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Laser frequency stabilization and large detuning by Doppler-free dichroic lock technique: Application to atom cooling

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Abstract. We present results of a study of frequency stabilization of a diode laser ($\lambda =$ 780 nm) using the Doppler-free dichroic lock (DFDL) technique and its use for laser cooling of atoms. Quantitative measurements of frequency stability were performed and the Allan variance was found to be 6.9×10^{-11} for an averaging time of 10 s. The frequency-stabilized diode laser was used to obtain the trapping beams for a magneto-optic trap (MOT) for Rb atoms. Using the DFDL technique, the laser frequency could be locked over a wide range and this enabled measurement of detuning dependence of the number and temperature of cold atoms using a relatively simple experimental set-up.

Keywords. Diode laser; frequency stabilization; laser atom cooling; magneto-optic trap.

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1. Introduction

Frequency-stabilized lasers are widely used for a variety of applications such as laser cooling and trapping of atoms, high-resolution spectroscopy, precision measurements and optical communication [1,2]. A typical experimental set-up for laser cooling and trapping of atoms employs several frequency-stabilized lasers tuned to different frequencies. The cooling laser is tuned to the red side of the center of the cyclic transition used for cooling while the re-pumping and the probe lasers are tuned to be resonant with the appropriate transitions. The commonly used method for frequency stabilization of these lasers is based on saturated absorption spectroscopy (SAS) [3]. The laser frequency is locked either at the center or at the side of a narrow peak in the Doppler-free high-resolution saturated absorption spectrum of the atom. Locking at the side of the peak is straightforward and is accomplished by using a PID controller. For locking at the peak, the derivative of signal is generated by frequency modulation and phase-sensitive detection.

Alternative methods for peak locking which generate a dispersion-like signal without laser frequency modulation and phase sensitive detection have also been proposed and demonstrated. These include the use of polarization spectroscopy [4] and several difference-based techniques [5,6]. An important advantage of the difference-based techniques is that these are less sensitive to fluctuations in the laser beam power. Among difference-based techniques, dichroic atomic vapor laser lock (DAVLL) [7] and recently demonstrated Doppler-free dichroic lock (DFDL) [8,9] exploit circular dichroism of an atomic vapor in the presence of a magnetic field. Due to the Zeeman splitting of the energy levels, the absorption peaks for the σ^+ and σ^- polarized light beams occur at different frequencies and the difference of the two absorption spectra produces a series of dispersion-like signals. An inherent advantage of the above two methods is that the spectral width of the signal can be manipulated by applying magnetic field. This allows laser frequency to be locked over a much broader range of frequencies. The DFDL technique has an advantage over DAVLL technique that, due to the hyperfine structure of the signal, it provides a frequency reference point for locking the laser frequency.

Here we report the use of DFDL technique to frequency stabilize a semiconductor diode laser used for cooling and trapping of Rb atoms in a magneto-optic trap (MOT). We present results of the measurement of frequency stability of lasers locked using the DFDL technique. Quantitative frequency stability measurements were not reported in the earlier studies of the DFDL technique [8,9]. Best frequency stability measured by us for optimum magnetic field and de-tunings of the two lasers corresponded to an Allan variance value of 6.9×10^{-11} for an averaging time of 10 s. The broad locking range of the DFDL technique enabled us to vary the cooling laser detuning over a wide range using a relatively simple experimental set-up as compared to the one based on the standard technique of shifting laser frequency using an acousto-optic modulator (AOM). The dependence of temperature and number of atoms in the MOT was studied for laser detuning up to about three and half line-widths and the results were found to be in agreement with those reported in earlier studies [10–12].

2. Experimental set-up for frequency stabilization

The experiments were performed using external-cavity diode lasers (TUI, Germany) operating at 780 nm with a maximum single mode (longitudinal) output power of ~40 mW and short term laser line-width of ~1 MHz. In this laser, feedback is provided by a diffraction grating (1800 lines/mm) in Littrow geometry. The laser can be coarsely tuned by manually adjusting the grating angle whereas fine-tuning is obtained by applying voltage to a PZT fixed on the grating mount. A 30 dB Faraday optical isolator (OI) was used to prevent feedback into the laser during experiments. The linearly polarized laser beam from the diode laser was divided into two beams of variable intensities by using a combination of a half-wave plate and a polarizing beam splitter (PBS) cube. The weaker beam was used for frequency stabilization and the stronger for experiments. Rb vapor cells (at room temperature of 25°C) of length 5 cm were used in the experiments. Magnetic field was generated using a 540 turn solenoid of length ~16 cm and inner diameter 6 cm. For a current of

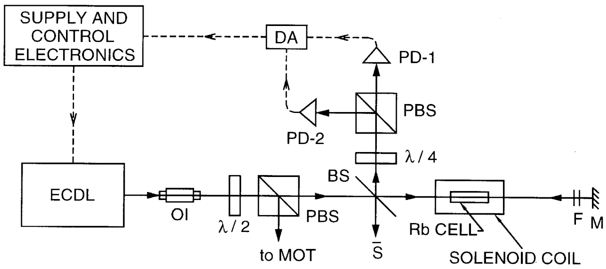

Figure 1. Schematic of the experimental set-up for frequency stabilization using Doppler-free dichroic lock. ECDL: External cavity diode laser; MOT: magneto-optical trap; BS: beam splitter plate; S: stopper; PBS: polarizing cube beam splitter; F: neutral density filters; M: mirror, OI: optical isolator; PD: photodiode; DA: difference amplifier.

$\sim$3 A, the peak magnetic field was $\sim$100 G with a variation of $\sim \pm 5\%$ over a 5 cm long region in the center. The lasers as well as the stabilization set-up were kept on a vibration isolated table to reduce frequency noise due to mechanical vibrations. To avoid noise due to stray light on detectors (PIN photodiodes), the experiments were performed in dark.

The experimental set-up used for generating the DFDL signal is shown schematically in figure 1. The beam coming out from the PBS served as the strong pump beam and the weak probe beam was obtained by attenuated retro-reflection of the pump beam from a mirror. The $\lambda/2$ plate–PBS combination was used to control the pump beam intensity whereas a set of neutral density filters (F) was used to control the probe beam intensity. The linearly polarized probe beam can be considered as a linear combination of two oppositely circularly polarized beams with σ^+ and σ^- polarizations. After exiting the cell, the probe beam passed through a $\lambda/4$ retardation plate which converted these two components into two orthogonally linearly polarized beams. The two beams were then separated by a PBS and detected by two PIN photodiodes. Subtraction and amplification of the signals from the two photodiodes by a difference amplifier (DA) produced the required dispersion-like DFDL signal when the laser frequency was scanned. The intensities of the pump and the probe beams used in the experiments were $\sim$2.2 mW/cm^2 and $\sim$0.7 mW/cm^2, respectively. The DFDL signal was fed to a PID controller to lock the laser frequency. The desired frequency was selected by setting the lock reference level equal to the signal level at that frequency. The laser was observed to remain frequency locked for several hours during the course of experiments.

In the DFDL technique, the frequency lock position can be changed either optically or electronically. The optical method involves rotating the $\lambda/4$ retardation plate before the beam splitter to make the two linearly polarized beams emerging from the PBS unequal. This results in shifting the locking frequency. The electronic method adds an offset voltage to the signal to change the frequency locking position. Here we have changed the locking position of laser frequency electronically.

The present locking set-up does not have a provision for electronic frequency scan while frequency of the laser remains locked. Such a requirement may arise for applications such as formation of molasses with larger detuning after cooling of

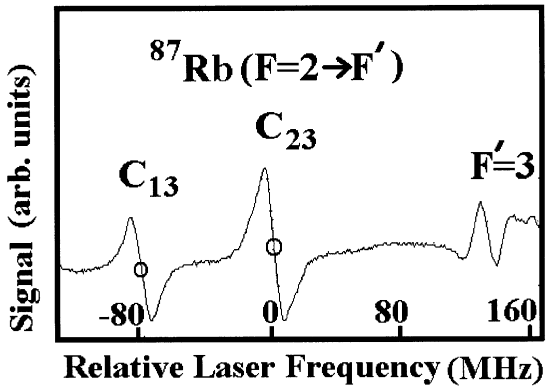

Figure 2. Oscilloscope trace of the DFDL signal. The circles denote frequencies at which the two diode lasers were locked. The applied magnetic field was 10 G.

atoms in the MOT. Usually this is accomplished by shifting frequency of the locked laser using acousto-optic modulators. However, this can also be achieved in the present method by electronically providing a DC offset to the signal to shift the frequency lock point.

3. Frequency stability measurements

Figure 2 shows the oscilloscope trace of the DFDL signal obtained by scanning the laser frequency. The DFDL signal is obtained by subtracting two SAS signals corresponding to different circular polarizations with their peaks shifted in frequency. As the shift is symmetric with respect to the peak position in the SAS signal in the absence of the magnetic field, the zero-crossings in the DFDL signal appear at various hyperfine and cross-over resonance frequencies when the two SAS signals are equal. The magnitude of the shift is dependent on the applied magnetic field, and therefore, the slope as well as the width (locking range) of the DFDL signal around zero-crossing vary with the applied magnetic field. We found that the slope of the signal at the zero-crossing was maximum for a magnetic field of ∼10 G and this field was used for frequency stability measurement.

To study the stability of frequency locking, two diode lasers were frequency locked using DFDL technique to two different transition frequencies of Rb vapor and their beat frequency was measured using a fast photodiode. One laser was locked at the cross-over C_{23} (corresponding to the transitions $F = 2 \rightarrow F' = 2$ and $F = 2 \rightarrow F' = 3$) and the other laser was locked at the cross-over C_{13} (corresponding to the transitions $F = 2 \rightarrow F' = 1$ and $F = 2 \rightarrow F' = 3$) of the $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ transitions of ^{87}Rb. These cross-over peaks have a frequency separation of ∼79 MHz. As shown in figure 2, for locking using the DFDL technique, the laser frequencies were chosen such that the slopes of the corresponding locking signals had nearly the highest values. The laser beams from the two lasers were combined on a fast PIN photodiode and the beat signal was fed to a frequency counter (Agilent, 53131A, 225 MHz). The frequency counter was interfaced to a computer to acquire the beat frequency data. We used different values of sampling time (τ) in the counter ranging from 0.4 s to 40 s and a total of 100 data points were collected for each sampling time (corresponding to an uncertainty of 10% for each estimate). The difference amplifier gain and the PID controller settings were kept the same while performing the frequency stability measurements.

A quantitative measure of frequency stability was obtained by calculating the Allan variance from the measured beat frequency data. This is defined as zero dead-time two-sample deviation of beat frequency and can be expressed as [1,13]

$$\sigma^2(\tau) = \frac{1}{2\nu^2}\langle[\Delta\nu(t) - \Delta\nu(t+\tau)]^2\rangle = \frac{1}{2\nu^2}\sum_{i=1}^{i=N}\frac{(\Delta\nu_i - \Delta\nu_{i-1})^2}{N},$$

where $\langle\ \ \rangle$ indicate time average, $\sigma^2(\tau)$ is the Allan variance, τ is the sampling time, ν ($\approx \nu_1 \approx \nu_2$) is the approximate central frequency of the beating lasers, and $\Delta\nu(t)$ and $\Delta\nu(t+\tau)$ are beat frequencies at time t and $t+\tau$ respectively. For a large number of beat frequency data taken with zero dead-time and sampling time τ, the variance can be calculated by using the summation, where $\Delta\nu_i$ is the beat frequency at time $t_i = t_0 + i\tau$ and $N+1$ is the number of beat frequency data (including $\Delta\nu_0$ at time t_0). Figure 3 shows a plot of σ (square root of Allan variance) as a function of sampling time τ when the lasers were free-running (i.e. unlocked) and when locked using the DFDL technique. The plot shows an increase in σ with increasing sampling time τ for unlocked lasers. This indicates the presence of a long-term drift in the individual laser frequencies. For locking using DFDL technique, σ was found to be $\sim 6.9 \times 10^{-11}$ for the sampling time of 10 s. It is also noted from figure 3 that the Allan variance data point for the sampling time of 40 s corresponds to the observation period of 4000 s for frequency stabilization.

In order to test the long-term stability of the lock, we measured beat frequency as a function of time. Figure 4 shows the observed variation in beat frequency with

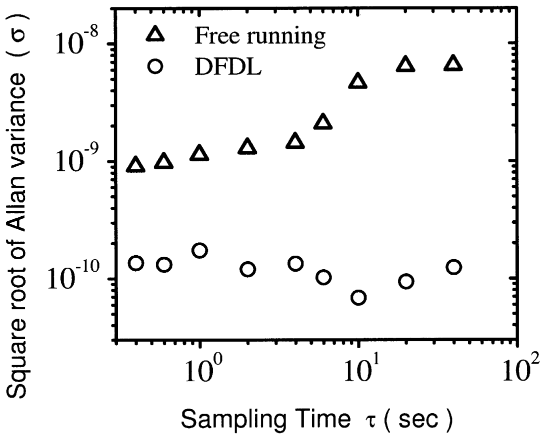

Figure 3. Variation of σ (square root of Allan variance) with sampling time τ, for lasers frequency locked (circles) using DFDL technique and for lasers in free running (triangles) mode.

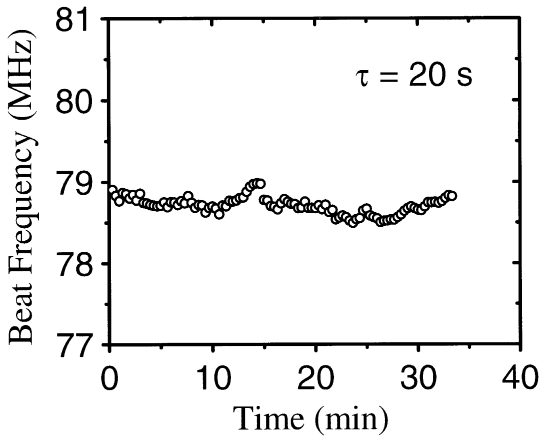

Figure 4. Variation of beat frequency with observation time for frequency-locked lasers using DFDL technique.

time for a fixed sampling time of 20 s. It is evident from the figure that fluctuation in beat frequency is ~500 kHz for an observation period of more than half an hour.

4. MOT set-up and characterization

In order to study the effects of detuning of trapping laser beam on MOT parameters, we used the DFDL technique to lock the trapping laser frequency. Figure 5 shows the DFDL signal near the closed transition ($F = 2 \rightarrow F' = 3$) of ^{87}Rb for different values of the magnetic fields. For large magnetic field, the shift in peaks is large which increases the locking range but reduces the slope near zero-crossing. On the other hand, for small magnetic field, the signal height reduces thereby reducing the slope. In our set-up, we can get frequency locking range of $\sim \pm 2\Gamma$ for $B = 5$ G to $\sim \pm 7\Gamma$ for $B = 20$ G where $\Gamma = 2\pi \times 5.9$ MHz is the ^{87}Rb natural line-width (FWHM).

The MOT is of standard design and basically consists of a glass cell with eight arms sealed with windows polished to good optical quality. The cell is pumped down to a pressure of $\sim 1 \times 10^{-8}$ Torr using a turbo-molecular pump and a sputter-ion pump. Rb vapor is injected in the chamber by passing a constant current of 3.5 A through two Rb-getters fixed (in series) in a glass bulb which is fused to the glass cell. The magnetic field gradient required at the center of the trap is produced by a pair of quadrupole coils. The coils (each having 80 turns and of 8 cm diameter) having oppositely directed currents are separated by ~4 cm. In the central region the magnetic field has nearly a linear variation with distance from the centre in axial as well as radial directions with radial field gradient being ~0.7 times the axial field gradient. The latter can be varied over a range of 5–20 G/cm. All stray magnetic fields were removed by using three orthogonal pairs of compensating coils. Three orthogonal pairs of σ^+ and σ^- trapping laser beams with nearly equal intensity were produced using PBS with $\lambda/2$ and $\lambda/4$ retardation plates. These

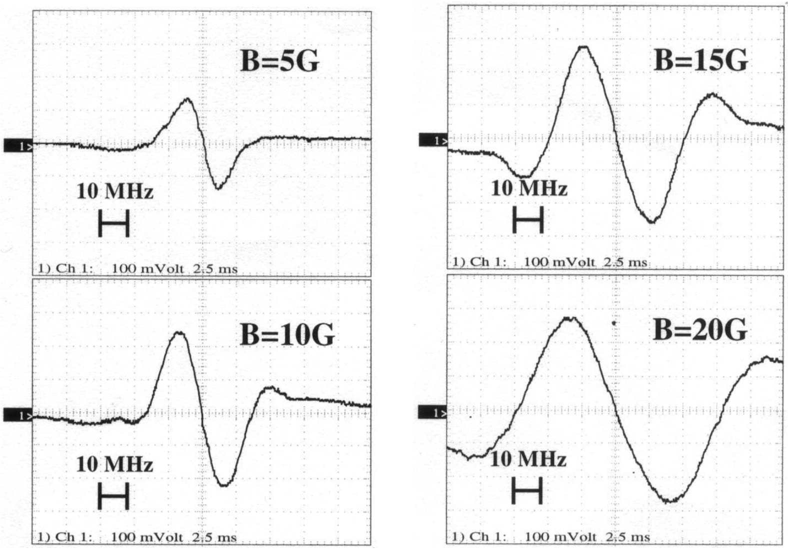

Figure 5. Oscilloscope traces of the DFDL signal (at transition $5^2S_{1/2}$ (F = 2)→$5^2P_{3/2}$ (F′ = 3) of ^{87}Rb) for different magnetic fields.

laser beams intersected inside the glass vacuum chamber. The intersection point is at the centre of the quadrupole coils where the magnetic field is zero. The laser beams are nearly Gaussian with a $1/e^2$ diameter of 5.9 mm. The trap lasers were red-detuned with respect to the cyclic transition $5^2S_{1/2}$ (F = 2)→$5^2P_{3/2}$ (F′ = 3) of ^{87}Rb at 780 nm with detuning Δ_L ranging from -1.5Γ to -3.5Γ using the DFDL technique by applying a magnetic field of ∼15 G to spectroscopic Rb-cell. To collect sufficient number of atoms the intensity of each beam was kept nearly three times the saturation intensity I_s which is ∼1.6 mW/cm^2 for the cooling transition. To prevent optical pumping into the lower ground-state hyperfine level, a repumping laser beam with 1 mW power and with frequency locked to the peak of $5^2S_{1/2}$ (F = 1)→$5^2P_{3/2}$ (F′ = 1) transition was combined with the trap laser.

We measured the average temperature of the trapped atoms by the free-expansion method. In this method, atom cloud expansion rate after release from the MOT is measured which is correlated to the initial temperature of the cloud. To perform these measurements, we switched off MOT laser beams by a mechanical shutter with a closing time of ∼250 μs. Magnetic field gradient produced by quadrupole coils was switched off within 50 μs of switching off the laser beams. Subsequently, after a specified time delay given for free expansion, a probe laser pulse of the duration 500 μs was used to shine the atoms to capture the cloud image by CCD camera. This sequence was repeated by increasing the delay by 1 ms to capture the free expansion images at intervals of 1 ms. Here, we have assumed that there is no significant shot-to-shot variation in the temperature of the cloud in each MOT loading cycle for a given set of MOT parameters. Using the expansion images of the cloud, the temperature (T) was estimated from the root-mean-square size in the density distribution as

$$\sigma_t^2 = \sigma_0^2 + \left(\frac{k_{\rm B}T}{M}\right) t^2,$$

where σ_0 is the initial size of the atom cloud, σ_t is the size at time t, M is the mass of Rb atom and $k_{\rm B}$ is the Boltzmann constant.

We estimated the number of trapped atoms in MOT by imaging the fluorescence from the trapped atoms onto a photodiode. The fluorescence emission power P at the photodiode is related to the number of trapped atoms N by the relation [12]

$$P = \frac{hc}{\lambda} \cdot \frac{\Omega}{4\pi} \cdot N \cdot \gamma_{\rm sc},$$

where Ω is the solid angle subtended by the collecting lens at MOT and $\gamma_{\rm sc}$ is the photon scattering rate given by

$$\gamma_{\rm sc} = \frac{\Gamma}{2} \cdot \frac{I/I_{\rm s}}{1 + I/I_{\rm s} + (2\Delta_L/\Gamma)^2},$$

where I is the total beam intensity from the six trapping beams, $I_{\rm s}$ is the saturation intensity and Δ_L is the detuning.

Figure 6 shows the observed variation of the temperature and number of trapped atoms with detuning of the trapping laser beam at a fixed magnetic field gradient of 12.6 G/cm. The error bar in the figure shows the statistical variation in the measured values. As can be noted from the figure, the temperature decreases with increasing laser detuning. This trend is in good agreement with the results of earlier studies [10]. For the temperature data shown in figure 6, we measured the expansion in the radial direction. We also found that within experimental errors the temperatures in the radial and axial directions were the same. It can be noted that the maximum number of atoms is obtained for the detuning $\Delta_L = -2\Gamma$ which is in good agreement with the results of earlier work [11,12].

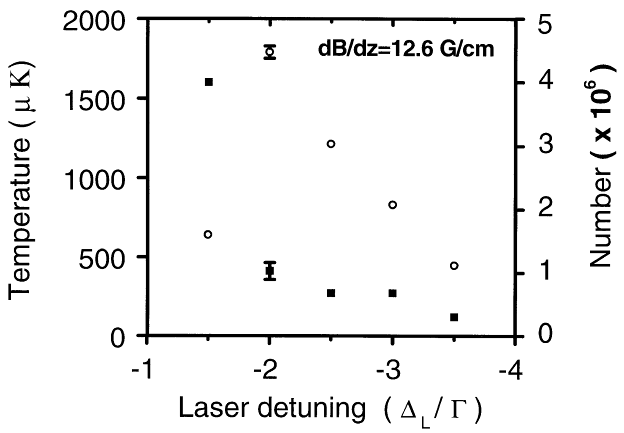

Figure 6. Dependence of temperature (squares) and number (circles) of trapped ^{87}Rb atoms on detuning of the trapping laser frequency in MOT.

5. Conclusion

To summarize, the results of a study of frequency stability of a diode laser locked using the DFDL technique and its use for laser atom cooling are presented. DFDL technique provides a large frequency locking range without using expensive frequency shifters such as AOMs needed with commonly used SAS technique. DFDL also provides dispersion-like signals, permitting both sides as well as peak locking without the need of laser frequency modulation and phase sensitive detection. Frequency stability of diode lasers locked using the DFDL technique was studied quantitatively and the square-root of Allan variance was found to be $\sim 6.9 \times 10^{-11}$ for the sampling time of 10 s. A diode laser frequency-stabilized using the DFDL technique was used to investigate detuning dependence of the number and the temperature of the cold Rb atoms in a MOT.

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