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Phase Sensitive Detection: Frequency Locking of a Laser Diode for Lithium Cooling and Trapping

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The frequency of a laser-diode can be locked by providing a negative feedback voltage to the piezo-electric transducer in the laser cavity. By phase-modulating the light and placing sidebands on the carrier frequency, the fluorescence of the atoms is modulated. The signal from this fluorescence is phase-sensitively compared with a phase-locked reference signal in a lock-in amplifier, and an asymmetric error signal is produced. With this feedback method a laser-diode is locked within a 75 Mhz doppler-broadened spectroscopic linewidth. The lock is robust enough to last a few hours at a time and is impervious to high amplitude, low frequency noise perturbations to the laser-diode and temperature changes that cause frequency drifting. The achievement and performance of this lock is essential for the stabilization of the five frequencies necessary to perform a magneto-optical trap of lithium atoms.

Introduction to the Locking Method

Frequency locking of a laser-diode has been performed using the techniques of absorption spectroscopy [1] and also excitation [2], or fluorescence spectroscopy. In both cases the phase of a carrier frequency is modulated in order to capture a beat-frequency signal with a changing phase. To achieve laser cooling of lithium for a magneto-optical trap, the fluorescence spectroscopy technique is employed to frequency lock the master laser-diode to a lithium transition. Laser-diodes are prone to drift in frequency, mostly due to changes in temperature, and the five frequencies required for the MOT must be stable so that the atoms respond properly to the incident photons. Because the five frequencies are obtained from a single LD frequency through acousto-optical modulators, as long as the master LD is stabilized the other four frequencies will be stabilized as well. The frequency lock must be strong enough to resist mechanical vibrations and temperature fluctuations, and tight enough to perform a MOT and (in the future) conduct experiments with the cooled and trapped atoms.

The locking process is performed using phase modulation of the laser beam and phase sensitive detection to create a feedback loop for the piezo-electric transducer driver on the laser. The tuned laser diode beam passes through an electro-optic modulator to modulate the phase of the light, which places 180° out of phase sideband frequencies onto the carrier frequency ν_o at separations of $\nu = \pm 100$ Khz. Because the observed spectroscopic linewidth of the lithium transition is about 75 MHz and the sideband separation is 100 KHz, when the LD is tuned both sidebands remain within the transition line and the atoms absorb all three frequencies. With this alteration to the master LD light fluorescence spectroscopy is performed. Unlike the absorption spectroscopy technique, fluorescence spectroscopy detects changes in the fluorescence of the atoms. As the three frequencies interact with the atoms, the population of the excited state of atoms (and therefore the intensity of the fluorescence) is time modulated at the driving frequency ν [2]. In fact, Eq. 1 below shows a component included in the calculation of p(t), the time-varying excited state population function [2]. This component is proportional to the difference in absorption from each of the sideband frequencies. A(ν) corresponds to the absorptive part of the linear susceptibility, and ϕ is a constant where $\tan(\phi) = \frac{\Gamma_{ff}}{\nu}$. Γ_{ff} is the decay rate of the excited population [2]. This allows for the detection of the ν_o drift as the amount of interaction between the two sidebands change.

$$[A(\nu_o + \nu) - A(\nu_o - \nu)] sin(\nu t + \phi) \tag{1}$$

The fluorescence is detected by a photo-multiplier tube, which outputs an RF component at the beat frequency ν. As the LD frequency (ν_o) drifts over time, the phase of this RF signal drifts due to the changing interaction between the atoms and the three frequencies as stated above. The fluorescence signal created by a photo-multiplier tube is processed in a lock-in amplifier in order to provide proper feedback to the PZT.

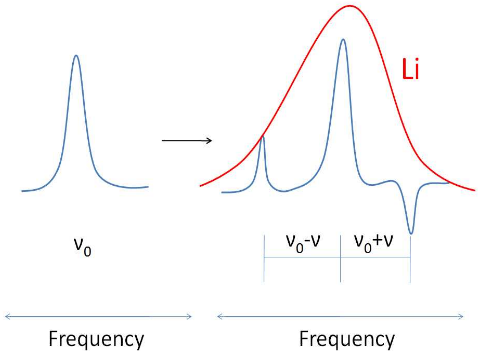

FIG. 1: Phase modulation, creating sideband frequencies at $\nu_o \pm \nu$ within the resonant transition linewidth (not to scale).

Method and Results

The master laser diode is first tuned to the D2 lithium transition line ($2^2S_{\frac{1}{2}} \rightarrow 2^2P_{\frac{3}{2}}$) at wavelength $\lambda = 670.9618$ nm, which is within 0.2 picometers of other accepted measurements for this transition [3]. This transition is commonly referred to as the #11 of out 12 transition lines, and is the selected transition to be used for the lithium MOT. The beam passes through an EOM driven by a local RF generator through a high-voltage amplifier at frequency $\nu = 100$ KHz. As shown in Fig. 1, this places sidebands onto the carrier frequency $\nu_o = \frac{c}{\lambda} = 446.81$ THz, separated at a distance ν. The lithium fluorescence from the combined frequencies is captured through an imaging system and the PMT, shown in Fig. 2. The distance in the chamber from the fluorescent atoms to an AR coated viewing window is 8 cm. Two identical AR coated lenses form the imaging system employed to collect as much light as possible and create a real image of the fluorescent atoms on the PMT eye. The components of this system are carefully configured so that the entire image is captured by the PMT. This ensures a collection of all the information from the fluorescent atoms in order to lock to the center of the linewidth. Care is taken to position the lenses centered and parallel to the viewing window, locate the real image in space using parallax and an aperture, and position the PMT eye at the image location and normal to the path of light. The image is also magnified by approximately $\frac{1}{2}$ to fit within the 1.5 cm PMT eye diameter.

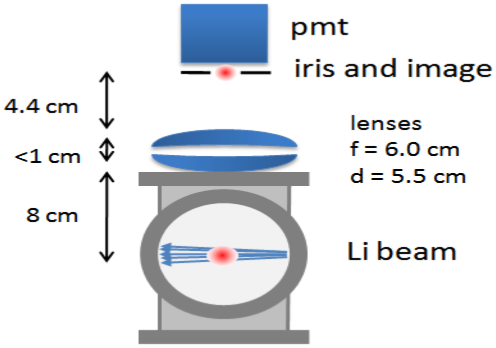

FIG. 2: PMT imaging system. The atomic lithium beam is shown within a six-way cross viewing chamber, and the probing beam is shown normal to the page. The fluorescence is imaged by two bi-convex lenses onto the PMT eye.

The photo-current is converted through a trans-impedance amplifier circuit to a signal containing a DC component and the RF component beat frequency at ν. The same local RF signal is sent to a SR850 lock-in amplifier [4], which uses the signal to create its own phase-locked reference signal. This phase-locked signal and RF beat signal from the PMT are described by Eq. 2 and 3 below [4], respectively. In Fig. 3 the two signals are phase-sensitively compared in the lock-in, where $\omega = 2\pi\nu$.

$$V_L sin(\omega t + \theta_{ref}) \tag{2}$$

$$V_{sig} sin(\omega t + \theta_{sig}) \tag{3}$$

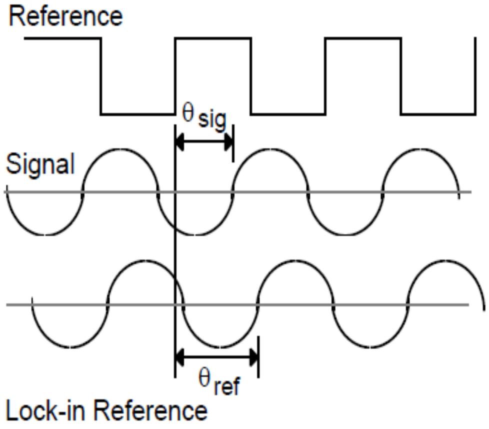

FIG. 3: SR850 lock-in signal comparison. The reference comes from the local RF generator, which is used to create the phase-locked reference signal. The phases between the RF beat signal from the PMT and the phase-locked signal are compared. [4]

The lock-in amplifier is used to amplify the PMT signal and multiply it by the phase-locked signal. The result is sent through an AC filter, leaving a DC output proportional to the phase difference between the two original signals, described by Eq. 4 [4].

$$V = \frac{1}{2} V_{sig} V_L cos(\theta_{sig} - \theta_{ref}) \tag{4}$$

The output from the lock-in is sent to a loop filter servo for better control on the gain of the feedback sent to the PZT controller. The loop filter also provides the advantage of a integrator circuit in order to tailor the gain for a given range of frequency perturbations. For low frequency, high amplitude disturbances in the laser frequency (due to voices, mechanical vibrations, tapping, etc.) the feedback has a high gain. The gain drops off as the frequencies become higher to avoid a 180° phase difference at unity gain and unwanted positive feedback. The output from the loop filter is sent directly to the PZT driver for the laser-diode, providing feedback as the laser drifts and causes the PMT signal to phase drift. If the LD is not drifting, the output of the loop filter will remain near zero. However, if the laser is drifting due to temperature changes, the loop filter output (feedback signal) will also drift off zero. In these likely circumstances the PZT DC bias can be manually tuned to keep the loop filter output from reaching the voltage rails, if necessary. The reference phase (θ_{ref}) in the lock-in can be chosen to create an asymmetrical locking error signal such that if the signals are 90 degrees out of phase, the LD is right on the resonant frequency and the lock-in output is 0 V. As the laser drifts to one side or the other in frequency space, the lock-in provides negative feedback through the loop filter to the PZT voltage. A drift that increases the LD frequency creates a negative sign feedback voltage, and a decrease in the LD frequency creates a positive sign feedback voltage (see Fig. 5). Fig. 4 shows a diagram of the feedback loop components.

With this system, excitation spectroscopy is successfully performed and an effective asymmetric error signal is created for negative feedback to the laser. In normal excitation spectroscopy, a DC fluorescence signal is generated with the PMT by scanning the PZT bias voltage and the error signal is produced with a 0 V output at the peak of the feature. This frequency will be the center of the resonant transition linewidth if the probing beam is orthogonal to the atomic beam, which can be ensured by performing dual beam spectroscopy. Fig. 5 shows the two signals created together with eight averages.

A nearby D2 line transition at $\lambda = 670.9605$ nm (#12) is separated from the #11 transition by approximately 813 Mhz [3]. The neighboring fluorescence peaks can resolved by scanning the LD frequency with the PZT bias. Using this frequency separation reference, the half-max doppler-broadened linewidth of transition #11 is measured at about 75 Mhz. Using this linewidth reference, the magnitude of the lock-in output per Mhz drift can be calculated. Applying a linear fit to the negative feedback error signal data, the lock-in outputs 471 mV for each Mhz perturbation in the laser-diode frequency, and the maximum voltage outputs at the extreme ranges of the negative feedback region are 4.8 V and -4.5 V.

When the probing beam intensity is high enough, saturation spectroscopy can also be performed, which makes it possible to frequency-lock the laser to a saturation dip in the fluorescence signal. This is a much narrower feature of about 15.9 Mhz, which can create a much tighter lock. Fig. 6 shows fluorescence signal with such saturation dip and an asymmetric error signal that produces an output of 0 V at three frequencies, both again with eight averages. The two outer 0 V outputs occur at the individual peaks outside the dip, and the center 0 V output occurs as inverse feedback at the negative saturation dip peak. If the laser receives a strong enough perturbation to push the frequency outside the 15.9 Mhz feature range, the signal switches from negative to positive feedback, and the laser frequency is kicked away from the transition.

Once more applying a linear fit to the data within the negative feedback region, the lock-in produces a signal of 1 V for each Mhz perturbation in the laser-diode frequency. The maximum voltage outputs at the extreme ranges of the negative feedback region are -2.7 V and 7.5 V.

Data for the fluorescence and error signals in Fig. 5 and 6 was collected with a lithium oven temperature of 481°C, 1.14 mW beam power, .3 V control voltage gain setting on the trans-impedance PMT circuit, and a signal-to-noise ratio of $\frac{475mV}{5mV} = 95$. The PZT scan rate was set to 10 Hz, and the lock-in amplifier had the following gain settings: 5 mV sensitivity, 46 dB dynamic reserve, 300 μS time constant, and a 12 dB/octave filter [4].

Analysis and Conclusion

Although frequency-locking to a saturation dip feature provides a tighter lock, this technique was not used for attempts of a magneto-optical trap because of the weakness of the lock. Normal low frequency, high amplitude perturbations such as tapping or voices caused the laser frequency to be kicked into the positive feedback region, and the lock did not last more than a few moments at a time. One factor of this was that the error signal only output a maximum of -2.7 V on one extreme of the negative feedback range compared to 7.5 V on the other side. This may occur because the position of the saturation dip is not in the center of the fluorescence linewidth. An increase of the gain in general on both sides of the feedback region would be necessary to perform a stronger lock to the saturation feature.

The opposite problem appeared for the regular fluorescence peak locking method. The first several attempts at frequency locking were hindered by feedback oscillation and a variety of clipping signals on the output. This was due to too much gain or an incorrect combination of gain settings between the op-amp gain circuit on the PMT, the lock-in amplifier itself, and the attenuation of the input for the PZT driver. After initial attempts, the loop filter servo was added to the system, which provided much better gain control and improved locking strength and efficiency. Even with the loop filter, it was found that a few specific settings on certain components greatly improved the locking method. The fluorescence signal was reduced with the gain control on the PMT op-amp circuit from a range of 1-2.5 V to 200-500 mV. Several other factors affect the fluorescence signal, such as beam power and lithium oven temperature. Typical values for these are 1-2 mW beam power and 450-490°C oven temperature. The error signal was also improved by a reduction in the scan rate of the PZT bias from 90 Hz to 20-30 Hz. In general, it was determined that the locking procedure was very sensitive to the gain settings on all of the components involved.

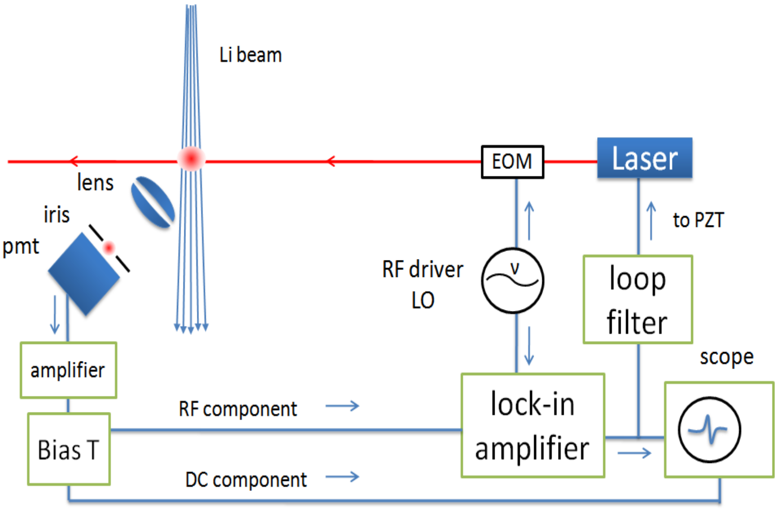

FIG. 4: Frequency locking and feedback loop components. The LD is phase-modulated with an EOM, which in turn modulates the fluorescence. The PMT photo-current is converted to a signal and processed by the lock-in amplifier, which provides negative DC feedback to the PZT controller.

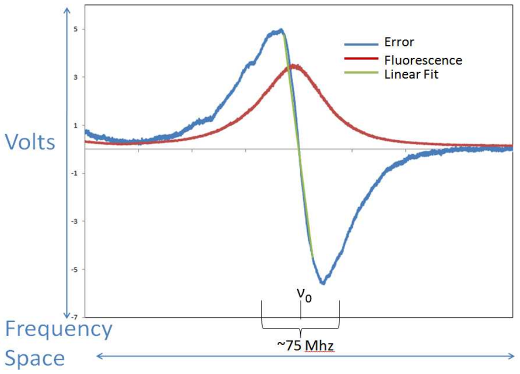

FIG. 5: The lithium fluorescence signal is shown in red, and the lock-in asymmetric error signal in blue. The error signal is 0 V at the peak of the fluorescence signal, which is the center frequency of the transition linewidth. A drift that increases the frequency (right) corresponds to a negative voltage feedback, and vice versa. The fluorescence signal is scaled by a factor of x10 to compare to the error signal, and the green plot is a linear fit to the negative feedback signal region.

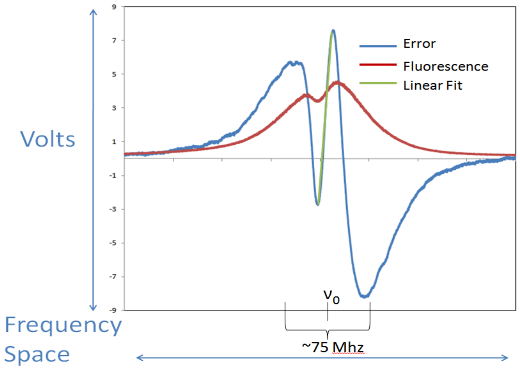

FIG. 6: Saturation fluorescence (red) and error (blue) signals. Within the saturation dip frequency width of 15.9 Mhz, the lock-in provides negative feedback opposite in sign with respect to the normal error signal in Fig. 5. There are three 0 V outputs at each of the two fluorescence maxima and the inverted dip peak. Outside the saturation region the feedback switches to positive. Again, the fluorescence signal is scaled by a factor of x10, and the green plot is a linear fit to the negative feedback signal region.

The phase-sensitive locking technique and system proved successful and provided for lengthy attempts of the magneto-optical trap. The component settings were optimized to create an efficient and consistent step-by-step procedure, which provided the capability to frequency-lock the laser within an average of 15 minutes from the time that the LD was tuned to resonant wavelength. If the frequency lock was intentionally broken after achieving the initial lock, it could then be re-locked within just a few moments. Furthermore, the frequency lock was extremely impervious to high amplitude, low-frequency perturbations. Once the locking system was optimized, the laser was never observed to be kicked out of the negative feedback region due to external noise effects. The lock was also robust enough to last up to 3 or 4 hours at a time by simply adjusting the PZT bias as needed to keep the loop filter signal from reaching its voltage rails. In some cases the laser drifted slowly, and the PZT bias had to be adjusted slightly (a few volts) about every 30 minutes. Other times the laser drifted more (PZT bias adjustment required every 2-5 minutes), but would change the direction of drift so that the over PZT bias would stay relatively centered. There were no trials in which the PZT bias had to be adjusted so much due to laser drift that it reached a 0 V or 200 V limit. If this had occurred, the lock would be broken, the PZT bias would be re-centered to 100 V, the LD would be retuned and re-locked. One circumstance that did cause the lock to break in a couple trials was the presence of laser diode mode hopping within the PZT scan range. In some cases a slight adjustment of a few tenths of a mA in current to the LD would easily decrease the presence of mode hopping. In one trial the number of mode hops within the scanning range was so large that the LD had to be re-optimized and re-tuned to acquire a mode hop free region.

One way to improve the locking method would be higher frequency phase modulation. A much higher frequency sideband separation in the Mhz range is more effective because is reduces contamination of the signal by high amplitude noise [1]. The upper limit of this frequency is 5.8 Mhz, the natural linewidth of lithium. As the modulation approaches this frequency, it becomes too fast for the excited state time response, and the fluorescence modulation does not appear [2]. A 100 Khz frequency was used in this system due to lock-in amplifier bandwidth limitations. A different lock-in amplifier with a much higher bandwidth would be a simple solution for this. High frequency modulation could enable a stronger, more robust lock to a saturation dip feature, which would greatly improve the frequency-lock.

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