Laser Frequency Stabilization
Using Linear Magneto-Optics: Technical Notes

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The design of a diode laser frequency stabilization system using the Zeeman effect is described. Various regimes of operation of the device are analyzed using the Jones matrix approach. The system is different from the original JILA design in that the magnetic fields are fully contained and thus it can be used in proximity of magnetically sensitive instruments.

1. Introduction

Recent progress in the investigation of the nonlinear magneto-optics effects \cite{1-3}, as well as progress in a variety of related research (see, e.g. \cite{4-6} and references therein) became possible largely due to the development of frequency stabilized diode laser systems. One of the simplest and most effective methods of laser frequency stabilization is based on the Zeeman effect \cite{7}. This technique was applied to diode lasers in the work of the JILA group \cite{8} who coined the term dichroic atomic vapor laser lock (DAVLL).

The core of laser frequency stabilization is the generation of frequency error signal passing through zero at the lock frequency. Frequency stabilization using the Zeeman effect employs circular dichroism of an atomic vapor in the presence of a magnetic field. Consider a simple case of a $F = 1 \rightarrow F' = 0$ transition – Figure 1. Linearly polarized light incident on the sample can be resolved into two counter-rotating circular components $\sigma^{\pm}$. In the absence of magnetic fields,
Figure 1: An $F = 1 \rightarrow F' = 0$ atomic transition. In the presence of a longitudinal magnetic field, the Zeeman sublevels of the ground state are shifted in energy by $g \mu B \cdot M$. This leads to a difference in resonance frequencies for left- and right-circularly polarized light ($\sigma^\pm$).

the ($M = \pm 1$) sublevels are degenerate and the optical resonance frequencies for $\sigma^+$ and $\sigma^-$ coincide. When a magnetic field $B$ is applied, however, the Zeeman shifts lead to a difference between the resonance frequencies for the two circular polarizations of $2g \mu B/h$, where $g$ is the Landé factor and $\mu$ is the Bohr magneton.

Spectral dependences of absorption parameters $\chi_{\pm}$ for the $\sigma^+$ and $\sigma^-$ polarization components are sketched in Figure 2. For typical experimental conditions in a vapor cell, the width of these curves $\Gamma$ is dominated by the Doppler width $\Gamma_D$ and is on the order of $2\pi \cdot 1 \text{ GHz}$ for optical transitions. Using a circular polarization analyzer, one can separately record the $\chi_{\pm}$ absorption profiles. For the purpose of laser frequency stabilization, the difference in transmitted light intensity for the two components is converted into an electronic signal used to generate the feedback signal. The difference between $\chi_+$ and $\chi_-$ is shown in the lower part of Figure 2. Its spectral dependence has a characteristic dispersion-like shape with width on the order of the Doppler width $\Gamma_D$.

In a conventional diode laser with grating feedback, in order to tune the laser frequency, the grating is adjusted by applying a voltage (usually, $0 \sim 200 \text{ V}$) to a piezoelectric transducer (PZT) (see e.g. [9,10]). The DAVLL technique allows locking the diode laser by feeding back a voltage to the PZT so that the differential signal is maintained at zero crossing.

A detailed description of the optical schematic of the DAVLL and methods of its adjustment can be found in the original publication of the JILA group [8]. Below, we give only a brief overview, concentrating on the features specific to our design.

We have developed a DAVLL system for use in the vicinity of equipment sensitive to magnetic fields and applied it in our work on nonlinear magneto-optic effects (NMOE) in rubidium. The main distinguishing feature is the cell-magnet system. It is designed to suppress the magnetic field spillage from the $\sim 200 G$ magnetic field which is applied over the Rb-cell volume. The properties of the
Figure 2: Dependence of absorption on light frequency detuning $\Delta$ in the absence ($\chi$) and in the presence ($\chi_{\pm}$) of a magnetic field. Shown is the case of $2g\mu B = \hbar \Gamma$ and a Lorentzian model for line broadening. Gaussian and Voigt models (see e.g. W. Demtröder. Laser Spectroscopy. Springer, 1996), which are most appropriate in the case of a Doppler-broadened line, lead to qualitatively similar pictures. The lower curve shows the difference in absorption for the two circular polarization components. This is the characteristic spectral profile of the DAVLL feedback signal.
stabilization system are analyzed using the Jones matrix approach. It is shown that the simple readjustment of the respective angles of optical elements allows one to extend the frequency tunability range to the wings of a resonance line. This possibility was crucial for our recent investigation of spectral dependence of the NMOE magnetometric sensitivity [1-3]. The details of the mechanical design and electronics are presented.

2. Laser locking using circular dichroism and optical rotation

Consider an atomic vapor cell placed in a magnetic field $g\mu B \sim h\Gamma_D$. As discussed above, in the presence of a longitudinal magnetic field, there is a difference in absorption for the two circular polarization - circular dichroism. In general, in addition to the difference in absorption, there is also difference in the refractive index for the two circular polarizations - circular birefringence. It leads to a difference in phase velocities of the two circular components of light and as a result, to a polarization plane rotation. Thus, a linear light polarization before the atomic vapor cell generally evolves into a rotated elliptical polarization after the cell. Here, the rotation is defined as the angle between the initial polarization direction and the principal axis of the final polarization ellipse. In fact, the chosen magnetic field $2g\mu B \approx h\Gamma_D$ corresponds to the maximum of the magneto-optical rotation (the Macaluso-Corbino effect; see, e.g., [11] and references therein). Even at room temperature, $Rb$ vapor possesses a relatively large optical thickness and the rotation magnitudes are as large as hundreds of mrad/cm.

In the conventional DAVLL technique [8], the polarization of the outgoing light is determined by a circular analyzer (see, e.g., [12]) which consists of a quarter-wave plate and a polarizing beam splitter (PBS) with the axis oriented at $\varphi = 45^\circ$ to the fast axis of the $\lambda/4$-plate. A circular analyzer in this arrangement is sensitive to the light ellipticity and insensitive to the angle of rotation. Correspondingly, the orientation of the input polarization is unimportant. The polarizer before the cell ensures that we have linear input polarization i.e. a superposition of two opposite circular polarizations with equal amplitudes. The measure of the vapor cell’s circular dichroism is the normalized difference in the intensities of two circular polarizations. The dispersion-like spectral dependence of this signal is used in the DAVLL.

In order to measure the polarization rotation caused by the vapor cell instead of the dichroism, one can use a balanced polarimeter (see, e.g., [13,11]) consisting of the linear polarizer and PBS as an analyzer. The axis of the PBS is rotated by $\alpha = 45^\circ$ with respect to the axis of the polarizer. In this arrangement, the normalized difference in the transmitted intensities in two PBS’s arms is the measure of the optical rotation. The spectral dependence of optical rotation due to the Macaluso-Corbino effect has characteristic resonance shape which is essentially different from the dispersion-like behavior of the ellipticity. The
slopes of the rotation resonance can also be used to generate the feedback signal locking the laser frequency near the wings of the absorption resonance. A simple reorientation of the relative angles of the optical elements allows one to transform a circular analyzer into a balanced polarimeter. Thus, both possibilities for locking can be realized with the same setup.

To analyze the properties of the present stabilization system we used the Jones matrix approach. The optical system is a sequence of a linear polarizer, an atomic vapor cell, a λ/4-plate, and a polarizing beam splitter. While the polarizers and the λ/4-plate are described in the usual way (see, e.g., [12]), the Jones matrix for the vapor cell should include the frequency dependence of both the real and the imaginary parts of the refractive index. In the presence of a longitudinal magnetic field and under certain simplifying assumptions (linear optics approximation, few absorption lengths, Lorentzian model for line broadening, zero transverse magnetic fields, etc.), the complex refractive index for light with σ± circular polarization is

\[ n_{\pm} = 1 + A \frac{c}{\omega_0} \frac{\Gamma_2}{(\Delta \pm \Omega - \frac{\Gamma_2}{2})}, \]

where \( A \) is a dimensionless coefficient, \( l_0 \) is the absorption length of the vapor, \( \Delta = \omega_0 - \omega \) is the laser frequency detuning, \( \omega_0 \) is the unshifted resonance frequency, \( \Omega = g\mu_B B/\hbar \) is the value of Zeeman shift of the transition frequency. The cell’s influence on circularly polarized light can be described as a frequency dependent complex phase shift. Due to the difference in the sign of Zeeman effect for the corresponding transitions (see Fig. 1 and Eq. (1)), the shifts for light with left and right circular polarization are opposite. This gives rise to elliptical polarization at the output of the cell with the ellipse’s principal axis rotated with respect to the initial linear polarization. The difference between light intensities in the PBS’s arms is given by:

\[ \Delta I \propto \frac{1}{2} \sin(2\varphi)[e^{-2\chi_+} - e^{-2\chi_-}] + \]

\[ \cos(2\varphi)e^{-\chi_+ - \chi_-} \cos(\eta_+ - \eta_- + 2\varphi - 2\alpha), \]

where \( \varphi \) is the angle between the λ/4-plate and the PBS; \( \alpha \) is the angle between the polarizer and the PBS. The frequency dependent refraction parameters, \( \eta_+ \) and \( \eta_- \), and absorption parameters, \( \chi_+ \) and \( \chi_- \), for σ+ and σ− polarization components are given by:

\[ \eta_{\pm} = A \frac{l}{l_0} \frac{(\Delta \pm \Omega)(\frac{\Gamma_2}{2})}{(\Delta \pm \Omega)^2 + (\frac{\Gamma_2}{2})^2}, \]

\[ \chi_{\pm} = A \frac{l}{l_0} \frac{(\frac{\Gamma_2}{2})^2}{(\Delta \pm \Omega)^2 + (\frac{\Gamma_2}{2})^2}, \]

where \( l \) is the length of the cell. For reference, the sum of the light intensities in the PBS’s arms is:

\[ I_{tot} \propto \frac{1}{2}[e^{-2\chi_+} + e^{-2\chi_-}]. \]
Figure 3: The results of the Jones matrix model calculations of the differential signal dependence on laser detuning. Here, we assume $\Omega = \Gamma/2$ and $\Delta l/l_0 = 1/2$. The latter condition means that the optical thickness of the atomic vapor is equal to one absorption length in the absence of magnetic field. (a) The differential signal spectra which correspond to the DAVLL method. (b) The differential signal spectra corresponding to the optical rotation method (see text). The zero crossing points on the slopes labeled by circles mark the approximate boundaries of frequency tunability ranges.
Figure 4: Schematic diagram of the experimental arrangement. Here, PBS is a polarizing beam splitter, PD1 and PD2 are the photodiodes.

From Eqs. (2,3), one sees that at $\varphi = \varphi_0 \equiv \pm 45^\circ$, the system has the properties of a circular analyzer. In this case, the differential signal which has a dispersion-like spectrum (see Fig. 3a) is independent of the mutual orientation of the polarizers, $\alpha$. A small rotation of the $\lambda/4$-plate around $\varphi_0$ with fixed $\alpha$ results in a common offset of the differential signal and a displacement of the zero-crossing points. This is used in the DAVLL systems to tune the laser frequency. At $\varphi = 0^\circ$ and $\alpha = \alpha_0 \equiv \pm 45^\circ$, the optical system transforms into a balanced polarimeter. The differential signal has a shape that is characteristic for the Macaluso-Carbino effect (see Fig. 3b)). Again, a small rotation of the polarizer around $\alpha_0$ at fixed $\varphi$ produces a common offset of $\Delta I$, while the zero crossing point moves along the frequency axis. One can use this behavior to tune the laser on the slopes of the resonance.

3. Experimental Setup

The experimental arrangement used to stabilize the laser frequency is shown schematically in Figure 4. A homemade tunable external cavity diode laser in the Littrow configuration produces cw light at 780 nm (the $Rb$ D2 transition). A small portion (light power $\sim$0.3 mW; beam diameter $\sim$3 mm) of the laser light is split to the DAVLL. After a film linear polarizer, the light passes through an
atomic vapor cell. The cell [14] (a cylinder, 2 cm in diameter and 2 cm long) contains rubidium with natural isotopic abundance: \(^{85}\text{Rb}\) (relative abundance 72%) and \(^{87}\text{Rb}\) (relative abundance 28%). The cell temperature is maintained around 42°C by a resistive heater built into the cell mount. At this temperature, the rubidium vapor density corresponds to approximately two absorption lengths for the center of \(F = 3 \rightarrow F' = 2, 3, 4\) transition group of the \(^{85}\text{Rb}\) D2 line. A magnetic field is applied along the light propagation direction to the atoms in the cell. The field magnitude is chosen to be \(\sim 200\) G at the cell. The design of the magnet provides confinement of the magnetic field inside the cell-magnet assembly thus suppressing the field diffused outside. A description of the details of the cell-magnet mechanical design is given in Section 4.

Consider the circular analyzer arrangement. (The operation of the stabilization system in the balanced polarimeter arrangement is essentially the same.) The \(\lambda/4\)-plate transforms the two circular polarizations into two mutually perpendicular linear polarizations, oriented at \(\pm 45^\circ\) to its fast axis. At \(\varphi_0 = 45^\circ\), there is a nominally zero difference in the signals measured by the photodiodes in the two arms of the beam splitter when the laser frequency is tuned to the center of the resonance (see Fig. 5). A rotation of the \(\lambda/4\)-plate within \(\varphi_0 \pm 10^\circ\) provides a reliable lock of laser frequency in the range approximately \(\pm 200\) MHz with respect to the center of the fluorescence line. In Figure 5a, this is the frequency range between zero-crossing points labeled with circles. Inside the frequency ranges labeled with the squares, the error signal has the opposite sign. Simple reversal of the polarity of the differential signal in the control box (see Fig. 4) allows extending lockable frequencies into these ranges. The electronics design also allows tuning the laser frequency lock point either by adding voltage offset or by varying the load resistor for one of the photodiodes. Pre-tuning of the laser frequency is accomplished by applying \(\text{frequency bias}\) voltage to the input of the high voltage amplifier from a built in source. The present design of the laser lock system does not have a provision for electronic frequency scanning with simultaneous locking: we switch off the feedback loop while the \(\text{frequency scan}\) regime is implemented. However, if necessary, this can be done in a straightforward manner. Details of the electronic schematic are given in Section 5.

The performance of our system has not been characterized in a systematic way. For our purposes it was sufficient that a reliable lock can be obtained for many hours, and the frequency drifts do not exceed several MHz on that time scale. It can be expected that the performance of the system is comparable to that of the DAVLL of Ref. [8], which was investigated in detail in that work.

4. The Cell-magnet System

A cross section of the cell-magnet system is shown in Figure 6. Magnetic field is produced between two cylindrical poles magnetically shorted with a magnetic iron yoke. Each pole is a set of stackable magnetic iron pucks and permanent magnets cut out of a flexible magnetic sheet [15]. The poles have through holes
Figure 5: Spectral dependence of the differential signal at various orientations of the quarter-wave plate and the input polarizer with respect to the polarizing beam splitter: (a) circular analyzer arrangement; (b) balanced polarimeter arrangement. The differential signal is measured at the output of the differential amplifier (see Fig. 4) when the laser frequency is scanned by changing the voltage applied directly to the input of the high voltage amplifier. The DAVLL vapor cell contains a natural mixture of the Rb isotopes. (c) Doppler broadened fluorescence spectrum corresponding to the $F = 3 \rightarrow F'$ transition in $^{85}\text{Rb}$. The fluorescence spectrum is recorded from $^{85}\text{Rb}$-vapor in an additional cell exposed to the output laser beam (see Fig. 4). The small but regular "notches" on both the differential and fluorescence signals are believed to be due to the light beam retro-reflected from the output window of the vapor cell. The primary beam and counter-propagating secondary beam constitute an arrangement for Doppler-free saturation spectroscopy. Analogous features have been observed in the spectra of the nonlinear optical rotation at comparable light power in another experiment [11].
Figure 6: Cross section of the cell-magnet system. 1, magnetic iron yoke plates; 2, magnetic iron pole pucks; 3, resistive heater; 4, aluminum cell mount; 5, flexible magnetic pole rings; 6, rubidium vapor cell; 7, plastic support for the cell mount.
allowing laser beam access. In order to confine the magnetic field inside the magnet assembly, the yoke is shaped as a cube closed from all sides. It consists of six plates of magnetic iron. On the inner side, each yoke plate has a conically shaped recession to increase the distance to the poles. The cube also serves as an enclosure for the cell and heater. In principle, the optical elements can be mounted directly onto the enclosure, so the entire opto-mechanical assembly will be a single compact unit.

The flexible magnetic material is very convenient for manufacturing permanent magnets of nonstandard dimensions like the pole rings used in our device. Moreover, changing the number of rings, one can vary the magnetic field in a wide range of values. It was determined that in the configuration shown in Fig. 6, five magnetic rubber pole rings generate a longitudinal magnetic field \( \sim 200 \) \( G \) at the cell. This corresponds to optimal magnetic field values for DAVLL for the rubidium D-lines [8].

Note that in the present design, the magnetic pole tips have soft iron pucks at their ends, and not the permanent magnet rings. This is important for minimizing magnetic field inhomogeneity at the cell. The reason for this is that the soft iron is far from saturation, and thus the effective electrical currents at the perimeter of the rings related to magnetization are much smaller than in the case of the permanent magnet ring (which is now also further from the cell). Placing permanent rings at the ends leads to a magnetic field reversing sign near the holes.

5. Control Box: Electronic Schematic

The laser stabilization electronics are shown in Figure 7. The photodiode signals are subtracted with A1, an Analog Devices AD624 instrumentation amplifier running at unity gain. The FEEDBACK switch allows phase reversal of the photodiodes. The LOCK switch can close the feedback loop in the ON position, provide no signal to the final amplifier in the OFF position or select an EXTERNAL SCANNING input in the EXT position. External or internal bias can be selected with the BIAS SOURCE switch. R7 and C3 reduce noise in the bias channel.

The output amplifier is a composite design which combines the excellent low DC drift characteristics of the Analog Devices OP177 with the high voltage capabilities of the Apex PA41 power amplifier. The overall gain of the composite amplifier established by R12 and R15 is 100. C6 and C16 are used to compensate the circuit and R13/C9, R22/C17 decrease high frequency noise. The output of the power amplifier can swing from -10V to +230V. A PZT MONITOR signal is available with an attenuation of 100. The electronics was built using printed circuit techniques and housed in an aluminum chassis for shielding.
Figure 7: Electronic schematic of the control box. All resistors are RN-55C, 1%.
6. Conclusions and Acknowledgements

We have described the details of a laser locking system based on linear magneto-optics allowing locking both on the center and the slopes of an atomic resonance. An important feature of the present design is confinement of the magnetic field inside the cell-magnet assembly allowing operation in the vicinity of magnetically sensitive instrumentation. The mechanical and electronic schematics are presented to facilitate construction of such a device.

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References


14. There are no special requirements to the cell quality. Appropriate cells are available, e.g., from Newport, Boulder, CO.

15. This looks like "refrigerator magnet" material, but it is polarized uniformly and is not periodically poled as the refrigerator magnets; such sheet is available from many permanent magnet suppliers and is quite cheap. We used Flexible Magnet, thickness 0.125", part number PSM4-125-4x5CN (a 4"x60" sheet; $32) from A-L-L MAGNETICS, INC. 930 South Placentia, Placentia, CA 92670 1-800-262-4638, Fax 714-632-1757.