

Laser frequency locking by direct measurement of detuning

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We present a new method of laser frequency locking in which the feedback signal is directly proportional to the detuning from an atomic transition, even at detunings many times the natural linewidth of the transition. Our method is a form of sub-Doppler polarization spectroscopy, based on measuring two Stokes parameters (I_2 and I_3) of light transmitted through a vapor cell. It extends the linear capture range of the lock loop by as much as an order of magnitude and provides frequency discrimination equivalent to or better than those of other commonly used locking techniques. © 2004 Optical Society of America

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Laser frequency locking is the process of controlling a laser's frequency, relative to some physical reference, by means of feedback. Various physical references, for example, cavities and atomic transitions,¹ may be used, and the methods described here apply equally well in both cases. In this Letter we focus on the spectroscopy of hyperfine transitions in Rb atomic vapor, which is relevant to research with ultracold atoms.

Many experiments in atomic physics require lasers to be locked to an atomic transition. Saturated absorption and polarization spectroscopy are two well-known techniques used for this purpose.¹ Both rely on counterpropagating pump and probe beams to measure a single longitudinal velocity group of atoms within a Doppler-broadened profile. In saturation spectroscopy, the laser may be locked to the side of an absorption peak² by comparison of a photodetector signal with a reference voltage. It is generally desirable to lock to the top of a peak, however, which one can achieve by dithering the laser frequency about a peak and performing lock-in detection.³ This provides a derivative signal with a zero crossing at the top of the peak that is convenient for locking. Polarization spectroscopy is somewhat more attractive, as it produces a narrow, sub-Doppler spectrum with a natural zero crossing at resonance⁴ without the need for dithering and lock-in detection.⁵

Pearman *et al.* have studied a form of polarization spectroscopy locking in detail.⁶ Their method corresponds to a measure of the circular birefringence (differential refractive index for orthogonal polarizations) of an atomic sample that is induced by a circularly polarized pump beam. The locking signal is linear over a range approximately equal to the power-broadened linewidth of the transition (typically 10–20 MHz in Rb vapor).

Our method combines polarization spectroscopy with a measure of the circular dichroism (differential absorption for two orthogonal polarizations) and greatly extends the linear region of the lock signal. Our method stems from the proposal of Harvey and White,⁷ which one can best understand by analyzing the Stokes parameters of the transmitted probe light.

We wish to quantify the change in the polarization state of an input laser beam in terms of the anisotropic properties of the sample. As the anisotropy is defined

in terms of circular polarizations, we choose to express the total electric field in the right–left (R–L) circular basis: $\mathbf{E} = \begin{bmatrix} E_R \\ E_L \end{bmatrix}$, where E_R and E_L are the right and left circular electric field components, respectively. In this basis the (nonnormalized) Stokes parameters are

$$I_0 = |E_R|^2 + |E_L|^2, \quad (1)$$

$$I_1 = 2|E_R||E_L|\cos\phi, \quad (2)$$

$$I_2 = 2|E_R||E_L|\sin\phi, \quad (3)$$

$$I_3 = |E_R|^2 - |E_L|^2, \quad (4)$$

where $\phi = \phi_R - \phi_L$ is the phase difference between right and left circular components. Equations (1)–(4) are equivalent to the familiar expressions in the horizontal–vertical (H–V) basis and could also be written on a diagonal–antidiagonal (D–A) basis. The normalized Stokes parameters, S_i , are obtained from the ratio I_i/I_0 . We recall the physical meaning of this notation: I_0 is the total irradiance and I_1 , I_2 , and I_3 are measures of the horizontal, diagonal, and right circular polarizations, respectively.⁸

With this in mind it is straightforward to design detectors for each of the Stokes parameters: for I_1 , a polarizing beam-splitter cube and two photodetectors; for I_2 a $\lambda/2$ plate and an I_1 detector; and for I_3 a $\lambda/4$ plate and an I_1 detector. Figure 1 shows such a detector schematically. I_0 is given by the sum of the two photodetector signals for any of the I_i measurements above. In all cases the beam splitter separates the horizontal and vertical components, which are then measured and subtracted. The wave plates convert D–A to H–V to measure I_2 and R–L to H–V to measure I_3 .

A measure of the phase difference between two orthogonal field components can provide an optimal feedback signal for locking a laser.⁷ In the circular basis, phase difference ϕ between the left- and right-handed components is obtained from Eqs. (2) and (3). The

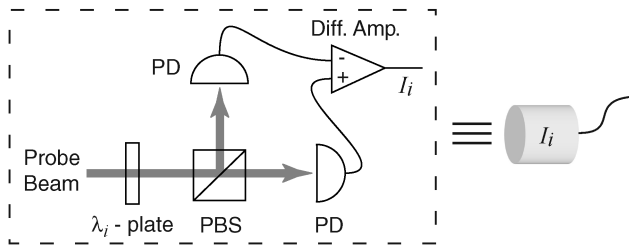


Fig. 1. Detector for measuring Stokes parameters I_i , $i = 1, 2, 3$: PD, photodetector; PBS, polarizing beam splitter; λ_i -plate, no-, half-, and quarter-wave plates for $i = 1, 2, 3$, respectively; Diff. Amp., differential amplifier.

arctangent of the ratio of measured Stokes parameters I_2/I_1 yields a direct measure of ϕ . In practice, calculating an arctangent in real time would require a digital signal processor. However, for small phase shifts, $\tan \phi \approx \sin \phi \approx \phi$, and I_2 provides a signal proportional to ϕ . In polarization spectroscopy⁶ the small-angle approximation is valid, and one obtains a signal directly proportional to ϕ by measuring the single Stokes component, I_2 . The shape of the I_2 signal is given by⁶

$$I_2(x) \propto \Delta n(x) = \frac{\Delta \alpha_0}{k} \frac{x}{1+x^2}, \quad (5)$$

where x is the laser detuning from resonance in units of the power-broadened transition linewidth, k is the (resonant) wave number of the laser, $n(x)$ is the real part of the refractive index of the vapor, and $\Delta \alpha_0$ is the difference in absorption at line center of the two circular components of the probe. This signal is dispersion shaped and free of a Doppler-broadened background (left- and right-handed components experience equal Doppler-broadened absorptions, and this is removed in the subtraction).

The phase shift of relation (5) depends only on $\Delta \alpha_0$, the differential absorption at line center. This difference originates from an anisotropy induced in atoms that have interacted with the circularly polarized pump laser. Atoms are optically pumped into one of the extreme magnetic substates, say, $m_F = +F$. Differential absorption $\Delta \alpha$ of the two circular components of the probe field is maximized in such a case. The σ^+ component experiences enhanced absorption, and the σ^- component decreased absorption, with respect to the Doppler background. For transitions between the ^{87}Rb $5S_{1/2}$ $F = 2$, $m_F = 2$, and the $5P_{3/2}$ $F' = 3$ levels, the difference in oscillator strengths for σ^+ and σ^- light is 15:1. As the Doppler-broadened absorption is the same for both components, the differential absorption profile is given by the Lorentzian:

$$I_3(x) \propto \Delta \alpha(x) = \frac{\Delta \alpha_0}{1+x^2}, \quad (6)$$

which is related to expression (5) by the Kramers–Kronig relation.¹ Expression (6) is the difference in absorption of left- and right-handed circular components (circular dichroism), which is equivalent to I_3 of

Eq. (4). Combining expressions (5) and (6) shows that their quotient,

$$Q(x) = \frac{I_2(x)}{I_3(x)} = \frac{x}{k}, \quad (7)$$

provides a signal directly proportional to x that does not decay as $1/(1+x^2)$ at large detunings. In polarization locking,⁶ I_2 is used as the error signal, and a controller provides feedback signal to the laser, which drives this to zero. $I_2(x)$ is linear for small x but not at large detunings, where it approaches zero. Our locking method compensates for this nonlinearity by dividing expression (5) by expression (6), which greatly extends the linear region of the locking signal.

We have implemented this method spectroscopically and constructed a simple control circuit for locking. Figure 2 is a schematic of our apparatus. We chose for our experiments the $5S_{1/2}$ $F = 2 \rightarrow 5P_{3/2}$ $F' = 1, 2, 3$ transition at 780.1 nm in ^{87}Rb . Light is provided by an external-cavity diode laser similar to that described in Ref. 9.

Four photodetectors at the output of the optical apparatus are connected to an analog circuit that performs the necessary subtractions and division in real time. The output of this device, either polarization spectroscopy signal I_2 or quotient I_2/I_3 , is fed into the laser lock circuit that provides feedback to the laser frequency by means of the injection current and a piezoelectric transducer. Additionally, the lock circuit has a differential input to which we can apply an offset voltage that shifts the lock point away from 0 V.

Spectra were obtained as the laser frequency was scanned across the transition by application of a triangular voltage ramp to the piezoelectric transducer. Figure 3 shows the results of such a scan. The topmost trace is a saturated-absorption spectrum, followed by the raw I_2 and I_3 scans. The lowest trace shows quotient $Q(x)$ obtained from the analog divider. The horizontal scale was obtained from the known energy-level spacings of ^{87}Rb in zero magnetic field. These curves show that our method greatly extends the capture range of the lock. The normalized gradients (signal-to-noise ratio) of the quotient

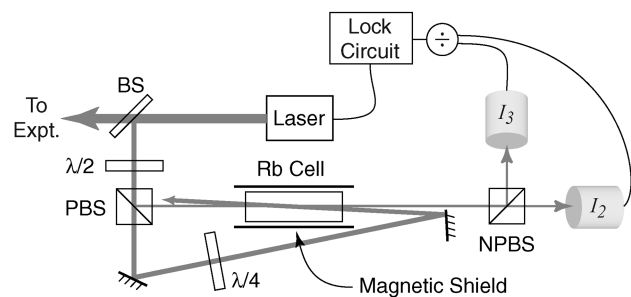


Fig. 2. Experimental setup for polarization quotient locking. A small fraction of light is split off the laser output and sent into a polarization spectrometer. The I_2 and I_3 Stokes parameters of the probe light are measured and used to provide feedback to lock the laser. BS, beam splitter; PBS, polarizing BS; NPBS, 50/50 nonpolarizing BS.

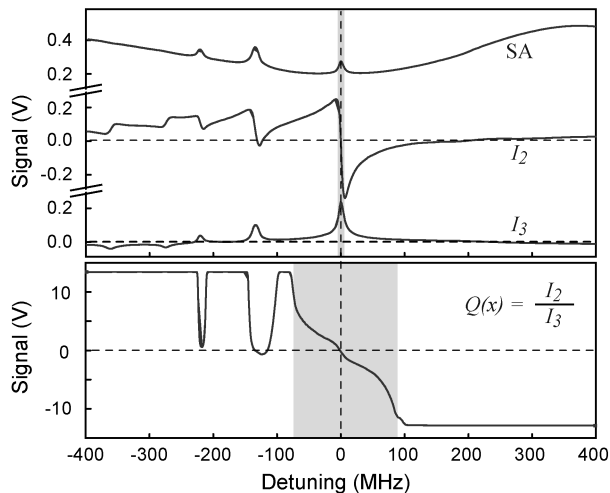


Fig. 3. Spectra for the $^{87}\text{Rb } 5S_{1/2} F = 2 \rightarrow 5P_{3/2} F' = 1, 2, 3$ transition. Top trace (SA), regular saturated absorption spectrum; spectra of I_2 and I_3 are shown. Bottom trace, the quotient $Q(x)$. Shaded regions indicate the monotonic capture range of I_2 (upper) and $Q(x)$ (lower) locking.

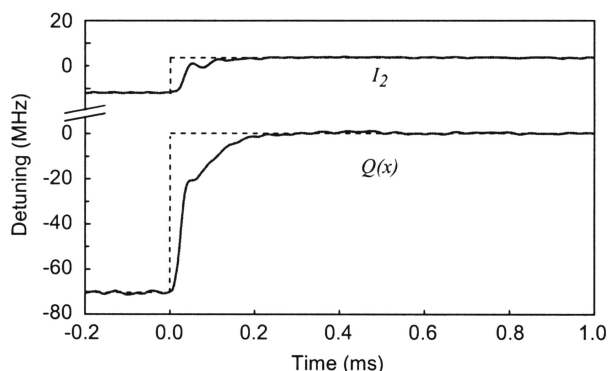


Fig. 4. Step responses of a laser locked by I_2 and $Q(x)$ locking after the dc lock point voltage is switched at $t = 0$. Solid curves, measured error signal after switching; dashed curves, ideal response. $Q(x)$ locking allows much larger jumps to be achieved without unlocking the laser.

$I_2/I_3 = S_2/S_3$ and $S_2 = I_2/I_0$ spectrum are the same at $x = 0$, but $Q(x)$ retains this slope at large detunings.

As I_3 approaches zero, $Q(x)$ becomes sensitive to electronic noise on the photodetector signals. We overcome this difficulty by low-pass filtering the output of the analog divider with a 50-kHz RC filter. Although this filtering limits the bandwidth of the lock loop, the linewidth and the long-term stability of lasers locked with both I_2 and I_2/I_3 feedback signals were similar (<1 MHz), as we determined by monitoring the error signals.

The linear region of the I_2 locking signal extends only over 20 MHz. Our $Q(x)$ signal, however, extends monotonically over a 200-MHz range, as indicated by the shaded regions in Fig. 3. At the left, it is limited by the proximity of the nearest crossover resonance; on the right, only by the voltage supplied to the analog controller. This increase in range helps in two important ways. First, it means that the laser can sustain

much larger perturbations without coming out of lock, and, second, it is possible to apply large and precise frequency steps without leaving the lock slope.

In laser cooling and Bose-Einstein condensate experiments it is often necessary to jump the frequency of a laser such that the laser can be used for multiple tasks. For example, one can achieve a compressed magneto-optical trap or polarization cooling stage by shifting the magneto-optical trap's laser frequency from a detuning of ≈ -12 MHz to ≈ -50 MHz. Ideally this would happen on a time scale of the order of 1 ms. Acousto-optical modulators can be used for this, but a simpler method is preferable. With our scheme, such frequency steps can be achieved simply by application of a dc offset voltage at the input to the lock circuit. Figure 4 shows an example of this use of dc offset voltage by plotting the step responses of a laser locked by regular I_2 polarization spectroscopy and by our quotient method. With I_2 locking, we can repeatedly jump the laser up to 15 MHz in less than 200 μs . Larger steps may take the laser off the lock slope and cause it to relock at another zero crossing. By using quotient locking, however, we can jump from -70 MHz back to resonance in approximately the same time, making this technique versatile for application to laser cooling experiments. Similar jumps above resonance can also be achieved.

In conclusion, for a Lorentzian transition, the ratio of dispersion and absorption spectra yields a measurement of detuning. Polarization spectroscopy obtains a Doppler-free dispersion spectrum by measuring nonnormalized Stokes parameter I_2 . A similar measurement yields parameter I_3 , the differential absorption. Combining these produces a spectroscopic measurement proportional to detuning that is ideal for use in laser locking that extends the capture region of the lock by as much as a factor of 10, which results in a robust lock and allows us to make rapid and precise jumps of laser frequency by as much as 70 MHz on either side of resonance.

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