An Auto-Locked Diode Laser System for Precision Metrology

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ABSTRACT

We present a unique external cavity diode laser system that can be auto-locked with reference to atomic and molecular spectra. The vacuum-sealed laser head design uses an interchangeable base-plate comprised of a laser diode and optical elements that can be selected for desired wavelength ranges. The feedback light to the laser diode is provided by a narrow-band interference filter, which can be tuned from outside the laser cavity to fine-adjust the output wavelength in vacuum. To stabilize the laser frequency, the digital laser controller relies either on a pattern-matching algorithm stored in memory, or on first or third derivative feedback. We have used the laser systems to perform spectroscopic studies in rubidium at 780 nm, and in iodine at 633 nm. The linewidth of the 780-nm laser system was measured to be ∼500 kHz, and we present Allan deviation measurements of the beat note and the lock stability. Furthermore, we show that the laser system can be the basis for a new class of lidar transmitters in which a temperature-stabilized fiber-Bragg grating is used to generate frequency references for on-line points of the transmitter. We show that the fiber-Bragg grating spectra can be calibrated with reference to atomic transitions.

Keywords: External cavity diode lasers, auto-locked diode lasers, laser spectroscopy, iodine and rubidium spectroscopy, lidar

1. INTRODUCTION

We have developed an interference filter (IF)-stabilized diode laser with an auto-lock controller for precision spectroscopy.[1–3] Low-cost laser systems of this design be integrated using components from original equipment manufacturers coupled with specially-machined parts and powerful central processors. The laser source depends on optical feedback from a narrow-band IF to reduce the laser linewidth to ∼500 kHz. The thermally-stabilized laser cavity can be evacuated within minutes and vacuum-sealed for several months, thereby reducing the sensitivity to environmental temperature and pressure fluctuations. The laser system can be locked or scanned with respect to a spectral line or solid-state frequency marker without the need for human intervention by using a digital controller. The controller is capable of storing a variety of algorithms in its memory for laser frequency stabilization, using techniques such as pattern matching and first or third derivative feedback. The laser cavity relies on an interchangeable optics kit consisting of a laser diode and optical feedback elements to operate in the desired wavelength range. The laser system appears to be suitable for wide-ranging applications that can be realized by power amplification, frequency locking to external cavities, and rapid amplitude modulation.

In recent work,[2] we reported the performance of the IF laser system under field conditions at 780 nm and 633 nm based on rubidium and iodine spectroscopy, respectively. We characterized the system performance through measurements of the Allan deviation of the beat note between two IF lasers, and through a measurement of the Allan deviation of the lock stability of a single laser. The laser frequency was stabilized using different auto-locking algorithms for these studies. We used third derivative feedback for iodine spectroscopy, and a simple 'push-pull' algorithm for rubidium spectroscopy. The time constants of these feedback loops was approximately 1 second. The laser linewidth and lock stability allowed precision measurements of gravitational acceleration

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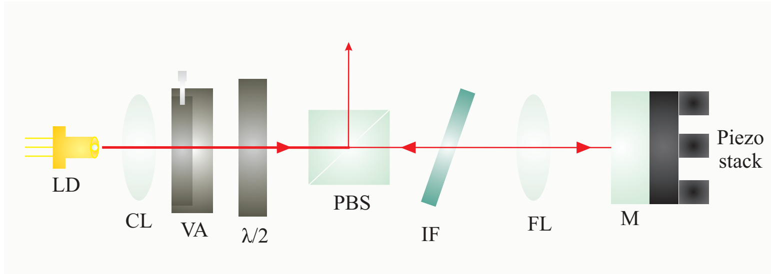

Figure 1: Schematic of IF laser design. The optical elements are: LD - laser diode, CL - collimating lens, VA - variable aperture, $\lambda/2$ - half wave-plate, PBS - polarizing beam splitter, IF - interference filter, FL - focusing lens, M - mirror.

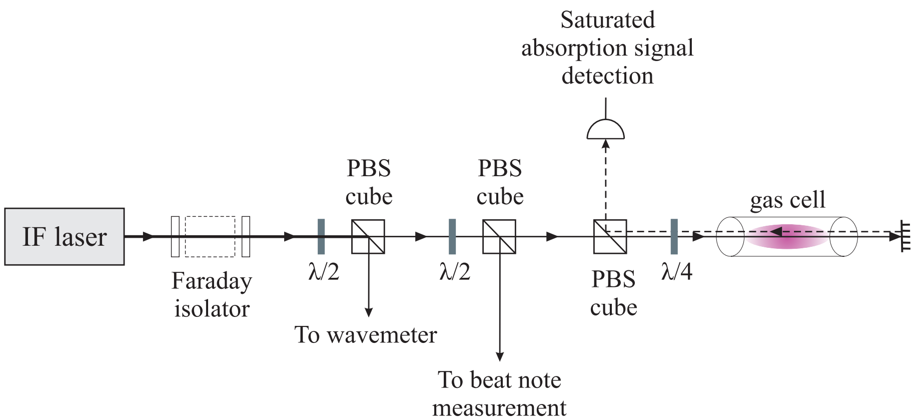

Figure 2: Dual-pass saturated absorption set-up for rubidium spectroscopy.

with an accuracy of 3 parts-per-billion (ppb) using a state-of-the-art industrial sensor. Our studies also showed that the correction signals were reduced by nearly an order of magnitude by evacuating the air in the laser cavity.

In this paper, we characterize the laser performance using a vibration-isolation platform and feedback loops with time constants ranging from 5–50 ms, with the goal of understanding the intrinsic stability of the IF laser system. Under these conditions, we find that the Allan deviation of the beat note between two identical IF lasers is $\sim$2.5 $\times 10^{-11}$ at $\tau = 40$ s, which represents a hundred-fold improvement compared to the results in reference [2]. The Allan deviation of the lock stability of a single laser is $\sim$2 $\times 10^{-11}$ at $\tau = 80$ s, which suggests a similar measure of performance. With the laser cavities evacuated to 1.6 Torr, the correction signals were reduced by an order of magnitude, as in our previous work. However, the Allan deviation of the beat note worsened by an order of magnitude, and the Allan deviation of the lock stability worsened by a factor of three.

We also demonstrate that the laser system can be used as the basis for a new class of lidar transmitters by auto-locking to the transmission spectrum of a fiber Bragg grating (FBG). We show that the laser frequency can be tuned and calibrated with respect to atomic spectral lines by temperature-tuning the FBG.

2. RESULTS AND DISCUSSION

Figure 1 shows the design of the laser head. Optical feedback from an interference filter with a transmission width of ± 0.3 nm is used to narrow the linewidth of a laser diode operating at 780 nm. The $\lambda/2$ wave-plate and the PBS are used to output-couple most of the laser light, and limit the optical feedback to approximately 15% of the power from the laser diode. The laser output is aligned through a dual-pass saturated absorption spectrometer (figure 2) that uses a rubidium vapor cell, and the laser frequency is stabilized with respect to the $5^2S_{1/2}$ $F = 3 \rightarrow 5^2P_{3/2}$ $F' = 2, 3, 4$ transitions in ^{85}Rb.

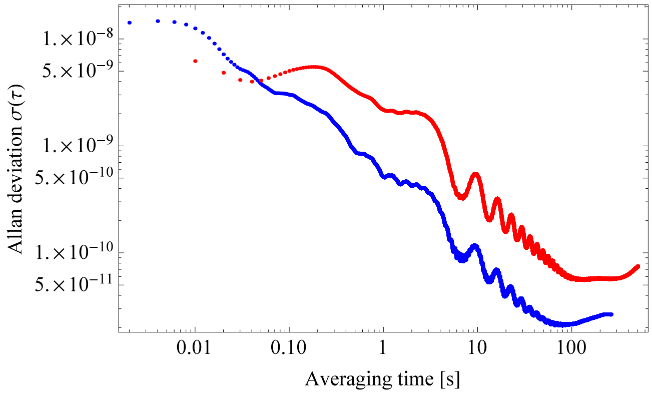

Figure 3: Allan deviation of the lock stability with the laser cavity hermetically sealed (blue) and with the cavity pumped out to 1.6 Torr (red). The low frequency modulation observed in the data is attributed to the resonance frequency of the vibration-isolation platform.

The lasers and the saturated absorption spectrometers were passively shielded from vibrations using a platform with a resonant frequency of $\sim$1 Hz. The laser frequency was actively stabilized on the basis of first-derivative feedback, with the corrections being fed exclusively to the piezo stack that controls the length of the cavity in figure 1. The current controller has a characteristic power spectral density of 200 nA/$\sqrt{Hz}$. The time-constant of the feedback loop ranged from 5–50 ms. Figure 3 shows the Allan deviation of the lock stability for a single laser. The Allan deviation was calculated based on the procedure outlined in reference [4]. The blue curve represents the data obtained at atmospheric pressure with a hermetically-sealed laser cavity. The minimum value of 2×10^{-11} at $\tau = 80$ s is significantly better than the value of 1×10^{-9} at $\tau = 600$ s reported in reference [2]. We attribute this improvement to the vibration isolation and the faster correction loop. The red curve in figure 3 shows the Allan deviation of the lock stability with the laser cavity evacuated to a pressure of 1.6 Torr. Here, the Allan deviation is worsened by a factor of three, an effect that we attribute to cavity stresses and mechanical resonances amplified by the pump-out. However, for all the recorded data, the laser remained locked on time scales of one hour. The reduction in the correction signal by an order of magnitude with pump-out suggests that the duration of the lock can be extended significantly if the instability associated with the pump-out can be eliminated through design changes to the laser head and by studying the effect of longer time constants.

The blue curve in figure 4 shows the Allan deviation of a 30-MHz beat note obtained by locking two lasers to adjacent cross-over resonances in ^{85}Rb. We find an Allan deviation of 2.5×10^{-11} at $\tau = 40$ s for a hermetically-sealed laser cavity. This measurement represents a nearly hundred-fold improvement compared to our previous work, in which the lasers were operated without vibration stabilization and locked with a 1-second time constant using a 'push-pull' algorithm.[2] The red curve in the figure shows that the Allan deviation is worsened by an order of magnitude when the laser cavities are pumped-out. In both cases, fits to the data were generated using power laws for noise sources for which the Allan deviation is known to converge.[4] In these data sets, the contributions of the resonance associated with the vibration isolation platform is reduced compared to figure 3, since these perturbations affect both laser cavities. The measured Allan deviations also represent improvements over the performance of other diode laser configurations.[5–7]

We now describe the first step to realize a lidar transmitter based on the stability and the auto-locking features of the IF laser. The standard measurement technique for differential absorption lidar (DIAL) involves the absorption of pulsed laser light propagating through the atmosphere. Light is emitted into the atmosphere, and the light that is scattered back is detected and recorded as function of distance. The density of the molecular species being detected is determined by comparing the intensity of laser backscatter at the absorbed wavelength to a reference signal at a second (off-line) wavelength. Pulsed lasers that use semiconductor waveguides to amplify light from the IF laser modules offer the possibility of developing a new class of DIAL transmitters. Unlike traditional DIAL-type transmitters that rely on two pulsed YAG lasers or diode lasers operating at

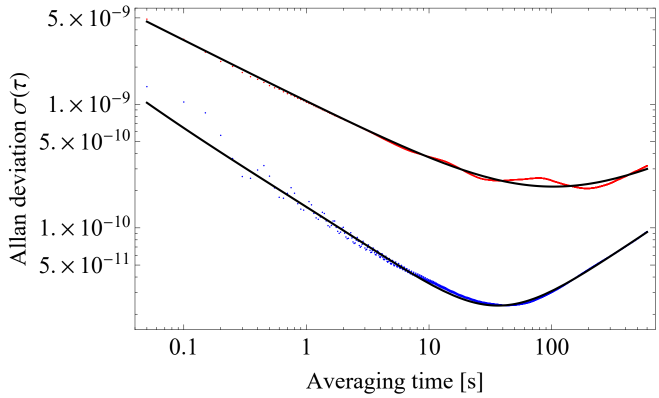

Figure 4: Allan deviation of the beat note with the laser cavities hermetically sealed (blue) and with the cavity pumped out to 1.6 Torr (red). The fit function for the blue curve is $(-2.78 \pm 0.02) \times 10^{-11}\tau^{0} + (1.87 \pm 0.05) \times 10^{-11}\tau^{-1} + (1.525 \pm 0.007) \times 10^{-10}\tau^{-0.5} + (4.07 \pm 0.02) \times 10^{-12}\tau^{0.5} + (2.37 \pm 0.05) \times 10^{-14}\tau$, and the corresponding fit function for the red curve is $(1.11 \pm 0.06) \times 10^{-11}\tau^{0} + (1.040 \pm 0.002) \times 10^{-9}\tau^{-0.5} + (1.005 \pm 0.00) \times 10^{-11}\tau^{0.5}$. The noise terms scaling as τ^{-1}, $\tau^{-0.5}$, τ^{0}, $\tau^{0.5}$, τ^{1} correspond to terms representing flicker phase modulation, white frequency modulation, flicker frequency modulation, random walk frequency modulation, and frequency drift, respectively. We speculate that the fit to the red curve has fewer noise terms due to the relatively large amplitudes of the coefficients of the surviving terms. The contributions of these noise terms will require further investigation.

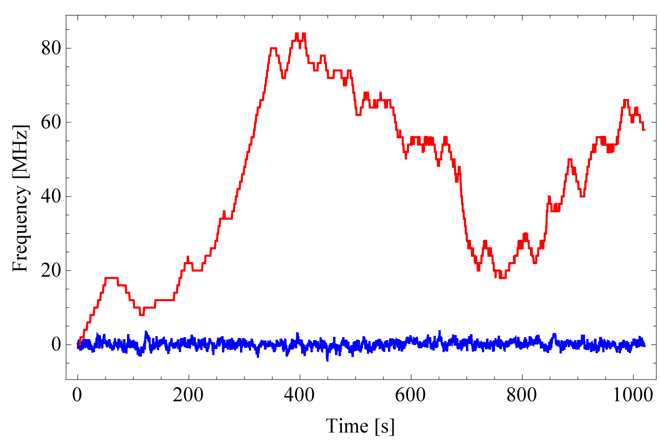

Figure 5: Frequency stabilization of the IF laser with respect to the transmission spectrum of an FBG. The error signal (blue) has a standard deviation of ~2 MHz, which is a short-term measure of frequency stability. The Allan deviation is 2×10^{-8} at $\tau = 100$ s without vibration isolation. The correction signal is shown in red.

different frequencies,[8,9] the transmitter we describe here can use a single, auto-locked master oscillator that can be locked and tuned to multiple frequencies with respect to atomic or molecular spectral lines. The accessible lock points and tuning ranges can be greatly expanded by stabilizing the master oscillator with respect to a temperature-tuneable solid-state frequency marker, such as an FBG. The motivation for developing such a lidar source stems from its potential for wide-spread applications, ranging from pollution monitoring to the detection of water vapor in planetary atmospheres.[10]

Figure 5 shows a short-term record of the IF laser locked to an FBG transmission peak with a width of ~50 MHz. We expect to achieve significantly better results for the lock stability and lock duration by improving the temperature stabilization of the FBG. We use Doppler-free resonances in ^{85}Rb and ^{87}Rb to demonstrate the calibration and tunability of the FBG peak, as shown in figure 6. The hyperfine separations between rubidium

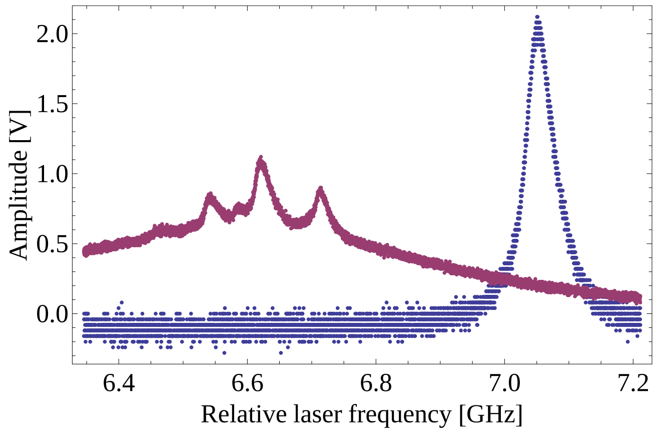

Figure 6: FBG calibration using rubidium resonances. The blue curve represents the FBG transmission peak, and the red curve represents a saturated absorption spectrum in ^{87}Rb.

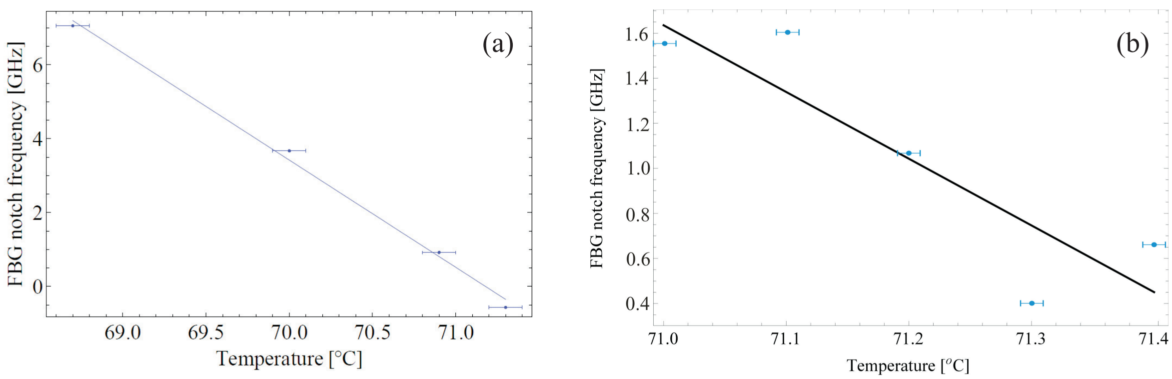

Figure 7: FBG temperature tunability using a Ti:Sapphire laser (a) and an IF laser (b). Fits to the data give a slope of -2.90 ± 0.13 GHz/°C in both cases.

ground states ensure that the FBG can be calibrated over ∼7 GHz. Figure 7(a) shows the tuning range attainable using a Ti:Sapphire laser with a scan range of 20 GHz. Figure 7(b) shows the limited tuning range obtained using an IF laser. We expect to expand the tuning range of the IF laser to several gigahertz using a feed-forward circuit that synchronously scans the laser diode current and the length of the laser cavity.

A prototype lidar transmitter will rely on amplifying the power output of the IF laser to ∼3 W using a semiconductor waveguide amplifier. The power output can be enhanced to approximately 10 W by transiently pulsing the waveguide amplifier current.[11–13] The calibration of the FBG can be improved by fabricating multiple peaks corresponding to the on-line and off-line points of the targeted species. However, the polarization and strain dependence of these solid-state frequency markers remains to be studied.

Amplitude modulation of the system can be achieved using an acousto-optic modulator (AOM). The pulsed output can be fiber-coupled and integrated with lidar receivers. Such a system will be capable of generating output pulses with durations ranging from 20 ns to 1 μs, a peak power of several watts, a pulsed linewidth of ∼10 MHz, and a repetition rate of up to 500 kHz.

3. CONCLUSIONS

The measured values of the Allan deviation of the beat note and the lock stability are significantly reduced compared to our previous work, and better than the specifications of some diode laser systems described in literature. It is likely that further improvements in performance can be achieved using commercial current controllers that have a much smaller power spectral density of 200 pA/$\sqrt{Hz}$, and by using a Pound-Drever-Hall-type feedback scheme, in which the high frequency components of the error signal are sent to the current, and the low frequency components are sent to the piezo element controlling the cavity length. Changes to the laser head design based on an analysis of the power spectral density of the laser output, and investigations of the feedback loop time constant are expected to address the performance limitations of the evacuated laser cavity. The key steps required to develop a prototype lidar transmitter are related to improving the temperature stabilization of the FBG.

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