# Laser frequency offset locking using electromagnetically induced transparency

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The authors have used an electromagnetically induced transparency resonance in rubidium as a dispersive reference to lock the relative frequency of two lasers to the atomic ground-state hyperfine splitting. The beat frequency between the two lasers directly generates a microwave signal at 3.036 GHz ($^{85}$Rb) or 6.835 GHz ($^{87}$Rb). High bandwidth (600 kHz) feedback was achieved with only low-frequency (10 MHz) electronics using the frequency modulation sideband method. The spectral width of the microwave beat frequency was reduced to less than 1 kHz. The technique offers a convenient and low-cost method suitable for many topical two-frequency experiments, including coherent population trapping, slow light, lasing without inversion, and Raman sideband cooling. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2734471]

Many interesting laser-atom interactions require two laser beams with a fixed frequency difference related to atomic energy level splittings. Examples include atomic coherence effects in the alkali atoms, such as slow light, lasing without inversion, electromagnetically induced transparency, and atomic clocks.[1] Laser cooling and trapping of alkalis require a repump laser to prevent dark-state losses, and Raman sideband cooling specifically relies on two lasers with precise offset frequency.[2]

The two frequency components needed for experiments can be generated from a single laser beam, with a modulator (acousto-optical[3] or electro-optical[4]), or by direct modulation of the laser current for diode lasers.[5]

Alternatively, two separate lasers can be used, individually referenced to atomic transitions[6] or to Fabry-Pérot etalon fringes, but in many experiments only the frequency difference must be controlled to high precision, while the absolute frequency is less important. The difference can be stabilized by offset locking the frequency of one laser relative to the other using the interference beat between the two. Offset locking requires electronics operating at the offset frequency,[7,8] typically in the microwave (gigahertz) for ground-state alkali atoms and diamond nitrogen-vacancy centers.[9] Microwave detectors, precision synthesized oscillators, and associated high-frequency electronics provide broad tunability, but can be expensive and complex, and the frequency difference is not intrinsic to the atomic system of interest.

An electromagnetically induced transparency (EIT) resonance provides a direct relative frequency reference. Using an EIT resonance, only low-frequency detectors and servo electronics are needed to lock the frequency difference between two lasers to an atomic hyperfine splitting. EIT resonances can be much narrower than natural transition linewidths, with greater dispersion and the potential for narrower relative frequency uncertainty. In early demonstrations,[10,11] absorption-based detection of the EIT signal limited the feedback bandwidth to a fraction of the natural spontaneous linewidth Γ (6 MHz for Rb), and the relative laser spectral width achieved was similar to that of individually locked lasers, ~100 kHz.

In our experiments, we use the frequency modulation (FM) sideband method,[12] modulating the laser frequency at 10 MHz to generate a feedback signal from the relative phase difference of the atomic vapor at the ±10 MHz sidebands above and below an EIT resonance. The feedback bandwidth limit is then determined by the modulation frequency[13] rather than the resonance width, and in our case, is greater than the linewidth of each individual laser, allowing line narrowing to achieve a noise-limited relative frequency spectral width below 1 kHz.

Figure 1 shows the relevant energy levels of rubidium and the photodetector signal as the probe laser was scanned through the EIT resonance. A narrow EIT peak (width

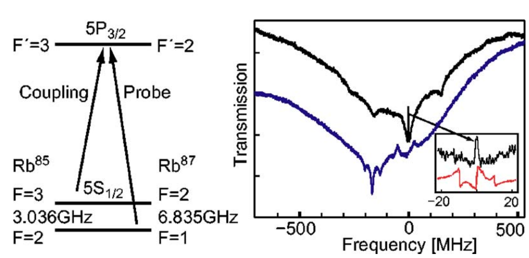


FIG. 1. (Color online) Rubidium energy levels, $^{87}$Rb EIT spectrum (upper), and $F=1$ ground-state saturated absorption spectrum for probe laser (lower). The inset shows expanded EIT region with FM sideband feedback error signal. EIT peak height 30% of Doppler absorption; width of 0.85 MHz limited by linewidth of unlocked (scanning) probe laser.

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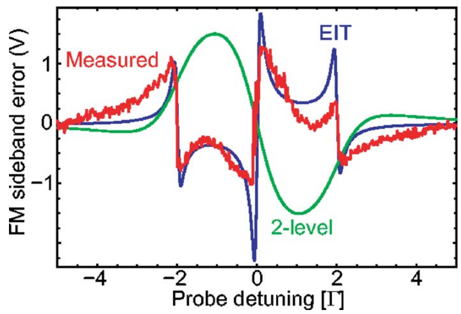


FIG. 2. (Color online) Measured FM sideband error signal for the EIT resonance compared to calculations for EIT and an equivalent two-level Doppler-free system. Opposite signs of error curves reflect sign reversal in refractive index for two- and three-level systems, calculated for strong coupling, weak probe, Rabi frequencies 2 and 0.01Γ, and modulation frequency 2Γ.

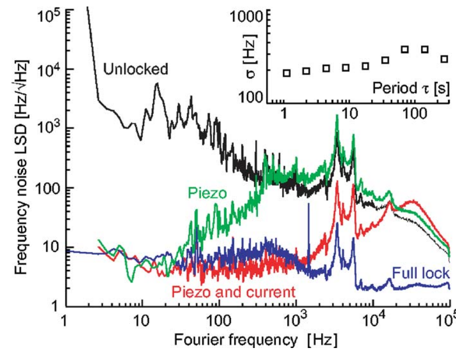


FIG. 4. (Color online) Frequency noise linear spectral density of feedback error signal; coupling laser locked, different probe laser feedback actuators enabled. Noise suppression extends to 600 kHz (not shown). Inset: overlapping Allan standard deviation $\sigma(\tau)$ of the offset beat note frequency.

<1 MHz) was observed when an atomic coherence was induced between the two atomic hyperfine ground states via a common excited state. The coupling laser was locked to a saturated absorption crossover peak, either $F=2\rightarrow F'=(2,3)$ for $^{87}$Rb or $F=3\rightarrow F'=(3,4)$ for $^{85}$Rb. Atoms with appropriate velocity in the direction of laser propagation were resonant on the $F=2\rightarrow F'=2$ transition. The probe was tuned to $F=1\rightarrow F'=2$ for atoms at the same velocity. The EIT resonance occurs where the frequency difference between the coupling and probe lasers precisely matches the ground-state hyperfine splitting, independent of fluctuations of the coupling laser frequency. Thus, as the coupling laser frequency changes, so too does the offset-locked probe, but their difference is maintained.

In Fig. 2, the EIT dispersion is compared with that for a conventional two-level Doppler-free saturated absorption signal. The calculated values are from an optical Bloch equation model[14] for the three-level two-laser Λ-configuration EIT system, solved for steady-state conditions using matrix inversion and averaged over appropriate Doppler detunings and weighting for a Maxwellian velocity distribution. The figure shows the calculated FM sideband error signal, a measured error signal, and the prediction for a two-level atom calculated by reducing the coupling laser power to a negligible value. The dispersion is clearly much greater at resonance for the EIT system, consistent with the narrow width of the EIT resonance relative to the natural linewidth.

The experimental setup is shown in Fig. 3. The two external cavity diode laser[15] beams were coupled into a single-mode fiber and copropagated through a room-temperature magnetically shielded rubidium cell. The coupling laser power was 2 mW, with $1/e^2$ radius of 2 mm, and linewidth of 300 kHz. The diode injection current of the probe laser (power of 1 mW) was modulated at 10 MHz. The combined probe and coupling lasers were incident on a Si *p-i-n* photodiode. The detector current was amplified and mixed with the phase-shifted reference, and the higher harmonics removed with a 2.5 MHz low-pass filter. The error signal (Fig. 2) was fed back to the probe laser to stabilize the coupling-probe frequency difference at the ground-state hyperfine splitting.

The probe laser frequency was controlled via two actuators and three feedback channels. A piezoelectric transducer provided feedback to the cavity length for Fourier frequencies up to 300 Hz. A second channel controlled the diode injection current supply,[16] with bandwidth of 20 kHz limited by the diode thermal response which dominates at low Fourier frequencies.[17] The error signal was also coupled directly to the diode via a capacitor and passive single-stage phase-lead circuit, providing feedback at higher Fourier frequencies where the diode response is determined by the change in refractive index due to charge-carrier density modulation.[17] Figure 4 shows the separate effects of these three feedback channels on the frequency noise spectrum of the locking signal.

The interference between the two laser beams on a fast (7 GHz) photodiode produced a microwave beat note at the difference frequency. Figure 5 shows the rf spectrum of the beat note for $^{87}$Rb, with a −3 dB width of 750 Hz for a 0.2 s sweep and 4 kHz averaged over 22.5 s. We measured the peak frequency once per second for 30 min to find an average of 6 834 649 630 Hz with one standard deviation statis-

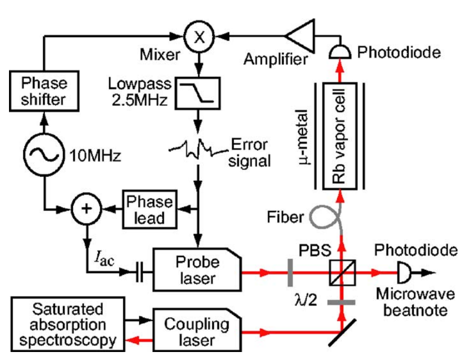


FIG. 3. (Color online) Experimental setup for frequency offset-locking using EIT. PBS polarizing beam splitter; λ/2 half-wave retarder.

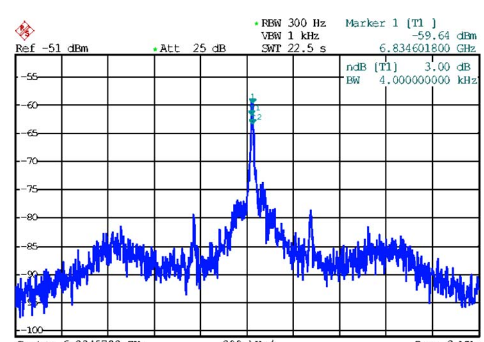


FIG. 5. (Color online) Spectrum of microwave beat note generated by interference for $^{87}$Rb. −3 dB width of 4 kHz (750 Hz in 0.2 s). 200 kHz/div horizontal; 5 dB/div vertical.

tical uncertainty of ±550 Hz. The Allan variance[18] of the data is shown in Fig. 4. The relative uncertainty of the beat frequency was below $5\times10^{-8}$, with a flat dependence on sampling time consistent with flicker frequency noise, as observed in some high precision oscillators including Cs clocks.[19]

The average frequency in this sample differed by 30 kHz from the best available measurement, 6 834 682 611 Hz.[20] Systematic variations between different measurements were up to ±50 kHz, thought to be caused by temperature-related drifts in the fiber coupling. The frequency was affected by both the absolute and relative intensities of the two beams, and their polarizations, due to ac Stark shift and optical pumping effects.[14] We were able to adjust the beat frequency via a dc offset to the error signal, up to ±250 kHz.

The broad shoulders on the beat note show the limited bandwidth of the diode response (600 kHz). Small peaks at ±250 kHz are due to induced currents from the Zeeman modulation coil used for locking the coupling laser.[15] Sidebands at the modulation frequency (10 MHz) are more than 20 dB below the peak. The technique works equally well with $^{85}$Rb, for which we measured a microwave frequency of 3.035 71 GHz.

In summary, we have combined a high bandwidth FM sideband frequency discriminator with a high-dispersion electromagnetically induced transparency resonance to lock two laser frequencies to an offset of the ground-state hyperfine splitting of rubidium. Our solutions to the three-level optical Bloch equations for a $\Lambda$-EIT system, convolved with the Maxwellian velocity distribution of a thermal vapor, support the relative benefits of the highly dispersive resonance compared to that of a two-level reference. We obtained a microwave beat note at 6.834 650 GHz for $^{87}$Rb with linewidth and statistical frequency uncertainty below 1 kHz, using only low-frequency feedback electronics. For experiments which require frequency variability near the resonance, a low-frequency (megahertz) optical modulator could be used on one of the laser beams, without compromising the high bandwidth and stability of the method. We expect that the approach could be applied to other alkali atoms and other two-laser resonances, and that substantial improvements to the beat note stability and linewidth can be achieved, in particular, by reducing intensity drifts in the laser beams.

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