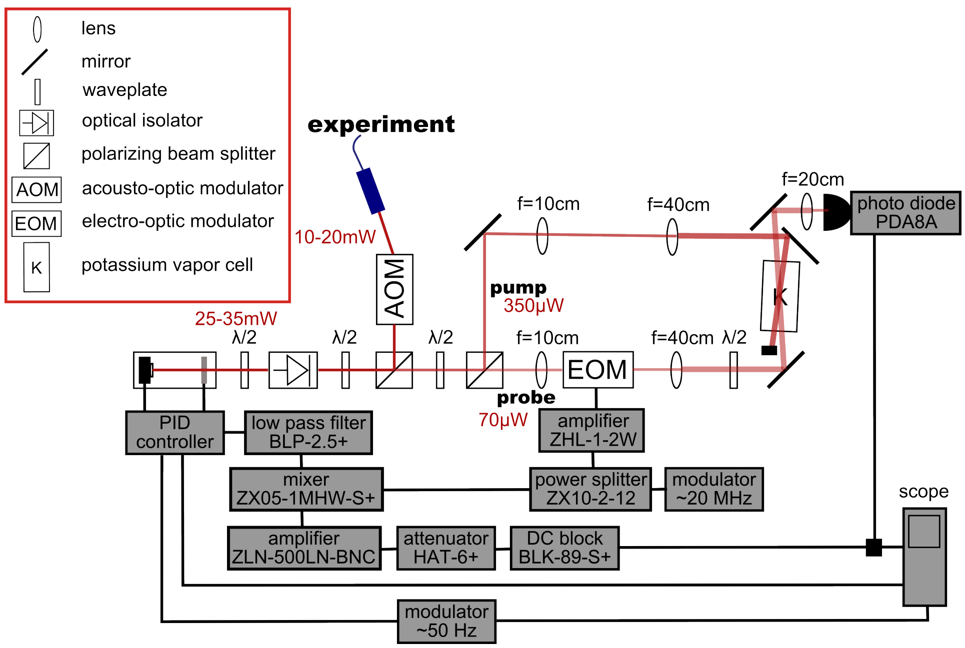

Figure 7: Laser Lock Setup. For reasons of simplicity most mirrors that are necessary for beam alignment are not shown in this schematic. Electronics from minicircuits are shown with part numbers.

amplifier again. However, this reduced the peak-to-peak amplitude and the signal-to-noise ration of the error signal significantly.

With this setup we achieve modulation amplitudes of around $V_0 = 40\,V$. The EOM has a half-wave voltage (voltage that has to be applied to create a 180 degree phase shift) at $767\,nm$ of $173\,V$ leading to $M \approx 0.7$. As shown in figure 5 the second order sideband is still negligible with a relativ intensity of $[J_2(0.7)/J_0(0.7)]^2 = 0.4\,\%$, where as $[J_0(0.7)]^2 = 75.9\,\%$ and $[J_1(0.7)/J_0(0.7)]^2 = 15.3\,\%$.

!! Make sure that you start the amplifier with low modulation powers of $< -30\,dBm$ before turning up to avoid high peak power in the amplifier!! If you are not sure if the function generator is turned down to low powers from the previous run, switch off the amplifier by unplugging the $24\,V$ bananas and check the power on the function generator) The power input for the amplifier should always stay under $10\,dBm$. The amplifier starts getting non linear for power input ($1\,dB$ Compr., see datasheet) over $4\,dBm$.

The beam through the EOM should be aligned by increasing the transmitted intensity first. When the error signal is obtained the alignment may be further improved by optimizing the error signal.

3.3. Vapor Cell

We heat the potassium vapor cell to increase the absorption rate with a current of $2\,A$ through a thin wire that is coiled around the cell on both ends but not in the middle. Thus the potassium atoms do not condense on the outer surfaces (but in the colder middle) of the cell which would lead to reflections of the beams. The current of two adjacent heating wires is always running in opposite directions to avoid strong magnetic fields. A fan on top of the power supply which produces a lot of heat is used for cooling.

We first tried to align the two counterpropagating beams through the vapor cell on top of each other and separating them with a polarizing beam splitter (PBS) reflecting the probe beam into the photo diode. This means that probe and pump must have perpendicular polarization in the cell which is no problem as long as there is no magnetic fields that lead to Zeeman-splitting of the absorption lines. However, the magnetic fields created by the heating wires of the vapor cell are strong enough to distort the error signal due to the splitting (even though the current of two adjacent heating wires is always running in opposite directions). Therefore, we switched to the alignment that is shown in the schematic using a $\lambda/2$-waveplate to get parallel polarization for pump and probe beam. The beams lie in one horizontal plane crossing each other in the middle of the vapor cell and having a horizontal distance of $\approx 5\,mm$ on the vertical input and output surfaces of the cell.

3.4. Photo Diode

In the current setup a PDA8A photo diode from Thorlabs is used. It has a fixed gain and a large bandwith from DC to $50\,MHz$. The detected and DC-blocked (since only the modulated components of the signal contribute to the error signal) signal has to be amplified by an external amplifier (minicircuits, ZLN-500BN-LN). To decrease the noise produced by the amplifier and the mixer an attenuator is used in front of the amplifier leading to a smaller peak-to-peak error signal. A good trade-off leading to an optimized ratio of signal to noise could be achieved by using a $6\,dBm$-attenuator (minicircuits, HAT-6+).

We previously used the slower PDA36A photo diode from Thorlabs with adjustable gain. Since the bandwith of $17\,MHz$ ($0\,dB$ gain, $12,5\,MHz$ for $10\,dB$ gain) was only about enough for no gain two external amplifiers had to be used leading to higher noise.

3.5. Getting started

In this section it is described how to start both lasers. The list refers to the setup when the two EOMs are driven by a single frequency modulator (SRS model DS345) with double tee output (modulation signal for both mixers and signal piezo ramp) and amplified by a single amplifier (minicircuits, ZHL-1-2W) with a power splitter (minicircuits, ZX10-12-2) at the output. Moreover the oszilloscope only shows the error signal. If you can't generate an error signal following this list, you should try to get the saturation signal first. Probably the electronics don't work correctly, the photo diode is saturated, the phase between the saturation signal and the modulation signal at the mixer might be wrong, the alignment is bad or the vapor cell isn't heated up enough. Moreover the saturation signal is easier to find because of the broad doppler peak that is suppressed in the error signal.

- Switch on the power suppliy that heats the vapor cells. Make sure that it runs at around $2.0\,A$ or $5.8\,V$. Fan will be turned on with ramp/lock box.

- Switch on laser to around $70\,mA$. All temperature controls should show values between $10\,k\Omega$ and $15\,k\Omega$. Make sure the beam isn't blocked.

Wait 10 minutes until cell temperature reaches equilibrium and laser stabilizes.

- Switch on photo diodes and oscilloscope.
- Switch on power supply for lock box, fans and amplifiers. Unplug and replug the $24\,V$ bananas to start fan. Make sure all fans are running.
- Turn ramp on/lock off and ramp up to maximum. Start piezo modulation function generator. Center piezo bias on lock box and piezo controller to around $70\,V$ to get maximum tuning range. (Check bias tuning range on lock box by turning it all the way up and down and watch the voltage on the piezo controller. Change bias to the middle of the tuning range and turn piezo controller to $70\,V$
- Start and turn up EOM modulation on function generator to around $0\,dBm$. (!!! read section about EOM first to avoid destroying the amplifier!!!)
- Tune laser diode current slowly between $60\,mA$ and $100\,mA$ until a signal appears on the scope. Make sure the scope diplays the whole piezo tuning range. You expect a signal with 20 to $200\,mV$ on the scope. Center signal around $t = 0\,s$ with piezo controller. This procedure sometimes requires a bit of patience. If you loose the mode, try again.
- Turn up EOM modulation to $5\,dBm$. This should be enough to see strong error signals.
- Optimize error signal:
  - Change pump-probe relation by turning the waveplate before the second polarizing beam splitter (PBS). Make sure you stay in the limit of a strong pump beam realizing at least $I_{pump} > I_{probe}$.
  - Change intensity in saturation arm by turning waveplate before the first PBS. Use beam intensities close to $I_{pump} \approx 350\,mW$ and $I_{probe} \approx 50\,mW$ to avoid power broadening of the saturation peaks and saturation of photo diode, signal amplifier or mixer.
  - Realign EOM by optimizing the error signal (Just look if you can increase the peak-to-peak signal by changing the mirror orientation).

- Change probe and pump alignment through vapor cell and realign probe to photo diode.
- Optimize phase between the two mixed signals (see theory) by changing the modulation frequency. Maximum peak-to-peak signal should be found for modulation frequencies between $10\,MHz$ and $30\,MHz$. For some frequencies the noise decreases significantly. Try to find a good trade-off between noise and amplitude of the signal. The slope of the linear area of the transition that you want to lock to has to be positive! You can also change the cable length to optimize the phase since the wavelength is in the order of $10\,m$. This is more effort and less elegant but would be necessary if a cheap fixed frequency modulator would be used. An alternative would be a homebuilt phase shifter. If you unplug cables, always switch off the amplifiers to avoid high peak currents and power reflections! If both EOMs are driven by one function generator the phase for one of them has to be optimized by the cable length or a homebuilt phase shifter.

- Ramp down to see only $F = 2$ peak (see figure 2) until ramp sweeps over the linear area of the error signal. Switch off the ramp and turn on the lock.
- The laser is locked! =)
- To see beat signal AOM has to be turned on ($-5\,dBm$ at function generator) because only the shifted first order beam of the left laser setup is coupled.
- !! If you shut down the setup always shut down the function generators continiously and before switching off the amplifiers!!

3.6. Beat Measurement

This section describes how to interpret the beat signal on the spectrum analyzer (SA) of two beams with different frequencies and amplitudes .

Linewidth

If we treat the random frequency distribution caused by random noise as a gaußian distributed error

$$\sigma_{beat} = \sqrt{{\sigma_1}^2 \left(\frac{\partial\omega_{beat}}{\partial\omega_1}\right)^2 + {\sigma_2}^2 \left(\frac{\partial\omega_{beat}}{\partial\omega_2}\right)^2}, \tag{6}$$

where σ_{beat}, σ_1 and σ_2 are the standard deviations of the frequencies $\omega_{beat} = \omega_1 - \omega_2$, ω_1 and ω_2, we get

$$\Delta\omega_{beat} = \sqrt{{\Delta\omega_1}^2 + {\Delta\omega_1}^2} \tag{7}$$

because $\sigma \propto \Delta\omega_1$ has no correlation with $\Delta\omega_2$. If one knows the linewidth of one laser or a relation between the linewidth of both lasers, one can calculate the linewidth of the other laser from the linewidth of the beat signal.

Intensity

The intensity I^{beat} of the beat signal can easily be derived from

$$\begin{aligned} I^{beat} &= |E_1(t) + E_2(t)|^2 = |A\cos(\omega_1 t) + |b\cos(\omega_2 t)|^2 \\ &= \frac{1}{4}[2A^2\cos(2\omega_1 t) + 2B^2\cos(2\omega_2 t) \\ &\quad + 4AB(\cos((\omega_1+\omega_2)t) + \cos((\omega_1-\omega_2)t))] \\ &\overset{filter}{\rightarrow} AB\cos((\omega_1-\omega_2)t). \end{aligned} \tag{8}$$

The low pass filtered detected intensity at the frequency $\omega_1 - \omega_2$ is therefore proportional to the product of the amplitudes AB of the electromagnetic fields of the two beams that are superimposed.

Sidebands

The intensity of the main peak is $I_0^{beat} \propto A_0 B_0$, with A_0 and B_0 being the amplitudes of the Fourier components of the main frequency ω_0^1 and ω_0^2 of the two beams. We assume that the second beam has first order sidebands with field amplitudes $B_{\pm1}$. For the intensity of the beat signal of the first order sidebands $I_{\pm1}^{beat}$ of the second beam and the main frequency of the first beam with field amplitude A_0 we get

$$I_{\pm1}^{beat} = cA_0B_{\pm1} = I_0^{beat}\frac{B_{\pm1}}{B_0} \tag{9}$$

The signal on the SA S_{SA} is proportional to the electronic power P_{el} which is proportional to the square of the voltage V_{PD} from the photo diode. The voltage itself is proportional to the intensity of the beat signal I^{beat}. Hence, we get

$$\sqrt{S_{SA}} \propto \sqrt{P_{el}} \propto V_{PD} \propto I^{beat}. \tag{10}$$

Therefore the ratio of the SA signals of the sidebands S_{SA}^{side} and the main frequency S_{SA}^{main} is proportional to the ratio of the intensities of the sidebands $I_{\pm 1}$ and the main frequency I_0:

$$\frac{S_{SA}^{side}}{S_{SA}^{main}} \propto \left(\frac{I_{\pm 1}^{beat}}{I_0^{beat}}\right)^2 = \left(\frac{B_{\pm 1}}{B_0}\right)^2 = \frac{I_{\pm 1}}{I_0} \tag{11}$$

This means that if the SA signal of the sidebands is $40\,dB$ smaller than the main peak on the SA the intensity of the sidebands in the experiment are also $40\,dB$ smaller than the intensity of the main frequency.

4. Perfomance of the System

4.1. Error Signal

Figure 8 shows exemplarily the frequency dependend error signal around the $F = 2$ transition. We get error signals with $600\,mV$ to $800\,mV$ peak-to-peak amplitudes and signal(peak-to-peak-voltage)-to-noise ratios of about 100. The noise is measured in the horizontal parts of the error signal.

4.2. Frequency Stability

The frequency stability of the (piezo, int) locked laser was measured in a beat measurement against a locked laser from another experiment. As long as the laser stayed locked, no frequency drift could be observed. The resolution of this measurement is limited because it is hard to locate the center of the frequency distribution. The peak has several local maximums caused by noise that change position continuously. As an upper limit for the drift we take the linewidth of the beat signal which is about $1\,MHz$.

4.3. Recapture Range

The recapture range of the laser lock is illustrated in figure 9. The frequency scale is calibrated with the SA. The laser frequency was detuned by changing the piezo voltage. Than the time shift of the error signal was compared to the

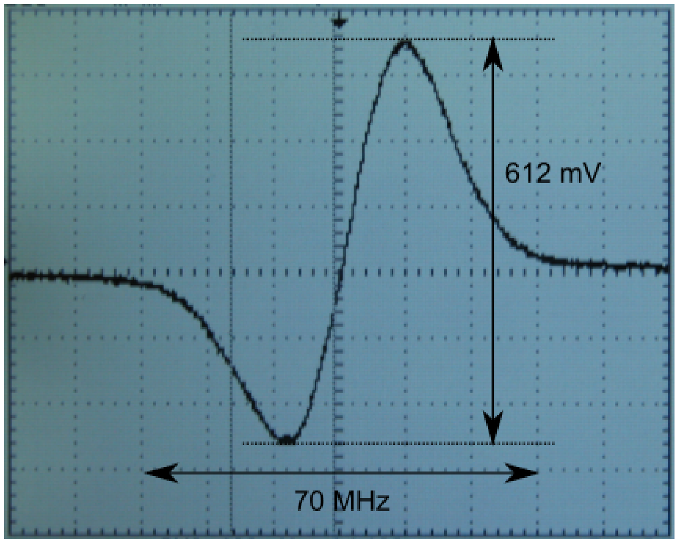

Figure 8: Error signal of the $F = 2$ transition.

frequency shift on the SA. This calibration has to be done each time because it depends on the sweep voltage. The large recapture range of $227\,MHz$ can hardly be realized since the error signal is slightly shifted horizontally over time leading to zero crossings between the peaks. Therefore the factual recapture range is about $70\,MHz$. The servo is usually fast enough to correct the laser frequency before it changes its frequency more than this.

4.4. Long-time drift

It is important to consider long-time drifts as a property of the laser when talking about a laser lock because it leads to losing the lock when the drifts get to large.

The frequency of the unlocked laser drifts over time due to temperature changes and other influences, even though the temperature is controlled close to the photo diode and on the bottom of the aluminium housing. Since these drifts are very slow on a timescale of minutes or hours as shown in figure 10 it is easy for the integrator in the servo loop to compensate them by changing the piezo voltage over time. However, the servo can only change the piezo voltage over $\pm 25\,V$ (if bias on servo box is perfectly centered). Because of the frequency tunability of the piezos ($(-53 \pm 2)\,MHz/V$ and $(-41 \pm 2)\,MHz/V$) the servo can compensate for long-time drifts in frequency of maximal $\pm 1.3\,GHz$ and $\pm 1.0\,GHz$ respectively. Therefore, the lock only

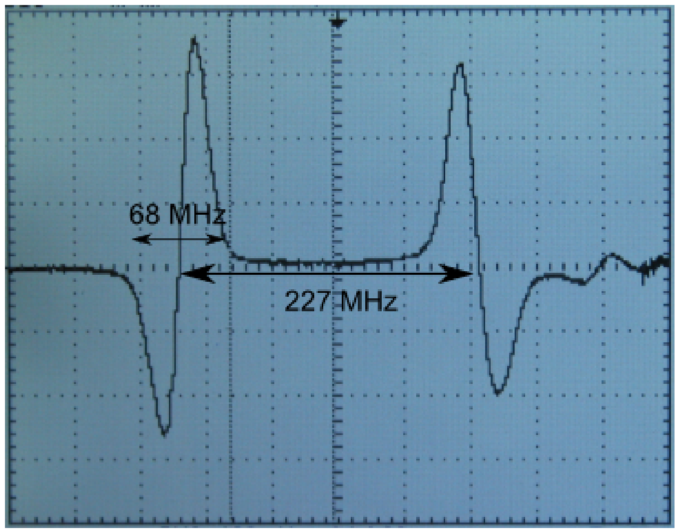

Figure 9: Frequency depend error signal with frequency scale. The frequencies refer to the distance between the tips of the arrows. The two peaks correspond to the $F = 2$ transition (left) and the crossover (right) between $F = 1$ and $F = 2$

works for several hours (the laser has never been seen to stay locked for more than 12 hours [over night]). The time can be extended if the piezo voltage controller is used to decrease the servo feedback voltage from time to time which can be realized by looking at the servo output voltage on a additional scope. The piezo controller has a tuning range from 0 to $140\,V$ which makes it possible to lock theoretically over maximal frequency drifts of $\pm 3.7\,GHz$ for the left setup ($R = 22\%$ or laser 3 in [1]) or $\pm 2.9\,GHz$ for the right setup ($R = 17\%$ or laser 4 in [1]).

4.5. Linewidth And Noise

To isolate the laser cavities from acoustic noise from the table, the lasers are mounted on absorbing rubber (sorbothane). The bolts that are connected to the table don't touch the cavity, either. They only touch the rubber. We had to wait several days until the output beam of the lasers stayed aligned. Therefore, you should not put to much weight on the laser cavities and squeeze the rubber because it could take time until the alignment stays stable again.

The cover for the cavity that protects the inside from air flows is also acoustically isolated through rubber on top of the cavity.

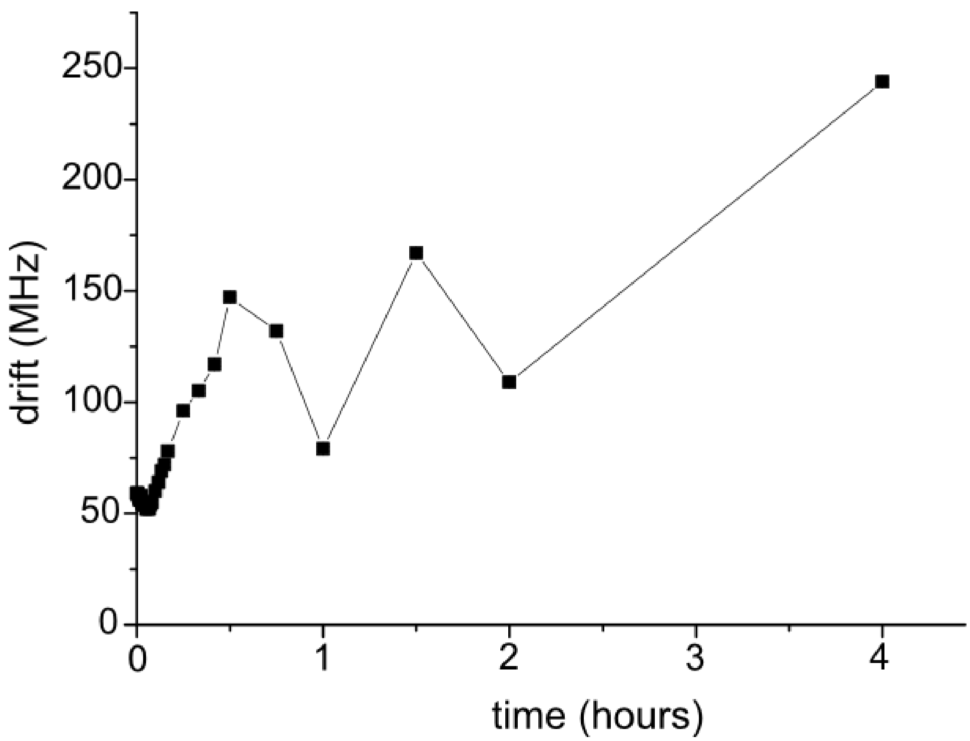

Figure 10: An exemplary measurement of the frequency drift of the unlocked laser 3 with the spectrum analyzer in a beat measurement against a locked laser from another experiment.

This and the strong error signal make the lock stable against metallic objects hitting the table, like a falling pedestal. Even hitting the table with a screw driver next to the laser doesn't unlock the laser.

After applying the rubber to the cavity, the noise measurement that is described in [1] was repeated on the linear slope of the error signal. No peaks could be found but only flat white noise.

The linewidth was measured by translating the noise of the error signal of the piezo feedback locked laser to frequency fluctuations, leading to a linewidth around $1\,MHz$ with $30\,\%$ high errors. This measurement overestimates the linewidth, however, because we took the maximum error signal fluctuations on the scope to calculate the frequency fluctuations. Measurements with the SA lead to similar results (using $\Delta\omega_1 = \frac{1}{\sqrt{2}}\Delta\omega_{beat}$ for two beams with same linewidth $\Delta\omega_1$). Since the piezo feedback is very slow in the order of $\approx 1\,kHz$ the lock without current feedback doesn't have any measurable influence on the linewidth of the laser compared to the case where it is free running.

However, it will be interesting to measure the linewidth of the current locked laser.

4.6. Sidebands

Since we spent a lot of thoughts on sidebands caused by longitudinal external cavity modes, this short section is talking about them.

The free spectral range of the external cavity is $1.7\,GHz$ as shown and explained in [1]. In the beginning, these sidebands showed up on the beat signals between our two ECDLs with minimal relativ intensities from $30\,dB$. Minimal means that they where sometimes even bigger depending on the laser diode currents. Also Matthias Scholl already observed them. Even after several internal alignments of the lenses and the interference filter they could only be decreased to relative intensities of $40\,dB$. After rearranging the setups on the optical table and reoptimizing the lasers the sidebands dissappeared from the SA signal. This means that they have smaller relative intensities than $50\,dB$ now.

5. What could be improved?

- Get power splitter after EOM amplifier with higher max. power input.
- Built fixed frequency modulator for sweep and EOM modulation and phase shifter to optimize error signals independendly.

- Measure linewidth and short time stability when lasers are locked with fast current feedback and piezo feedback to correct slower frequency drifts.

6. Conclusion

We have been able to build an interference-filter-stabilized external-cavity laser in the lab and lock it to the $^{3}9$K D2-line transitions via frequency modulation spectroscpy. Even with a slow integrator feedback to the piezo we achieve favorable linewidth and frequency stability of less than $1\,MHz$. The error signal and the isolation of the cavity from the optical table using rubber pads are good enough to keep the laser locked even when people are moving metallic objects over the optical table. The laser normally stays locked over several hours. If the current error signal is used with a fast current feedback a significant improvement in linewidth and short time stability is expected. The laser is ready to be used in cold atoms experiments in the lab!

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