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Increased Power and Detuning of Diode Lasers for Magneto-optical Trap of Lithium

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Precision experiments such as laser cooling and trapping using diode laser systems are increasingly prevalent in the fields of modern atomic, molecular and optical physics. Multiple laser diodes of precise frequencies and significant output power are often needed for such research. Here, a method for injection locking a slave laser to a master laser stabilized to an atomic line of lithium is described. The slave laser is a free running diode that is injection-locked by a small portion (2 mW) of the frequency shifted master laser light. Evidence of incomplete injection locking is described, in addition to a technique for improving the precision and robustness of the lock. Furthermore, a method for shifting the frequency of the slave laser in order to produce multiple beams of different detunings, (from 110 MHz to 406.5 MHz) is demonstrated. This provides the frequency detuned beams of adequate power (2.5 mW to 4.0 mW) in each beam needed for a magneto-optical trap of lithium atoms.

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Introduction

Atomic, molecular and optical physics has received significant recognition in the last few decades. The primary advances in this field have been made using known physics to create new and inventive techniques to better isolate and control the atomic system. This nearly ideal system is then exploited to achieve higher precision and discover new physical phenomena [1]. Twenty-one individuals have been awarded the Nobel Prize in this area and advances such as the Stern-Gerlach magnet and optical pumping have allowed preparation and investigation of internal quantum states. Additionally, quantum states have been controlled using resonance techniques. Inventions such as the maser and laser have come from this control of internal states [1].

Laser cooling and trapping has been of particular interest since the late 1970s. The strong forces of electric and magnetic fields on ions allow ions with high kinetic energy to be trapped and then cooled in a variety of ways [1]. In order for trapping to occur, neutral atoms must typically be cooled below 1 K by radiation pressure. Trapping has been achieved for cold atoms using field gradients that act on either the atom's magnetic moments or induced electric dipole moments in addition to resonant radiation pressure. The force that acts on the electric dipole moment is produced by a tightly focused laser beam that is near-resonant. These traps and cooling methods have created the best physical systems yet for precision spectroscopy, frequency standards, and tests of fundamental physics [1].

When an atom scatters a photon, there is a transfer of momentum, and therefore radiation pressure arises. When light is tuned just below the atomic resonance frequency, the atoms moving toward the light see the light Doppler shifted nearer to the resonance, so more photons will be scattered by the faster atoms than the slower atoms. The faster atoms are thus slowed down and the velocity distribution is compressed [1]. One laser beam is able to cool a sample of trapped atoms or ions, but any free atoms must be irradiated from all directions. Because of this, multiple lasers of similar frequencies and appreciable output power are needed for an experiment such as a magneto-optical trap (MOT) [1].

Magneto-optical trapping has been demonstrated for all alkali elements and also some metastable noble gases and rare earth elements [2]. Of the trappable atoms, lithium is of particular importance. Lithium is the most hydrogen-like element, therefore many properties of lithium can be calculated from first principles. Precise measurements of fundamental quantities like the Rydberg constant can be made, therefore, as well as precise determination of atomic properties such as scattering lengths of the ground state. In addition, ^{6}Li is a fermionic isotope, and ^{7}Li is a bosonic isotope, both of which naturally occur in high abundances. Because bosonic lithium is a quantum gas with both repulsive and attractive interactions, experiments relating to quantum-degeneracy are promising with lithium [2].

Diode Lasers

Diode lasers have been of specific interest for use in laser cooling and trapping and high-resolution atomic and molecular spectroscopy. These lasers provide coherent light and have reasonable output power, high electrical to optical efficiency, continuous wavelength tunability and are relatively small and low cost [3]. For these reasons, they are particularly appealing for atomic physics. Because, however, these diodes have a large linewidth (50-100 MHz), and a majority of experiments need linewidths less than 1MHz, diode lasers have been manipulated and studied in order to optimize their frequency stability and absolute frequency. In many instances, this is done by locking the laser to an atomic or molecular transition frequency that is well-known [3]. In our experiment, we locked the master diode laser frequency to the ${}^2S_{\frac{1}{2}}(F=2)2 \rightarrow {}^2P_{\frac{3}{2}}(F=2)$ transition of ^{7}Li.

In order to significantly reduce the bandwidth of a diode laser, an external or extended cavity that has frequency selecting optical elements is needed. In our work at Bethel University, both the Littrow [4] and Littman-Metcalf [5] configurations have been used because of their simple construction and alignment. We have used an EagleYard laser diode (EYP-RWE-0670-00703-2000-SOT02-0000) with a free running wavelength of around 670 nm. The Littman-Metcalf configuration has provided the best results, because it has allowed for better continuous tuning, stability, and ease in alignment of the output beam. This configuration is shown in FIG. 1. The alignment of the collimating lens is of particular importance, therefore, a separate housing with fine adjustment capabilities is incorporated. Continuous tuning of about 7 GHz mode-hop free tuning has been achieved, which is sufficient for frequency locking the laser to an atomic line.

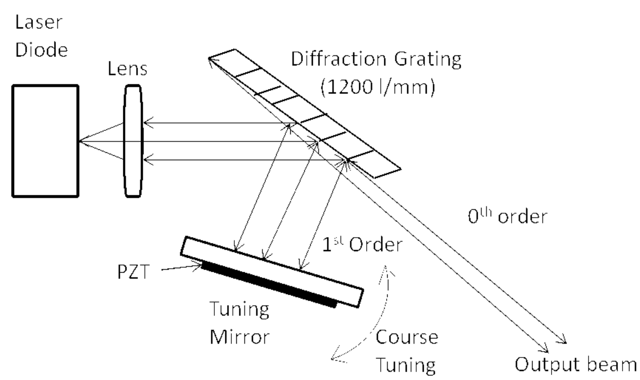

FIG. 1: Litman-Metcalf external cavity laser diode configuration. The diffraction grating is stationary, therefore the location of the zeroth order does not change. A tuning mirror is used to feed back the first order into the laser diode for stabilization and tuning.

Injection locking

After locking the master diode laser to a resonant frequency, it is used to injection lock a higher power slave laser. For laser cooling and trapping, multiple beams of nearly the same frequency are needed. The master laser supplies an output power of about 8 mW, measured from the output of the laser box, when locked to a lithium resonance. Nearly 60 mW can be obtained, however, from a diode laser that is free running with a wavelength within

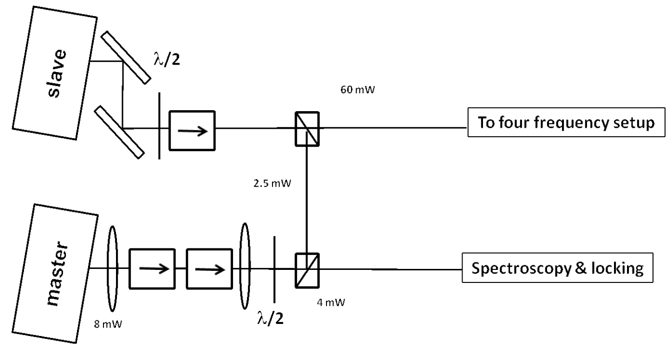

FIG. 2: Schematic of injection locking setup. A half-wave plate is incorporated in order to couple the intensity of the master light in the polarization direction of the slave laser. The first polarizer on the optical isolator is removed to avoid unwanted feedback to either the master or slave laser.

a few nanometers of the master using a simple injection locking technique. For our slave laser, we use an Opnext (HL6555G:G2) laser diode with a maximum output power of 60 mW and a free running wavelength of 664 ± 2 nm. Injection locking is a successful way to obtain the needed identical light sources for trapping free atoms, because one can achieve high output power while still maintaining the needed frequency lock and stability.

Consider a single-frequency laser operating at a frequency ω_0 with an output power I_0. A weak single-frequency beam with frequency ω_1 and I_1 is incident on the high-power laser cavity's output coupler. The way the weak beam is amplified depends on its power and frequency. Even though the high-power laser is producing maximum power at ω_0, there is still gain at ω_1. This is due to the fact that the high-power laser operates below threshold for the weak beam, and an oscillator below threshold acts like a regenerative amplifier. When ω_0 is about equal to ω_1, the regenerative gain for the electric field of a weak beam reflecting from the higher-power laser cavity can be written as $g(w_1) = \frac{\gamma_e}{i*(\omega_0 - \omega_1)}$, where γ_e is the cold-cavity decay rate. The weak input beam, therefore, is rapidly amplified as ω_1 approaches ω_0. When it begins to rival the output intensity I_0, frequency of the laser beam changes from ω_0 to ω_1 [6].

The injection locking schematic used is shown in FIG. 2. The master laser light is sent through two optical isolators to prevent feedback from the light of the slave or reflections from spectroscopy that can affect the stability of the master. A half-wave plate is incorporated to control how much of the master light goes to the slave for injection locking (about 2.0 mW). The horizontal polarization, therefore, passes directly through the first polarizing beam splitter (PBS) to be used for spectroscopy and frequency locking the master to the atomic line. The vertical polarization goes through another arm by way of the PBS, and is sent toward the slave laser through a second PBS.

The beam that is sent toward the slave laser goes through a third optical isolator with the first polarizer removed. We use a lens on each side of this isolator to focus the light into the isolator and recollimate it. Each lens is about 200mm in order to maintain the beam size. The vertically polarized light from the master is then rotated by the second polarizer of the isolator so that it is now horizontally polarized. Then, a second half-wave plate is encountered, which is adjusted to couple the intensity in the polarization direction of the slave laser. When the polarization of the master laser is crossed with the preferred direction of polarization of the slave laser, injection locking no longer occurs, so by rotating the half-wave plate, the injected intensity can be varied without needing to change the current of the master laser or use attenuating filters. Finally, two fine adjustment mirrors are used to optimize the alignment of the incoming master beam and therefore the output beam of the slave. Upon leaving the slave laser box, the polarization of the output beam of the slave is rotated to horizontal by the half-wave plate. The polarizer on the isolator then rotates the polarization again, so that the slave output beam is vertically polarized upon leaving the injection locking setup. Using this configuration, only the vertically polarized master light can enter the injection locking setup, and only the horizontally polarized slave light can leave. This avoids unwanted retro-reflections to both the slave and master.

For efficient injection locking, the injected beam needs to be mode-matched (i.e. same beam parameters) with the slave laser beam. If the two lasers are the same type, this can be achieved by orienting the laser junctions parallel to each other by careful collimation of both lasers. As such, the slave laser beam propagates collinearly with the injected beam but in the opposite direction [3].

As a diagnostic, we use a stray reflection of the slave light coupled into a low resolution spectrometer so that we can monitor whether or not the slave is injection locked. We also have two flip-mirrors incorporated into the set-up. When these mirrors are inserted, the light is sent through an optical fiber to a sub-picometer resolution wavemeter, in which the wavelength of the light can be measured; one mirror sends the master light and one sends the slave light. Figure 3 shows the spectrum of the slave laser with and without injection locking.

An important note is that injection locking does not work for all possible currents of the slave laser. Also, there are different regions of injection locking, the lowest being when the injected intensity of the master laser is large enough to overcome the slave's preferred gain. In this region, the locking does not depend on the position of either the master or slave lasers longitudinal modes. In regions where the slave laser gain is high, the regions of injection locking depend on the relative positions of the two laser's longitudinal modes. Because of this, the slave laser temperature must be changed (therefore shifting the longitudinal modes) in order to compensate for different slave laser currents for injection to work [7]. We found that with 2.0 mW of injection power from the master laser, a slave temperature of 47.6° C and an operating current of around 130 mA ± 2 mA was sufficient for injection locking.

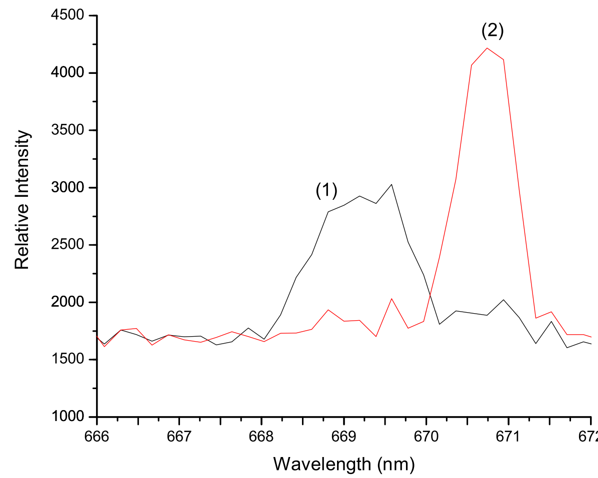

FIG. 3: Slave laser spectrum with and without injection locking using OceanOptics spectrometer with resolution ± .25 nm. Slave laser operates at 47.6° C and 130 mA ± 2 mW, with an output power of approximately 61 mW. (1)Free running slave laser spectrum. (2) Injection-locked spectrum of slave laser. Incomplete injection locking was experienced, which was unresolvable with the OceanOptics spectrometer.

Further Injection Locking Improvements

In our attempts for a magneto-optical trap using this set-up, we realized that while our OceanOptics spectrometer (USB4000) indicated that injection locking was occurring, as in FIG. 3, the injection locking was incomplete. We noticed this through observation of the slowing laser beam, which was supposedly locked to the master. The slowing beam counterpropogates the atomic beam in a magneto-optical trap. The purpose of this beam is to decelerate the atomic beam and thus enhance the flux of slow atoms that can be trapped. The frequency of the slowing beam determines the final atomic velocity of the slowed atoms in a magneto-optical trap [2]. It is necessary that atoms are slowed in order to be captured by a MOT, however, if the final velocity is unnecessarily small, the flux of slow atoms into the trapping volume could be reduced because of an enlarged divergence of the transversely hot atomic beam [2].

In our initial attempts at trapping atoms, we saw no fluorescence in the atomic beam. We, therefore, had reason to believe that the slowing beam was not fulfilling its purpose and slowing atoms. We would expect that when the slowing beam is blocked, no atoms are captured [2].

As we were troubleshooting the ineffectiveness of the slowing beam, we slightly adjusted the current of the slave laser by about 0.5 mA, which caused the atomic beam to fluoresce. A change in the injection current of the slave laser results in a change in the frequency of the slave laser as well. As a result of this observation, we could conclude that only a portion of the slave light was locked to the master, therefore the injection lock is incomplete.

In order to ensure that the slave laser is operating at the exact frequency of the master, a further diagnostic is needed. To do this, we plan to measure the beat signal between the master and slave. This can be accomplished using a high speed detector and an RF spectrum analyzer. The quality of coupling between the lasers is determined by the frequency width of the signal. A sharp peak, with a small full-width half maximum, indicates a strong phase correlation between the slave and the master when the slave is injection locked [3]. Another solution is to avoid the slave altogether, and introduce a commercial laser amplifier to the setup.

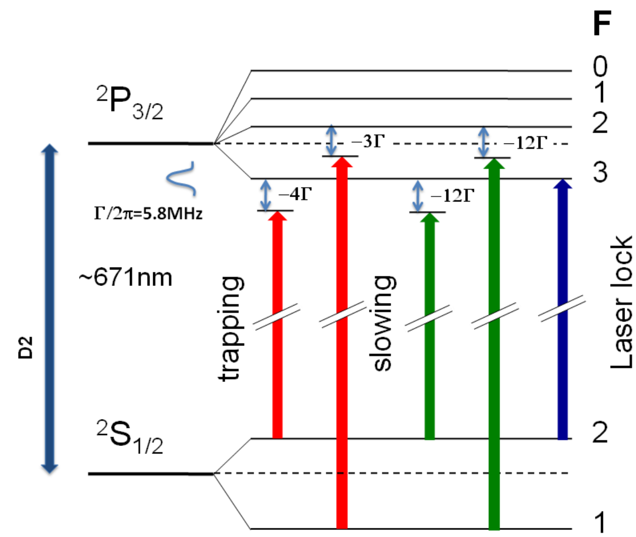

FIG. 4: Relevant energy levels in ^{6,7}Li. Each hyperfine level is labeled with the value of its quantum number F. The frequency detunings from the master laser lock for the trapping and slowing beams are labeled. Figure created by C.W. Hoyt. [D. Das, and V. Natarajan,“Absolute frequency measurement of lithium D lines,” Physical Review A, **75**, 052508 (2007)].

Frequency Shifting

The master laser is locked to the $^2S_{\frac{1}{2}}(F=2) \rightarrow {}^2P_{\frac{3}{2}}(F=2)$ transition, which corresponds to a wavelength of 670.9620 nm [10], as seen in Figure 4. In order to compensate for the Doppler shift and the detuning that occurs in a MOT, one must use beams with slightly different frequency shifts of comparable strength. In our experiment, we use acousto-optical modulators (AOMs) to obtain the frequency detuning needed.

Electrons that are excited by the locking frequency in the MOT have the potential to relax back to the $^2S_{\frac{1}{2}}(F=1)$ subshell, instead of the original subshell. To account for this, we incorporate “optical pumping”. We accomplish this by frequency shifting the master light to a nearby transition, which corresponds to a wavelength of 670.9608 nm [10], a frequency difference of 813.1 MHz. This shifted beam serves to pump the electrons back into the cycle.

To calculate the detunings needed for each beam, we use Eq.1

$$\delta = \omega - \omega_r + \frac{\omega}{c} v \quad (1)$$

where ω is the master laser frequency, ω_r is the frequency of the resonance to which the master laser is locked, v is the velocity of the atoms addressed, c is the speed of light, and δ is the detuning due to the Zeeman splitting effect. The $\frac{\omega}{c}v$ term, therefore, is the frequency shift due to the Doppler shift.

For our MOT set-up, we incorporate both a trapping and slowing beam. The trapping beam must have both transition frequencies present in order to effectively address and slow atoms. Because of the Doppler shift, the trapping beam will need to be red detuned from the resonant master light. For our set-up, a trapping beam detuning of 25 MHz is used, which is approximately 4Γ, where Γ is the transition linewidth of 5.8 MHz. The slowing beam must also have both frequencies. Because the slowing beam counterpropatates the atomic beam, a greater red detuning is needed. A detuning of 71.5 MHz from the master’s locked frequency is used, which corresponds to approximately 12Γ.

The optical set-up used to obtain the detunings needed for our MOT is shown in FIG. 5. The master light that is not used for injection locking is sent through an EOM that creates frequency sidebands that are used in locking to the atomic transition. Then, a second AOM is encountered, providing an offset detuning of 85 MHz for the slowing and trapping beams. We obtained a diffraction efficiency of approximately 85% through this AOM.

The output beam of the slave laser is horizontally polarized and follows the same path as the master. The slave beam then encounters a half wave plate followed by a PBS. The half wave plate is rotated to control the percentage of light that is sent into the pumping beam setup. The vertically polarized light is sent to the pumping beam set up, in which AOM2 shifts the frequency of the beam by 406.5 MHz. A quarter waveplate is in-

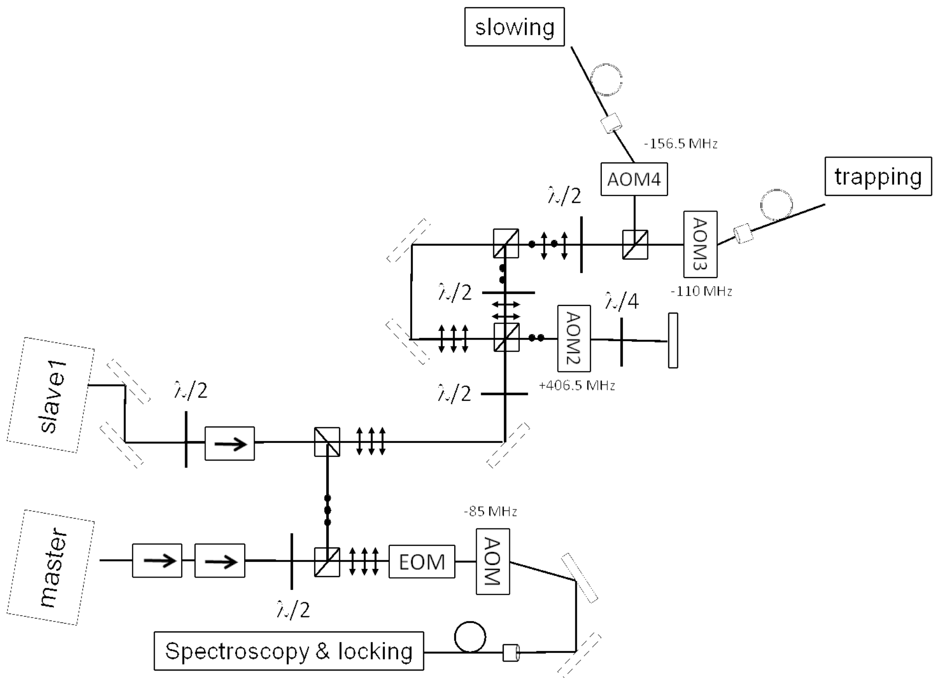

FIG. 5: Complete optical set up prior to magneto-optical trap alignment. The frequency shifts needed for the slowing and trapping beams in order to compensate for the Doppler shift and the detunings that occur in a MOT are accomplished using acousto-optical modulators. Injection locking of slave laser and set up for the trapping, slowing, and locking beam are shown.

serted after AOM2, which circularly polarizes the light. The beam then encounters a mirror, and is retroreflected back through the quarter waveplate. The light therefore becomes linearly polarized again, but is now rotated 90 degrees with respect to the light before AOM2. This horizontally polarized light then passes through AOM2 for a second time, for a total frequency shift of 813.1 MHz. We were able to obtain about 35% diffraction efficiency after both passes through this AOM.

The light that was not sent to the pumping setup is horizontally polarized until it reaches another half waveplate, where it becomes vertically polarized. The horizontally polarized light that is shifted in the pumping setup is then recombined with the unshifted, vertically polarized light in this PBS, and the combined beam continues to the setup for the slowing and trapping beams.

A half-wave plate is incorporated after this PBS, which allows us to send both shifted and unshifted light to both the trapping and slowing setup by way of another PBS. The beam that travels directly through the PBS goes to the trapping beam setup, in which AOM3 shifts the frequency of the beam by -110 MHz. Because of the 85 Mhz shift of the master laser, the trapping beam is shifted a total of -25 Mhz from the frequency of the locked master. Using Eq.1, we have

$$\omega_0 + 85MHz + \delta_l - \omega_t = \omega_0 - \delta_t \tag{2}$$

$$\omega_t = 85MHz + \delta_l + \delta_t \tag{3}$$

where δ_l is the frequency detuning of the locking beam due to Zeeman splitting, δ_t is the frequency detuning of the trapping beam due to Zeeman splitting, and ω_t is the magnitude of the frequency shift applied to the trapping beam through AOM3. We optimized for a diffraction efficiency of approximately 85% through this AOM. The other beam from the PBS goes to the slowing beam setup. Again using Eq.1, we calculate a frequency shift of -156.5 MHz for AOM4, the slowing beam. This results in a total shift of 71.5 MHz from the locked master frequency, and efficiency of about 75%. The trapping and slowing beams are each coupled into a polarization maintaining optical fiber and sent to the MOT chamber. In the trapping fiber, we obtained a input-to-output efficiency of 55%, and in the slowing fiber, an efficiency of 42%.

Conclusion

We have demonstrated an efficient method of providing increased power of a stable, locked frequency using a simple master-slave injection locking technique with diode lasers. We plan to improve our method of diagnosis for assessing the precision and robustness of the lock using a simple beat frequency analysis of the master and slave lasers. In addition, a method for obtaining frequency shifted trapping, slowing, and locking beams to be used for a magneto-optical trap of lithium atoms is described. With other adjustments made to complete and optimize the MOT setup, further experiments of ^{6}Li and ^{7}Li can be attempted.

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