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Laser frequency stabilization using a balanced bi-polarimeter

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ABSTRACT We report on a Doppler-free polarization spectroscopy based technique of laser frequency stabilization using a balanced bi-polarimeter set-up. Two linearly polarized weak laser beams are used to probe birefringence induced by two oppositely circularly polarized strong pump beams in a vapour cell. Subtraction of balanced polarimeter signals obtained from the two probe beams results in a background-free dispersion-like reference signal without frequency modulation. The dispersion-like signal corresponding to the closed transition $5\ ^2S_{1/2}\ (F=2) \rightarrow 5\ ^2P_{3/2}\ (F'=3)$ of ^{87}Rb was used for frequency locking of a diode laser. The frequency fluctuations and the drift were measured to be less than 0.25 MHz and 0.02 MHz, respectively, for an observation period of more than 10 hours.

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1 Introduction

Laser frequency stabilization plays an important role in many atomic physics experiments which require lasers to be locked to an atomic transition [1]. An absolute frequency reference signal required for this purpose is commonly provided by spectroscopic techniques producing either Doppler-broadened or Doppler-free atomic spectrum. The spectrum obtained using a DAVLL setup [2] and using a balanced polarimeter [3] are examples of a Doppler-broadened reference signal with the advantage of a wide capture range but with no provision for locating exact atomic resonance positions. The Doppler-free technique of saturated absorption spectroscopy (SAS) [4] is therefore most commonly used for laser frequency stabilization. The laser frequency can be locked using the side of a SAS resonance peak by comparing it with a set voltage. However, this method is sensitive to fluctuations in beam power, hence, it is desirable to lock at the resonance peak in the absorption spectrum. Modulating the laser frequency about a peak and performing lock-in detection [5] provides a dispersion-like signal with a zero crossing at the peak which is convenient for locking. Polarization spectroscopy [1] provides an attractive alternative for generating a narrow and Doppler-free dispersion-like signal near the resonance without the need for frequency modulation and lock-in detection. However, the background level present in the polarization spectroscopy signal limits the signal-to-noise ratio.

A simple technique based on polarization spectroscopy has recently been demonstrated to generate a dispersion-like signal [6, 7]. This technique uses a polarization beam splitting cube and two detectors to measure rotation of the polarization axis of a weak probe beam due to birefringence induced by a strong pump beam. The zero crossing position of the signal, however, is susceptible to the temperature-dependent birefringence properties of the vapour cell and optical components used in the experimental set-up. This can result in a slow drift of the laser frequency which is undesirable during the experiments. In this paper, we present a Doppler-free frequency stabilization scheme in which a balanced bi-polarimeter is used where two linearly polarized probe beams are overlapped with two oppositely circularly polarized pump beams in a vapour cell. A background-free dispersion-like signal is obtained by subtracting balanced polarimeter signals corresponding to the two probe beams. The zero crossing position of this signal at the resonance peak is independent of the birefringence properties of the vapour cell and optical components used in the experimental set-up. Using this technique, we were able to lock a semiconductor diode laser at the resonance peak of the closed atomic transition $5\ ^2S_{1/2}\ (F=2) \rightarrow 5\ ^2P_{3/2}\ (F'=3)$ of ^{87}Rb. The measured frequency fluctuation and the drift of the locked laser frequency was found to be less than 0.25 MHz and 0.02 MHz, respectively, for an observation period of more than 10 hours.

2 Principle of the method

Our method is based on the principles of polarization spectroscopy [1]. Let us consider a linearly polarized probe beam overlapped by a strong counter propagating circularly polarized pump beam in an atomic vapour cell. This results in a difference in absorption and refractive index for the two counter-rotating circularly polarized components $\sigma^{\pm}$ of the probe beam. The probe beam, as a result, has a rotated elliptical polarization at the exit of the atomic vapour cell. The difference in absorptions for the two probe beam components represents circular dichroism which makes the polarization of the probe beam elliptical whereas the difference in the re-

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fractive indices for the two probe beam components describes circular birefringence and causes a rotation of the plane of polarization of the probe beam. The rotation is defined here as the angle between the initial polarization direction and the principal axis of the final polarization ellipse. The frequency dependence of this polarization rotation is dispersive in nature and can be used to obtain a dispersive signal for laser frequency locking. In order to measure the polarization rotation of the probe beam caused by the vapour cell, one can use a balanced polarimeter [3] consisting of a polarizing beam splitter (PBS) cube as an analyzer. The axis of the plane of polarization of the probe beam is generally at an angle of 45° with respect to the axis of the PBS cube. In this arrangement, the difference in the transmitted intensities of two arms of the PBS cube is the measure of optical rotation. A general expression for the difference between light intensities in the PBS's arms, ΔI_1, is given by [6],

$$\Delta I_1 = I_0\,\mathrm{e}^{-\alpha L - 2b_l} \cos\left(2\varphi + L\Delta n\frac{\omega}{c} + \Delta b_{\mathrm{R}}\frac{\omega}{c}\right), \tag{1}$$

where I_0 is the incident probe beam intensity on a vapour cell of length L and cell window thickness l. αL and b_l are the probe beam absorptions by atomic vapour and vapour cell windows, respectively. Δn and $\Delta b_{\mathrm{R}}/l$ are the differences in the refractive indices for two oppositely circularly polarized components of the probe beam due to the atomic vapour and vapour cell windows, respectively. Here, φ is the angle between the initial plane of polarization of the probe beam and the PBS cube. The refractive index Δn near an atomic resonance has a dispersive spectral line profile given by [1],

$$\Delta n = \frac{c}{\omega_0}\Delta\alpha_0\frac{x}{1+x^2} \tag{2}$$

with

$$x = \frac{\omega - \omega_0}{\Gamma/2},$$

where ω_0 is the frequency of the transition line centre, $\Delta\alpha_0$ is the difference in absorption coefficients of the oppositely circularly polarized components of the probe beam in the presence of the pump beam at the line centre, and Γ is the power broadened linewidth. For $\varphi = 45°$, the polarimeter signal in (1) is given by,

$$\Delta I_1 = -I_0\,\mathrm{e}^{-\alpha L - 2b_l} \sin\left(L\Delta\alpha_0\frac{x}{1+x^2} + \Delta b_{\mathrm{R}}\frac{\omega}{c}\right). \tag{3}$$

As a result of the symmetry in the transition strengths for transitions starting from the $+m_F$ and $-m_F$ sub-levels for σ^+ and σ^- polarized light [8], $\Delta\alpha_0$ changes sign for two oppositely polarized pump beams. Therefore, for an identical linearly polarized probe beam, if the circular polarization of the pump beam is opposite, the expression for the difference between light intensities in the PBS's arms, ΔI_2, is given by,

$$\Delta I_2 = -I_0\,\mathrm{e}^{-\alpha L - 2b_l} \sin\left(-L\Delta\alpha_0\frac{x}{1+x^2} + \Delta b_{\mathrm{R}}\frac{\omega}{c}\right) \tag{4}$$

In our scheme we use two probe beams, which are overlapped by counter-propagating oppositely circularly polarized pump beams. Consequently, this results in two balanced-polarimeter signals. Subtraction of these two signals gives the balanced bi-polarimeter signal,

$$\Delta I_{\text{bi-pol}} = \Delta I_1 - \Delta I_2 = -2I_0\,\mathrm{e}^{-\alpha L - 2b_l} \times \cos\left(\Delta b_{\mathrm{R}}\frac{\omega}{c}\right) \sin\left(L\Delta\alpha_0\frac{x}{1+x^2}\right). \tag{5}$$

Under typical experimental conditions, $L\Delta n\frac{\omega}{c} \ll 1$; $\Delta b_{\mathrm{R}}\frac{\omega}{c} \ll 1$. Therefore, the bi-polarimeter signal can be approximately given by,

$$\Delta I_{\text{bi-pol}} = -2I_0\,\mathrm{e}^{-\alpha L - 2b_l}\left[1 - \frac{1}{2}\left(\Delta b_{\mathrm{R}}\frac{\omega}{c}\right)^2\right]\left(L\Delta\alpha_0\frac{x}{1+x^2}\right). \tag{6}$$

Under similar conditions, the simple polarimeter signal [6] can be obtained by approximating (3) as,

$$\Delta I_{\text{pol}} = -I_0\,\mathrm{e}^{-\alpha L - 2b_l}\left(L\Delta\alpha_0\frac{x}{1+x^2} + \Delta b_{\mathrm{R}}\frac{\omega}{c}\right). \tag{7}$$

In addition to a dispersive part, this signal contains a nearly frequency independent background because of the term $\Delta b_{\mathrm{R}}\frac{\omega}{c}$. As a result of this background, the zero-crossing position of the signal and hence the frequency locking at this point are susceptible to laser intensity fluctuations and temperature dependent birefringence properties of the vapour cell. Furthermore, any change in the overlap of the pump–probe beams, for example, due to vibration of optical mounts, may also disturb the frequency locking signal. On the other hand, the bi-polarimeter signal given by (6) is free from the background term as it has been obtained from subtraction of two polarimeter signals. Frequency locking at the zero crossing position is therefore expected to be more robust. Also, this signal is obtained from the overlap of a pair of pump–probe beams and subsequent subtraction of probe signals, therefore any change in the signal due to overlap is likely to be cancelled. Further, the slope of the signal is twice that of a simple polarimeter signal for the same pump–probe beam intensity ratio. Finally, we note that by adding a dc offset voltage to the bi-polarimeter signal, the zero crossing position can be tuned around the resonance frequency.

3 Experimental

A schematic diagram of the experimental setup is shown in Fig. 1. An extended cavity diode laser (ECDL) system (TOPTICA, Germany) operating at 780 nm with a maximum output power of ∼ 40 mW and short term laser linewidth of < 1 MHz was used in this experiment. 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. The linearly polarized laser beam from the diode laser was divided into two beams of variable intensities using a combination of a half-wave plate and a PBS cube. The weaker beam was used to generate the locking signal and the stronger beam to perform experiments using the frequency stabilized laser. The weaker laser beam was divided into three beams by a thick glass block made of BK-7 glass. Two parallel beams, used as the probe beams, were produced by reflection at both surfaces of the glass block. The transmitted beam was passed through a combination of a half-wave

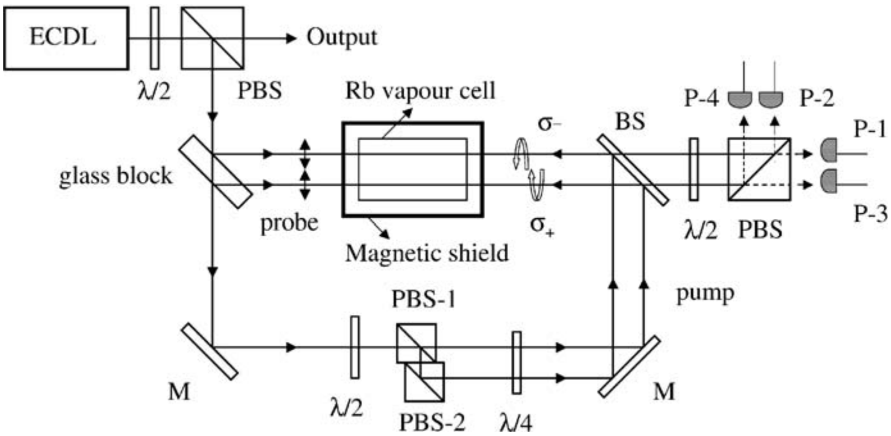

FIGURE 1 A schematic diagram of the experimental setup. ECDL: extended cavity diode laser; PBS: polarizing cube beam splitter; λ/2: half-wave retardation plate; λ/4: quarter-wave retardation plate; BS: beam splitter; M: Mirror; P-1, P-2, P-3, P-4: PIN-photodiodes

plate and two PBS to generate two parallel beams of equal intensity with polarizations perpendicular to each other. These parallel beams when passed through a quarter-wave plate generate two oppositely circularly polarized σ^+ and σ^- pump beams which overlap with the two linearly polarized probe beams with a crossing angle of 15 mrad in a 5 cm long Rb vapour cell at a temperature of 25 °C. The vapour cell was covered with a μ-metal magnetic shield to reduce the stray magnetic field to $\sim$ 10 mG. The powers of each of the pump and probe beams were 100 μW and 30 μW, respectively. The spot sizes ($1/e^2$ intensity) of the laser beams were 0.85 mm vertically and 1.9 mm horizontally. Each probe beam, after passing through the Rb vapour cell, half-wave retardation plate and a PBS cube, was detected by two PIN-photodiodes. The half-wave plate was set to rotate polarization of the probe beam by an angle of 45° with respect to the PBS cube in the absence of the pump beam. The subtraction of signals from photodiodes P-1 and P-2 in presence of the pump beam generated a balanced polarimeter signal. Similarly, a balanced polarimeter signal with opposite slope was obtained from the other probe beam on subtracting signals from the photodiodes P-3 and P-4. The balanced bi-polarimeter dispersion-like locking signal was obtained by subtracting the two polarimeter signals. Figure 2 shows the typical balanced bi-polarimeter signal recorded in our experiments corresponding to the ^{87}Rb D_2 line. This shows $5\ ^2S_{1/2}\ (F = 2) \rightarrow 5\ ^2P_{3/2}\ (F' = 1, 2, 3)$ transitions of ^{87}Rb and the cross-over resonances denoted as C_{ij}.

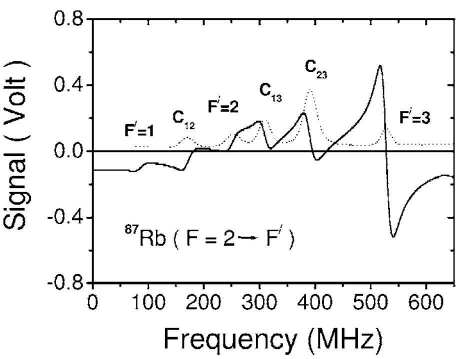

FIGURE 2 The *continuous curve* shows the balanced bi-polarimeter spectrum of $5\ ^2S_{1/2}\ (F = 2) \rightarrow 5\ ^2P_{3/2}\ (F')$ transition of ^{87}Rb. The *dotted curve* shows a simultaneously recorded SAS signal from a different setup for identification of hyperfine resonance peaks

A simultaneously recorded SAS signal from a different setup is also shown for identification and calibration. The largest signal is obtained for the closed transition as the atoms are prevented from being lost to other F-levels of the ground state. Furthermore, due to optical pumping by either the σ^+ or the σ^- pump beam, the atoms are transferred to the extreme m_F sub-level of the ground state. The magnitude of the signal is proportional to the difference between the relative transition strengths of σ^+ and σ^- transitions from the extreme m_F sub-level which is larger in closed transition as compared to other transitions. The dispersive nature of the signal corresponding to open and cross-over transitions is not so clear because of the large overlap of long tails of nearby dispersion-like profiles [9].

Laser frequency stabilization of the ECDL system was studied using the dispersion-like signal corresponding to the closed transition $F = 2 \rightarrow F' = 3$ of ^{87}Rb. The signal was fed to a proportional-integral-differential (PID) controller. The output of the PID controller was fed back to drive the PZT, used for tuning the laser frequency. The laser frequency fluctuation was observed by measuring the amplitude fluctuation in the locking signal. The amplitude of the signal was calibrated to the laser frequency by using the factor of 20 MHz/V obtained from the nearly linear variation around the $F = 2 \rightarrow F' = 3$ transition centre, as can be seen from Fig. 2. To monitor the laser frequency fluctuation with time, we continuously recorded this signal through a data acquisition system connected to a PC. Figure 3 shows the measured frequency fluctuations for a free-running as well as a frequency locked diode laser for a sampling time of 250 ms. The inset in the Fig. 3 shows the frequency fluctuation of the locked laser for an observation period of more than 10 hours. The data for the initial observation period of 4 hours corresponds to the time during which the frequency fluctuation was less than 0.25 MHz. It further reduced to a lesser value for the rest of the observation period. The drift of the locked laser was found to be less than 0.02 MHz during this whole 10 hours of observation period. The frequency stability of the laser lock was also monitored by performing heterodyne measurement using two ECDL laser systems stabilized with identical balanced bi-polarimeter setups. The experimental setups were not enclosed to reduce the ambient temperature fluc-

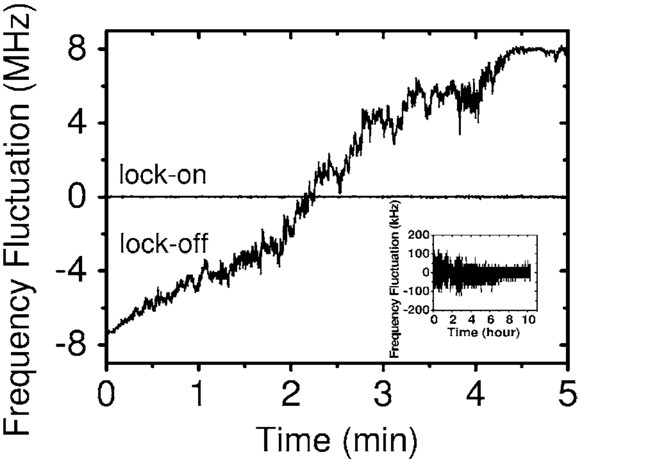

FIGURE 3 Frequency fluctuation of an extended cavity diode laser (ECDL) system under lock-on and lock-off conditions. The *inset* shows laser frequency fluctuation for more than 10 hours under lock-on condition

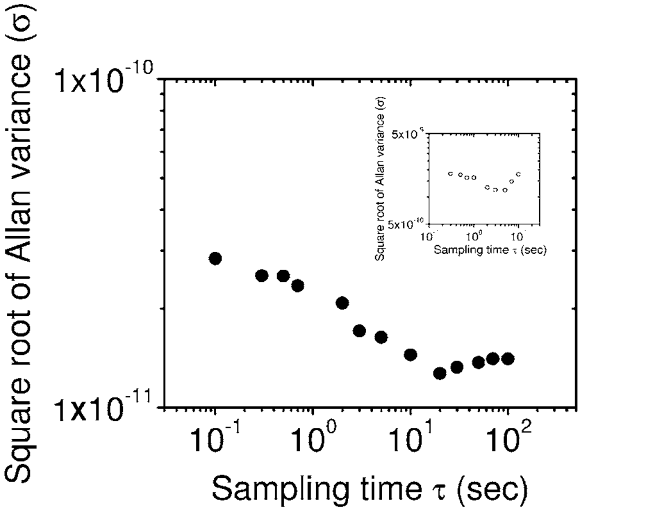

FIGURE 4 The square root of the Allan variance (σ) calculated from the beat frequency data of the stabilized lasers. The *inset* shows the square root of the Allan variance (σ) for free-running lasers

tuations. The lasers were locked to the centre of the closed transition $F=2 \rightarrow F'=3$. One of the lasers was frequency shifted by 81 MHz using an AOM and the two laser beams were combined at a beam splitter and detected using a fast photodiode. The resulting beat frequency signal was fed into a high-speed counter interfaced with a computer. During the observation period the AOM frequency drift was found to be only a few KHz. Using the beat frequency data, we calculated the Allan variance [1], as a function of sampling time τ. The results are shown in Fig. 4. The open circles in the inset represent the square root of Allan variance, $\sigma(\tau)$, when the lasers were free running. The $\sigma(\tau)$ for stabilized lasers is shown by the filled circles. The minimum $\sigma(\tau)$ for the free running lasers is 1.2×10^{-9} at 5 seconds and for the stabilized lasers is 1.3×10^{-11} at 20 seconds. These results demonstrate the effectiveness of this simple method of laser frequency stabilization.

4 Conclusion

Based on polarization spectroscopy, we have demonstrated a new experimental technique termed as balanced bi-polarimeter to generate a background free and dispersion-like signal for laser frequency locking. The dispersion-like signal obtained from this setup was used for frequency stabilization of lasers at the peak of a closed transition without the need for laser frequency modulation and phase sensitive detection. A diode laser system locked using the signal corresponding to the $5\,^2S_{1/2}$ $(F=2) \rightarrow$ $5\,^2P_{3/2}$ $(F'=3)$ transition of ^{87}Rb, has been found to have a laser frequency fluctuation and drift of less than 0.25 MHz and 0.02 MHz, respectively, for an observation period of more than 10 hours. The measured square root of Allan variance from the beat frequency data was 1.3×10^{-11} for sampling time of 20 seconds.

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