

Absolute frequency stabilization of a 1.56 μm laser by locking to sub-Doppler lines of Rb at 0.78 μm

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ABSTRACT

A 1560 nm external cavity diode laser was efficiently doubled in a periodically poled LiNbO₃ waveguide and locked to ⁸⁷Rb sub-Doppler lines near 780 nm. Its frequency stability was characterized by measuring the beat frequency relative to a 780 nm external cavity diode laser which was locked to sub-Doppler lines of another Rb cell. The root Allan variance reached a minimum value of 6.9·10⁻¹² in 1 s, which corresponded to frequency variations of 1.3 kHz for the 1560 nm laser.

1. INTRODUCTION

Absolute frequency stabilization of lasers near the 1550 nm transmission window of optical fibers is required for several applications: Frequency standards for wavelength division multiplexed systems¹, coherent optical communication², optical frequency synthesizers³, fiber-optic sensing⁴, laser spectroscopy and metrology⁵. Numerous studies have been devoted to the absolute stabilization of 1550 nm lasers. Frequency stabilization was achieved by locking to molecular lines of C₂H₂ [6], NH₃ [7], HCN [5] and HI [8], as well as by locking to optogalvanic lines of noble gases^{2,9} or to optically pumped Rb lines¹⁰. In most of these experiments, the locking was done to Doppler-broadened lines whose linewidth is relatively broad - i.e., several hundred MHz. As a result, the frequency stability was typically in the range of 10⁻⁹-10⁻¹¹ and the accuracy was ~ 10⁻⁷. Improved stability and accuracy were recently obtained by de Labachellerie et al¹¹ by locking to narrow *sub-Doppler* lines of C₂H₂ and HCN. However, since the saturation intensity of ¹³C₂H₂ for example is 1.8 kW/cm² at a pressure of 0.1 Torr, a Fabry-Perot enhancement cavity was employed to achieve sufficient power for saturation spectroscopy of these weak molecular lines¹¹.

An alternative approach for frequency stabilization is second harmonic generation (SHG) and locking to the atomic rubidium D₂ lines near 780 nm. Although the saturation intensity of this line¹² is only 1.65 mW/cm², efficient frequency doubling is required to obtain a sufficiently powerful second harmonic signal from low-power single-frequency diode lasers at 1.5 μm. The required SHG power levels for saturation spectroscopy of Rb can be reached by quasi-phasematched¹³ (QPM) frequency conversion in a LiNbO₃ waveguide. In QPM doubling, a periodic modulation of the material nonlinear coefficient compensates for the phase velocity mismatch between the fundamental and second harmonic waves. This technique permits the use of large nonlinear coefficients, e.g. d₃₃ in LiNbO₃, which are not accessible by birefringent phase matching and the improvement in conversion efficiency is (2d₃₃/πd₃₁)² ~20, where 2/π is the QPM reduction factor, and d₃₁ is the effective nonlinear coefficient for birefringent phasematching. Further improvement in conversion efficiency is obtained by waveguide confinement. Furthermore, room temperature operation, as well as relaxed temperature and wavelength tolerances, are possible. The use of QPM waveguides for optical frequency standards at the 1300 nm fiber-optic transmission window has already been demonstrated¹⁷: The second harmonic of a 1319 nm Nd:YAG was locked to I₂ transitions near 660 nm.

Since the natural linewidth of the Rb lines is only 6 MHz, the Rb lines are considerably narrower frequency discriminators than the Doppler-broadened lines used in⁶⁻¹⁰, hence we expect to obtain improved stability and accuracy. To verify this, we have constructed a reference system which is based on a 780 nm external cavity diode laser locked to Rb sub-Doppler lines, and in this paper we report the results of the frequency stability measurements.

2. EXPERIMENTAL RESULTS

The setup for doubling the 1560 nm laser and locking to Rb was described in detail in¹³ and was slightly improved since then. Our light source, an external cavity diode laser (New Focus 6262) was passed through an optical isolator (reverse isolation 75 dB) and coupled into a 3 cm long periodically-poled LiNbO₃ waveguide doubler. Ferroelectric domain inversion with a period of 14 μm was obtained by electric field poling and the channel waveguide was fabricated by annealed proton exchange. The single-pass efficiency for SHG of 1560.5 nm in the waveguide was 120% W^{-1} at 33 $^{\circ}\text{C}$. We coupled ~ 1 mW into the waveguide and obtained ~ 1.2 μW at 780.25 nm. The waveguide output face was polished at a 15 degrees angle with respect to the waveguide in order to avoid etalon effects which cause wavelength-dependent output power fluctuations. The ratio of the minimum to maximum second harmonic power generated as the wavelength was tuned was ~ 0.5 with perpendicular faces¹³ and 0.96 with the angled face. Anti-reflection coatings could significantly reduce this effect.

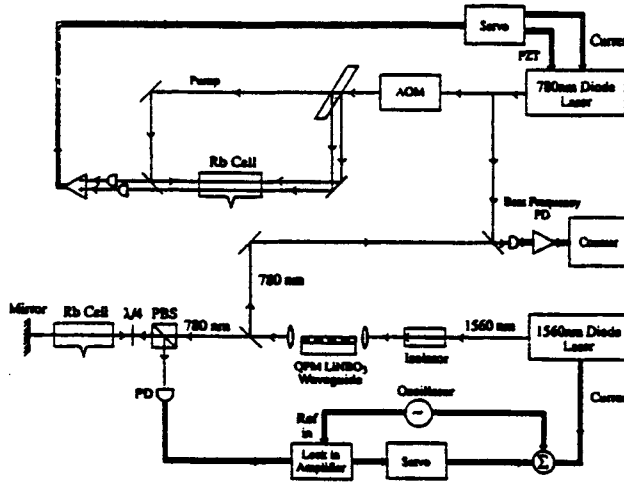


Fig. 1: Experimental setup for characterizing the frequency stability of the Rb-locked 1560 nm diode laser. AOM - acousto-optic modulator; PD - photodetector; PBS - polarizing beam splitter.

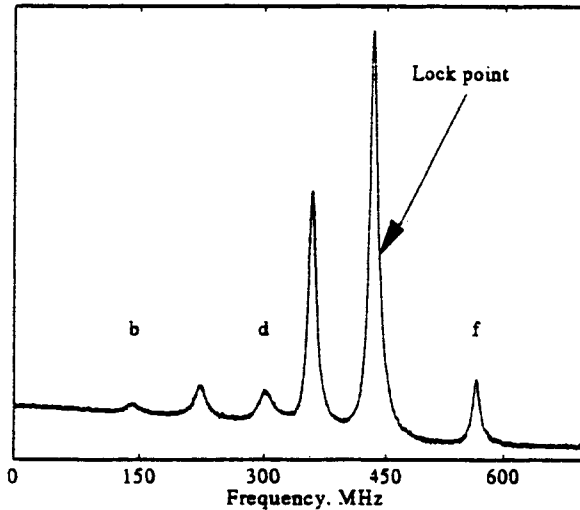


Fig. 2: Sub-Doppler spectrum of ^{87}Rb $5S_{1/2}$ ($F''=2$) \rightarrow $5P_{3/2}$ ($F'=1,2,3$) transitions, labeled b, d and f respectively, obtained with the 780 nm diode laser. The laser was locked to the side of the d/f cross-over line.

The SHG was split by a 50/50 beamsplitter: 0.6 μW were sent to the beatnote detector and the remaining light was used for saturation spectroscopy in a 7.5 cm Rb cell. A quarter-wave plate and a polarizing beam splitter were used in order to direct the forward light into the cell and the reflected light onto the detector. The frequency was dithered using the laser current at a frequency of 1.8 kHz and the third harmonic component at 5.4 kHz was measured using a lock in amplifier. The laser frequency was locked to the relatively narrow (~ 8 MHz, experimentally measured) sub-Doppler d/f crossover line of Rb by feeding the lock in output through a servo amplifier back to the laser. Frequency corrections can be obtained either using a piezoelectric transducer (PZT) which rotated the feedback mirror inside the laser cavity or by adjusting the laser current. Both options were tested and better results were obtained using the laser current. The open loop gain of this system as a function of frequency f was $\sim 700/f$.

Our reference system was based on a home-made external cavity diode laser. We used a 50 mW SDL-5401 diode laser in a Littrow configuration: The laser light was collimated and sent to a 1200 lines/mm ruled diffraction grating. The first order diffracted beam was fed back into the laser diode, whereas the reflected beam from this grating was the

light source for our experiment. Wavelength tuning was achieved by rotating the grating with a fine adjustment screw or, for finer tuning, with a piezoelectric transducer. The diode laser was driven by a low noise current controller and its temperature was stabilized at the milliKelvin level using a small heater and a PID temperature controller. We used a different scheme to detect sub-Doppler lines with this system (see Fig. 1): The laser light was split into two probe beams and one counter-propagating pump beam which coincided with one of the probe beams. Subtracting the output of the two detectors that detected separately the two probe beams provided a sub-Doppler signal. The sub-Doppler spectrum of $^{87}\text{Rb } 5S_{1/2} \rightarrow 5P_{3/2}$ is shown in Fig. 2. The obtained linewidth, ~ 10 MHz, was slightly broader in this system, possibly due to gas contamination in this cell¹⁴. The laser frequency was locked to the side (rather than the peak) of the d/f cross-over line. This locking method does not require frequency modulation of the laser. Both the laser current and the piezoelectric voltage were used to keep the laser locked: The error signal, after passing through an integrator, was fed to the piezo. Higher frequency corrections, up to ~ 10 kHz, were employed by passing the error signal through a bandpass filter and adding the correction signal to the laser bias current. For isolation from reflections into the laser and to keep the beat frequency away from dc we shifted the laser beam by 29.5 MHz using an acousto-optic modulator.

The beat frequency between the two lasers was measured by a fast Si photodiode followed by an RF amplifier and a frequency counter, SRS 620. The root Allan variance¹⁵ of the beat frequency of the locked lasers is shown in Fig. 3. A similar measurement while the 1560 nm was free running is also shown for comparison. As can be seen, the frequency stability was improved considerably. The best result of $6.9 \cdot 10^{-12}$ was reached at 1 s. This corresponded to frequency fluctuation of 1.3 kHz at 1560 nm. This level of stability is approximately an order of magnitude better than the results obtained by locking to Doppler-broadened lines at 1550 nm [6-9].

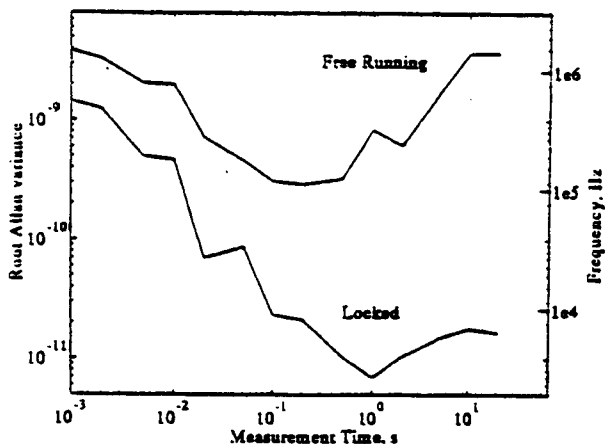


Fig. 3: Root Allan variance between the doubled 1560 nm laser and the 780 nm reference laser. The 1560 nm was free running in one measurement and under lock in the other measurement. The 780 nm laser was kept locked in both cases. The right axis scale refers to frequencies at 780 nm.

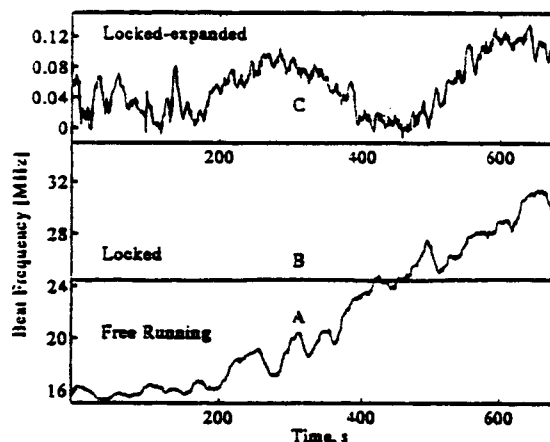


Fig. 4: Variation of the beat frequency (at 780 nm) between the two lasers. (A) The 1560 nm was free running; (B) The 1560 nm under lock; (C) Expanded frequency scale of (B). The 780 nm laser was kept locked in all measurements.

Fig. 4 shows the time variation of the beat frequency. As can be seen, during the measurement period, the locked lasers were kept within 120 kHz (at 780 nm). For comparison, we have made another measurement in which the 1560 nm laser was free running. In this case the drift of the doubled 1560 nm laser frequency was ~ 16 MHz at 780 nm.

The beat frequency was measured several times over a period of one month. During this time the lasers were locked and un-locked for numerous occasions, and the beams alignment was also occasionally adjusted. The peak to peak beat frequency excursions (excluding one measurement) at 780 nm was 795 kHz and the standard deviation was 285 kHz. The main cause for these long term frequency deviations was power level variations of the 780 nm, which led to different saturation levels and hence to a shift of the locked frequency. Locking to the center of the sub-Doppler line, as done with the doubled 1560 nm system, should therefore improve the accuracy. As shown recently with Ti:sapphire lasers¹⁶, it is possible to obtain an accuracy of $1.5 \cdot 10^{-11}$ and reproducibility of $1 \cdot 10^{-11}$ by locking to Rb transitions at 780 nm.

We have also stabilized the laser frequency by locking to the side of the Doppler broadened $^{87}\text{Rb } 5S_{1/2} \rightarrow 5P_{3/2}$ transition. In this case, the doubled 1560 nm laser was split using an additional beam splitter into a signal beam, which passed through the Rb cell, and reference beam which did not pass through the cell. The two beams were detected with separate detectors, and their difference photocurrent was set to zero at a specific frequency on the side of the Doppler-broadened transition. The 780 nm laser was locked in this case to the side of the b/f cross-over line. The root Allan variance was at a level of $\sim 1 \cdot 10^{-10}$ for measurement times in the range 0.1-5 s. The estimated reproducibility of this system was $2.5 \cdot 10^{-8}$. The results we obtained by locking to sub-Doppler lines are better by more than an order of magnitude than those obtained using Doppler-broadened lines, owing to the considerably broader Doppler linewidth of ~ 500 Mhz.

3. SUMMARY

QPM frequency doubling in a waveguide and locking the second harmonic to atomic lines can also be done at other wavelengths in the 1300 [17] and 1550 nm fiber-optic transmission windows. Possible candidates include Rb two photon transition at 778 nm and K D₁ line at 770 nm [18]. The advantages of locking to sub-Doppler resonant atomic lines, rather than to Doppler-broadened lines, include improved frequency stability and reproducibility. Furthermore, in locking schemes which require dithering of the laser frequency, the dither amplitude, which is of the same order as the absorber linewidth, is much smaller when sub-Doppler lines are used. Owing to the low saturation intensities of atomic lines, sub-Doppler lines are obtained by standard saturation spectroscopy techniques, and a Fabry-Perot enhancement cavity¹¹ is not required.

4. ACKNOWLEDGMENT

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5. REFERENCES

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