Laser Frequency Stabilization Primer

This application note demonstrates how the New Focus™ LB1005 High-Speed Servo Controller can be used to stabilize the frequency of a laser. To illustrate the versatility of the LB1005, we demonstrate two types of laser frequency locking schemes. The first is a "side" lock to a broad Doppler-broadened molecular gas resonance using a single piezoelectric transducer (PZT) for feedback. The second is a lock to a more narrow sub-Doppler atomic gas resonance that uses feedback to both a PZT and the diode laser injection current. The goal of this application note is not to fully describe the rigorous methods of feedback control theory, but to instead introduce some general concepts about laser frequency locking and guidelines for setting up each type of lock.

I. Introduction

The optical resonator of a laser is naturally subject to myriad environmental disturbances that will change its optical path length and hence add noise to the optical frequency (wavelength) output of a laser. As an example, a common cause of laser frequency drift is from thermal fluctuations. A good first step, then, is to control the temperature of the laser cavity. However, this strategy places unrealistic limits on the temperature control for even a modest requirement on the long-term stability of the optical frequency. As an example, if the laser frequency ν was required to stay within 100 kHz of its desired operating point of 400 THz (750 nm), the requirement on the length L of a laser cavity is

$$\frac{\Delta\nu}{\nu} = \frac{\Delta L}{L} = \alpha\Delta T < \frac{10^5\,Hz}{4\times10^{14}\,Hz} = 2.5\times10^{-10}.$$

Despite constructing the laser from relatively low expansion materials like Invar and glass ($\alpha \sim 10^{-6}$/°C), the temperature fluctuations ΔT of the *entire* cavity would have to be stabilized to less than 0.25 mK, a daunting engineering task to say the least. Additionally, many other disturbances attack the laser cavity at increasingly faster time scales with decreasingly smaller frequency excursions, for instance: air currents, vibrations, acoustic noise, and pump noise (e.g. injection current noise for diode lasers). While passive stabilization efforts can (and should) be used to reduce these harmful effects on the frequency, active feedback control is often necessary to meet the frequency stability required for many AMO applications like laser trapping and cooling[i].

A. Elements of Feedback Control

A general arrangement for active feedback control of the laser frequency is shown in Figure 1. A laser undergoes disturbances that cause frequency noise. A portion of the light from the laser is sampled by the discriminator, which converts these frequency fluctuations to voltage fluctuations. A loop filter conditions this error signal for stable, optimal feedback. The control signal from the loop filter is then sent to the transducer, which makes the correction to the laser frequency.

1. Discriminator

To control laser frequency, a discriminator is required that responds to changes in optical frequency with a proportional voltage output. The discriminator needs to have a locally monotonic slope that provides an unambiguous readout of the sign of the frequency change. We refer to the slope of the discriminator as having a gain D, or sensitivity, typically in units of V/Hz. Usually discriminators are sought that have better frequency stability than the laser system that is being controlled. Under tight locking conditions, the better frequency stability of the discriminator is then ideally transferred to the laser. Common frequency discriminators are the resonances of atomic/molecular transitions or the modes of a stable optical cavity/interferometer. Laser light is sent through an optical cavity or gas absorption cell with an optical frequency that overlaps the resonance. A variety of detection techniques exist that use the filter-like response of the resonance to convert optical frequency changes to optical intensity changes, which can then be detected by square-law photoreceivers to produce useful electrical voltage differences. In this paper, the electrical output of the discriminator is referred to as the error signal.

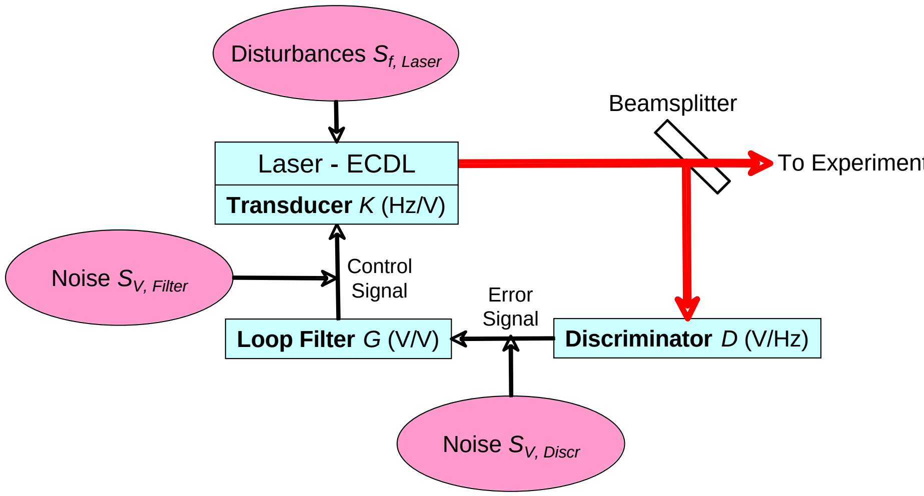

Figure 1: Basic elements of feedback control of laser frequency. The goal of feedback is to reduce the frequency noise $S_{f, Laser}$ by applying correction signals back to the laser (negative feedback). Also shown are voltage noise sources S_V from the loop filter and discriminator.

2. Transducer

Once a frequency deviation has been measured, a method for applying an appropriate correction is needed. Typically, the laser will comprise one or more electrically tuned transducers (actuators) that can change the optical path length of the resonator, which in turn changes the optical frequency. For instance, New Focus external cavity diode lasers (ECDLs) have two analog electrical inputs commonly used for tuning the laser frequency: a piezoelectric transducer (PZT), and a DC-coupled electrical port for modulating the diode laser injection current. The gain coefficient K of the transducer is commonly given in units of Hz/V. All transducers have a limited tuning range, which is the gain multiplied by the maximum allowed input voltage to the transducer. Another important characteristic of transducers is their operating bandwidth. The speed with which disturbances can be corrected is usually limited by the finite bandwidth of the transducer. Generally, the bandwidth of a transducer is inversely proportional to its tuning range.

3. Loop Filter

The loop filter provides the signal processing electronics that convert the error signal to a transducer control signal. With proper shaping of the filter frequency response, the feedback can be optimized to reduce laser frequency noise while maintaining stable operation. The loop filter usually provides integral gain G, which is required for driving the error signal to zero voltage. These electronics typically give the user control over the corner frequencies and the overall gain of the feedback loop.

B. Feedback Considerations

The frequency domain is often used to describe and understand feedback control systems. We can describe the laser optical frequency ν as being disturbed by noise processes characterized by the frequency-dependent quantity $S_{f, Laser}$, which is the spectral density of frequency fluctuations. $S_{f, Laser}$ (with units Hz/Hz$^{1/2}$) is a measure of the RMS frequency excursion in a 1-Hz bandwidth centered about a given Fourier frequency. For instance, at very low frequencies, we might expect $S_{f, Laser}$ to be large, owing to significant cavity length changes due to ambient temperature fluctuations. However, at larger Fourier frequencies, fluctuations due to “fast” noise in the diode laser injection current are much smaller and hence have decreased values of $S_{f,\,Laser}$.

1. Critical role of gain in feedback

The goal of the feedback loop is to force the error signal to zero volts for frequencies below the unity gain frequency. Ignoring other noise sources in the feedback loop, the spectral density of frequency noise for the laser $S_{f,\,Laser}$ is reduced by the total gain in the feedback loop:

$$S_{f,Closed} = \frac{S_{f,Laser}}{|1+KGD|}.$$

To minimize noise, the feedback system needs to be designed to maximize the overall loop gain KGD. However, the finite bandwidths of the feedback elements (discriminator, transducer, loop filter) limit the total amount of gain that a feedback system can have (see Section I.B.3.) Therefore, feedback design generally concentrates on increasing the servo gain by maximizing the bandwidth for components and optimizing the frequency response of the loop filter.

2. Practical performance limit due to noise

In real systems, one must contend with noise in the discriminator and filter electronics. (Any noise contributions from the transducer effectively amount to disturbance noise $S_{f,\,Laser}$.) Summing these contributions in quadrature, the closed loop spectral density of frequency noise is [ii]:

$$S_{f,Closed} = \frac{\sqrt{|S_{f,Laser}|^2 + |KS_{V,Filter}|^2 + |KGS_{V,Discr}|^2}}{|1+KGD|}.$$

In the limit where the servo gain G is large and dominates the other gain terms, the measurement noise and the slope of the discriminator completely determine the minimum closed loop spectral density:

$$S_{f,Closed}^{(\min)} = \frac{S_{V,Discr}}{D}.$$

This important result is quite intuitive: the limit is set by the inherent frequency noise generated in the discriminator measurement. The feedback loop cannot distinguish between a real perturbation to the laser frequency and noise generated in the measurement process, and ultimately the best one can do is “write” this measurement noise onto the laser frequency. From this result, feedback performance is increased in the following two ways:

- *Minimize the discriminator noise*. The best that can be achieved is the quantum-limited shot noise. Reaching this limit is difficult with DC-coupled measurements because “technical” *1/f* noise can be overwhelming at low frequencies. For instance, laser intensity noise is often a dominant contribution to errors in the frequency discrimination, electronic amplifiers have intrinsic flicker noise at low frequencies, and AC-coupled line noise from overhead lights, ground loops, switching power supplies, and sensitive amplifier electronics are ubiquitous in most measurements. For this reason, a variety of modulation-based phase-sensitive (“lock-in”) detection schemes have been developed that translate the discrimination information to higher frequency bands away from *1/f* noise. Although this paper focuses on simpler DC-coupled detection methods, the reader is invited to read New Focus Application Notes 7 and 14, which are excellent introductions to some of these more powerful detection techniques.
- *Increase the discriminator slope*: This is typically achieved by discriminating with more narrow optical resonances. The narrowness of atomic and molecular resonances is limited by their natural linewidth. In practice, even this linewidth is difficult to realize because of broadening due to Doppler, collisional, saturation, wavefront, transit-time, and electromagnetic effects. Techniques like saturation spectroscopy and laser cooling can significantly reduce some of these effects. Large discriminator slopes are

achieved by coupling into modes of a high-finesse ("vacuum-gap") optical cavity. Unlike quantum resonances, an optical cavity does not suffer from saturation effects and its linewidth can be engineered to be very narrow by using low-loss, high-reflectivity mirrors. However, because their resonance locations depend on physical separation of the cavity mirrors, their long-term stability suffers when compared to quantum-based resonances. The degree to which the discriminator is engineered for high slope (and environmental stability) depends on the requirements of the application.

3. Limits due to frequency response

The reader should note that all aforementioned gains and spectral noise densities are (Fourier) frequency dependent. Each component in the feedback loop has a finite operating bandwidth, and understanding the combined frequency response of these elements is critical to achieving stable feedback. Basically, the requirement for stability restricts the achievable gain in a feedback system. To illustrate, imagine that each component in the loop has a frequency response that is flat (constant) until its specified -3 dB bandwidth is reached, after which the response rolls off at -6dB/octave. This decreasing amplitude response necessarily corresponds to a -90° phase lag (characteristic of an integrator). Because each loop component contributes some phase lag, a certain frequency always exists where the total accumulated phase for the closed loop signal will be -180°. At this frequency, the feedback is now positive: the applied correction signal is no longer canceling the disturbance noise but is instead *reinforcing* it. If the total loop gain at this frequency is above unity (amplifying), the system will become unstable and strongly oscillate at this frequency. The gain at this frequency needs to be reduced below unity (attenuating) for the feedback to operate in a stable manner. As an alternative to lowering the gain, stable operation can also be achieved by raising the frequency at which the oscillation occurs. For example, one of the components could be made to have a higher -3 dB corner frequency such that it introduces less phase lag.

A fundamental treatment of control theory is outside the scope of this paper, and the reader is encouraged to become familiar with the basic theory of feedback, including stability requirements and intuitive frequency response (Bode plot) design methods.[iii] Here are some general guidelines that might prove useful when designing feedback systems:

- *Use an integrator to maximize gain at low frequencies*. From the above discussion, the use of an integrator in a control system might seem undesirable because of its -90° phase lag. In fact, integral control is necessary to provide high gains at low frequencies so that the DC steady state error is reduced to zero. Proportional-only control is usually not recommended.
- *Know the bandwidth limitation of every component in the feedback loop*. Use photoreceivers and signal conditioning electronics that have operating bandwidths several times that of the transducer. The frequency response of the transducer then becomes the sole "speed" limit, which makes the loop filter compensation easier to design. (The LB1005 Servo Controller with its >10-MHz bandwidth should not be the limiting factor in most laser stabilization systems.) This guideline applies beyond electronic bandwidths: be aware of when the frequency response or time delay associated with an optical or mechanical process limits the achievable bandwidths of transducers and discriminators. For example, though a PZT has a limited frequency response associated with driving its large capacitance, mechanical resonances often place more restrictive limits on useable bandwidth.
- *Make sure the transducer has adequate dynamic range*. Although high-bandwidth transducers will allow higher closed-loop gains, they typically sacrifice tuning range. Transducers need an adequate dynamic range for correcting for the largest frequency excursions within their operating bandwidth. For instance, fast corrections to laser frequency can be made by applying feedback to the current modulation port on an ECDL, but its DC tuning range must be constrained so that large optical power changes are not experienced. Thus, current feedback is not capable of correcting large frequency excursions that occur due to thermal drift. On the other hand, a PZT can have very large dynamic range, capable of

correcting for thermal drift, but its operating bandwidth is usually many times smaller due to mechanical resonances. A strategy that overcomes this limitation employs multiple transducers in the feedback loop and is discussed in Section III.

II. Side Lock to a Doppler-broadened Gas Resonance

A relatively common laser frequency lock is the side lock, so called because it uses the side slope of an optical resonance as the frequency discriminator. The laser is passed through a gas vapor and the transmission is measured by a photoreceiver. As the laser frequency is scanned across a resonance, the gas absorbs the laser light, and the detected transmission signal has a corresponding dip where the resonance occurs. Either side of the transmission dip provides a discriminator slope for locking the laser frequency off resonance. This lock is often employed by the laser cooling and trapping community because the laser frequency can be conveniently located to the "red" side (lower wavelength) of a cycling transition for Doppler cooling.

In this setup, only the single-pass absorption is measured, and so the acetylene gas resonance used for discrimination is Doppler-broadened to a full width half-maximum (FWHM) of about 1 GHz. For laser locking purposes this provides a very low gain slope for discrimination, allowing us to lock the laser over a wide frequency range but ultimately limiting our ability to reduce the laser frequency noise. This locking scheme uses feedback to the built-in PZT of a New Focus extended cavity diode laser.

A. Laser/Transducer System

A schematic for this lock is shown in Figure 2. A New Focus TLB-6328 Velocity™ ECDL is stabilized. This laser has a tunable wavelength range of 1520—1570 nm, a typical power output of 20 mW, and consists of a laser head (fixed to an optical table) connected to a separate laser controller box. The optical output of the laser is passed through an optical isolator to prevent optical feedback into the laser. Use of an optical isolator is recommended because even very small amounts of return light (for example, from back reflections) into the laser can cause unpredictable behavior that prevents the laser from being stabilized. After passing through the isolator, the light is then coupled into a single-mode optical fiber and sent to the discriminator system.

Coarse wavelength control occurs by placing the laser in Track Mode and adjusting the Wavelength Adjust knob on the front panel. With this mode a DC motor is actively controlled to tune the wavelength in 0.01 nm steps. In this experiment, the absorption resonance was located first in Track Mode, after which the laser is placed into Ready Mode and the PZT voltage was adjusted for fine frequency control. When performing the laser frequency lock, the laser was placed in the more stable Ready Mode, as Track Mode actively tries to maintain a set wavelength as determined by the grating angle. Hence the Track Mode would compete with the LB1005 external lock mechanism.

The Frequency Modulation Input port on the rear panel of the laser controller allows external analog control of a PZT. The feedback control signal from the LB1005 is input to this port. The PZT was measured to have a dynamic range of 30 GHz, and a sensitivity (gain) of 5 MHz/mV. In our lab, the (open-loop) laser frequency was observed to drift on the order of 100 MHz/hour, depending on ambient temperature variations, so the PZT has more than enough tuning range to compensate thermal fluctuations over long time periods. (Some New Focus laser controllers have a low and a high gain setting for the PZT, which can be set by software commands. For laser locking applications, it is typically best to set the gain to the Low gain setting.)

Although the PZT can also be controlled manually from a Piezo Voltage knob on the laser controller front panel, it is more convenient to control tuning of the laser through the Sweep controls of the LB1005. The LB1005 output voltage limits were set to the input voltage limits for the Frequency Modulation Input port, and the Piezo Voltage knob on the laser controller is set to its midpoint value of about 50 V. In this manner, the laser can be tuned throughout its full piezo tuning range with the Sweep Center (Output

Offset) knob on the LB1005 front panel. To sweep the laser, the triangular output (30-100 Hz rate) from a function generator is input to the front panel Sweep In BNC of the LB1005. The amplitude of the triangle waveform corresponds to the maximum tuning range of the PZT transducer in the laser. The function generator output is also used to trigger the oscilloscope that is used to monitor the error signal. The Sweep Span knob is then adjusted for desired sweep range, and the Sweep Center (Output Offset) knob adjusts the center frequency for the sweep.

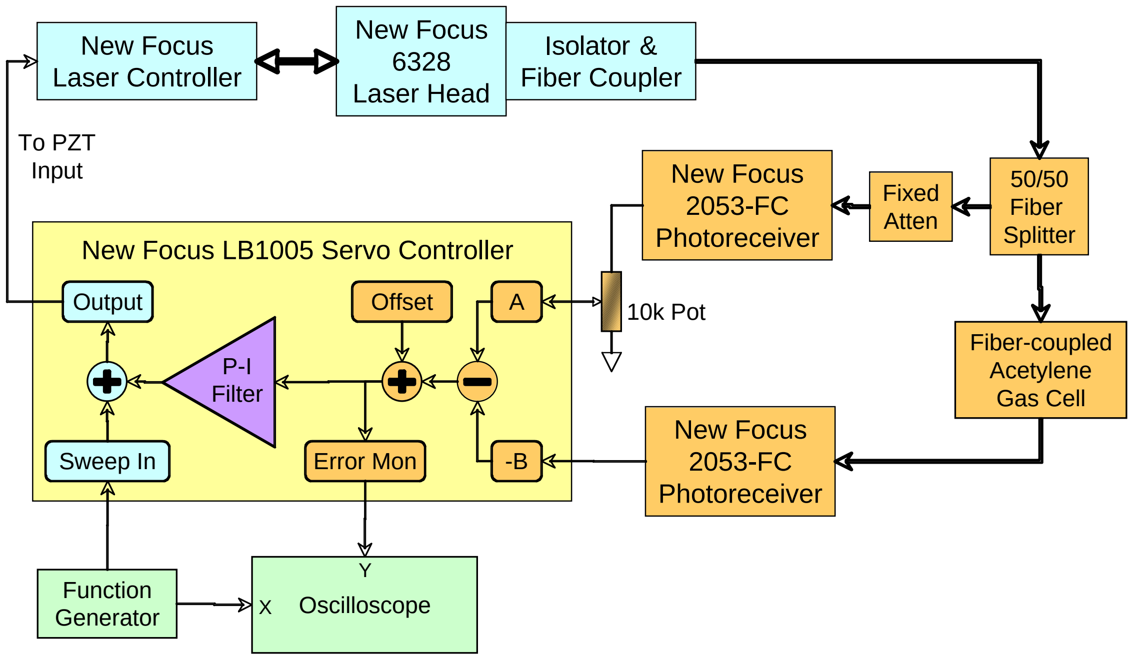

Figure 2: System for locking laser to acetylene gas resonance.

B. Frequency Discrimination System

Frequency discrimination was performed with the P19 line of the $\nu_1 + \nu_3$ band of acetylene ($^{12}C_2H_2$) gas (Figure 3: Transmission spectrum for single-pass through acetylene gas cell., which has been measured to have a center resonance of 1536.7 nm [iv]. The laser wavelength is parked on the side of this resonance such that laser frequency changes are converted to amplitude changes in the transmitted cell light, which are detected by a photoreceiver. A common systematic effect is from laser intensity noise, which mimics a real frequency change. To correct this effect, a simple subtraction scheme attempts to cancel the laser intensity noise. From the laser output, a 50/50 fiber coupler first splits the laser light. Half the light is sent to a reference photoreceiver with 10-MHz bandwidth, and the other half passes through a fiber-coupled acetylene gas cell with 50-Torr pressure. The transmission through the gas cell (~70% single pass) is measured by a photoreceiver identical to that used in the reference channel. For good common-mode rejection ratio (CMRR), both photoreceivers are set to the same gain and filter settings (DC to full bandwidth). Since there are fiber-coupling losses associated with the acetylene gas cell, a fixed optical attenuator is used to lower the reference light intensity to near that of the gas absorption signal intensity, so that both detectors could operate at the same gain setting. In our setup, the reference light intensity is slightly higher than the cell transmitted light intensity.

The goal of this detection method is to cancel the intensity noise that is common to both photoreceivers. The differential input of the LB1005 Servo Controller is used to construct the error signal. A simple 10-kΩ potentiometer divides down the voltage output of the reference photoreceiver. Depending on the desired gain sign, the reference voltage is input to either the A or –B input channel; the cell transmission voltage is input to the other channel. (Reversing these inputs changes the gain sign.) With the offset voltage set to zero (the offset voltage can be set identically to zero by setting the rear-panel Input Offset Range switch to Off), the potentiometer is adjusted to place the zero crossings for the error signal on the side of the resonance. Figure 4 shows the output from the Error Monitor. Known intervals between observable resonances in the acetylene spectra were used for calibrating the relative frequency from the oscilloscope trace. The discriminator gain is measured to be ±200 kHz/mV; the sign depends on the side of the resonance that is used. (Note that the Error Monitor output has unity gain.)

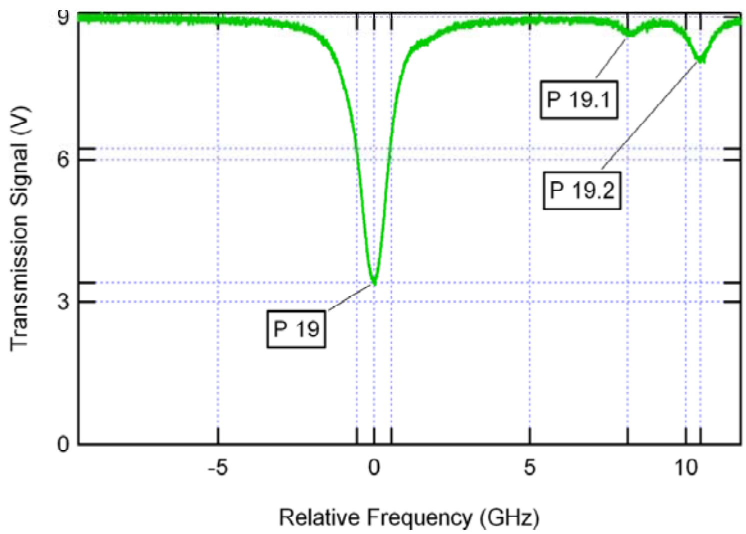

Figure 3: Transmission spectrum for single-pass through acetylene gas cell.

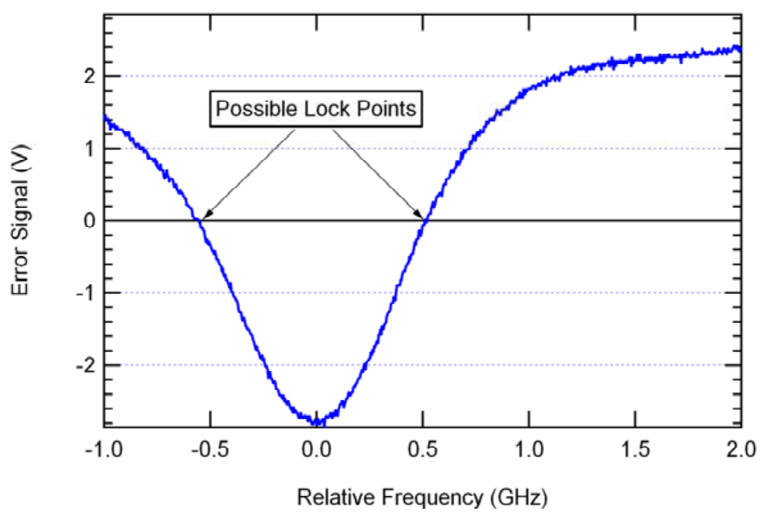

Figure 4: Error Monitor output showing two possible lock points on side of acetylene resonance.

C. Lock Performance

1. Determining the gain sign

As discussed above in Section I.B.3, having the proper phase for the control signal is critical for stable feedback. Electronics for amplifiers, filters, transducer drivers, and photodetection are often composed of both inverting and non-inverting stages, and it can be difficult to fully keep track of the total gain sign for the feedback. One way to determine the gain sign is to slowly increase the gain from zero while the laser is sweeping over the resonance, as shown in Figure 5. Here, the feedback is set to proportional-only gain (Prop. setting on LF Gain Limit switch and Acquire switch set to the middle LFGL position) and the Gain knob slowly increased until distortion on the resonance is observed. Different behaviors are observed for each slope. On one side of the resonance, the slope is increased, indicating a positive feedback condition that is unstable. In the other, a distinct decrease in the gain slope is observed, indicating a stable lock point. In this case, the negative feedback is attempting to force the error signal to zero as the laser frequency is scanned. If the desired lockpoint is the other slope, the inputs to A and –B can be switched to invert the gain sign (the input offset will also have to be inverted.)

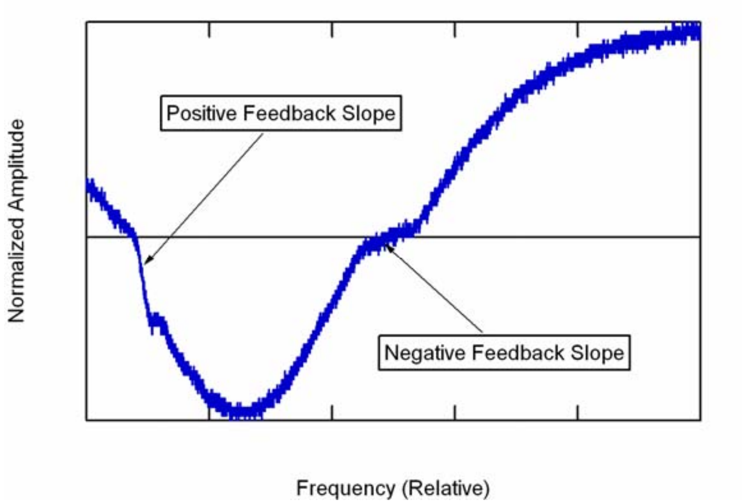

Figure 5: Applying gain while sweeping laser to determine gain signs.

2. Optimizing the Lock

The lock is acquired by narrowing the sweep span to include only the side of the transition of interest and increasing the LF Gain Limit to 20 dB or higher. While the laser frequency is sweeping, one should observe the negative feedback working to keep the error signal near zero. Turning the Sweep Span to Off and switching the Acquire switch to Lock On (full integrator) locks the laser frequency to the side of the resonance. The error signal should be flat and near zero voltage. Next, the feedback gain is increased until an oscillation is observed. The LB1005 has a large dynamic gain range (-40 to +40 dB), which is usually sufficient to obtain an oscillation. (If this is not the case, the user should consider adding more gain to the feedback system.) In this case, the PZT has such large gain that the feedback signal is actually attenuated by the LB1005.

Proportional-integral (P-I) control is a good way to compensate most systems that are limited in their bandwidth by a single isolated pole (frequency rolls of at -6 dB/octave after -3 dB corner frequency.) Placement of the P-I Corner frequency somewhere near the pole frequency location usually results in an increased unity gain frequency, and hence higher overall gain. In this case, the PZT is limited by its mechanical resonance, which is not a simple pole response, and in fact has a gain enhancement and a corresponding sign reversal at its resonance. However, for this laser, we observed the PZT response to be damped enough that there was some benefit to compensating with P-I control. Through trial and error, we found a range of P-I corner frequency settings where there was stable operation. A good way to monitor performance is by examining the error signal in the frequency domain with a Fast Fourier Transform (FFT) spectrum analyzer. With this measurement, the noise suppression can be directly measured. (Knowledge of the discriminator slope at the lock point allows one to convert the error signal voltage to the closed loop spectral density of frequency fluctuations $S_{f,Closed}$.) Setting the P-I Corner frequency to 1 kHz resulted in the highest obtainable gain. The oscillation frequency was about 1.6 kHz for this setting.

Sometimes PZT resonances can have large Q factors with significant gain enhancement at the resonant frequency. In this case, the resonance may prevent appreciable gain at DC from occurring, producing a very “loose” lock. To combat this effect, a good strategy is to try an integrator-only lock (P-I Corner to Int.), as this will better suppress any noise feedback from exciting the resonance. For very high Q factors, sometimes it is helpful to introduce into the feedback loop an additional low-pass filter that has its -3 dB corner frequency an octave or so below the resonance, so that the gain rolls off at a “faster” -12 dB/octave slope. For example, assume a strong 2-kHz PZT resonance prevents the laser from being tightly locked, i.e., the feedback system oscillates strongly at 2-kHz resonance even for very low gain settings. One strategy is to set the low-pass corner frequency of the photoreceiver to 1 kHz and use integrator-only control, thereby sharply attenuating frequencies above 1 kHz.

3. Characterizing the lock performance

Since the bandwidth of the PZT on New Focus lasers is between 2—4 kHz, higher Fourier frequency contributions to the laser noise from acoustic disturbances and injection current noise will not be suppressed, and significant narrowing of the laser linewidth should not be expected. With the known discriminator slope, voltage fluctuations on the error signal can be mapped to optical frequency fluctuations. Figure 6 shows two locked error signals. One trace shows the error signal for a proportional-only lock. A better lock is obtained with P-I control, which is shown by the other trace. Converting the oscilloscope trace to frequency deviations, the rms of frequency fluctuations $\Delta\nu_{rms}$ for P-I control is measured to be 630 kHz. For proportional control, it is significantly worse at 2.1 MHz.

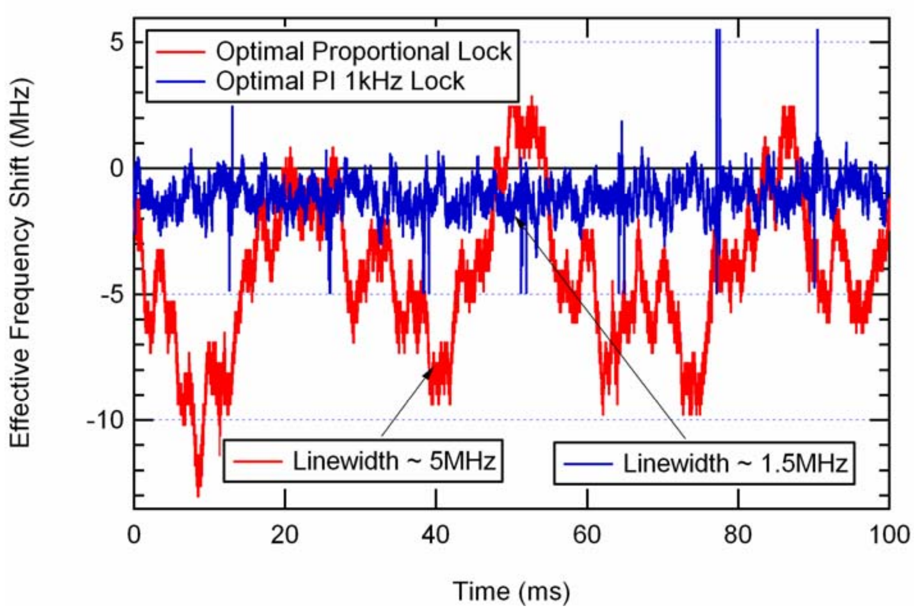

Figure 6: Oscilloscope traces of locked error signals. Red trace, proportional-only control. Blue trace, P-I control. Linewidths are estimates calculated in the limit that large frequency excursions are dominant, which produces a Gaussian optical lineshape given by $\Delta\nu_{FWHM} = 2.355\Delta\nu_{rms}$.[v]

III. Side lock to a Sub-Doppler Gas Resonance

With feedback to the PZT, a closed-loop bandwidth is limited to only a few kHz, and disturbance rejection beyond this frequency limit is not possible. For instance, acoustic noise is typically present in the laser environment at higher Fourier frequencies. The PZT will not be able to correct this noise, and for large disturbances (e.g., a lab mate with a particularly stentorian speaking voice!), the laser may be prone to unlocking. Feedback to the diode laser injection current offers a possible method for applying frequency corrections at substantially higher speeds. For instance, the current modulation bandwidth of New Focus ECDL's is 1 MHz, which should allow for large feedback gain at acoustic frequencies and beyond. However, now we must contend with the corresponding optical power changes that simultaneously occur when the diode laser current is modulated. One consequence is that the tuning range should be limited so that large power fluctuations are not incurred. Another is that the discriminator needs to have high rejection of any amplitude-modulated (AM) noise that arises from feedback to the current.

In this stabilization scheme, shown in Figure 7, the tuning range limitation of the diode current is overcome by also providing feedback to the PZT. In effect, fast corrections are made by feedback to the diode current, while the slowest corrections (presumably with the largest frequency excursions) are handled by the PZT. To obtain a steeper discriminator slope, saturation spectroscopy probes more narrow sub-Doppler resonance features. The combination of a larger closed-loop bandwidth and a higher slope discriminator should allow laser frequency stabilization to better precision and accuracy than the locking scheme developed in Section II.

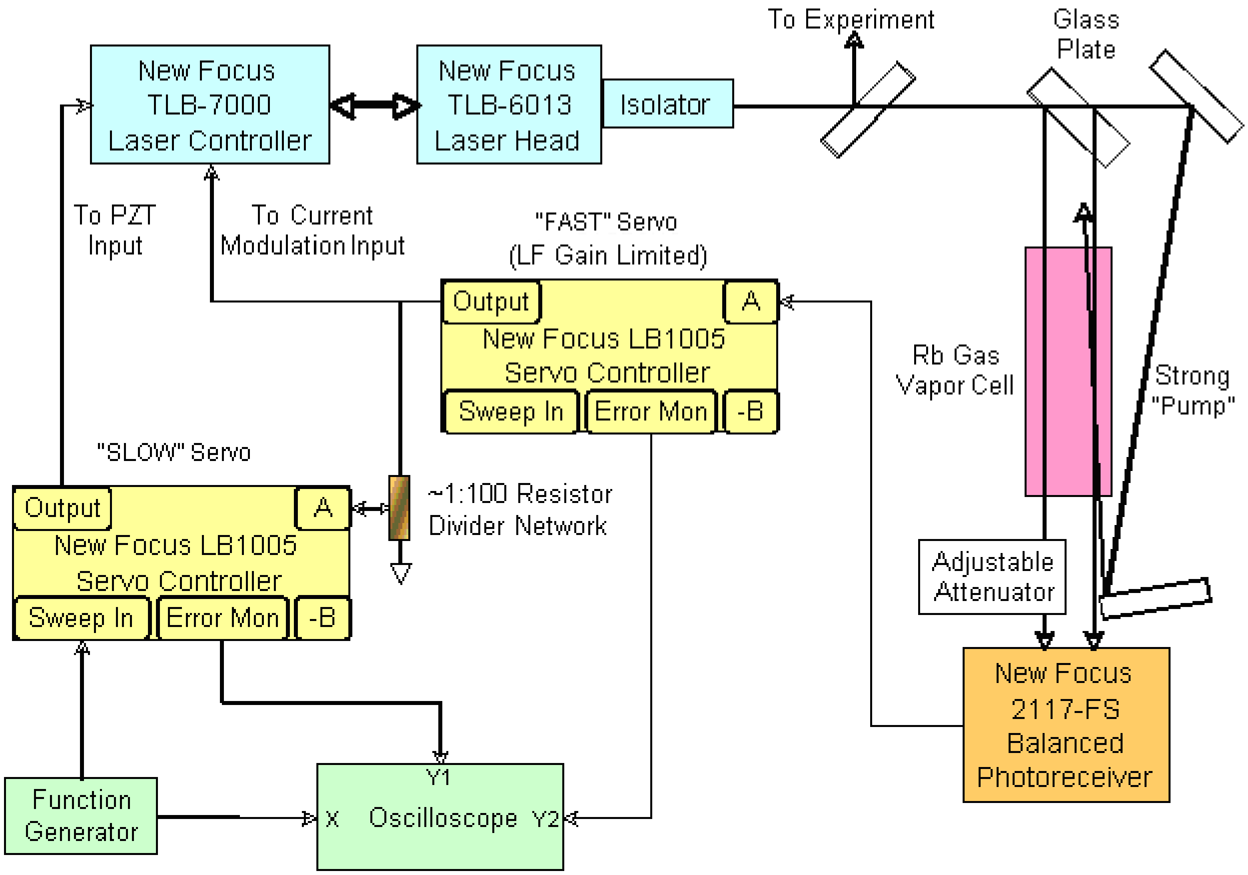

Figure 7: Laser stabilization to sub-Doppler Rb resonance with dual PZT/current feedback.

A. Laser System

A New Focus TLB-6013 Vortex™ laser is stabilized to one of the hyperfine transitions of the rubidium (Rb) D2 transition near 780 nm. The output light from the laser is first passed through an optical isolator. The free-space output light is then picked off by a beamsplitter that sends a majority of the light to the experiment. The small, transmitted portion (<10% total power) from the splitter is sent to the Rb spectrometer, which is described in the next section. A New Focus TLB-7000 Laser Controller is connected to the TLB-6013 laser head. This controller has a DC-coupled Frequency Modulation input for coarse frequency tuning by the PZT, as well as a DC-coupled Current Modulation port for fine-tuning the frequency with the diode injection current. Each of these input ports is controlled by the signal from the Output port of a LB1005.

The full tuning range for the PZT is 75 GHz with a specified (small) signal bandwidth of 3.5 kHz. Best performance is obtained by reducing the PZT gain from 25 (default) to 1 by software control (see laser manual). The LB1005 output voltage limits are set to the PZT maximum input voltage of ±2.25 V. At the Low gain setting, the PZT could electrically tune the optical frequency about 3 GHz, which is sufficient for compensating thermal drift over several hours. As discussed in Section II.A, a function generator is used to configure the LB1005 for scanning the PZT. To locate the Rb resonances, coarse tuning of the PZT is performed with the Laser Controller front panel adjustment knob. To acquire lock, the LB1005 Sweep Center and Sweep Span knobs fine-tune and sweep the PZT, respectively.

The Current Modulation port of the Laser Controller (rather than the High-Speed Current Modulation input on the Laser Head) is used for feedback to the diode current. This input has a specified bandwidth of 1 MHz, a transimpedance gain of 0.2 mA/V, and maximum input voltage of ±10V. The bias current for the diode was set to near its maximum (see Acceptance Test Data Sheet; make sure to account for current swing from modulation input), where the laser was found to have the least amount of frequency noise. Note that the laser should be operated in constant current mode, not constant power mode.

B. Rubidium Spectrometer

Frequency discrimination is achieved with a Rb spectrometer configured for saturation spectroscopy[vi,vii], which allows narrow sub-Doppler resonances (on the order of the natural linewidth) to be obtained. Additionally, balanced detection is used to cancel laser intensity noise and the Doppler-broadened background absorption. Light passes through an uncoated 3º wedge (New Focus 5801.) The two Fresnel reflections of near-equal intensity form the probe beams and pass through a Rb gas vapor cell. (These beams should have intensities less than the saturation intensity to avoid saturation broadening.) The transmitted remainder of the light comprises the saturating pump beam and is directed with steering mirrors to be near counter-propagating with one of the probe beams.

A New Focus 2117-FS Balanced Photoreceiver, set to its maximum bandwidth of 10 MHz, detects the vapor cell transmission for each of the two probe beams. With balanced detection, the photocurrents from each of the diodes are directly subtracted with a high common-mode rejection ratio. An adjustable (gradient) neutral density filter attenuates one of the probe beams so that equal optical powers are measured by each photoreceiver. (The pump beam can be blocked, and the attenuator adjusted to null the photoreceiver output.) Under this condition, power variations common to each beam are subtracted, and only the power imbalance due to the pump beam is detected. As discussed in Section II.B, the side slopes of the resonances are used as optical frequency discriminators. The voltage output from the photoreceiver is input to an LB1005, which adds an appropriate voltage offset for locking to the side of the sub-Doppler resonance, and the derived error signal is observed on the LB1005 Error Monitor output.

C. Feedback Strategy

In this locking scheme, two feedback loops are utilized, each controlled by an LB1005. Most of the heavy lifting is performed by the first feedback loop that makes fast frequency corrections via the diode current. In an effort to raise the feedback bandwidth, the P-I Corner frequency for this fast loop is set to 1 MHz to roughly match the -3 dB corner frequency of the laser's current modulation port. Since the goal is to have low frequency corrections made by the PZT, the gain of the fast loop is limited by setting the Acquire switch to LFGL; the Lock On (full integrator) position is not used. With the LF Gain Limit knob set to 60 dB, the loop filter gain becomes flat (constant) below 1 kHz. The PZT feedback can now be organized to have more gain than the current feedback for low frequencies. These values for the P-I Corner and LF Gain Limit are reasonable starting points, and it is expected that various laser systems will have slightly different values that optimize lock performance.

To better understand the function of the second "slow" loop, it is instructional to lock the laser using only the fast loop. For this system, the current modulation input has just enough dynamic range that the fast loop can usually maintain lock for a few minutes. One observes that the control signal drifts towards one of its voltage rails, probably in response to small temperature changes in the laser cavity. A method for applying a cavity length correction is desired such that the current modulation voltage stays centered at its operating midpoint (zero voltage, in this case.) Careful adjustment of the Sweep Center (Output Offset) knob of the "slow" LB1005 controller should convince one that the PZT could perform this duty. Thus, the function of the PZT feedback loop is to force the DC operating point for the current modulation to zero volts. The control signal from the fast loop becomes the error input to the slow loop. The PZT sensitivity is usually much larger than for current modulation, and so a simple voltage divider attenuates the fast loop control signal. Integrator-only feedback is used for this loop, so that the PZT gain rolls off quickly at high frequencies to avoid exciting any resonances. Note that one must account for the filter transfer function of the fast loop (including its gain sign) when determining the closed-loop frequency response of the slow loop.

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