General comments on Frequency Locking of the DL 100

1. Introduction

When using tunable diode lasers, in particular when built with extended cavities like inside the DL 100, there are multiple ways to stabilize the laser output with respect to an external reference. When deciding which technique to use, one should try to weigh the effort against the wanted result. The DL 100 has a fast line width (µs) in the few 100 kHz range, however due to technical noise it is broadened to about 1 to 2 MHz in the ms range, where usually line width of a laser is given. For longer time scales changes in wavelength are usually referred as drifts or more precisely as long-term drifts. The ideal laser source would be as narrow-band as possible, for as long a period of time possible and would not start to drift in its center frequency in time.

The external reference can be either a relative frequency reference, like an Etalon or a Fabry-Perot-Interferometer, or well-known atomic or molecular lines. In a standard application the tunable laser output will be passed through a spectroscopy unit where the frequency of this light is spectrally analyzed. Most commonly people use single pass absorption or saturated absorption, or more sophisticated, polarization spectroscopy to generate a suitable error signal that is then fed back into the laser tuning control input. Another very common technique to lock a diode laser is the RF sideband modulation technique described first by Pound and then realized in the optical domain by Drever and Hall (Pound-Drever-Hall method).

2. Changing the laser frequency of the DL 100

The laser head DL 100 provides three means to change its output frequency:

1. DC driving temperature
2. DC driving current
3. Piezo voltage, controlling the grating angle in the ECDL.

While the first is impractical in most cases, the following two are used. It is important to realize that they differ dramatically in bandwidth: in practice this leads to the situation that low speed electronic feedback is fed to the grating piezo (3) using frequencies from DC close to the first mechanical resonance of the extended cavity (few kHz range), while for faster electronic feedback, the driving current can be quickly changed, adding a variable AC component to the driving current of the laser diode.

When using a relative reference, like a high finesse FPI, the laser line can be narrowed if a fast feedback loop is used, however the absolute stability of the laser is as good as the stability of the reference. Of course one can add an additional stabilization circuit to stabilize (or lock) the relative reference to an absolute or at least better long-term reference. This can make sense if either there is no absolute reference available close to the wanted emission frequency or when using an absolute reference the preparation of a sharp error signal is not possible. The relative reference will be used as a transfer reference to shift the wavelength of the atomic reference to the wavelength of interest.

3. Different Tools for Locking provided by TOPTICA Photonics

3.1 General

TOPTICA Photonics provides three modules LIR 100, PID 100 and PDD 100, that make three different locking schemes possible. These schemes have different advantages and also different costs. The simplest set-up can be achieved with the PID 100 and an external frequency reference.

The PID 100 is a proportional (P), integrative (I) and derivative (D) action controller that processes the error signal of the laser frequency and then amplifies it to the power level of the frequency determining element. These elements are the grating angle via piezoelectric actuator and the laser diode current via feed forward, via BIAS-T or via FET CURRENT CONTROL.

The LIR 100 performs a phase sensitive measurement (Lock-In technique) of the external frequency reference using a built-in modulation source. It has implemented a PID regulator that uses the Lock-In output signal as laser frequency error input. The module output then usually drives the grating angle via the piezoelectric actuator and the laser diode current via the feed forward from the scan controller module SC 100 to the diode current controller module DCC 100.

The PDD 100 also performs a phase sensitive measurement, but due to the modulation frequency of 10 MHz provided by an internal local oscillator it is not called Lock-In measurement, but this set-up usually is described in the frequency regime (carrier frequency and sidebands) and it is called Pound-Drever-Hall-lock. The PDD 100 needs the BIAS-T option (only possible with the DL 100 L) and the PID 100 controller. In addition, it is strongly recommended to use the FET CURRENT CONTROL so that the control loop comprises the frequencies above the piezo bandwidth. Using this setup, the low frequency regulations affect the laser frequency via the grating angle and the feed forward. The fast regulations directly affect the laser frequency via the laser diode current that itself is changed by the FET CURRENT CONTROL.

3.2 Advantages of Locking schemes using the different modules

Set-up	Regulation Bandwidth	Line width enhancement	Top of Fringe
LIR 100	max. 7kHz	not possible, small modulation in the 10 kHz range	possible
PID 100	kHz-range	not possible, no modulation	not possible
PID 100 + FET CURRENT CONTROL	MHz-range	possible, no modulation	not possible
PDD 100 + PID 100 + BIAS-T + DL 100 L	kHz-range	not possible, 10 MHz modulation	possible
PDD 100 + PID 100 + BIAS-T + DL 100 L + FET CURRENT CONTROL	MHz-range	possible, 10 MHz modulation	possible

Table 1: Advantages of Locking schemes using the different modules

Regulation bandwidth is the bandwidth at which the laser frequency can be readjusted. Which disturbations have to be considered? RF-noise is usually shielded by the laser head housing. The effects of acoustic noise in the 10 to 100 kHz range can only be reduced by a regulation bandwidth 100kHz upwards. Since it is difficult to fight mains noise, it should be avoided by any other means and sources for mains noise (e.g. ground loops) should be eliminated as far as possible. Drifts can be eliminated by all the set-ups mentioned in table 1.

Line width norrowing needs the MHz regulation bandwidth. The remaining modulation from LIR 100 respectively PDD 100 does not affect the customer's experiment in two cases:

1.) The phase modulation index $M = \Delta\omega/\omega_m$ is small and $\gamma / \omega_m >> 1$ or from a different point of view $\Delta\omega \times S' << 1$, where γ and S´ are line width and signal derivation in the customer's experiment (not in his control loop!) and the modulation amplitude $\Delta\omega$ and the modulation frequency ω_m have the same definition like in appendix B. It means that the measurement signal does not change relevantly within the modulation range $\Delta\omega$.

2.) $\gamma / \omega_m << 1$. In this case the sidebands can not be measured in the experiment since they are off-resonant. A typical scheme is to lock the laser using the PDD 100 to a high finesse cavity for resonant second harmonic generation (SHG 100). In this case the sidebands do not enter the cavity.

While the first case usually leads to the Lock-In set-up, the second case leads to the Pound-Drever-Hall set-up.

It usually depends on the specific experiments, if top-of fringe locking is preferred. One has to compare the advantages of top-of-fringe:

- Usually the listed references in the library are the line centers. They are easier to compute than complex line shape functions.
- The line center has little to no sensitivity to the total light intensity in the probe laser or in the detection arm.

and the advantages of side-of fringe:

- much easier to realize
- allows very nice offset locking by control of external fields for example

with each other, to find the most suitable scheme.

Appendix

A. Operating Principle of the PID 100 Controller

We can not describe the theory of PID controllers here. But we show in Figure 1 a typical output generated by a symmetric square pulse at the input. The slow increase is made by the I-contribution, the slope depends on the time constant setting. The peak at the step is made by the D-contribution, the height depends on the D time constant setting. The step itself belongs to the P-contribution, the height depends on the gain setting.

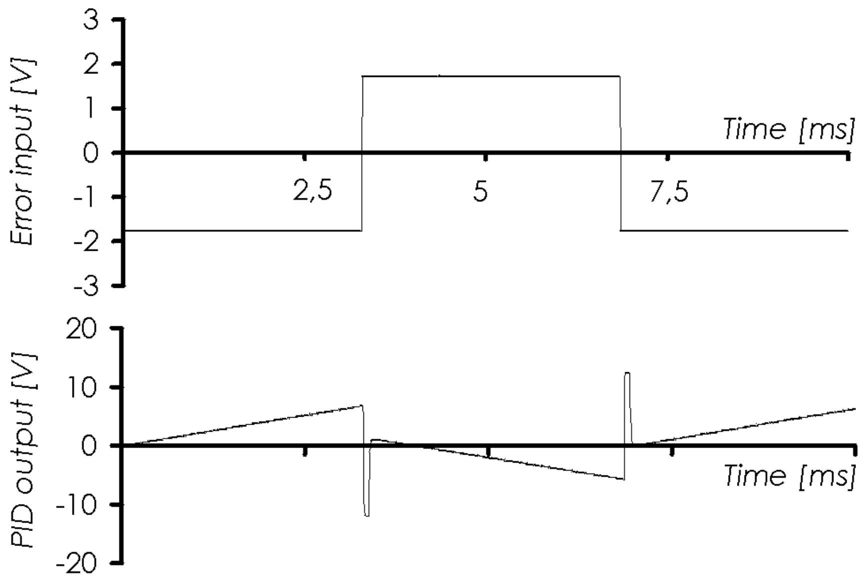


Figure 1: Response of the PID 100 controller on a square pulse error input.

The PID 100 controller provides most of the necessary parameters for the individual set-up of an control loop at the front panel. Additional parameters that are usually set once when locking the diode laser for the first time can be set inside the module. Thus, the PID 100 controller provides every parameter the necessary for a locking scheme.

The typical set-up for a control loop with PID 100 and without FET CURRENT CONTROL is shown in Figure 2. (The internal connection between SC 100 and DCC 100 typically allows an tuning range of more than 10 GHz)

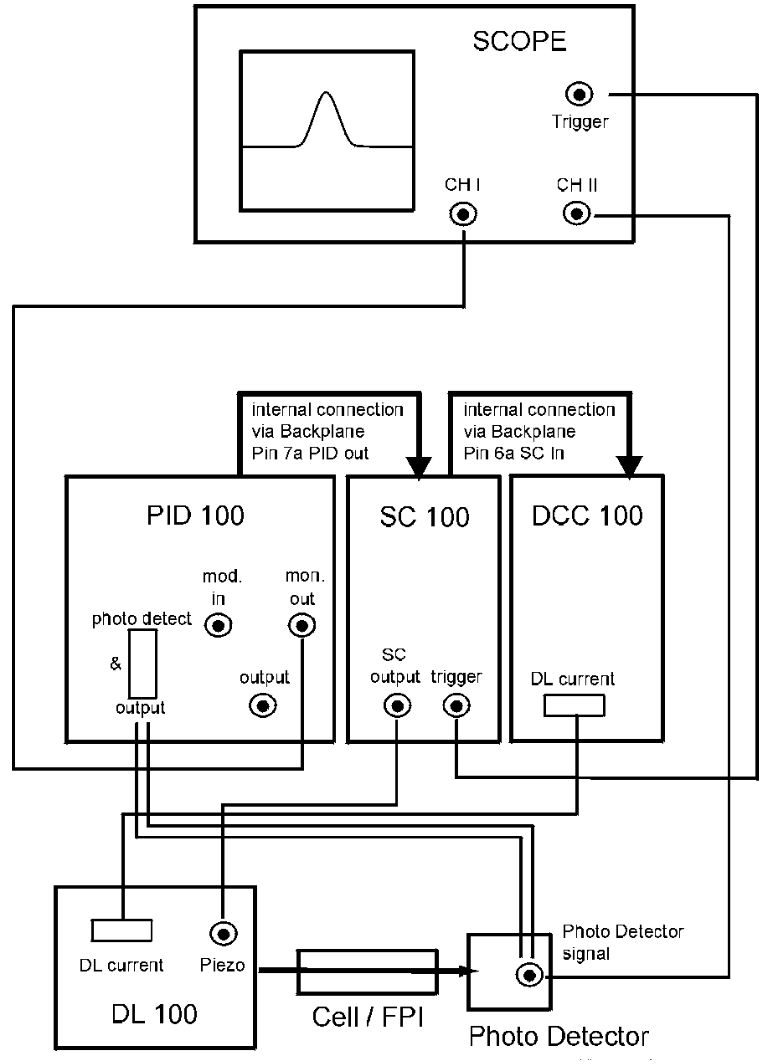


Figure 2: The typical set-up for a side-of-fringe lock using the PID 100 controller without the FET CURRENT CONTROL

B. Operating Principle of the Lock-In Regulator LIR 100

The Lock-In-Regulator LIR 100 consists basically of a lock-in detection unit and a PID regulator. Therefore, it is typically utilized to lock the laser to the top of a signal (top of fringe). Please refer to Appendix A for further information about PID regulators.
The laser light is fed into a external frequency detector which supplies a laser frequency dependent signal. The principle of the Lock-In detection is to modulate the laser frequency ω_0 by a small change $\Delta\omega$ and to compare the detector signal at $\omega_0 + \Delta\omega$ with the signal at $\omega_0 - \Delta\omega$. In this way the LIR 100 determines whether the signal slope is positive or negative and calculates the absolute value of the signal slope (see Figure 3).

If the laser frequency ω(t) is slightly modulated ($\Delta\omega << \Gamma$, FWHM of signal of interest) like

$$\omega(t) = \omega_0 + \Delta\omega \times \sin(\omega_m t)$$

the detector signal S(t) is approximately

$$S(t) = S_0 + S'(\omega_0) \times \Delta\omega \times \sin(\omega_m t) \ .$$

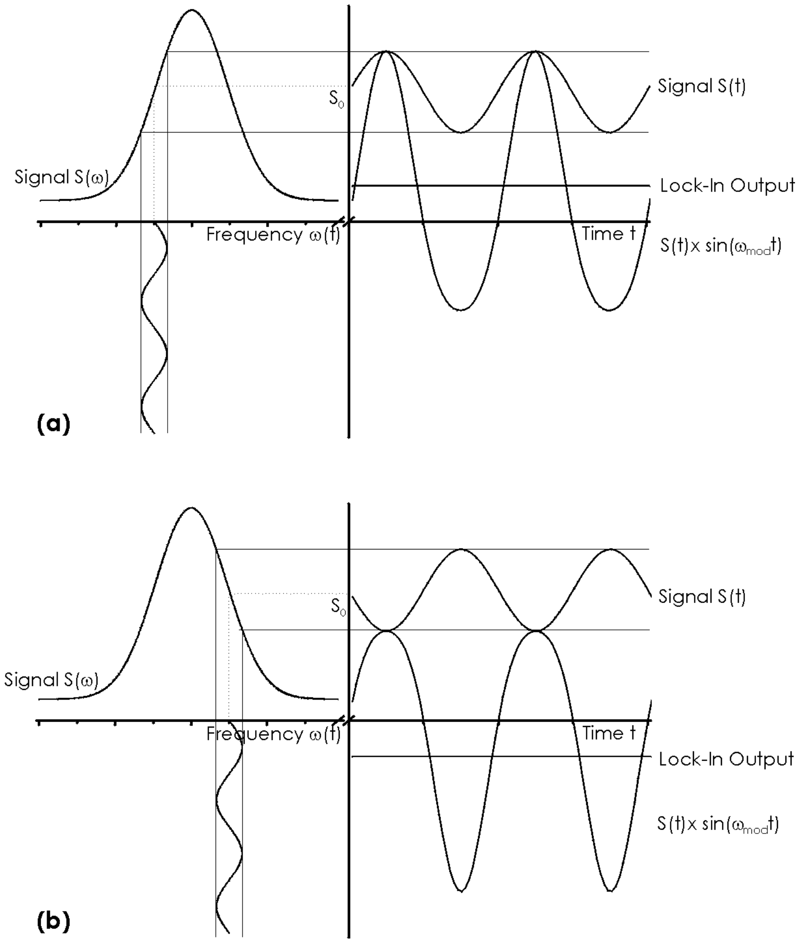


Figure 3: Principle of the Lock-In Detection
(a) rising edge
(b) falling edge

Inside the lock-in detector the signal is mixed with the modulation itself:

$$S(t) \times \sin(\omega_m t) = S_0 \times \sin(\omega_m t) \quad + \quad S'(\omega_0) \times \Delta\omega \times \sin(\omega_m t)^2$$
$$= \tfrac{1}{2} \times S'(\omega_0) \times \Delta\omega + S_0 \times \sin(\omega_m t) - S'(\omega_0) \times \Delta\omega \times \cos(2\omega_m t)$$

Furthermore, the lock-in detector uses a low pass in order to filter all time dependent contributions (see Figure 4):

$$\text{Lock-In Output}(\omega_0) = \text{Low pass}(S(t) \times \sin(\omega_m t)) = \tfrac{1}{2} \times S'(\omega_0) \times \Delta\omega$$

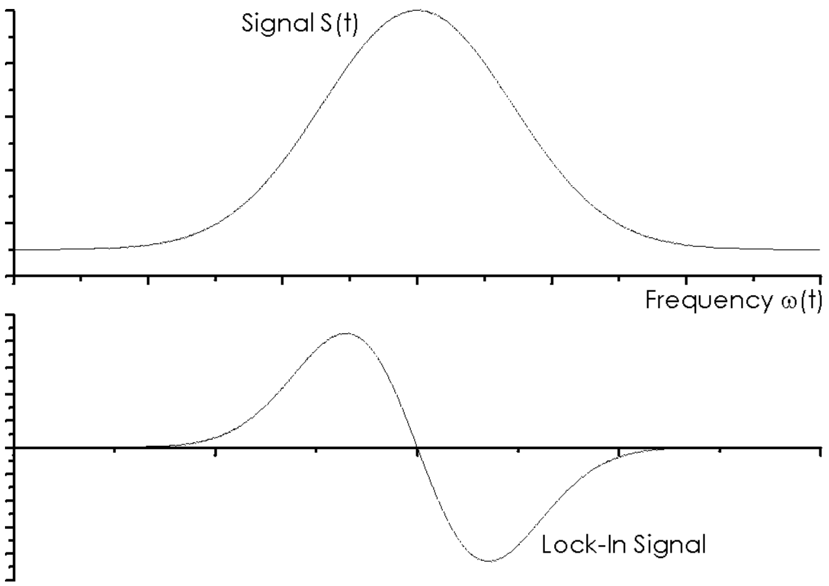


Figure 4: Lock-In Signal as "derivative" of the input signal S.
(a) Scanning the laser frequency leads to signal S in the external frequency reference.
(b) The Lock-In generates the derivative of the signal S during the scan.

Therefore, the Lock-In bandwidth can never be faster than its low pass filter and thus is always slower than its modulation frequency ω_m. For the Lock-In detector the modulation amplitude $\Delta\omega$ should be small in order to get a narrow laser spectrum. On the other hand it can not be zero because the amplitude of the Lock-In signal is proportional to $\Delta\omega$. The Lock-In detector generates a signal which is proportional to the derivation of the original signal $S(\omega)$. The original signal $S(\omega)$ can be calculated by integration of the Lock-In signal.

C. Operating Principle of the Pound-Drever-Hall Detector PDD 100

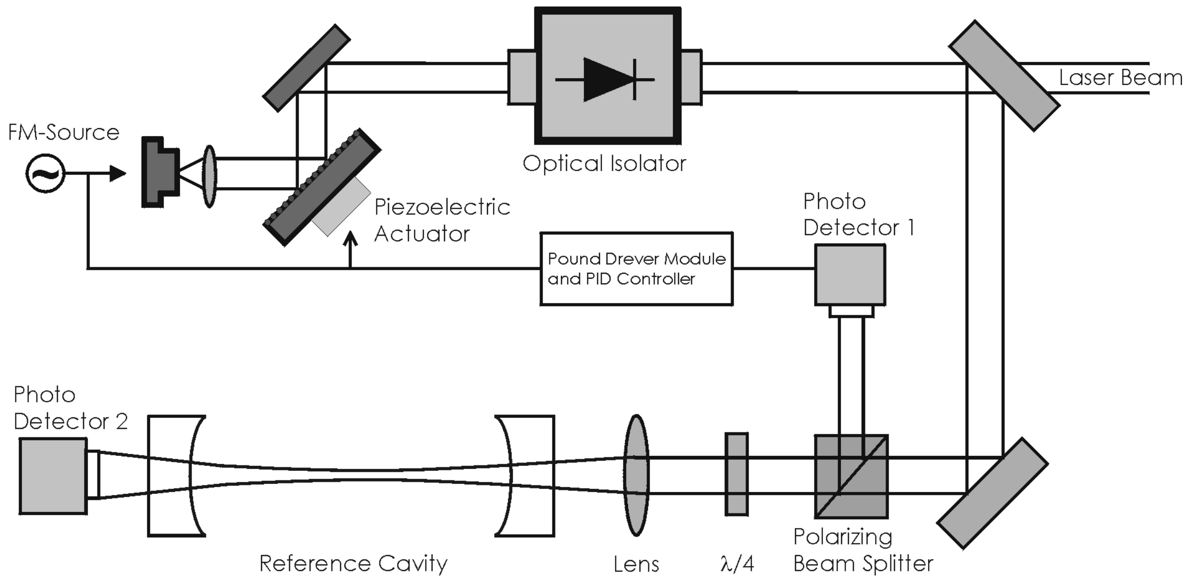


Figure 5: Schematic set-up for a Pound-Drever-Hall lock with respect to an external reference cavity

The typical set-up of the control loop with the PDD 100 is shown in Figure 5. The FM-source is already included in the PDD 100 module. The PDD 100 determines the phase delay (dispersion) of modulated laser light while passing through a reference medium by comparing the phase of carrier and side bands and generates the Pound-Drever signal. Due to Kramers-Kronig relation, maximum absorption is equal to zero dispersion. With the help of the PID 100 controller one can use the Pound-Drever signal output to lock the laser to the frequency of maximum absorption in the reference medium.
Neglecting amplitude modulation, a current modulated laser diode emits the following electric field

$$E(t) = \frac{E_0}{2} \exp[i(\omega_0 t + M \sin(\omega_m t))] + c.c.$$

where ω_0 denotes the emission frequency of the unmodulated laser light and ω_m denotes the modulation frequency. M is the so-called phase modulation index, $\Delta\omega = M \times \omega_m$ is the so-called frequency modulation index. Using a series expansion by Bessel functions $J_k(x)$ we get:

$$E(t) = \frac{E_0}{2} \sum_{k=-\infty}^{\infty} J_k(M)\, e^{i(\omega_0 + k\omega_m)t} + c.c.$$

The modulation yields a great number of new frequency components, so-called sidebands of the carrier frequency ω_0, each with a frequency distance of ω_m to the next. E.g. for M = 1 the relative intensities of the k-th side bands $I_k = |a_k|^2 / |a_0|^2$ can be calculated to:

$I_0 = 1$; $I_{\pm 1} = 0{,}33072$; $I_{\pm 2} = 0{,}02255$; $I_{\pm 3} = 0{,}00065$.

For most applications the second side band may be already ignored. The electric field after passing the reference medium is

$$E_T(t) = \frac{E_0}{2} \sum_{k=-\infty}^{\infty} J_k(M)\, T_k\, e^{i(\omega_0 + k\omega_m)t} + c.c.$$

whereas the transmission coefficients

$$T_k = \exp(-\delta_k - i\phi_k)$$

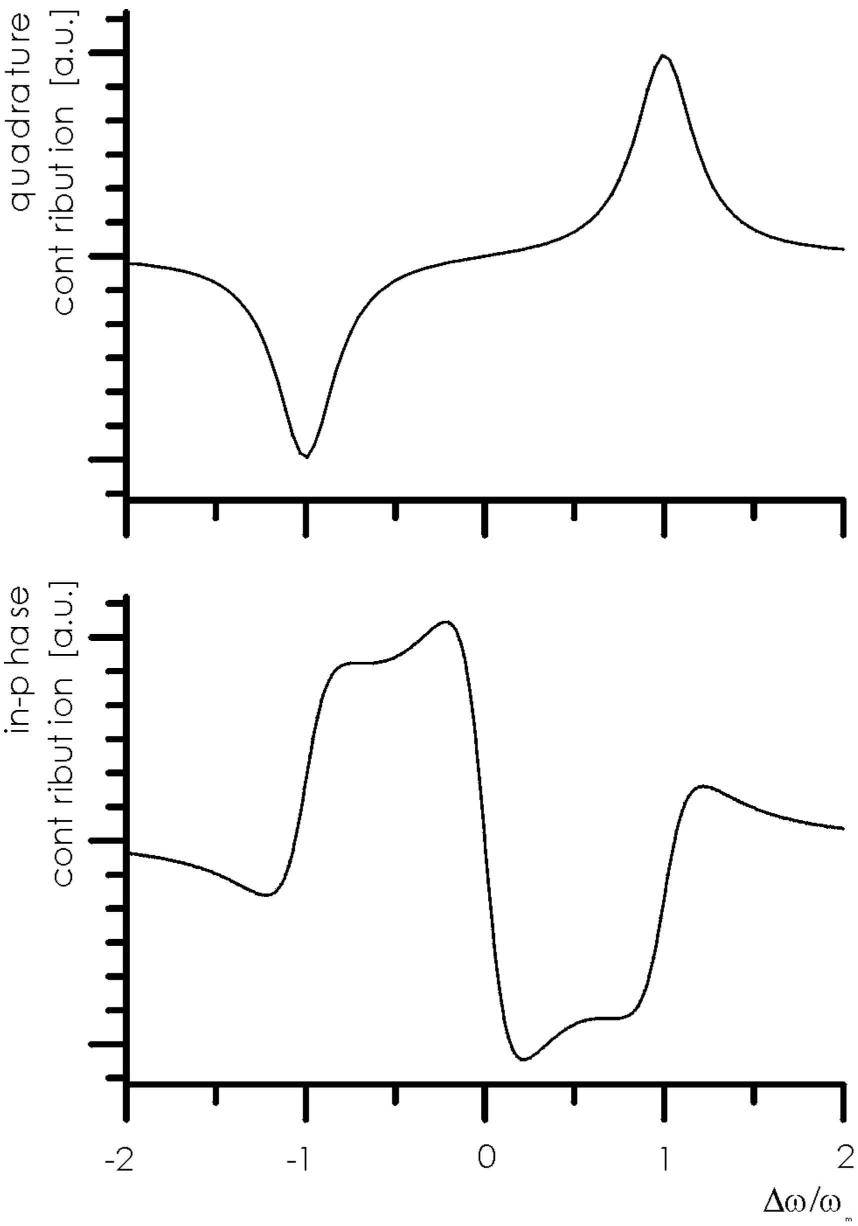
describes both absorption $\delta_k = \alpha_k l/2$ and phase delay $\phi_k = n_k\, l\, \omega_k / c$ in the reference medium. The index k indicates that the particular value has to be calculated for the frequency $\omega_0 + k\,\omega_m$. A photo detector with a detection bandwidth higher than the modulation frequency ω_m detects all frequency components with DC and $1 \times \omega_m$ of the transmitted intensity:

$$I_T(t) = \frac{c\varepsilon_0}{2} |E_T(t)|^2$$

In the approximation of slowly varying absorption and phase delay and for a small phase modulation index M, the contributions of the $I_T(t)$ signal measured by the photo diode can be calculated as:

$$I_T(t) \propto e^{-2\delta_0}\, M \left[1 + (\delta_{-1} - \delta_1)\cos(\omega_m t) + (\phi_1 + \phi_{-1} - 2\phi_0)\sin(\omega_m t)\right]$$

The signal consists of an in-phase contribution $\phi_1 + \phi_{-1} - 2\phi_0$ and the quadrature contribution $\delta_{-1} - \delta_{+1}$. The signal of the photo detector is fed into the phase detector of the PDD 100. In this section the frequency components with 1 x ω_m are mixed with $\sin(\omega_m t)$ and converted to a DC signal by the aid of a low pass filter (compare “Functional principle of the LIR100”).



In Figure 6 the resulting signal for absorption and phase delay of a Lorentz shaped resonance are shown for $\omega_m / \Gamma = 5$. Γ is the full width at half maximum of the resonance.
The steep slope of the in-phase contribution is fed into the PID 100 controller as error signal.

Figure 6: Typical Lineshape of PDD100 Error Output.
Upper Figure: Phase shifted by 90°.
Lower Figure: Phase well adjusted.
ATTENTION: $\Delta\omega / \omega_0$ means here: $(\omega - \omega_0) / \omega_0$