Vibrational Analysis of Stabilized Lasers

K. J. Hughes, A. Hati, C. Nelson, D. Howe
National Institute of Standards and Technology
Boulder, CO/USA
Email: jhughes@nist.gov

***Abstract*—Frequency-stabilized lasers are routinely used in a variety of research and application areas relating to laser-cooled atoms. Important applications in the cold-atom regime include atomic time keeping, inertial navigation, gravitational sensing, and magnetometry. The number of applications based on frequency stabilized lasers is increasing and at the same time, there is a push to miniaturize devices base on these applications. As devices become smaller and more mobile, it will become increasingly important to be able to measure and understand the effects of vibration on the individual devices as a whole, as well as the frequency-stabilized laser subsystems. Here we present preliminary vibration studies of a lab-built laser system based on a monolithic semiconductor laser diode frequency stabilized to the D2 transition in ^{87}Rb using FM saturated absorption spectroscopy.**

I. Introduction

The field of cold atom physics was born over three decades ago with the seminal discovery of laser cooling [1]. Since that time, this area of physics has seen an explosion of interest as well as notable achievements that include the first observations of Bose-Einstein condensates [2]–[4], degenerate Fermi gases [5] and ultracold molecules [6]. Today, cold atom research is driven, in part, by advanced military applications for which cold and ultracold atoms may provide a significant advantage over conventional technologies. Such potential applications include magnetic sensing, atomic time keeping and atom interferometry for inertial navigation and gravitational mapping. While cold atom technologies have been demonstrated in the laboratory, they have struggled to make the transition from these protected and controlled environments to field use. Vibration can wreak havoc on certain subsystems, including the stabilized laser systems required for preparing and probing cold atoms. In this paper we present vibration data for a discrete mode semiconductor laser stabilized to an atomic transition.

II. Laser system

A frequency-stabilized laser system consists of a laser, a frequency discriminator, and feedback control. As the laser drifts in frequency, the frequency discriminator detects the drift and a control signal is applied to bring the laser back to the desired frequency. The control signal provides a representation of the laser frequency excursion as measured by the discriminator. This signal can be monitored during normal operation or when subjected to extreme conditions such as vibration. The details of the system are shown in Fig. 1 and are described below.

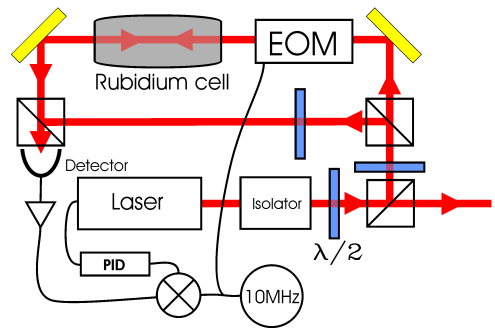

Fig. 1. Schematic diagram of the laser system. The output of the laser passes through an optical isolator and a portion of the beam is sent to the spectroscopy setup. The probe beam is phase modulated at 10 MHz with an EOM and then passes through a rubidium vapor cell. A photodetector detects a beat signal in the probe beam that is phase shifted depending on the frequency of the laser relative to the resonance. A counter-propagating saturation beam allows for access to the nuclear hyperfine transitions and phase sensitive detection using a mixer generates an error signal which is used for locking.

A. Monolithic semiconductor lasers

For this work we are mainly interested in monolithic semiconductor lasers because of their inherent reduced sensitivity to vibrations as compared to lasers based on external or large cavities. Monolithic semiconductor lasers of particular interest include distributed feedback (DFB) lasers, distributed Bragg reflector (DBR) lasers, vertical cavity surface emitting lasers (VCSELs), and discrete mode laser diodes (DMLDs). These types of lasers typically offer narrow linewidths of less than a few MHz and frequency tuning is performed in one of two ways; slow frequency tuning is achieved with temperature adjustment and fast tuning with adjustment to drive current. For the setup described here we incorporate a DMLD with a center wavelength at 780 nm. The DMLD is packaged in a standard TO-9 can and the output beam from the diode is collimated using a commercial collimation tube designed for diode lasers and a translatable aspheric lens. The entire collimation package including the diode is temperature stabilized at about 28 °C with a thermo-electric cooler (TEC), a 10 kΩ thermistor, and a commercial temperature controller. Typical operating current for the diode is about 150 mA and is supplied using an ultra-low noise current driver. The driver has a modulation port with a modulation 3 dB bandwidth of about 1 MHz. The tuning rate of the diode is about 4.5 GHz per volt applied to the modulation port. The optical output of the laser first passes through an anamorphic prism pair for further beam shaping and then through a 30 dB optical isolator to protect the diode from back reflections. The output is then directed to a frequency discriminator as described in the following subsection.

B. Frequency discriminator

The frequency discriminator serves two related purposes: first, it provides a reference for the laser lock itself, and second, it provides a signal that relates to the frequency excursion of the laser; in other words, it shows the amount the laser has deviated from where it is supposed to be. In general, a optical frequency discriminator can be anything that shows dispersion at the frequency of interest. Examples of optical frequency discriminators include Fabry-Perot cavities, optical gratings, and spectroscopy signals based on atomic or molecular resonances. For the work here, we use spectroscopy of an atomic rubidium vapor.

We use the well-known method of frequency modulation (FM) spectroscopy [7] to generate a lock signal. As shown in Fig. 1, a probe beam is phase modulated using an electro-optic modulator (EOM) driven at a frequency of 10 MHz. The beam passes through a cell containing rubidium vapor and non-linearities near an atomic resonance cause a phase shift in the beat signal between the carrier and side bands. The beat signal is detected on a silicon photodetector and the phase shift is compared with the original 10 MHz EOM drive signal using a double-balanced mixer as a phase detector. For the single beam setup described thus far, the hyperfine excited state structure will not be distinguishable due to thermal Doppler broadening of the resonances. Adding a counter-propagating saturation beam to the rubidium vapor comprises a technique known as saturated absorption spectroscopy [8] and allows us to distinguish the individual nuclear hyperfine transitions. The output of the mixer is filtered with a 5 MHz low-pass to produce an error voltage which is a close approximation to the derivative of the absorption with respect to the laser frequency.

C. Laser system package and feedback control

The mounting platform shown in Fig. 2 contains all the optical components for locking the laser. The optical isolator (which includes a very strong magnet) was mounted in a cylindrical metal housing designed to contain the magnetic field and shield the nearby rubidium cell. The optical components were carefully aligned and fixed to the platform with high-strength epoxy.

Feedback control was implemented with a commercial, high-speed PID controller, and the P-I corner was set to 100 kHz; well above the vibration frequencies that we expected to subject the laser system to during vibration testing. For the vibration tests, the laser was locked to the ^{87}Rb transition from the $5^2S_{1/2}$ $F = 2$ ground state to the $5^2P_{3/2}$ $F = 3$ excited state.

III. Vibrational Measurements

The vibration measurements are performed on a commercial shake table that is powered by a 480 volt 3-phase dynomotor

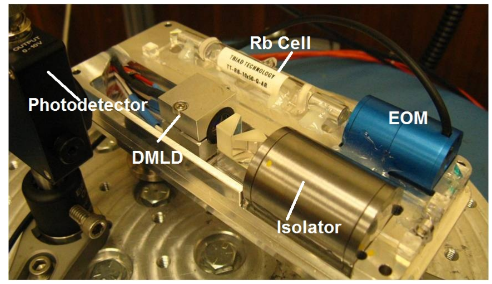

Fig. 2. The laser system platform is about 7 cm × 150 cm and houses the DMLD laser, beam shaping optics, an optical isolator (silver cylinder), an EOM (blue cylinder), a rubidium cell and miniature optics like beamsplitters, waveplates and mirrors. The components are secured to the platform with high-strength epoxy. The optical layout closely follows that of Fig. 1.

and is capable of producing peak accelerations of 68 g's. The shaker uses an accelerometer for closed-loop operation taht provides precise, programmable, vibration profiles.

We calibrated the frequency tuning of the laser by applying a triangle waveform to the modulation input of the laser current driver and observing the voltage required to scan continuously across the 6.8 GHz ground state splitting of the D2 transition in ^{87}Rb. We measured a tuning rate with modulation voltage of 4.5 GHz per volt. Under vibration, the product of the control voltage from the PID and this calibration gives the frequency shift of the laser system. The vibration sensitivity can then be calculated. Typically the vibration sensitivity of a frequency source is related to the fractional frequency uncertainty and given by

$$\Gamma = \frac{\Delta\nu}{\nu_0 a} \tag{1}$$

where $\Delta\nu$ is the frequency shift, ν_0 is the nominal frequency, and a is the acceleration along the axis of measurement.

We started with a white vibration spectrum that spanned from 10 Hz to 1 kHz with an acceleration amplitude of 0.1 g/$\sqrt{\text{Hz}}$. With these operating parameters, we found it difficult to maintain a laser lock during the measurement. It was unclear if the problem was due to vibration sensitivity of the system, electrical interference of the shaker with the locking circuitry, or magnetic fields from the shaker degrading the spectroscopy.

A. Tonal excitation

Next we subjected the system to discrete sinusoidal tones ranging from about 20 Hz to about 1 kHz in frequency, each with an acceleration amplitude of 2 g's pk-pk. The system stayed locked and the control signal at each frequency was recorded on an FFT analyzer. During the measurement, the signal level would vary on slow irregular time scales of 10 to 60 seconds by as much as a factor of 10. The variation did not appear to be regular and the time scale did not seem to be correlated with the drive frequency. It is assumed that this effect was due, at least in part, by electrical interference of the shaker with the control electronics, but further investigation will be required to come to a definitive conclusion. To eliminate irregular fluctuations, a large number of averages

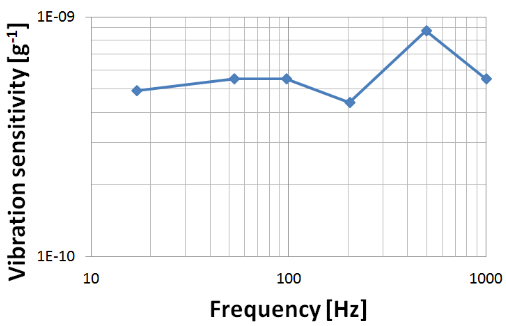

Fig. 3. Tonal response of the stabilized lasers system. Discrete sinusoidal vibrational tones were applied to the laser system having an acceleration amplitude of 2 g's pk-pk and ranging in frequency from about 20 Hz up to about 1 kHz. A large number of averages were used to suppress fluctuations in the signal. Overall sensitivity seems relatively flat over the test frequency range, with an average value of about 6×10^{-10} g^{-1}.

were used. Fig. 3 shows the calculated vibration sensitivity of the system based on the averaged signal inasmuch as the frequency excursion is due entirely to vibrations. This is likely not the case and we hope to further our understanding through continued investigation.

B. Shock excitation

To eliminate possible effects due to electrical interference and magnetic fields, it was decided to manually actuate the unpowered shaker platform. We began first by lightly tapping the platform with screwdrivers and Allen wrenches and saw essentially no effect on the control voltage from the PID. We moved up to very hard blows from a large rubber mallet and the system remained locked although the lock signal clearly showed a frequency excursion as seen in Fig. 4. From the figure, we can estimate the sensitively to be $\Gamma = 2.6 \times 10^{-10}$ g^{-1}. In other "data runs" the maximum recorded acceleration was limited by our accelerometer which saturates the drive electronics at 120 g's. Even in these extreme cases the system remained locked.

C. Random vibration

We performed a reduced random vibration test where we limited the vibration to the frequency range from 100 Hz to 500 Hz while maintaining an amplitude of 0.1 $g/\sqrt{Hz}$ as in the previous attempts. The laser was still able to maintain lock and the resulting sensitivity is plotted in Fig. 5. We note the unexpected difference between traces (2) and (3) of Fig. 5 for the same vibration profile. This changing level may be another manifestation of the variations that we saw with the tonal excitation. The measured sensitivity across this spectral range is $\Gamma = 4 \times 10^{-10}$ g^{-1}.

IV. Conclusion

In this work we built a compact frequency stabilized laser module based on a DMLD and FM spectroscopy and subjected it to a variety of vibrations. We have made preliminary measurements of the vibration sensitivity of this device using three different techniques and we conclude that the vibration

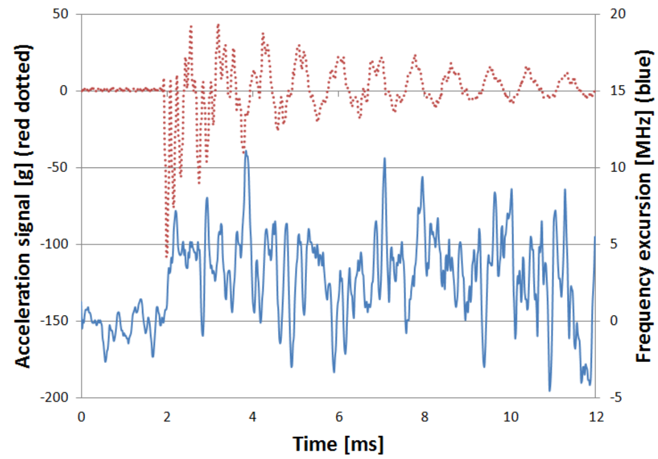

Fig. 4. Results of shock excitation. A large rubber mallet was used to administer heavy blows to the unpowered vibration platform. From this, we calculate a rough estimate of the vibration sensitivity to be $\Gamma = 2.6 \times 10^{-10}$ g^{-1}.

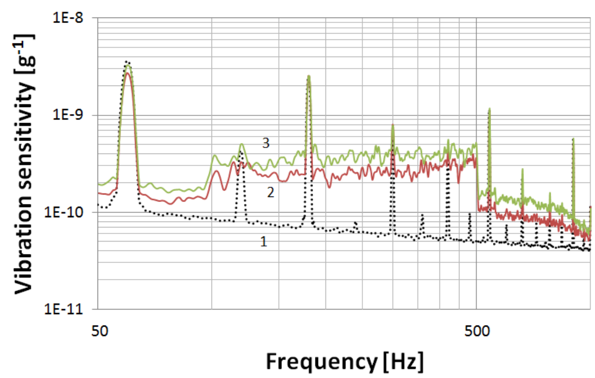

Fig. 5. Reduced random vibration tests. A reduced flat vibration profile from 100 Hz to 500 Hz with an amplitude of 0.1 $g/\sqrt{Hz}$ was applied to the laser system. Black dotted line (1) shows the noise floor measured without active vibrations. Red solid line (2) is with vibrations. Green solid line (3) is a repeat measurement. We are working to understand the offset between (2) and (3), which seems to be similar to the variations that we saw with tonal excitation of the laser system.

sensitivity over the frequency range that we tested is better than 6×10^{-10} g^{-1}. We acknowledge that there is more work to be done to understand and eliminate frequency excursions due to non-vibratory effects such as electrical interference and magnetic fields. Also, this work does not distinguish independently between the effects of vibration on the laser source and the spectroscopy setup. Possible sources for frequency excursion may include length fluctuations in the internal cavity of the semiconductor laser as well as fluctuations in beam pointing on the photodiode which may erroneously appear to the control loop as a fluctuation in frequency. More research will be required in order to sort out the dominant effects. As cold atom devices are miniaturized into portable form factors, the effects of vibrations will become increasingly important. This preliminary work is a first step in being able to understand and measure the effects of vibrations on frequency stabilized laser subsystems for portable devices.

Acknowledgment

The authors would like to thank Jason DeSalvo, Danielle Lirette, and Corey Barnes (Association: NIST, CO) for helpful discussions. We would also like to thank Archie Brown (Association: Triad Technology, Inc., CO) for the use of equipment integral to performing this work.

References

[1] D. J. Wineland, R. E. Drullinger, and F. L. Walls, "Radiation pressure cooling of bound resonant absorbers," *Phys. Rev. Lett.*, vol. 40, pp. 1639–1642, 1978.

[2] M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell, "Observation of Bose-Einstein condensation in a dilute atomic vapor," *Science*, vol. 269, p. 198, 1995.

[3] K. Davis, M. Mewes, M. Andrews, M. van Druten, D. Durfee, D. Kurn, and W. Ketterle, "Bose-Einstein condensation in a gas of sodium atoms," *Phys. Rev. Lett.*, vol. 75, p. 3969, 1995.

[4] C. C. Bradley, C. A. Sackett, J. J. Tollett, and R. G. Hulet, "Evidence of Bose-Einstein condensation in an atomic gas with attracktive interactions," *Phys. Rev. Lett.*, vol. 75, p. 1687, 1995.

[5] B. DeMarco and D. S. Jin, "Exploring a quantum degenerate gas of Fermionic atoms," *Phys. Rev. A*, vol. 58, p. R4267, 1999.

[6] C. A. Regal, C. Ticknor, J. L. Bohn, and D. S. Jin, "Creation of ultracold molecules from a Fermi gas of atoms," *Nature*, vol. 424, pp. 47–50, 2003.

[7] G. C. Bjorklund, "Frequency-modulation spectroscopy: a new method for measuring weak absorptions and dispersions," *Optics Letters*, vol. 5, pp. 15–17, 1980.

[8] G. R. Hanes, J. Lapierre, P. R. Bunker, and K. C. Schotton, "Nuclear hyperfine structure in the electronic spectrum of $^{127}I_2$ by saturated absorption spectroscopy , and comparison with theory," *Journal of Molecular Spectroscopy*, vol. 39, no. 3, pp. 506–515, 1971.