

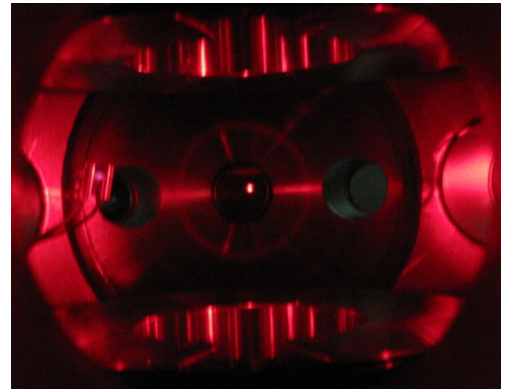
## Diode Laser Control Electronics

# Diode Laser Locking and Linewidth Narrowing

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### Introduction

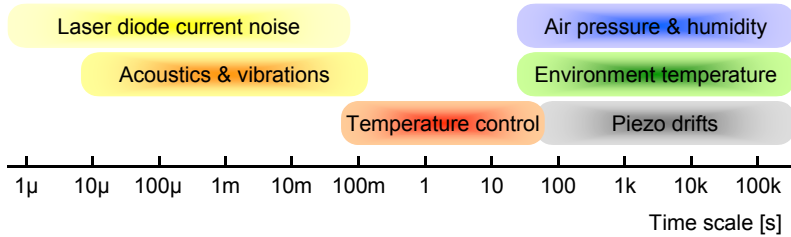
Stabilized diode lasers are well established tools for many scientific and industrial applications. Spectroscopy, atom/ion trapping and cooling, Bose-Einstein condensates, interferometry, Raman spectroscopy and microscopy – to name only a few – are all based upon such lasers. The frequency stabilization of laser diodes is possible with wavelength selective feedback, for example in external cavities (ECDLs) or with gratings written into the semiconductor (DFB/DBR diodes). The result is a laser linewidth in the MHz range with drifts in the 10s of MHz to GHz range. While this already is a narrow linewidth and small drift, some applications are even more demanding. Laser locking can completely eliminate laser drifts and with modern locking electronics, linewidths of diode lasers in the kHz range and even below one Hz are possible. This article introduces some basics on frequency stabilization and linewidth measurement in the box below. It gives a short introduction into feedback control loops, and explains common laser locking schemes and techniques. A comparison of available hardware follows and leads to a discussion of digital locking and a description of the DigiLock 110, the first Feedback Controlyzer. The article ends with application examples.



**Fig. 2:** Lithium (Li) Magneto-Optical trap (MOT): To trap the Li atoms in the small cloud in the middle of the trap, the 671 nm laser has to stay resonant with an atomic transition. This can only be achieved, if the laser frequency is stabilized, or locked (picture courtesy of Jochen Steinmann, MPI Heidelberg).

### Basics: Frequency measurement, linewidth and drift

To better understand demands and specifications, it is important to clarify the connection between laser frequency measurement, linewidth and drift. If one measures the spectrum of a laser, this measurement is done in a certain time. Processes that influence the laser frequency within this measuring time will broaden the spectrum or the *linewidth* of the laser, while processes slower than the measurement will cause the measured spectrum to *drift* between measurements. Typical timescales for laser frequency measurements lie between microseconds and seconds. The difference between drift and linewidth therefore depends on the timescale of the measurement. Typically faster processes like laser current noise, vibrations and acoustic noise add to the linewidth, while temperature and air pressure changes cause drifts. If the measurement is done on short time scales ( $\mu\text{s}$ , i.e. very quickly), the acoustic noise and vibrations will not show in the linewidth measurement, but contribute to the variation of successive measurements. Therefore, linewidth specifications only make sense with a corresponding time scale. Main noise sources that contribute to linewidth and drift and their characteristic time scales are shown in Fig. 1.



**Fig. 1:** Main causes for frequency fluctuations of diode lasers and their respective time scales.

### Feedback control loops

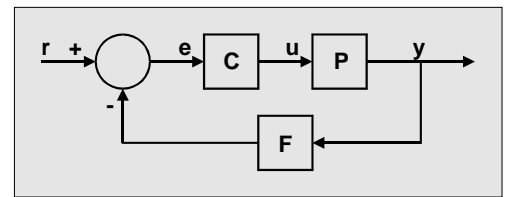
In today's world, feedback control loops are widely used. Apparent examples are thermostats for room or water temperature regulation, and cruise control in cars. They are used for stabilizing certain parameters like temperature or speed. In such systems, the output of the system  $y(t)$  is fed back through a sensor measurement  $F$  to the reference value  $r(t)$ . The controller  $C$  then takes the error  $e$  (difference) between the reference and the output to change the inputs  $u$  to the system under control  $P$ . The schematic diagram is shown in Fig. 3. Depicted is a single-input-single-output control system.

In most cases, the error is fed to the system through a PID (proportional-integral-derivative) controller. The PID controller takes the error signal and optimizes the feedback for the system to reach its set point as fast as possible. For more information on PID controllers, please see [http://en.wikipedia.org/wiki/PID\\_controller](http://en.wikipedia.org/wiki/PID_controller).

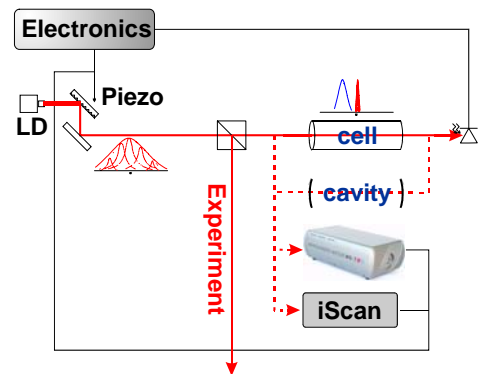
### Laser locking

In order to stabilize a laser's frequency, the frequency must be measured and frequency changes need to be detected, so that they can be corrected. The general setup for stabilizing a laser's frequency is shown in Fig. 4. On the bottom right various references or frequency discriminators are shown. Some of these have built in electronics that can feed directly back to the laser, others like the cell and cavity utilize specialized locking electronics as described later in this article. The measurement of the references is compared with the set value, and the electronics drive the laser frequency back towards the set value.

A direct way of measuring frequencies or wavelengths is to use wavelength meters: Wavelength meters like the HighFinesse WS series are available with accuracies down to 10 or even 2 MHz, and if this is sufficient, they can be used to feed back to the laser: The control software measures the laser frequency and addresses the laser with a control voltage in order to keep the wavelength at the set value. Using a wavelength meter for compensating drift has the advantage, that the wavelength can be set to any value within the measurement range of the wavelength meter and does not require a natural absorption line. The locking bandwidth is limited



**Fig. 3:** Feedback control loop. The output of the system  $y(t)$  is fed back through a sensor measurement  $F$  to the reference value  $r(t)$ . The controller  $C$  then takes the error  $e$  (difference) between the reference and the output to change the inputs  $u$  to the system under control  $P$ .



**Fig. 4:** General laser frequency locking setup. Some references like the iScan and wavelength meter can include locking electronics, others are combined with TOPTICA's selection of locking electronics as described in Table 1.

however by the measuring time of the instrument (few ms), and is therefore very low. Other references are atomic absorption lines or optical resonator modes:

Atomic transitions can have very well defined optical frequencies and can be largely independent of the surroundings, while cavities do normally drift. However, special ULE (ultra low expansion) cavities can show drifts below 50 Hz in several hours<sup>1</sup>.

A stabilized laser naturally has a fixed frequency. If the laser frequency needs to be scanned relative to a fixed frequency, acousto-optic modulators (AOMs) can be utilized – or if the reference is a scanning FPI, the reference itself can be scanned.

### Diode laser frequency control

For ECDLs, slow feedback to the laser can be applied via the laser's Piezo, for DFB based lasers via the diode temperature. Both change the wavelength by changing the optical cavity length. Piezos generally have resonance frequencies that can limit the regulation bandwidth. While conventional ECDLs have resonance frequencies around 1 kHz, modern ones like TOPTICA's DL pro show their first resonance frequency above 4 kHz, allowing for higher locking bandwidths with the Piezo. For even faster frequency deviations, the diode current can be changed. This has an influence on the index of refraction in the diode, and therefore again on the optical cavity length of the laser. TOPTICA's diode laser systems are available with a current modulation board, DL-Mod, that is designed for this purpose. It features a DC coupled and a very fast AC coupled modulation input. The very fast input can be used to put side bands on the laser (see Pound-Drever-Hall locking below), while the DC coupled input is ideally suited for feeding back on the laser current.

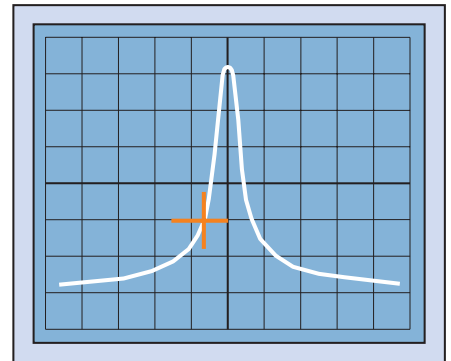
### Side-of-fringe locking

Classically, optical absorption lines of atomic gases or modes of cavities are utilized to detect frequency changes. They translate a frequency change into an intensity change, when the laser frequency lies on a slope of such an absorption or transmission. A frequency dependent intensity can be detected with a photo detector, and the photo detector output voltage can be used for comparison with a reference voltage. As the laser frequency lies on a slope, the frequency can thus be locked *side-of-fringe* to an absorption line or cavity transmission (see Fig. 5).

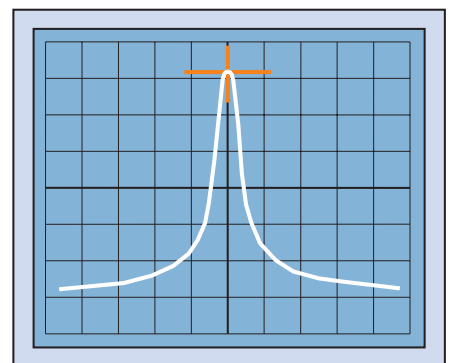
The absolute stability with side-of-fringe locking often depends on the laser intensity. Even with normalizing setups, the absolute frequency for a given set voltage can change, as it also depends on the linewidth of the reference feature and on background noise.

### Top-of-fringe locking, Lock-In technique

If the laser must stay "on top" of a resonance (Fig. 6), it is not obvious from the intensity measurement in which direction the frequency has changed, since the measured voltage decreases in both directions. In this case, a modulation or Lock-In technique



**Fig. 5:** Side-of-fringe lock. A cavity transmission translates frequency changes into intensity changes. These can be used to feed back to the laser to keep it (lock it) on the side of the cavity fringe.



**Fig. 6:** Top-of-fringe lock. To keep the laser on the top or bottom of a fringe modulation techniques must be used.

must be used:

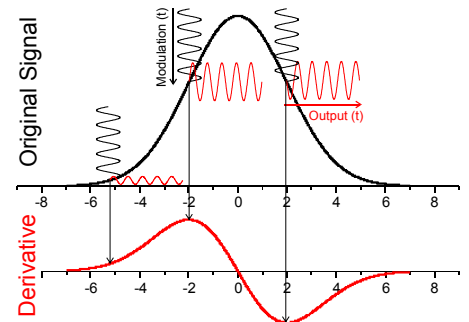
By slightly modulating the laser frequency and demodulating (multiplying) the photo diode signal with the modulation input, the derivative of the input signal can be obtained. It shows a continuous slope and a zero crossing at the resonance frequency and is well suited as an error signal for locking (see Fig. 7). This is hard to grasp without looking at the mathematics behind it, but by looking at the sign of the output in Fig. 7, it is obvious, that it is opposite on the left and right of the absorption line – and on top of the resonance the amplitude should approach zero. The demodulation makes this visible, and the result is shown in the bottom of the figure.

### Top-of-fringe locking, Pound-Drever-Hall

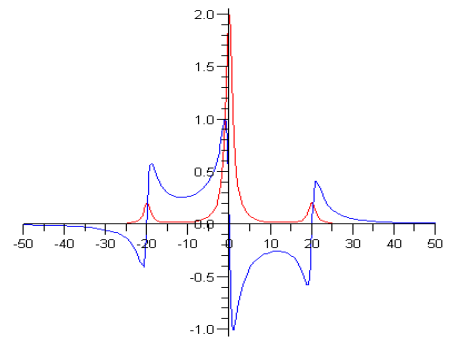
The Pound-Drever-Hall locking technique is very similar, only that it uses much higher modulation frequencies. It is most often used to lock to cavities. If the modulation frequency is higher than the laser and cavity linewidth, the cavity reflection and transmission show side bands at the modulation frequency. The derived error signal for top-of-fringe locking has an improved capture range that spans from one side band to the other and it features a very steep slope with zero crossing at the frequency, where the cavity transmission shows the maximum (see Fig. 8). In Fig. 9 the Pound-Drever-Hall error signal for different modulation frequencies is depicted. The largest and steepest error signal is achieved with a modulation frequency in the range of the cavity linewidth. Larger modulation frequencies result in a wider capture range, as the side bands move away from the carrier, and also to higher locking bandwidths, because obviously, the locking bandwidth is limited by the modulation frequency.

### Linewidth reduction

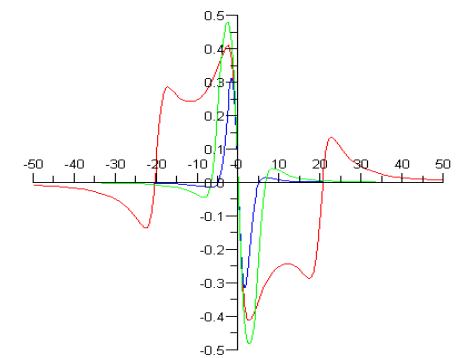
If the laser's linewidth limits the resolution or precision of a measurement, the linewidth can often be reduced for higher resolution measurements. In this case, a fast lock is required for eliminating frequency fluctuations that are faster than the measurement or experiment and that therefore add to the laser's linewidth (see page 1). One can assess the frequency noise spectrum of the processes that widen the linewidth by tuning the laser to the side of an etalon fringe or atomic resonance and measuring the noise spectrum of the resulting amplitude noise. In the side-of-fringe locking approach, linewidth reduction can be accomplished by TOPTICA's FALC 110, a fast PID regulator (FALC = Fast Analog Linewidth Control). It is optimized for such applications and features a signal delay time of less than 15 ns. In addition to fast locking electronics, also the linewidth measurement or frequency discriminator has to be fast. If a fast top-of-fringe lock is required, the modulation frequency has to be high enough, as the locking bandwidth is limited by the modulation frequency. Therefore normally Pound-Drever-Hall locking is used. TOPTICA is developing a version of the Pound-



**Fig. 7:** Modulation (Lock-In) technique for *top-of-fringe* locking. Note the sign and amplitude of the output oscillation: by demodulation, this information results in the derivative of the original signal. The derivative features a zero crossing with a steep slope at the maximum of the original signal.



**Fig. 8:** Cavity transmission with side bands (red) and Pound-Drever-Hall error signal (blue). The error signal shows a steep slope with zero crossing at the transmission maximum.



**Fig. 9:** Pound-Drever-Hall error signal for different modulation frequencies. The cavity linewidth in this calculation was 5 MHz, the modulation frequency 20 MHz (red), 5 MHz (green), and 2.5 MHz (blue).

Drever-Hall detector that is optimized for small signal delays and linewidth reduction. As a frequency reference, the reflection off a Fabry-Perot cavity is ideally suited: It quickly responds to laser frequency changes, has a good signal/noise ratio and a steep slope at the resonance frequency. A linewidth narrowing setup with Pound-Drever-Hall technique utilizing an FPI as a reference is shown in Fig. 10.

By locking two DL pro to different modes of one common FPI 100 with either FALC 110 or DigiLock 110, TOPTICA was able to demonstrate beat widths of less than 300 Hz (see Fig. 11). As both lasers contribute to this beat width, the linewidth of the identical lasers was about 150 Hz (i.e. half as large, assuming Lorentzian line shapes).

Janis Alnis at MPQ in Garching, a customer of TOPTICA Photonics, has managed to achieve Sub-Hz linewidths over 8 s with TOPTICA's FALC 110, locking two diode lasers to individual super high-finesse ULE cavities<sup>1</sup>. For such stabilities the frequency deviations of the lasers are mainly given by the stability of the reference cavities.

### TOPTICA locking electronics & references

TOPTICA Photonics offers a wide range of locking electronics that covers almost any locking demand. Table 1 contains a list of readily available electronics with its main characteristics and differences.

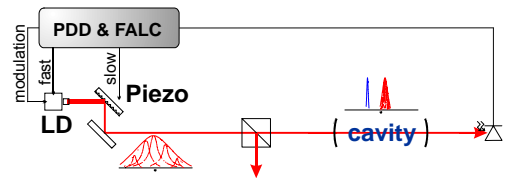
The **PID 110** is a general purpose PID controller, that is not only used for stabilizing lasers. It features HV output for direct Piezo driving and some relock logic for comfortable and reliable locking. The **LIR 110** is a flexible Lock-In regulator, that is ideally suited for locking onto absorption lines etc. It is mainly used for drift compensation and also offers HV output for Piezos.

The **PDD 110** is a Pound-Drever-Hall detector: it includes a high frequency generator, a phase shifter for the local oscillator, a demodulator and filters. It generates a derivative error signal for top-of-fringe locking and together with either PID 110 or FALC 110 it is ideally suited for locking diode lasers to optical cavities.

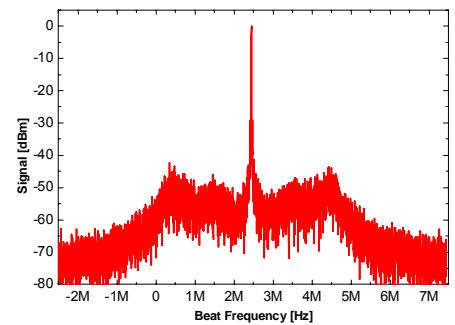
The **FALC 110** is an extremely fast PID controller with signal delay times of less than 15ns. It is specifically designed for stabilizing and linewidth narrowing of diode lasers. Flexible corner frequencies, gains, and multiple integrators allow optimized feedback to the laser current for higher frequency corrections and to the Piezo or temperature for drift compensation.

The **LaseLock** is a general purpose, stand-alone locking solution, that is also suited for third-party lasers. It combines the functionality of PID and LIR.

Both the HighFinesse **wavelength meter** series and TOPTICA's iScan include locking electronics with a reference. A wavelength meter determines the absolute wavelength by analyzing a number of interferometers. It compares the actual number with the set value and computes an output signal to correct the laser frequency utilizing a PID controller (bandwidth  $\approx$  100 Hz).



**Fig. 10:** Experimental setup for narrowing the linewidth of a single frequency diode laser.



**Fig. 11:** Beat spectrum of two DL pro, locked to one FPI 100. The beat width is 284 Hz (FWHM, sweep time 100 ms).

The **iScan** is a system based on low finesse etalons that allows stabilizing the laser at any wavelength with an accuracy in the several MHz range. It can also be used to make very linear wavelength scans and well defined, quick frequency jumps. Unless it is calibrated against an absolute reference, the iScan is used for relative stabilization, scanning and jumping. The iScan also utilizes built-in PID electronics. It is a lot faster than the wavelength meters and can address not only the laser's Piezo or temperature, but can also make use of the higher bandwidth of laser diode current modulation.

A very helpful tool for absolute frequency stabilization to atomic resonances is the **CoSy**, a compact spectroscopy unit (see figure Fig. 12). The fiber coupled unit holds a gas cell, with Rubidium or Cesium for example. The input beam is split into several beams and detected by a number of photo diodes to give normalized Doppler-free and Doppler-broadened absorption signals. These can then be used by the locking electronics described above to stabilize the laser frequency. Top-of-fringe locking is also supported – however the CoSy bandwidth is limited to 50 kHz .. 1 MHz (gain dependent), and high frequency modulation cannot be detected. A 5 MHz CoSy version is available upon request.



**Fig. 12:** CoSy, a compact spectroscopy unit, that readily gives normalized Doppler-free and Doppler-broadened absorption signals of atomic Rb or Cs.

	PID 110	LIR 110	PDD 110	FALC 110	DigiLock 110	LaseLock	Wavelength Meter	Iscan
Description / Type			Pound-Drever-Hall Signal Generation	Fast Analog 2-Channel PID	Versatile Digital Locking Solution	Suited for third party lasers	Wavelength meter with PID option	Low finesse etalons as reference with Lock-Electronics
Side-of-fringe	✓			✓	✓	✓	not applicable	
Top-of-fringe	With PDD	✓	✓	With PDD	✓	✓	not applicable	
Locking bandwidth*	kHz .. MHz	kHz range		≈ 10 MHz	≈ 10 MHz	1 MHz	< 100 Hz	kHz range
Modulation frequency		0.6 Hz .. 14 kHz	20 MHz **		17 Hz .. 25 MHz	33 Hz .. 1 MHz	not applicable	
Accuracy	depends on reference (can be very good)						> 10 MHz	1 MHz (relative)
Signal analysis					✓			
Relock mechanisms	✓	✓			✓	✓		✓
Computer control					✓		✓	✓
High voltage output	✓	✓				✓		✓
High bandwidth output				✓	✓			
Two channel version			✓					
SYS DC 110 module	✓	✓	✓	✓	✓			
Stand-alone						✓	✓	✓
Catalog page	35	36	36	35	37	40	55	42
	low budget		high end & preferable					

\*Estimated bandwidth depends on gain and PID settings \*\*5- 40 MHz versions available

Table 1: Overview of TOPTICA's locking electronics.

## Digital locking with DigiLock 110

Recently, TOPTICA Photonics has introduced a completely new locking solution: the **DigiLock 110**, a digital Feedback “Controlizer”. It combines all the functions of various locking modules in one single unit. It offers computer control of laser parameters, laser frequency scans and locking parameters. It includes multiple PIDs, a Lock-In regulator, and a Pound-Drever-Hall detector. It is a digital locking solution that takes advantage of digital filtering techniques and gain-independent signal delay times. It helps the user with AutoLock, “Click & Lock” and relock features. And in addition to all this, it also offers a multitude of tools for analyzing error signals (spectrum analysis), frequency actuators (network analysis) and regulator parameters (regulator simulation). While being flexible, it is also fast: It is based on a 100 MHz field programmable gate array (FPGA) and high quality DA/AD converters that go up to 21 bit precision and clock speeds up to 100 MHz. The overall delay time in the module is less than 200 ns, enabling digital locking bandwidths in the multiple MHz range. And an analog bypass that is controlled by the FPGA enables even higher locking bandwidths e.g. for linewidth narrowing. The DigiLock 110 combines ease of use with flexibility and speed and is therefore ideally suited for most locking applications. The DigiLock module is shown in Fig. 13, and the Software interface in Fig. 14.

## Applications

One major application for stabilized diode lasers is laser cooling and trapping of atoms and ions. Often the optical transitions used for doing so, are as narrow as a few MHz, and the laser must stay resonant with a transition for long times. For this purpose, lasers are directly locked to these transitions to eliminate drift.

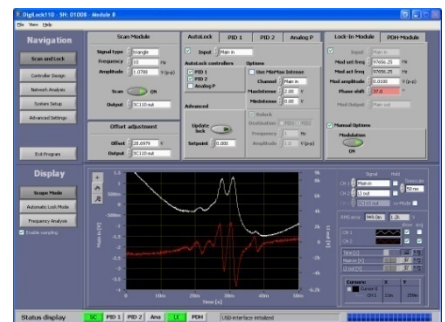
Fig. 15 shows a Doppler-free Rubidium spectrum taken with a combination of TOPTICA’s DL pro diode laser, a compact spectroscopy unit CoSy, and the DigiLock 110 locking electronics and software.

Quantum optics and quantum computing are becoming more and more important. Often, such experiments are done with lasers, atoms and ions, and the lasers need to be locked during an experiment to stay resonant with a specific transition of the atom or ion. Only then can the lasers be used to modify and probe quantum states in a reliable way.

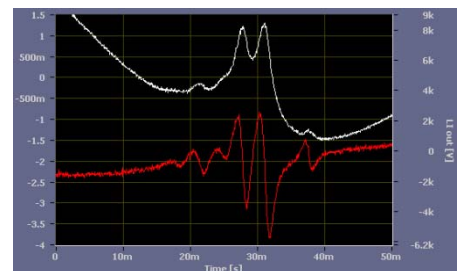
For TOPTICA, the most important application is to lock enhancement cavities to diode lasers for second harmonic generation (SHG). SHG is done in nonlinear crystals, and the process is a lot more efficient with higher powers. Enhancement cavities can produce much higher intra-cavity powers, that lead to increased second harmonic output powers if the crystal is placed inside the cavity. The enhancement does only work however, if the cavity stays resonant with the laser. So the cavity length has to be



**Fig. 13:** DigiLock 110 – the Feedback Controlizer – the most versatile laser locking solution.



**Fig. 14:** DigiLock 110 graphical user interface. The module does all the locking internally. The computer interface is used for control and analysis.



**Fig. 15:** Doppler-free absorption spectrum of Rb. White trace: Rb transmission, red trace: derivative obtained with Lock-In technique.

stabilized. Here, the Pound-Drever-Hall method is the best: it offers high locking bandwidth and an increased capture range. Based on this technology, TOPTICA has built numerous laser systems for exotic wavelengths, that could otherwise not have been reached – not only SHG systems, but also fourth harmonic and sum frequency generation systems.

No matter what your laser locking needs are, please contact TOPTICA Photonics. We offer a wide range of locking electronics and tools, and look forward to supporting you with your specific stabilization requirements.

Literature:

- <sup>1</sup>J. Alnis, A. Matveev, N. Kolachevsky, Th. Udem, and T.W. Hänsch, Physical Review A 77, 053809 (2008).
- John L. Hall, Matthew S. Taubman, and Jun Ye, "Laser Stabilization", OSA Handbook v14, 1999
- [http://en.wikipedia.org/wiki/PID\\_controller](http://en.wikipedia.org/wiki/PID_controller)
- Scientific Lasers Catalog, TOPTICA Photonics AG, <http://www.toptica.com/>



**Fig. 16:** TOPTICA's DL-SHG 110 module: by locking the resonator of the SHG 110 module to the diode laser, and therefore resonantly enhancing the fundamental light, 5 mW @ 614 nm could be generated from 12 mW @ 1028 nm.