# Optical transfer cavity stabilization using current-modulated injection-locked diode lasers

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It is demonstrated that rf current modulation of a frequency stabilized injection-locked diode laser allows the stabilization of an optical cavity to adjustable lengths, by variation of the rf frequency. This transfer cavity may be used to stabilize another laser at an arbitrary wavelength, in the absence of atomic or molecular transitions suitable for stabilization. Implementation involves equipment and techniques commonly used in laser cooling and trapping laboratories and does not require electro- or acousto-optic modulators. With this technique we stabilize a transfer cavity using a rf current-modulated diode laser which is injection locked to a 780 nm reference diode laser. The reference laser is stabilized using polarization spectroscopy in a Rb cell. A Ti:sapphire ring laser at 960 nm is locked to this transfer cavity and may be precisely scanned by varying the rf modulation frequency. We demonstrate the suitability of this system for the excitation of laser cooled Rb atoms to Rydberg states. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2337094]

## I. INTRODUCTION

It is often necessary to stabilize lasers at frequencies where direct locking to an atomic or molecular reference line is not possible. Several methods are commonly used for this purpose. One is to stabilize the target laser by comparison with a second laser (reference laser), which is stabilized to an absolute frequency reference such as an atomic or a molecular absorption line. If the frequency of the reference laser is sufficiently close to the frequency of the target laser, the two lasers may be heterodyned on a photodetector and the resulting beat note can be used to stabilize the target laser.[1] However, this is only practical up to a certain frequency difference due to the bandwidth of the photodetector.

Alternatively, for large frequency differences it is possible to use an optical cavity to "transfer" the stability from a stabilized reference laser to the target laser.[2–9] One way this may be accomplished is by repetitively scanning the length of a "transfer cavity" (TC) with piezoelectric transducers (PZTs). The transmission fringe positions of the target laser are then compared to the reference laser using specialized digital circuitry[2] or computers.[3,4] This comparison is used to derive an error signal which may be fed back to the target laser for stabilization. Using this technique, Zhao *et al.*[3] have demonstrated a long-term frequency drift on the order of 1 MHz. However, the scanning rate of the cavity puts a limit on the maximum rate of error correction. We have also found that this approach is sensitive to low frequency vibrations. The complexity of the fringe comparison is an additional drawback.

Scanning the cavity length may be avoided by making the transmission maxima of both the reference laser and the target laser coincide at the same cavity length.[5–9] In this case, the cavity is locked to the reference laser and the target laser is locked to the cavity using analog circuitry. To make the fringes coincide it is possible to frequency shift either the reference or the target laser using an electro-optic modulator[5] (EOM) or an acousto-optic modulator (AOM).[7,9] In this way, frequency stability and precise rf frequency tunability can be obtained. Since, in general, frequency shifts on the order of the free spectral range of the cavity may be required, the modulator in these systems should be capable of producing a broadband of frequency shifts in order to avoid an inconveniently long transfer cavity.

In this article, we present a technique for obtaining these frequency shifts that is inherently broadband and relatively easy to implement without using AOMs or EOMs. A Fabry-Pérot TC is stabilized using a tunable sideband from a current-modulated diode laser that is injection locked to a master laser.[10–12] The master laser is stabilized using an atomic reference. By adjusting the rf frequency of the current modulation of the injection-locked slave laser, the TC may be tuned to the desired length for stabilization.

## II. EXPERIMENTAL SETUP

The stabilization scheme has been developed for a 960 nm commercial ring Ti:sapphire laser (Coherent MBR-110). This laser is frequency doubled in an external ring resonator (Coherent MBD-200) to produce approximately 70 mW at ≈480 nm and used with 780 nm lasers to excite cold Rb atoms to Rydberg states.[13] Since frequency stabilized 780 nm lasers are required in our experiment to laser cool Rb atoms, they are convenient references for transfer cavity stabilization.

The locking procedure is as follows: The 960 nm laser is tuned by hand to the desired frequency. The master (reference) 780 nm laser is locked using polarization spectroscopy[14] at a frequency $f_r$. With the TC in scanning mode, injection-locked operation of the slave laser is verified. rf current modulation at a frequency $f_m$ is then applied to the slave laser. Due to phase[10] and/or amplitude[11] modu-

 

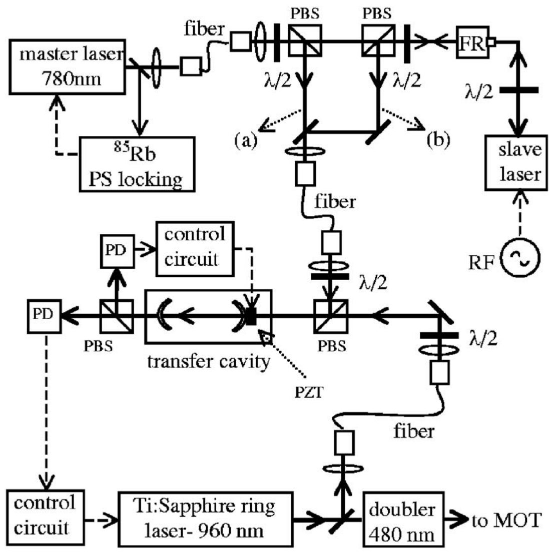


FIG. 1. Experimental setup. PBS, polarizing beam splitter; PD, photodiode; FR, Faraday rotator; PS, polarization spectroscopy.

lation this produces significant optical sidebands at $f_r+f_m$ and $f_r-f_m$. The rf modulation frequency is chosen so that a transmission peak of a 780 nm sideband coincides at the same TC length as a 960 nm transmission peak. Cavity ramping is then stopped and the cavity is locked to the 780 nm sideband transmission peak and the 960 nm laser is locked to its own transmission peak. The lock point of the 960 nm may be varied by changing the frequency of the slave laser current modulation, $f_m$.

Figure 1 illustrates the experimental setup. The reference laser is an external cavity, grating stabilized, diode laser (Toptica, DL100) operating at 780 nm with a maximum output power of ≈150 mW and short term frequency stability of ≈1 MHz. The laser can be coarsely tuned by manually adjusting the grating angle, and fine tuning is obtained using a PZT. A small fraction (10%) of the output is split off into three beams. One beam is used for Rb saturation absorption spectroscopy (SAS),[15] which serves as a frequency identifier, and another beam is directed to a Rb polarization spectroscopy setup for frequency locking.[14] The third beam is used as a reference for beat-note locking the cooling and trapping lasers (see below). The remainder of the reference laser beam is attenuated and coupled into a single mode fiber. The collimated output beam from this fiber is used to injection lock the slave laser. For reliable injection locking while the slave laser current is modulated, we find that an injected power of 0.6–1 mW is typically required (measured between the Faraday rotator and slave laser). With improved mode matching it is possible that this could be reduced.

The slave laser is a commercial 780 nm diode laser (Sanyo, DL7140-201S) in a temperature stabilized mount (Thorlabs, TCLDM9). Current modulation is applied using a bias-T, driven by a rf synthesizer (typically operated at 100–400 MHz, 18 dBm). The slave laser is coupled into a single mode fiber [path (b) in Fig. 1]. The output beam from the fiber is passed through a half wave plate and a polarizing beam splitter (PBS) to obtain a well-defined polarization. This beam is then fed into the TC, which may be temporarily operated as a scanning Fabry-Pérot interferometer. A small fraction of the master laser beam is also fed into the TC for verifying the injection locking [path (a) in Fig. 1].

Why not simply current modulate the reference laser directly[16] and lock the cavity to one of the resulting sidebands? Although in principle this will work, there are a number of reasons to prefer the use of a current-modulated slave laser, despite the additional complexity. If the reference laser were directly modulated, the stability of its frequency lock would be compromised, particularly if the modulation frequency $f_m$ were varied. In addition, by leaving the stabilized laser unmodulated, we can use part of its beam for other purposes. For example, in our experiment it is also used as a reference for beat-note locking[1,17] the diode laser systems used for a magneto-optical trap.

The TC is of the confocal Fabry-Pérot type, consisting of two mirrors with radii of curvature $R=9.18$ cm, separated by $L\approx R$ with a free spectral range of 817 MHz. It is desirable to have good finesse, thus good reflectivity at both 780 and 960 nm. It was possible to choose a standard dielectric mirror coating which exhibits high reflectivity at these two wavelengths (Newport, BD2). A PZT is mounted on one of the end mirrors. The typical finesse of the TC is 100 and is limited by beam alignment and difficulty in obtaining the exact confocal condition.

A small fraction of the Ti:sapphire target laser beam is coupled into a single mode fiber. On emerging from the fiber, the light is passed through a PBS to ensure that the beam is linearly polarized, and then aligned into the TC. After the orthogonally polarized 780 and 960 nm laser beams emerge from the TC, they are separated by a PBS and directed onto photodiodes.

The TC length is dithered slightly at 1.6 kHz using the PZT by an amplitude on the order of the cavity linewidth. Lock-in amplifiers are used to demodulate the transmission through the TC for both wavelengths.[6,8] This provides a derivativelike line shape error signal for locking the transmission maxima. The 780 nm error signal is used in an integrator feedback loop which adjusts cavity length using the PZT. This stabilizes the TC length. The 960 nm error signal is fed into another integrator control loop which uses the "Ext Lock" of the target laser control box to adjust the frequency. This Ext Lock control has a relatively low bandwidth ($f_{3\ \mathrm{dB}}\approx 10$ Hz).[18] However, this laser system is prestablized using a low-finesse cavity in a similar manner to the system described in Ref. 8.

## III. RESULT

The tuning accuracy and the drift behavior of the frequency locked target laser are characterized using Rydberg atom excitation in a $^{85}$Rb magneto-optical trap (MOT). The details of this apparatus appear elsewhere.[13,19]

The excitation of cold $^{85}$Rb atoms to 46$d$ Rydberg states occurs as a two-color process with nearly resonant 780 nm light ($5s_{1/2}-5p_{3/2}$) and 480 nm light ($5p_{3/2}-46d$). The 780 nm light is necessary for the $^{85}$Rb MOT and is detuned 12 MHz to the red of the $5s_{1/2}$ $F=3$ to $5p_{3/2}$ $F=4$ transition.

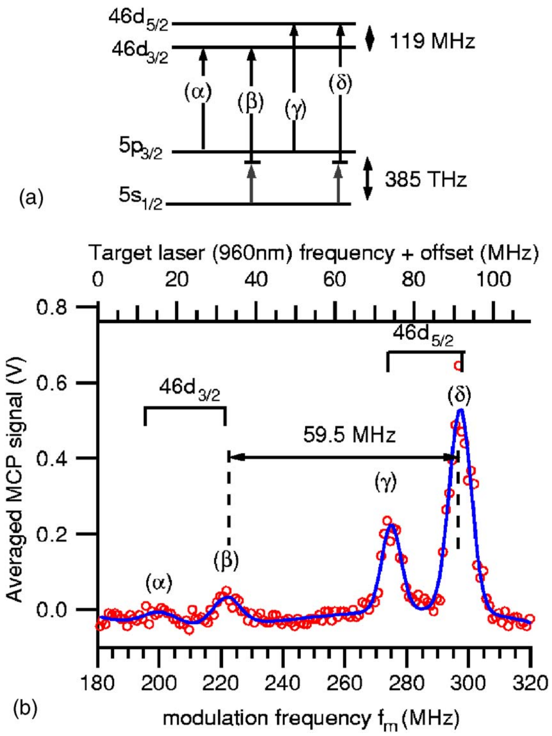


FIG. 2. (Color online) (a) Energy level diagram. (b) Spectrum of $^{85}$Rb $5p_{3/2}$ to $46d_{3/5}$ and $46d_{5/2}$ Rydberg state transitions obtained by scanning the rf modulation frequency $f_m$. The upper horizontal axis is obtained from Eq. (1). The observed peaks correspond to the labeled transitions shown in part (a). The Autler-Townes splitting of the transitions is observed due to the presence of 780 nm cooling laser (Refs. 20 and 22). With the red detuning of the 780 nm light (for MOT operation), the ($\beta$) and ($\delta$) peaks may be roughly understood as corresponding to two-photon absorption from the $5s_{1/2}$ ground state, whereas the ($\alpha$) and ($\gamma$) peaks arise from stepwise excitation through the $5p_{3/2}$ state (Ref. 21).

The 480 nm light is obtained by frequency doubling the output of a 960 nm Ti:sapphire ring laser—the target laser for our stabilization scheme.

The 780 nm cooling and trapping light remains on continuously. The 480 nm light is pulsed on for 1 $\mu$s using an acousto-optic modulator. A pulsed electric field is then applied to field ionize any Rydberg atoms and draw the resulting ions to a microchannel plate (MCP) detector. A boxcar integrator is used to gate on the signal. The excitation and detection sequence repeat at 10 Hz.

When the 960 nm target laser is locked using the scheme described in the previous section, its output frequency may be scanned by varying the rf modulation frequency $f_m$. Figure 2 shows the resulting spectrum in the range of the $^{85}$Rb $5p_{3/2}$–$46d_{3/2}$ and $5p_{3/2}$–$46d_{5/2}$ transitions. The strong 780 nm field is responsible for the splitting of the lines into doublets. This is the Autler-Townes effect,[20,21] similar to the results presented in Ref. 22.

We expect the target laser frequency shift $\Delta f_t$ to be related to the slave laser modulation frequency shift $\Delta f_m$ by

$$\Delta f_t = \frac{\lambda_{r,\mathrm{air}}}{\lambda_{t,\mathrm{air}}} \Delta f_m, \qquad (1)$$

where $\lambda_{r,\mathrm{air}}$ and $\lambda_{t,\mathrm{air}}$ are the air wavelengths of the reference laser and the target laser. In our case, the frequencies of the reference and target lasers are well known, but we must estimate the corresponding refractive indices to determine the air wavelengths. Equation (1) can be tested using the observed separation of the ($\beta$) and ($\delta$) peaks in Fig. 2, together with the known $46d_{3/2}$–$46d_{5/2}$ energy separation.[23] As shown in Fig. 2, the Autler-Townes splittings of $46d_{3/2}$ and $46d_{5/2}$ lines are identical and thus we do not expect these to contribute to the separation of the ($\beta$) and ($\delta$) peaks. We find $\Delta f_t / \Delta f_m = 0.80 \pm 0.015$, compared to Eq. (1), which predicts $\Delta f_t / \Delta f_m = 0.812$.

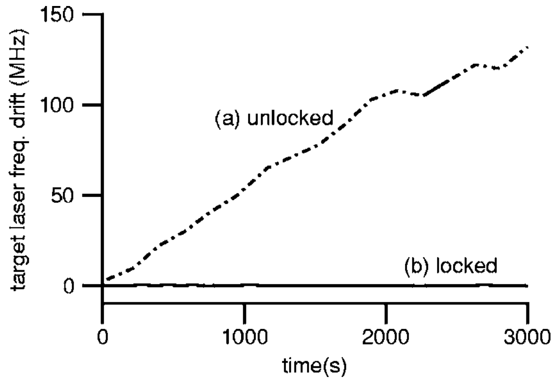


FIG. 3. Frequency drift of the target laser system (Ti:sapphire, 960 nm) as a function of time under (a) unlocked and (b) locked conditions.

By repetitively scanning over the spectrum shown in Fig. 2 and recording the peak positions, we can monitor the frequency drift of the locked target laser. The positions of the ($\alpha$) and ($\gamma$) peaks are less dependent on the frequency fluctuations of the 780 nm cooling laser than the ($\beta$) and ($\delta$) peaks. Therefore, the stronger ($\gamma$) line is used to quantify the stability of the target laser. With the locking system activated, the control voltage applied to the Ti:sapphire laser varies as time progresses. Since the approximate relationship between a change in the control voltage and the corresponding change in the output frequency is known, we can use this to estimate the frequency drift that would have occurred if the laser were not stabilized. Figure 3 is a comparison between (a) the estimated unlocked and (b) the locked frequency drifts over $\approx$1 h. There is a dramatic reduction in the long-term frequency drift when the laser is locked.

## IV. PERFORMANCE LIMITATIONS

Since the TC is not evacuated, it is limited in performance by variations in the refractive indices of air for the target laser and the reference laser wavelengths, $n_t$ and $n_r$, respectively. The environmental influences on the locked target laser frequency can be approximated using

$$\frac{\partial f_t}{\partial \alpha} = \left[ \frac{(\partial n_r/\partial \alpha) n_t - (\partial n_t/\partial \alpha) n_r}{(n_t)^2} \right] \frac{n_t}{n_r} f_t, \qquad (2)$$

where $f_t$ is the target laser frequency and $\alpha$ represents an environmental parameter such as pressure, temperature, or humidity. The resulting sensitivities are tabulated in Table I.

Figure 4 illustrates the frequency drift of the locked target laser as a function of time collected at various times over several months (obtained using repetitive scanning over the Rydberg excitation lines, as discussed in the previous section). From nine such data sets we observed an average long-

TABLE I. Frequency sensitivity of the locked target laser to environmental conditions for $\lambda_{t,vac}$=960 nm, $\lambda_{r,vac}$=780 nm, $P$=760 torr, $T$=20 °C, RH =50%, and $CO_2$=450 ppm. To evaluate Eq. (2), we used the NIST refractive index calculation program (Ref. 24), which is based on the Ciddor equation (Ref. 25).

| $\alpha$ | $\partial f_t/\partial\alpha$ |
|---|---|
| Pressure | 350 kHz/torr |
| Temperature | −850 kHz/°C |
| Relative humidity | 19 kHz/% |

term (≈1 h) frequency drift of −0.141±0.90 MHz/h. This is consistent with the typical variation of environmental parameters listed in Table I. Thus, we expect that the frequency stability of the target laser will be improved if the TC is evacuated to minimize the environmental effects.

Ultimate long-term stability is also limited by the frequency drift of the reference laser. The reference laser is frequency stabilized using polarization spectroscopy (PS) in a Rb vapor cell.[14] To observe the drift of this laser we have monitored the beat note between this laser and a 780 nm laser stabilized using saturated absorption spectroscopy with third-harmonic lock-in detection. The relative drift of these two systems was typically less than 100 kHz/h. We have found polarization spectroscopy locking to be a good compromise between several factors, including long-term stability, robustness, and complexity. However, if necessary, less long-term reference laser drift could be obtained using alternative techniques.[26–28]

It is essential to be able to vary the TC length over several free spectral ranges. This is to ensure that the slave laser sideband and 960 nm transmission peaks are well removed from the carrier transmission, which is stronger and may interfere with cavity locking to the sideband. This requires a long extension PZT, which limits the bandwidth of the cavity lock and consequently the target laser lock. An improved system could use a fast short extension PZT on one end mirror and a slower long extension PZT on the other end mirror. The fast PZT would be used for dithering and fast cavity stabilization, whereas the slow PZT would handle long-term drift.[29] With these improvements it is expected that the bandwidth of the error signal would be sufficient to directly stabilize external cavity diode lasers for many applications.

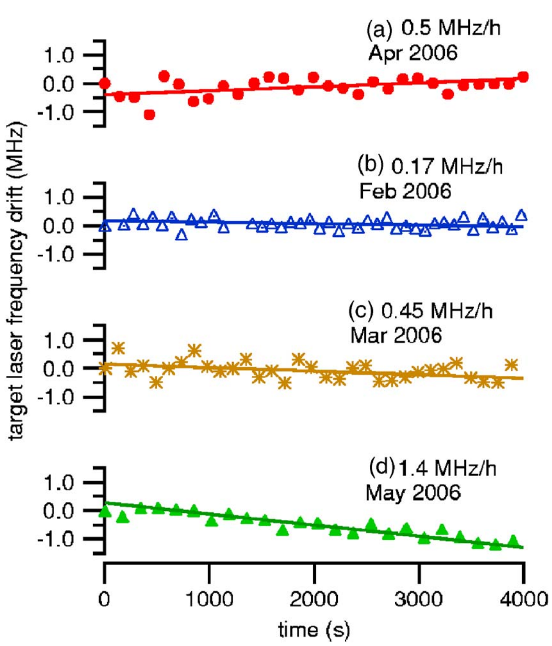


FIG. 4. (Color online) Frequency drift of the locked target laser system (Ti:sapphire, 960 nm) for several time periods over a few months.

## V. DISCUSSION

In this article, we report a general technique for laser frequency stabilization at arbitrary wavelengths using a reference laser and transfer cavity. A target laser frequency drift of <1 MHz/h has been demonstrated. The equipment involved is commonly used in laser cooling and trapping laboratories and does not require special modulators and drivers. A controllable frequency source is required, but this is the same as for electro-or acousto-optic modulators. If precise rf scanning is not required, the rf synthesizer could be replaced by inexpensive voltage controlled oscillators, as in Ref. 12.

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