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Doppler-free spectroscopy using magnetically induced dichroism of atomic vapor: a new scheme for laser frequency locking

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Abstract. We demonstrate a Doppler-free spectroscopic method that we test on ^{87}Rb and ^{85}Rb vapor. By using a magnetic field to induce a dichroism on the sample, we generate a dispersive signal with low background, which allows us to lock a diode laser even on small spectroscopic features. We elaborate the advantages of this simple and easy method by comparing it to other methods.

PACS. 39.30.+w Spectroscopic techniques – 33.55.Ad Optical activity, optical rotation; circular dichroism

1 Introduction

Stabilizing lasers to atomic transition frequencies is commonplace in today's physics laboratories and the experimentalist may choose between a variety of different methods [1]. All active frequency stabilizations have in common that they require a dispersive signal with a zero-crossing at the lock point. We distinguish between two different classes of spectroscopic methods that differ in the generation of this dispersive signal from atomic spectra.

The first class uses modulation and demodulation of light, such as frequency-modulation spectroscopy [2] or modulation-transfer spectroscopy [3], to derive a dispersive signal. These techniques are very powerful and provide high signal-to-noise ratios at the price of expensive optic modulators and electronic components. The methods of the second class do not include modulation and generally imply less optical and electronic components, which makes them easier to implement. Still, they are mostly able to fulfil the demands in atomic and laser physics. Polarization spectroscopy [4], Dichroic Atomic Vapor Laser Lock (DAVLL) [5] and side-locking on saturated absorption spectroscopy signals [6–8] belong to this class.

We present a spectroscopic method, which can be described as a combination of saturated absorption spectroscopy and DAVLL. For this reason, we choose the name Doppler-free DAVLL. The technique makes use of the Zeeman shift to induce a dichroism in an atomic vapor and is explained in the next paragraph, which is followed by the experimental realization. We will then present spectroscopy signals of the D2 lines of ^{87}Rb and ^{85}Rb, before we finally compare this method to other spectroscopic methods, always considering the suitability for locking.

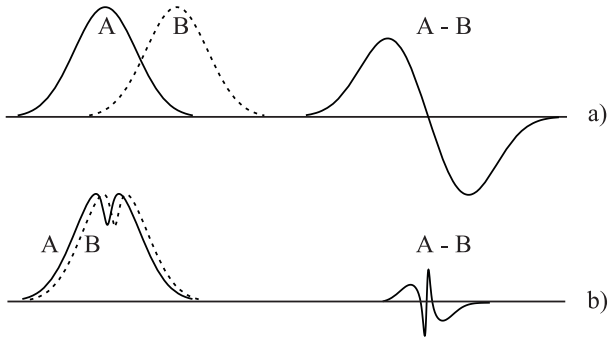

Fig. 1. (a) The subtraction of two relatively shifted Doppler-broadened Gaussian line profiles generates a DAVLL signal. (b) The subtraction of two relatively shifted saturated absorption lines generates a Doppler-free DAVLL signal.

2 General idea

The underlying idea of DAVLL is illustrated in Figure 1a. Two Doppler broadened Gaussian line profiles are shifted in frequency relatively to each other. The difference $A-B$ between the two signals results in a dispersive curve. The slope at the zero-crossing gets maximum at a relative shift of half the Doppler broadened linewidth.

Doppler free DAVLL does the same with two relatively shifted Lorentzian dips in the Doppler profile. The difference signal will be a narrow dispersive signal on top of a very low and broad DAVLL background as illustrated in Figure 1b. To get a difference signal with maximum slope, both Doppler-free lines should be shifted against

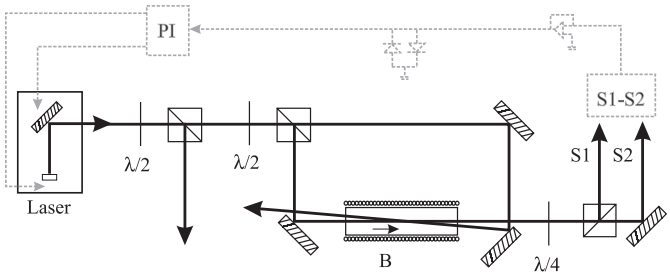

Fig. 2. Setup of the Doppler-free DAVLL. The laser is split into pump and probe beam, and the σ^+ and σ^- components of the probe beam are detected independently after the passage of a rubidium vapor cell. They are subtracted from each other and the resulting signal is used to lock the laser frequency.

each other by 0.58[1] times their linewidth. At zero crossing, the difference signal hence has got a slope twice as big as the slope of the absorption dip and a magnitude of 1.6 times the magnitude of the Doppler-free dip.

To generate such a relative shift in frequency between two saturated absorption signals, we use magnetically induced dichroism. A vapor cell is exposed to a magnetic field along the propagation axis of two counterpropagating pump- and probe beams. The σ^+ and σ^- components of the linearly polarized probe beam are both generating a saturated absorption profile, each Zeeman-shifted by the same amount but in different directions. By separately detecting the two components and subtracting their signals from each other, a Doppler-free DAVLL signal is created.

3 Description of the setup

Our setup for the Doppler-free DAVLL is shown in Figure 2 and is explained by following the laser path from the laser to the photodetector and the electronic feedback signal back to the laser.

An extended cavity diode laser (Sharp LT024MD0) in Littrow configuration [9] serves as a light source. A variable part of the laser power is taken off for spectroscopy, split into counter-propagating pump and probe beam and sent through a cell of rubidium vapor. The cell is slightly tilted relative to the beam propagation to avoid reflections of the pump going to the detectors. Around the cell, we coiled up a wire (90 windings, radius: 12.1 mm, length 80 mm) to be able to apply a magnetic field up to 40 Gauss along the propagation axis of the beams – and at the same time to slightly heat the vapor up to 30 °C. The heating increases the pressure and therefore the absorption signal.

We regard the linear polarized probe beam as a superposition of clockwise and counterclockwise circularly polarized light. Inside the vapor cell, these two components are affected by magnetically induced dichroism. The passage through a quarterwave-plate behind the vapor cell transforms the two circularly polarized components into two orthogonal linearly polarized beams, which are separated by a polarizing beamsplitter and detected independently with two detectors. The difference between these two signals forms a dispersive Doppler-free DAVLL signal. The detection and subtraction is done within a single self-made unit.

[1] The maximum slope of a Lorentzian is found at $1/\sqrt{3} \approx 0.58$ times its linewidth.

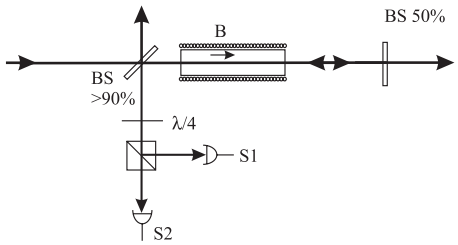

Fig. 3. Proposed simple setup. The first beamsplitter should transmit 0.5 to 0.7 mW.

For locking the laser, the amplified spectroscopic signal is sent to a PI-controller with two outputs. The slow output (bandwidth of 1 kHz) will cause a piezoelectric element to correct the frequency error by adjusting the laser-cavity length, whereas the signal from the fast output will be added to the laser current to correct for high-frequency jitter.

We experimentally optimize the total power used for spectroscopy and the power ratio between pump and probe beam for a maximum size of the signal. We find the following values: pump power 480 μW, probe power 220 μW (beam diameter of 2.5 mm). The magnetic field has been optimized to a value of 11 Gauss in order to give maximum signals.

We suggest an even simpler setup as shown in Figure 3, which is consuming less optical components but does not allow the easy experimental optimization of the power.

4 Results on the rubidium D2 line

The ^{87}Rb and ^{85}Rb, as well as the ^{133}Cs D2 lines [10] have been subject to various studies for their importance in laser-cooling. For a better understanding of the following discussion, Figure 4 shows the absorption transitions from the upper hyperfine-level of the ground state within the ^{85}Rb and ^{87}Rb D2 line. The saturated absorption signal is getting complex, if the atoms are exposed to a magnetic field bigger than 30 Gauss because the Zeeman-splitting exceeds the linewidth of the transition and the first level crossings occur. This effect was examined in [11,12].

In our case, we apply a magnetic field, causing a Zeeman-splitting smaller than the power broadened linewidth of about 17 MHz (the natural linewidth is 5.9 MHz), so that splittings cannot be resolved. The magnetic field defines the quantization axis, which is slightly tilted with respect to the beam propagation by the earth magnetic field ($\approx$ 0.5 Gauss). Dividing the component of the earth magnetic field orthogonal to the propagation axis by the total magnetic component parallel to it, gives the reduction factor of the signal.

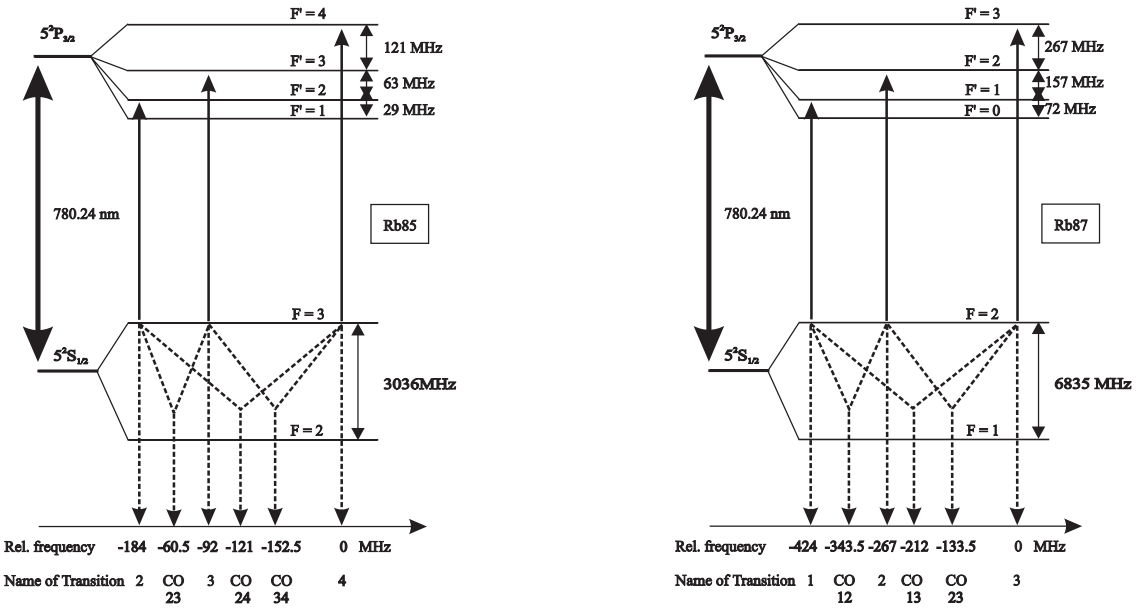

Fig. 4. Transitions from the upper hyperfine-level of ^{85}Rb and ^{87}Rb D2 lines. CO: cross-over transitions.

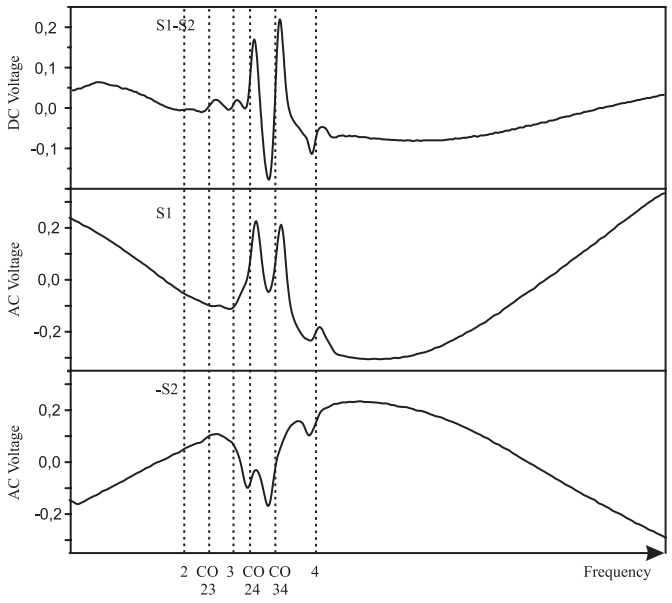

Fig. 5. Spectroscopic signal of the ^{85}Rb D2 transition. The signals S1 and S2 are shifted in opposite directions and the subtraction delivers a dispersive spectroscopic signal with low background.

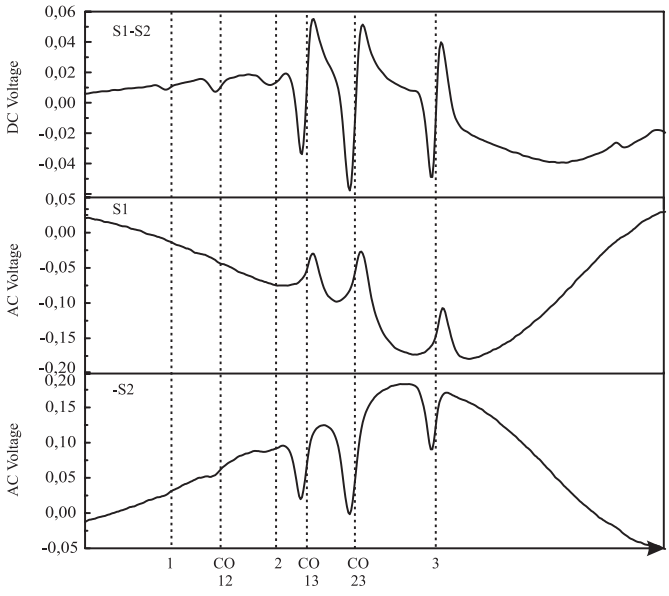

Fig. 6. Spectroscopic signal of the ^{87}Rb D2 transition. Only the transitions from the upper hyperfine level of the ground state are indicated.

The zero-crossing of the spectroscopic signal corresponds to the unperturbed transition-frequency and is neither altered by stray magnetic fields nor by power fluctuations, which both only vary the size of the signal[2].

Figures 5 and 6 show on the ^{85}Rb and ^{87}Rb D2 transitions, how the spectroscopic signal is generated. The two symmetrically shifted saturated absorption signals S1 and S2 add to a dispersive spectroscopic signal S1-S2. The difference does not totally cancel out the background, because also the Doppler-broadened profiles are slightly shifted in opposite directions. This will underlay the signal with a broad and flat dispersive signal of the same origin (see also Fig. 1b). Heating the cell will not only enlarge the number of atoms but also broaden the Doppler-profile and flatten the background. To evaluate the maximum possible background, we assume the Doppler broadening to be Gaussian of a width of 570 MHz (corresponding to 30 °C). Taking the difference between two Gaussians, each shifted

[2] Fields parallel to the propagation axis will shift the two signals into opposite directions leaving the zero crossing unaffected, whereas fields perpendicular to the propagation axis will reduce both signals and just change the size of the signal.

by half the Doppler-free linewidth of 17 MHz, we find the maxima to be reduced by a factor of 60 compared to the height of the Doppler broadened profile.

Assuming the power fluctuations of the laser to be the dominating noise, we can state that the noise is proportional to the background and also greatly reduced by taking the difference. A further source of additional background is the slight rotation of the probe beam by the Faraday effect. By adequately rotating also the last quarterwave-plate and polarizing beamsplitter (see Fig. 2), this effect can be compensated.

In order to lock the laser on a transition, which creates only a small dip in the absorption profile, like the CO23 of ^{85}Rb (see Fig. 5), we have to amplify the signal by a factor of 20. The large signals originating from the adjacent transitions CO24 and CO34 are also amplified. If the laser jumps out of lock and drifts towards these transitions, the large signals are fed into the feedback loop and cause damage on the laser. To bypass this problem, we add a voltage delimiter consisting of two diodes in opposite directions to ground, cutting the voltage at ± 0.7 V.

We locked a laser on the small crossover resonance CO23 of ^{85}Rb and conservatively estimated from the error signal a frequency noise of 350 kHz. Locking at the larger transition CO34 (see Figs. 4 and 5), we again estimated a frequency noise of 120 kHz.

5 Comparison to other spectroscopic methods

In this paragraph, we want to emphasize the respective qualities of modulation free spectroscopy methods such as side-locking of saturated absorption signals, DAVLL, polarization spectroscopy and Doppler-free DAVLL.

The DAVLL scheme [5] has got a large capture range of the size of the Doppler-broadened linewidth and a slope comparable to that of saturated absorption spectroscopy. The locking point can be chosen anywhere within the Doppler-broadened profile. However, if not locking on the exact zero-crossing, the method is very sensitive on power fluctuations and drifts. This results in a change of the lock point that can exceed several MHz for ordinary diode-lasers. In addition, it is hard to determine the actual frequency. Doppler-free DAVLL offers higher frequency accuracy and a bigger slope of the signal but enables locking only at certain frequencies.

Side-locking on a saturation spectroscopy signal has the intrinsic disadvantage of being sensitive on effects that change the size of the signal, like varying stray magnetic fields. To evaluate the noise on a lock signal, we consider the Doppler-background to be subtracted from the Doppler-free signal, and we assume the power-fluctuations of the laser to be the limiting source of noise. Then, the noise is directly proportional to the size of the signal at the lock point. This point is at half height of the absorption dip, whereas with Doppler-free DAVLL the signal at the lock-point is determined by the background. For absorption dips bigger than the thirtieth part of the size of the Doppler line, Doppler-free DAVLL signals offer lower

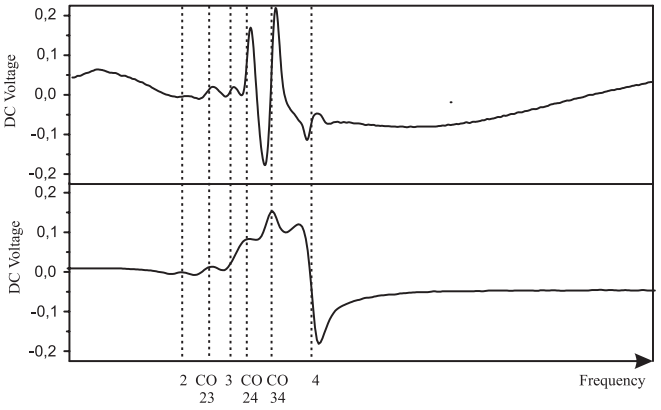

Fig. 7. Spectroscopic signal of the Rb D2 line with (a) Doppler-free DAVLL and (b) polarization spectroscopy under equivalent conditions.

noise and in addition a steeper slope, a bigger signal and a larger capture range of the lock (see Sect. 2).

Instead of using absorption like the above mentioned methods, polarization spectroscopy [4,13] makes use of dispersion to generate spectroscopic signals, which can reach high signal-to-noise values. Generally, one can comment that polarization spectroscopy exhibits its full potential and superior for small peaks on a big background and for thin or low-pressure samples.

In spite of this fact, we set up a simple polarization spectroscopy apparatus using the same large vapor cell and standard optical components as in DAVLL, in order to compare the methods under the same conditions.

For a better understanding, we first give a small review on polarization spectroscopy. The classical pump-probe configuration is used, the pump being circularly polarized. The circular polarization pumps the atoms into one of the magnetic hyperfine sublevels, what results in a macroscopic polarization of the sample, causing an optically induced dichroism. The σ^+ and σ^- components of the linear polarized probe beam experience different amounts of absorption and dispersion around a transition frequency; in contrast to a relative shift of the transition frequencies generated by magnetically induced dichroism in Doppler-free DAVLL. The difference in dispersion of the two components results in a rotation of the linear polarization of the probe beam. On each side of the transition, the rotation has got a different sign and the detection of the rotation gives a dispersive-like spectroscopic signal. The difference in dispersion depends a lot on the amount of polarization the pump is able to induce, what again depends on the particular transition.

If atoms are pumped into an atomic state, which allows them to decay into a different ground state, like the $F = 2$ level of ^{85}Rb in Figure 4, the probe beam reveals a smaller polarization of the sample. The resulting signal is smaller than that of a pure two-level system. In ^{85}Rb, the only pure two level system is pump and probe being in resonance with the $F = 3$ to $F' = 4$ transition (transition 4 in our notation). Figure 7 shows that this transition produces by far the strongest spectroscopic signal. The crossover

resonances CO34 and CO24, which show the biggest absorption dips in saturation spectroscopy, are very small using polarization spectroscopy and of predominantly absorptive character, as Figure 7 shows. In our 7 cm long vapor cell, big differences in absorption between the σ^+ and σ^- components can arise, giving a symmetric contribution to the dispersive signal, thus adding an offset to the lock point and shifting the zero crossing.

Stray magnetic fields reduce the polarization of the sample and the signal is reduced[3].

The detection of transitions with small difference in dispersion and small rotation of the polarization requires good quality polarizers and beamsplitters. These imperfections contribute to a flat background, which also exists for Doppler-free DAVLL, where it is adding to the small characteristic curved background (see Fig. 7).

Again assuming the power fluctuations on the laser light to be the limiting noise, the noise of the zero-crossing of the signal depends only on the size of the background. Considering this, we conclude that in a setup with standard, economical optical components and for the same absolute size of the signal, the noise of Doppler-free DAVLL is comparable to that of polarization spectroscopy, but the first method offers good signals for more transitions and shows a bigger slope of the dispersive signal.

6 Conclusion

We demonstrated a simple and low cost spectroscopic method with Doppler-free resolution. It can be described as a combination of saturated absorption spectroscopy and dichroic atomic vapor laser lock (DAVLL). The spectroscopic signal is relatively insensitive to power fluctuations and varying stray magnetic fields. It produces a dispersive signal with a zero-crossing at the unperturbed transition frequency with low offset, on which a laser can easily be locked. Doppler-free DAVLL will be a good choice, whenever a laser needs to be stabilized to a precision of 100 to 500 kHz at the very frequency of a Doppler-free transition.

After this work was completed, we became aware of a similar work done at Uniwersytet Jagiellonski in Krakow, Poland [14].

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[3] The signal in Figure 7 is taken without magnetic shielding. Instead, we added a small magnetic field along the propagation axis to the earth magnetic field to enlarge the field-component parallel to the axis of propagation in order to enhance the signal.