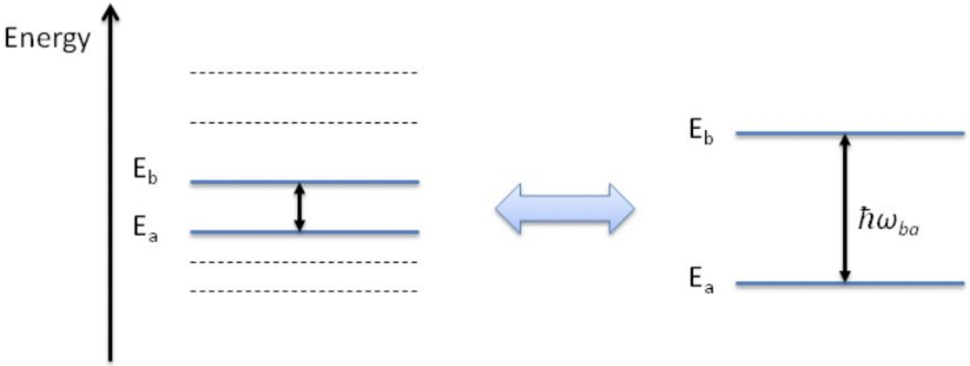
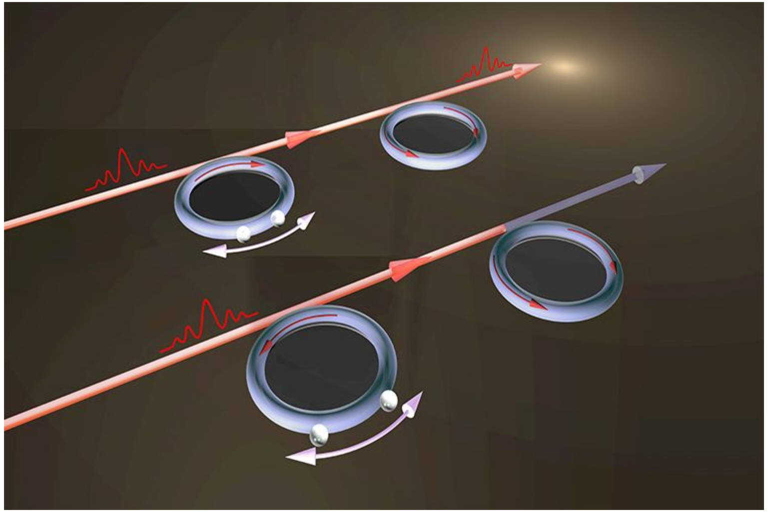
PDH laser locking

- Motivation
- Feedback Control (PID)
- Obtaining an Error Signal (PDH)
- Locking results

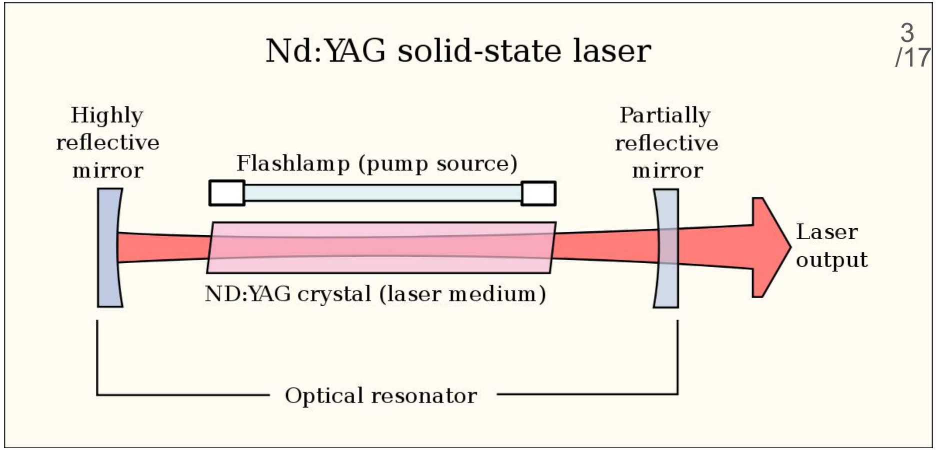
Motivation

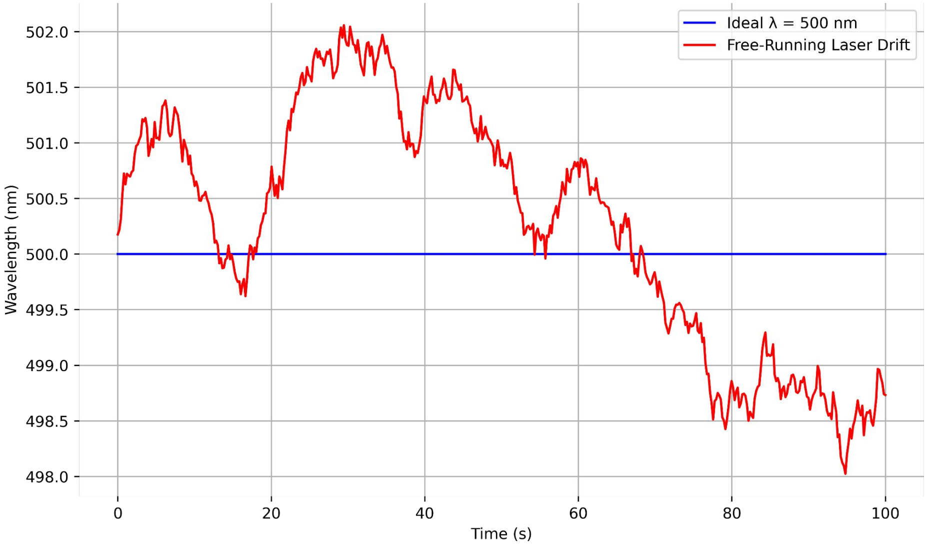
- Any sensitive system that requires an exact band gap to have some transitions benefits from this technique

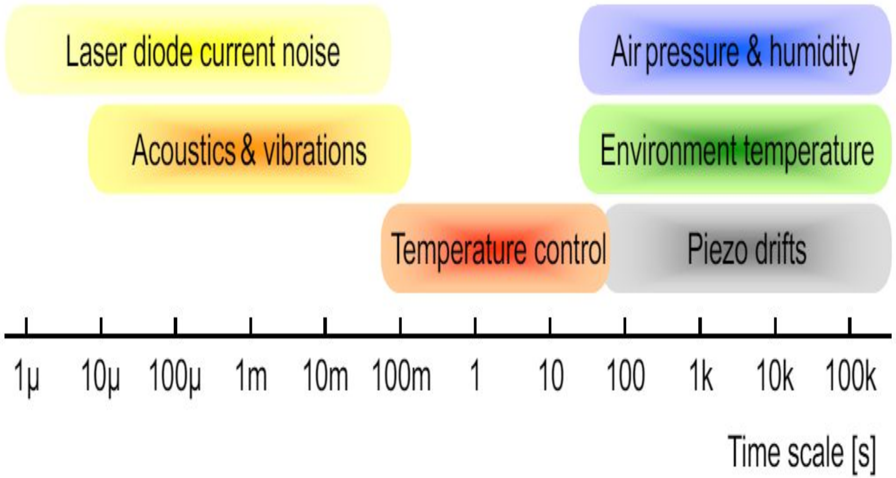




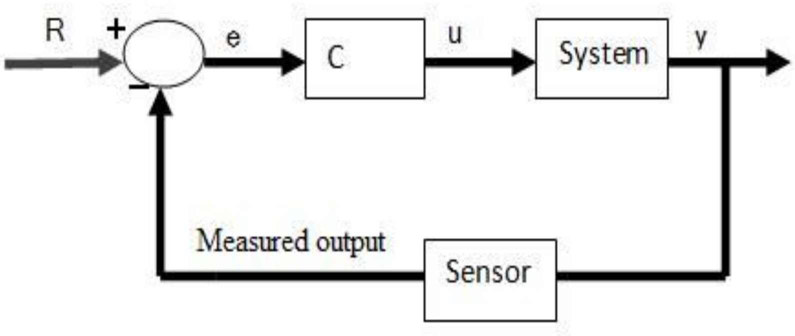
Laser Drift


Nd:YAG solid-state laser
Highly reflective mirror
Flashlamp (pump source)
Partially reflective mirror
Laser output
ND:YAG crystal (laser medium)
Optical resonator


Ideal λ = 500 nm
Free-Running Laser Drift
Wavelength (nm)
Time (s)
502.0
501.5
501.0
500.5
500.0
499.5
499.0
498.5
498.0
0
20
40
60
80
100


Laser diode current noise
Air pressure & humidity
Acoustics & vibrations
Environment temperature
Temperature control
Piezo drifts
1µ
10µ
100µ
1m
10m
100m
1
10
100
1k
10k
100k
Time scale [s]

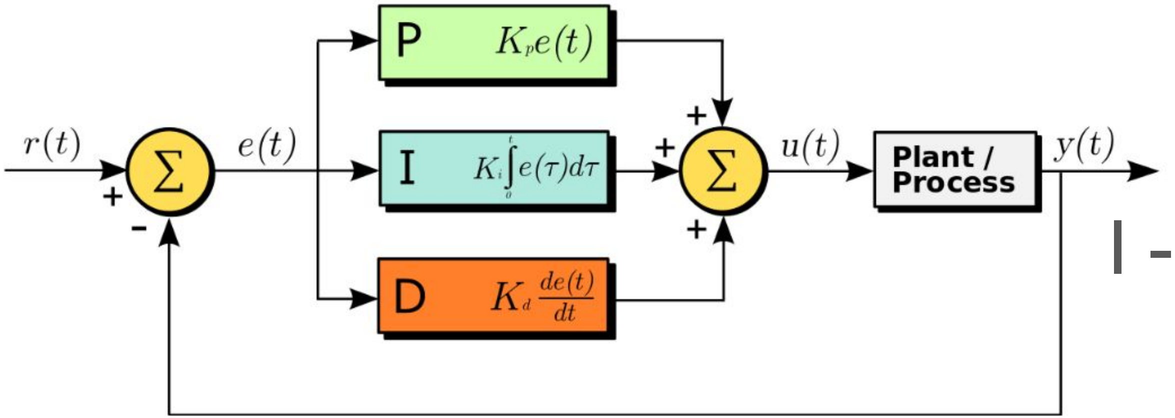
Feedback Control

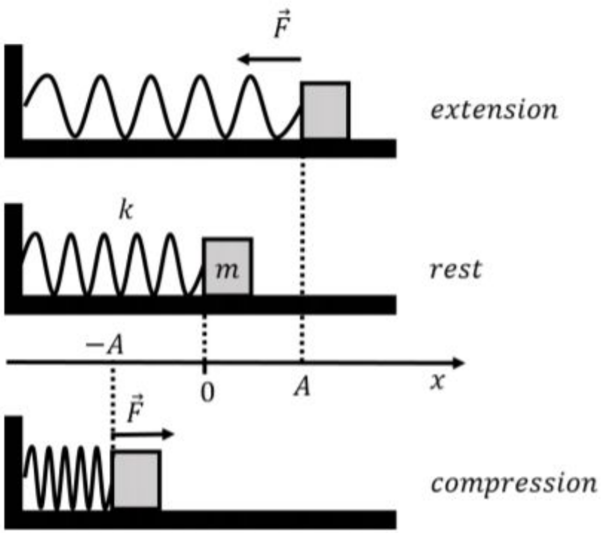


- Feedback = Adjust output based on input
- Control = maintains the output at a constant
- **Input should be <u>antisymmetric</u> around the constant you want to maintain**

PID:Proportional–integral–derivative

Damped harmonic oscillator

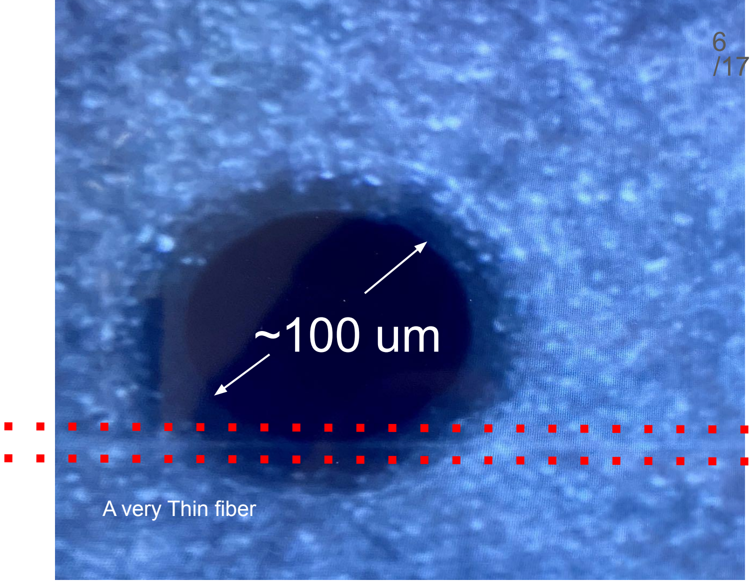


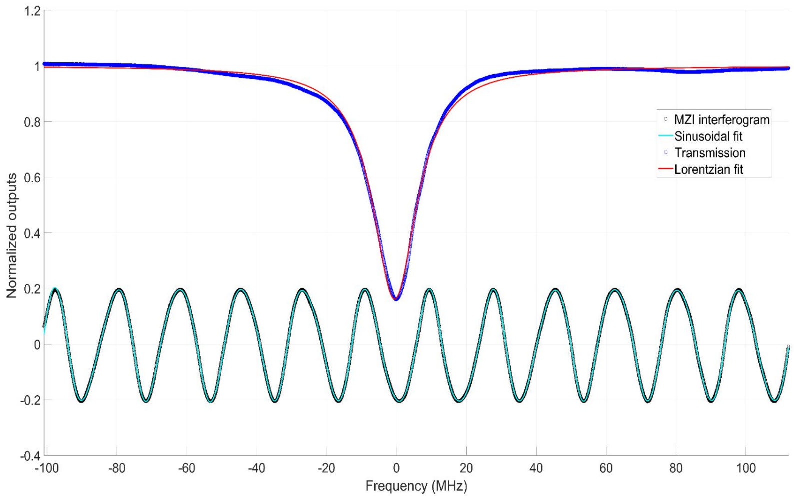


P - Spring
I - counter steady state errors
(inertia)
D - Damping

Transmission From Ring Resonator

Ringing the Resonator
Resulting Transmission
Not a good Error Signal…





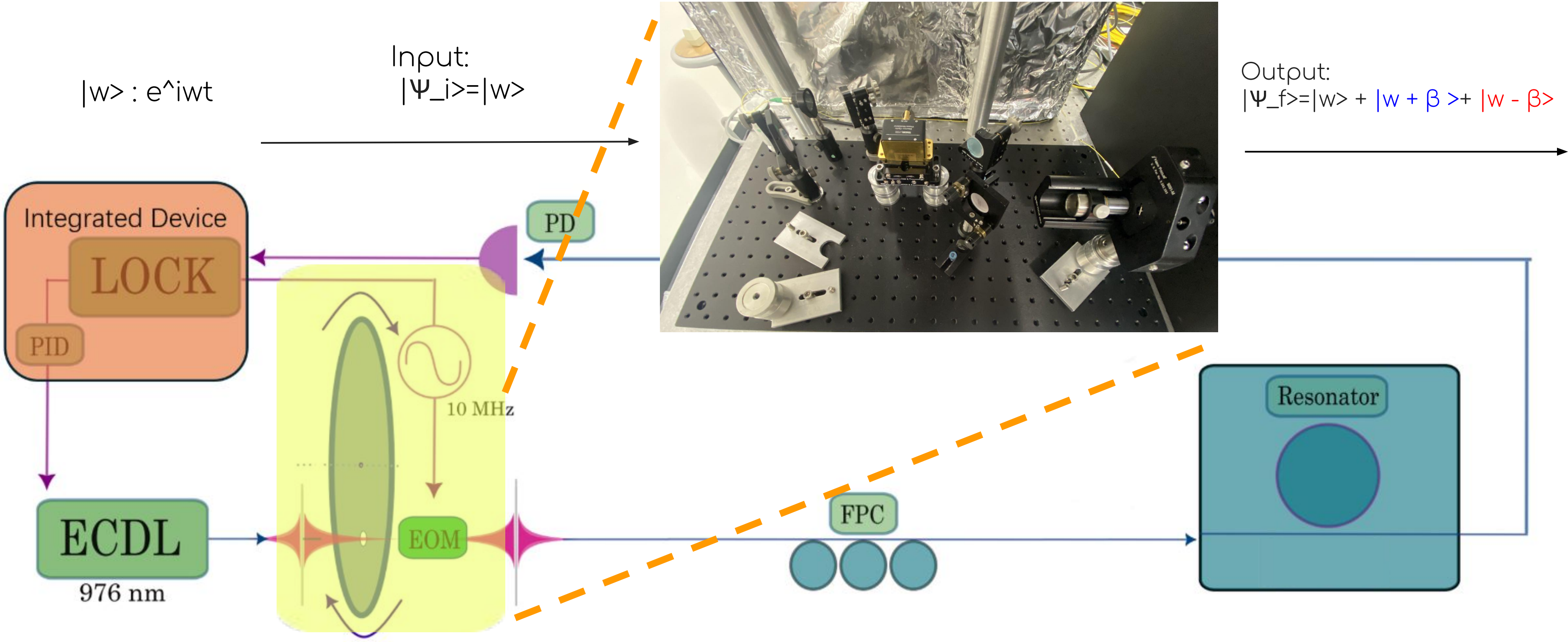
Are we able to construct an antisymmetric signal around the resonance?

PDH: Pound Drever Hall

$|w\rangle : e^{iwt}$

Input:
$|\Psi_i\rangle = |w\rangle$

Output:
$|\Psi_f\rangle = |w\rangle + |w + \beta\rangle + |w - \beta\rangle$



PDH: Pound Drever Hall

$<\Psi_f|FF|\Psi_f>$

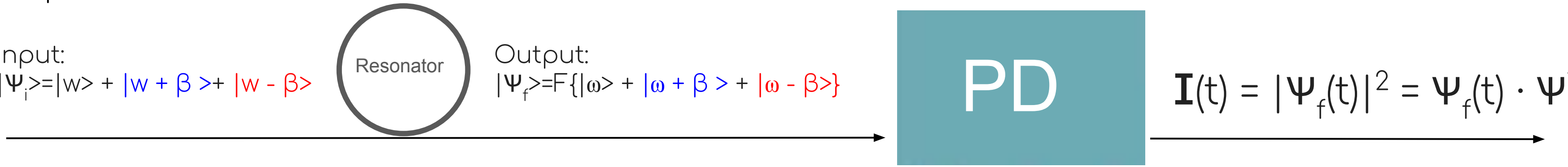
Intensity: $<\Psi_f|\Psi_f>$
compute an inner product

Interference among the sidebands!

|w> : e^iwt

Input:
$|\Psi_i>=|w> + |w + \beta > + |w - \beta>$

Output:
$|\Psi_f>=F\{|\omega> + |\omega + \beta > + |\omega - \beta>\}$



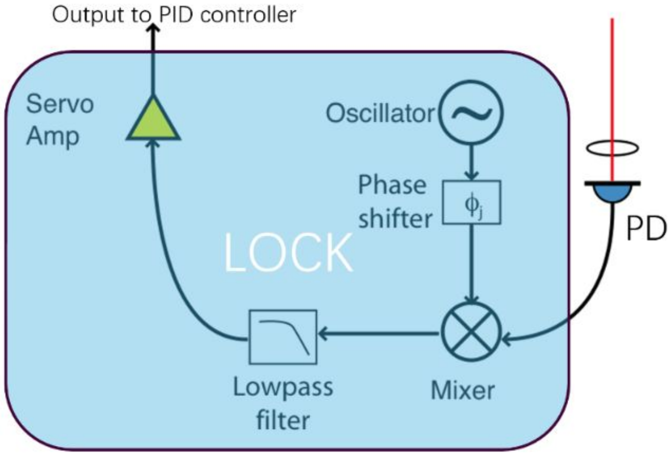
$\mathbf{I}(t) = |\Psi_f(t)|^2 = \Psi_f(t) \cdot \Psi^*_f(t)$

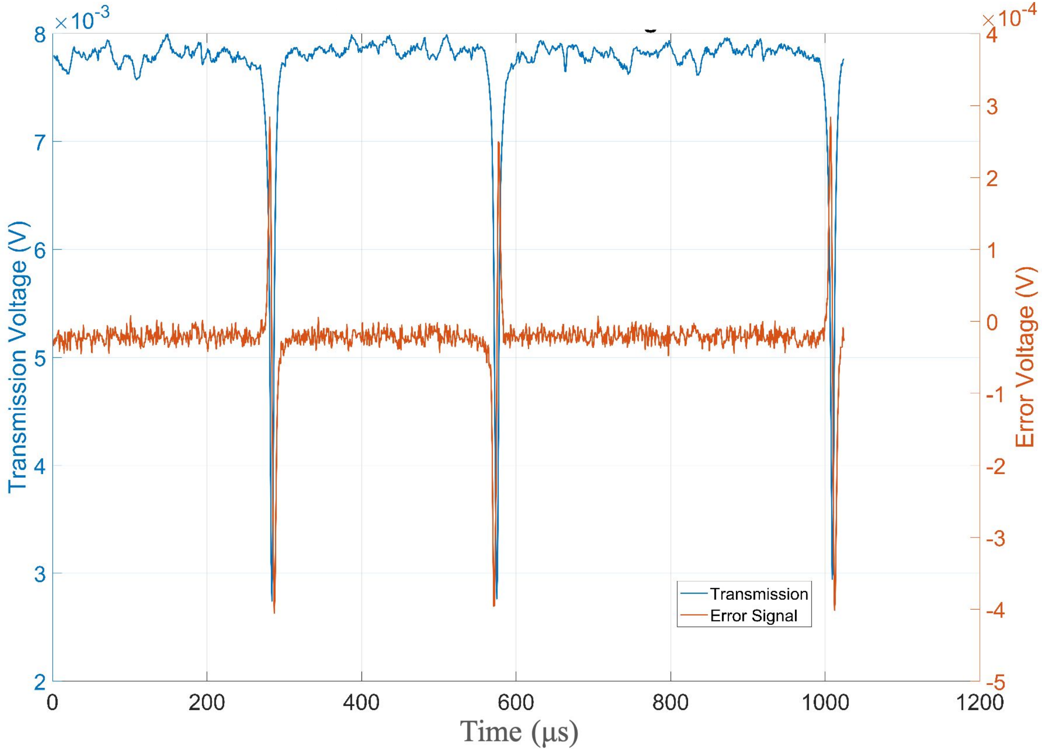
$$
\begin{aligned}
P_{\text{out}} &= |\hat{F}|input\rangle|^2 \\
&= P_c|F(\omega)|^2 + P_s\left\{|F(\omega+\beta)|^2 + |F(\omega-\beta)|^2\right\} + \\
2\sqrt{P_cP_s}\text{Re}&\left\{\boxed{F(\omega)F^*(\omega+\beta) - F^*(\omega)F(\omega-\beta)}\right\}\cos\beta t + \\
\text{Im}&\left\{\boxed{F(\omega)F^*(\omega+\beta) - F^*(\omega)F(\omega-\beta)}\right\}\sin\beta t + \\
&(2\beta \text{ terms}).
\end{aligned}
$$

	ω	$\omega+\beta$	$\omega-\beta$
ω	0	β	$-\beta$
$\omega+\beta$	$-\beta$	0	-2β
$\omega-\beta$	β	2β	0

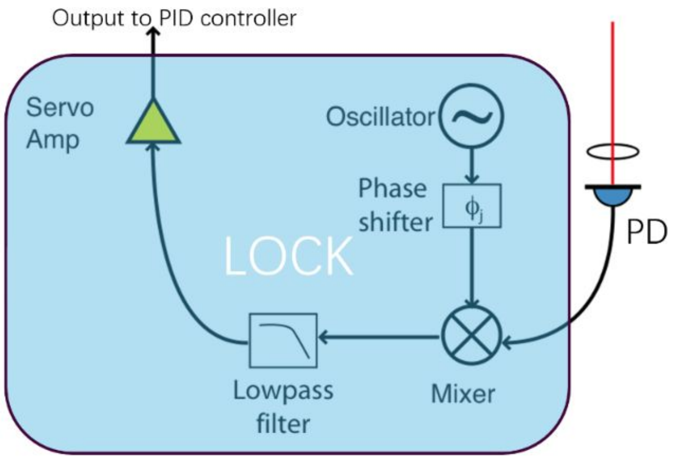
<ω|ω+β> = e^{iw+βt}*e^{-iwt} = e^iβt

Error Signal



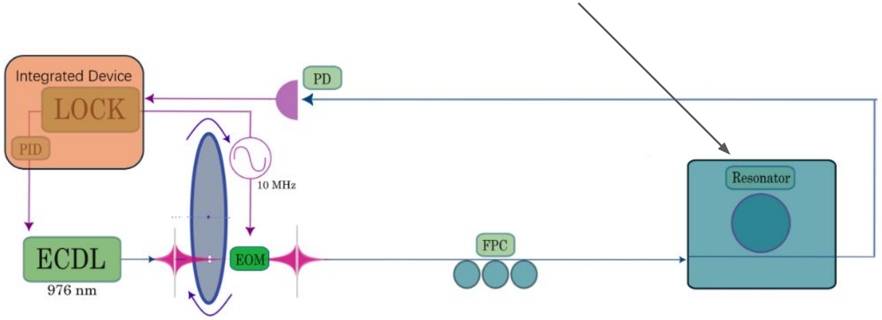


What happens after photodiode.



$$
\begin{aligned}
P_{\text{out}} &= |\hat{F}|input\rangle|^2 \\
&= P_c|F(\omega)|^2 + P_s\left\{|F(\omega+\Omega)|^2 + |F(\omega-\Omega)|^2\right\} + \\
&2\sqrt{P_cP_s}\,\mathrm{Re}\left\{\boxed{F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)}\right\}\cos\Omega t + \\
&\mathrm{Im}\left\{\boxed{F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)}\right\}\sin\Omega t + \\
&(2\Omega \text{ terms}).
\end{aligned} \tag{5}
$$

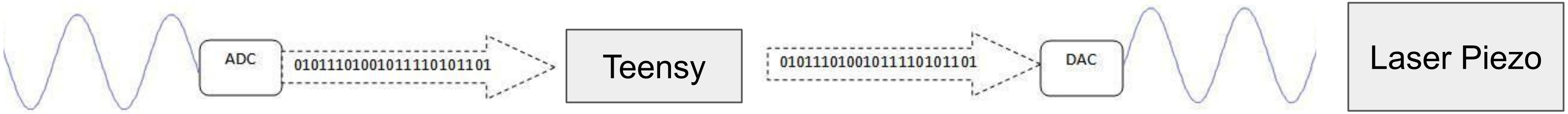
Intensity of light is proportional to E^2
This is taking the inner product
Taking the inner product of our signal we obtain 9 terms where 3 are DC and 6 are changing in frequency
Applying a low pass filter are left with error signal oscillating at our modulation frequency from our EOM



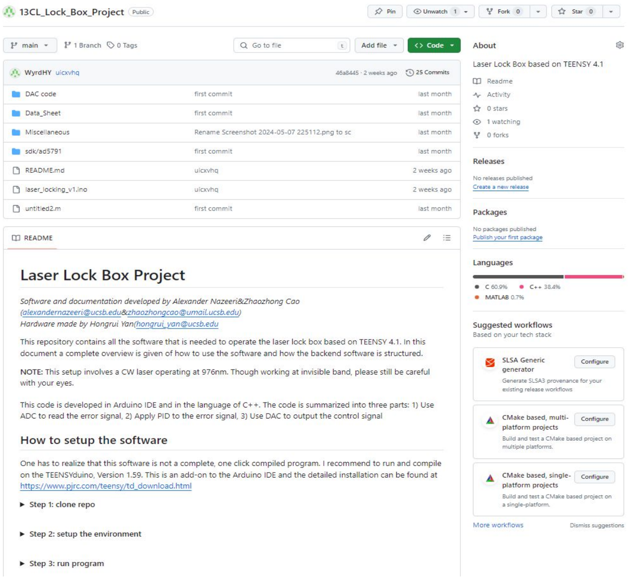
	ω	$\omega+\beta$	$\omega-\beta$
ω	0	β	$-\beta$
$\omega+\beta$	$-\beta$	0	-2β
$\omega-\beta$	β	2β	0

With all these information given,
here is our experiment result

Implement PID



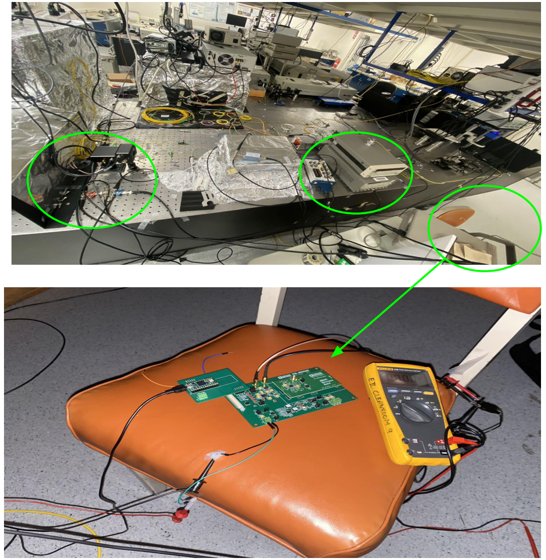
Main Clock



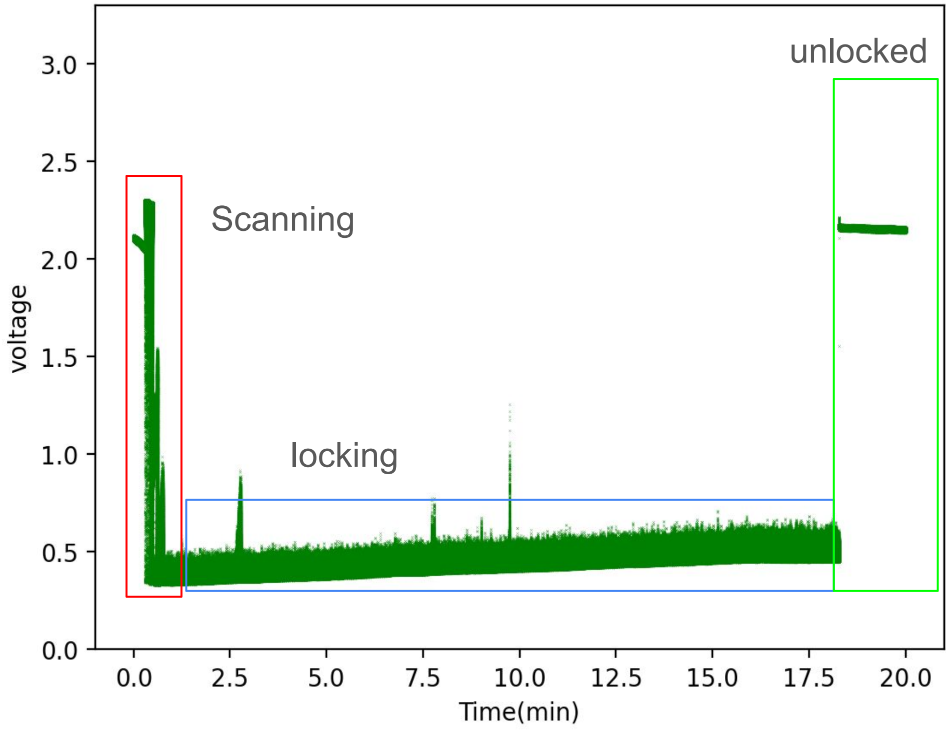
CPU Timer 1: Scanning

CPU Timer 2: PID

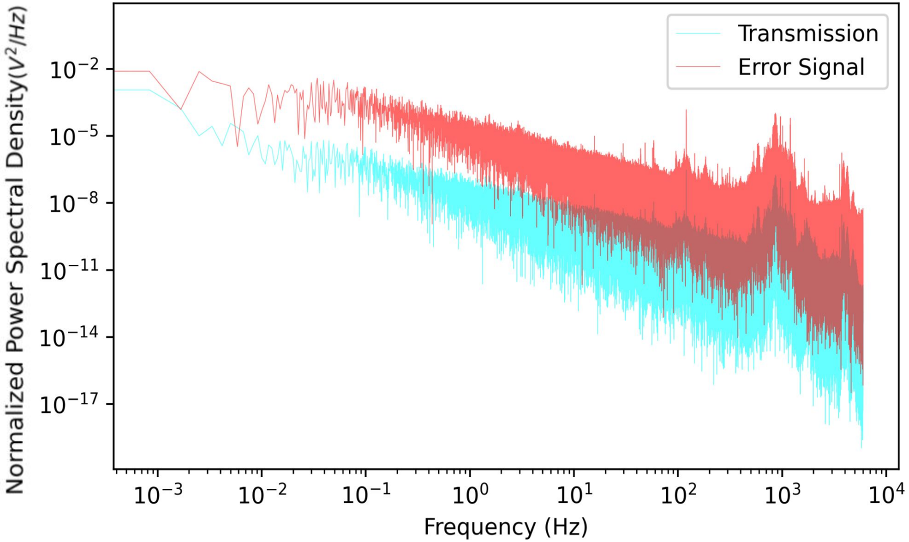
CPU Timer 3:
Read Instruction Set from the User

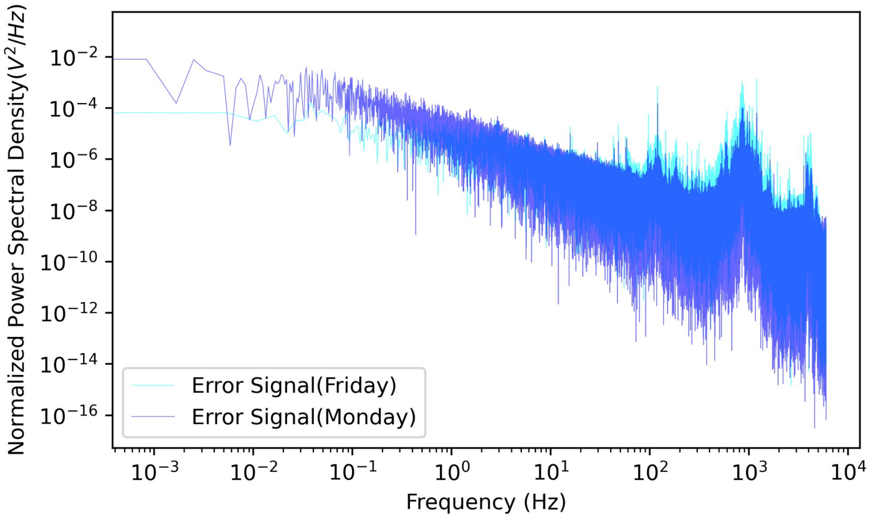


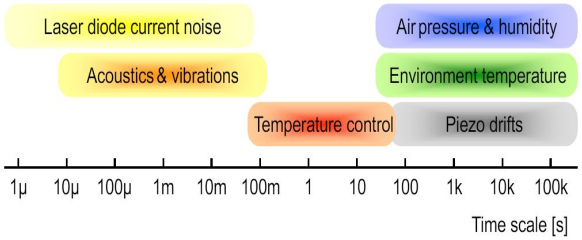
Time Domain Measurement



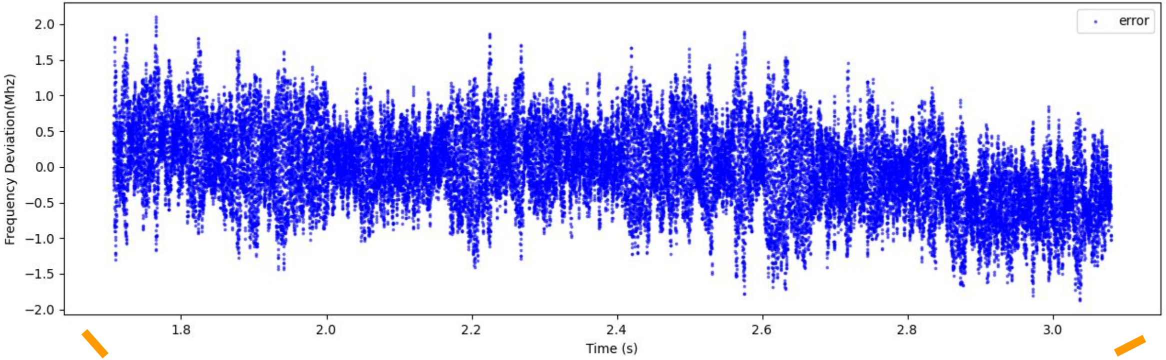
Power Spectrum Density



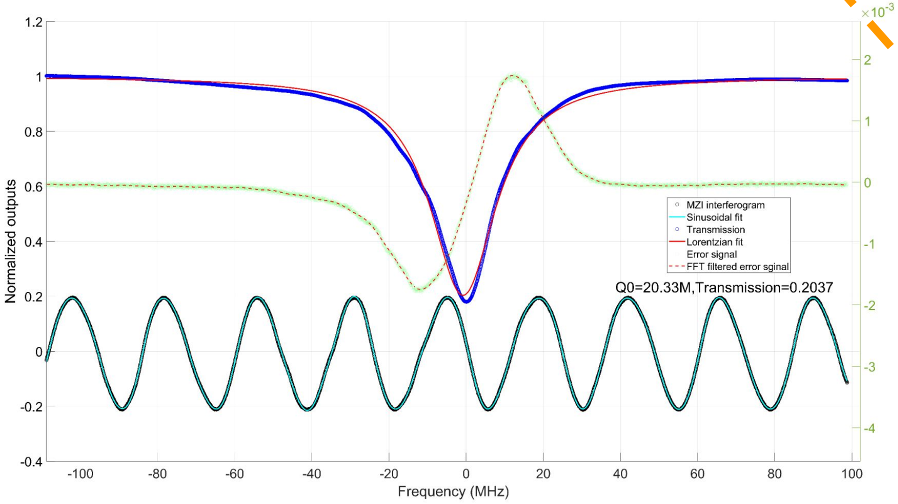


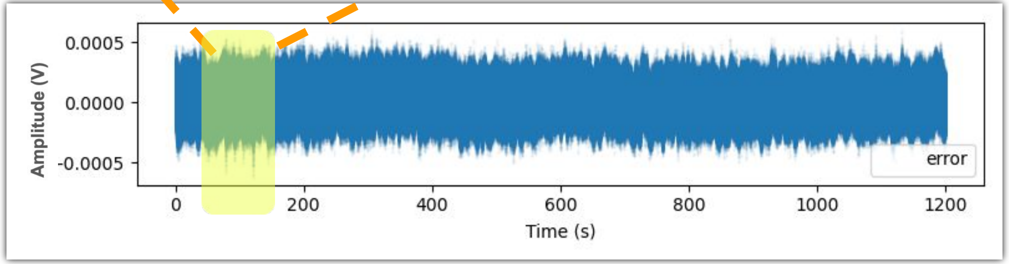


Quantify Frequency Deviation



$f_0 \pm$ 2.822125Mhz





Future work

1. Isolate the setup in vacuum chamber
2. Auto Tuning PID
3. GUI interface that is more user friendly

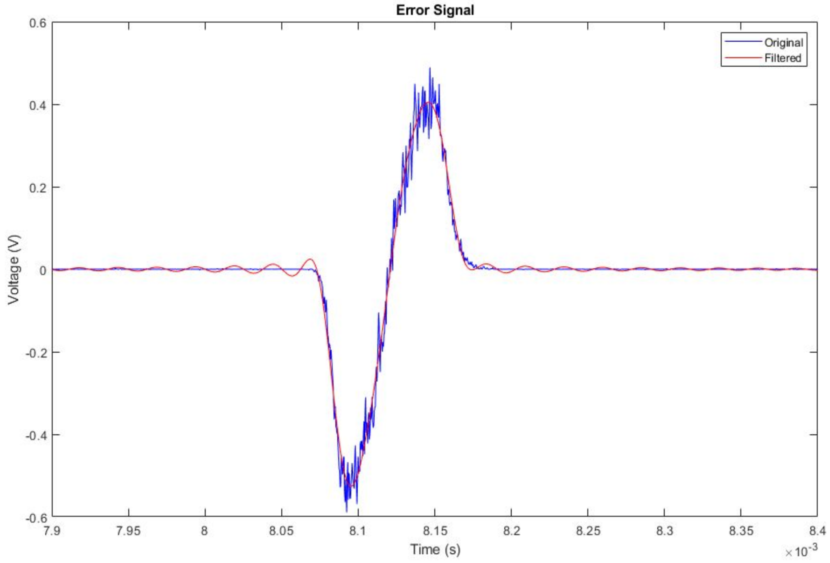
Reference

Black, Eric D. "An introduction to Pound–Drever–Hall laser frequency stabilization." *American journal of physics* 69.1 (2001): 79-87.

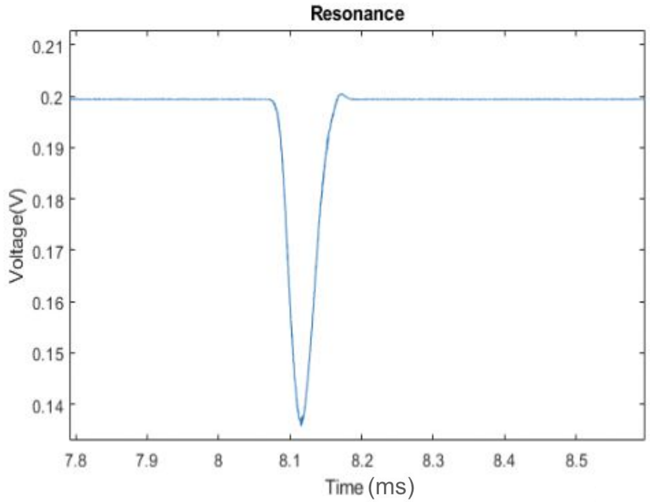
https://www.toptica.com/fileadmin/Editors_English/12_literature/05_HighFinesse/toptica_Diode_Laser_Locking_and_Linewidth_Narrowing.pdf

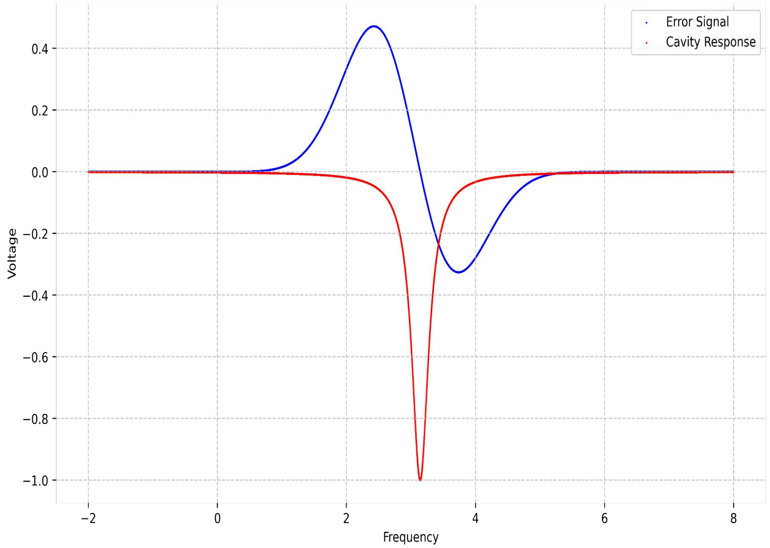
Error Signal

$$\epsilon = -2\sqrt{\frac{P_c}{P_s}}\,\Im\left\{F(\omega)F^*(\omega+\Omega) - F^*(\omega)F(\omega-\Omega)\right\}$$

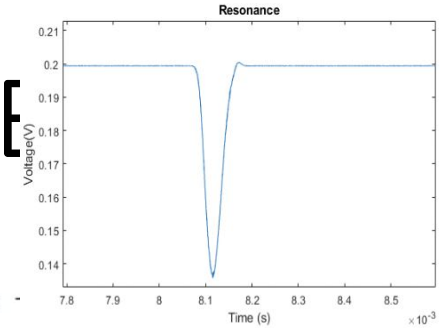


0.4

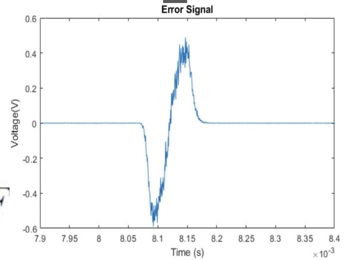


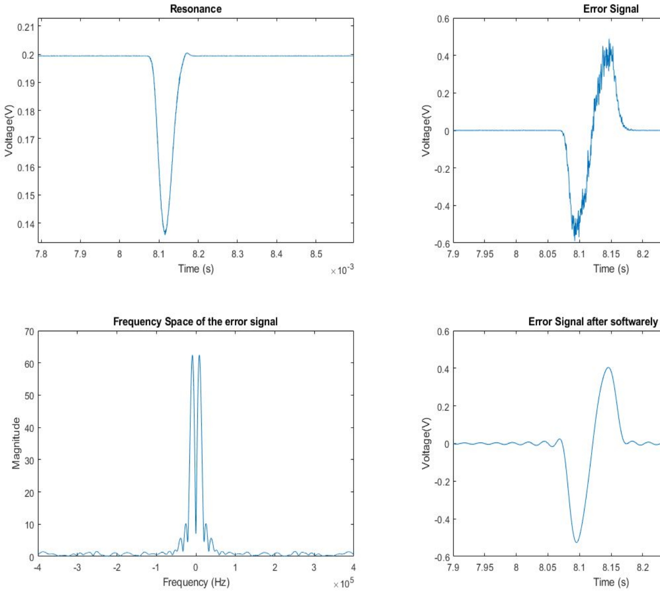


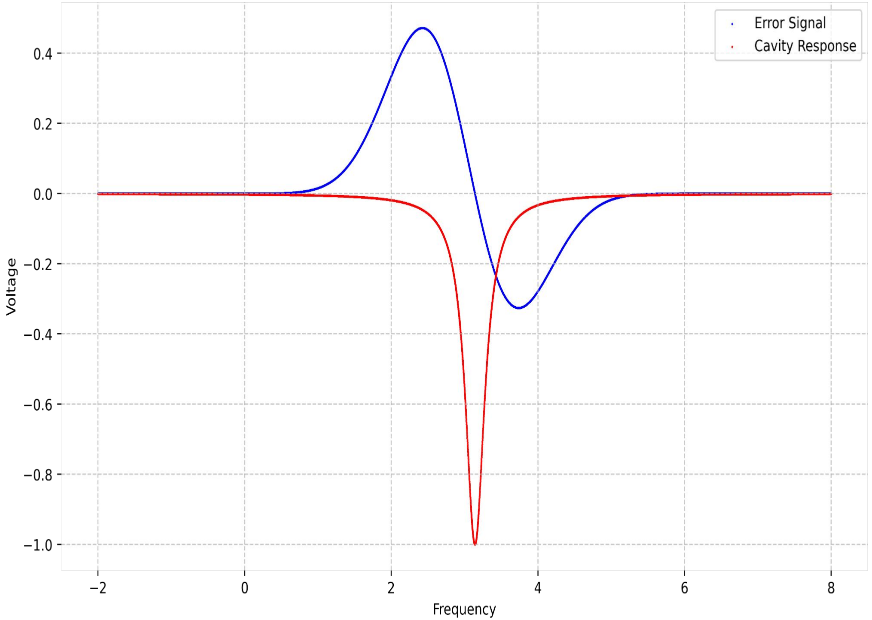
E nal

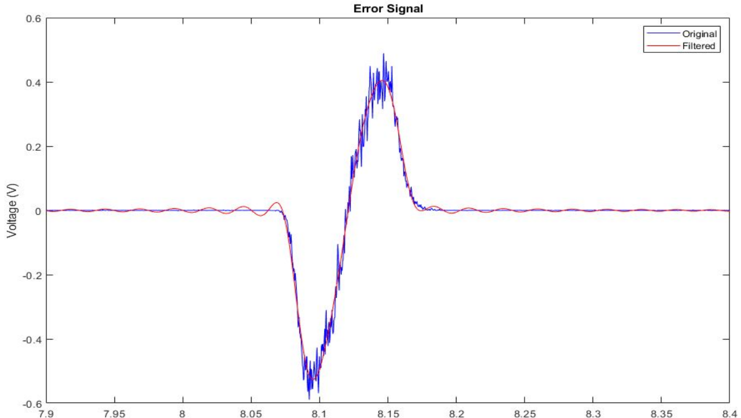


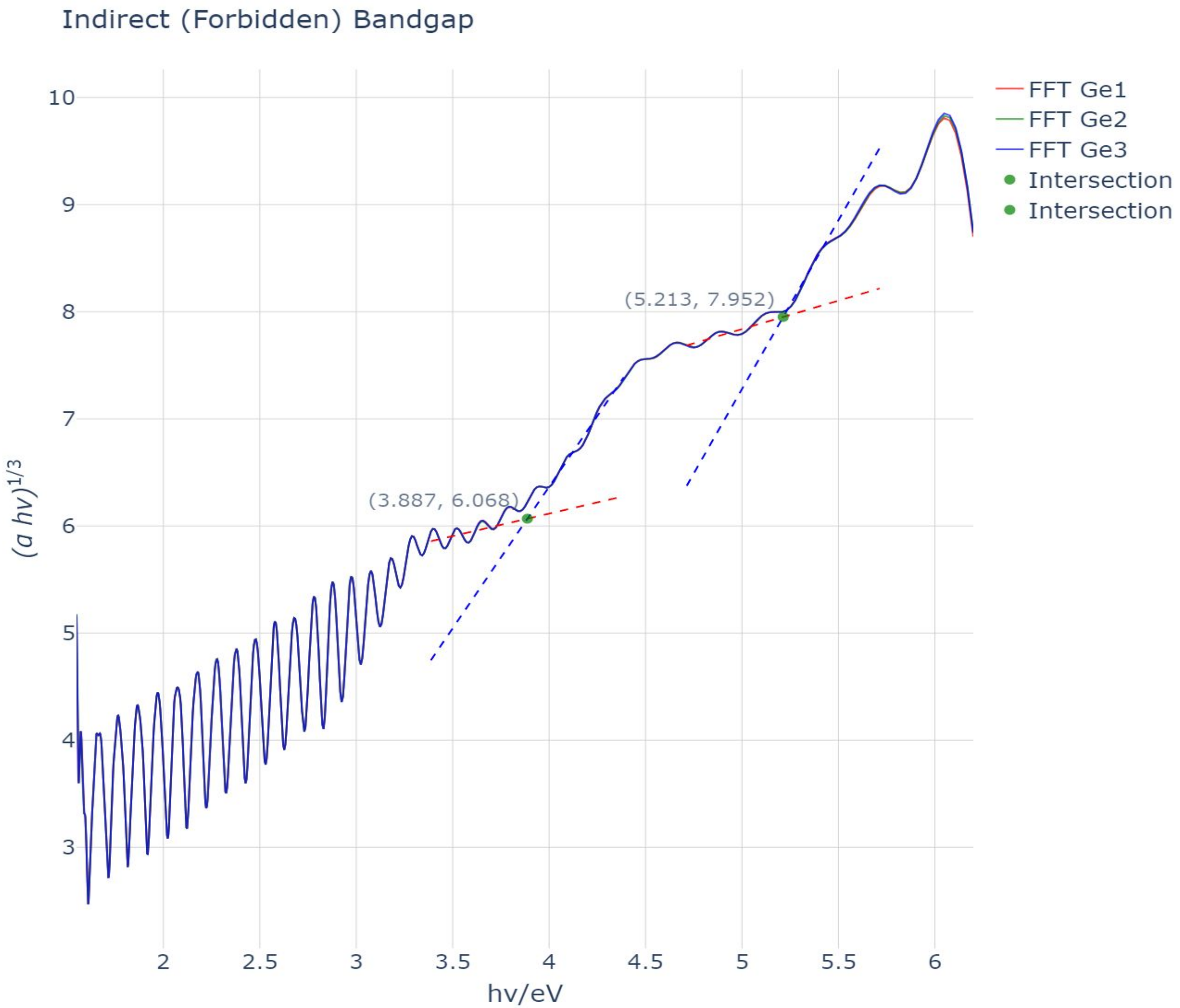
$\epsilon = \quad) - F^*(\omega)F$



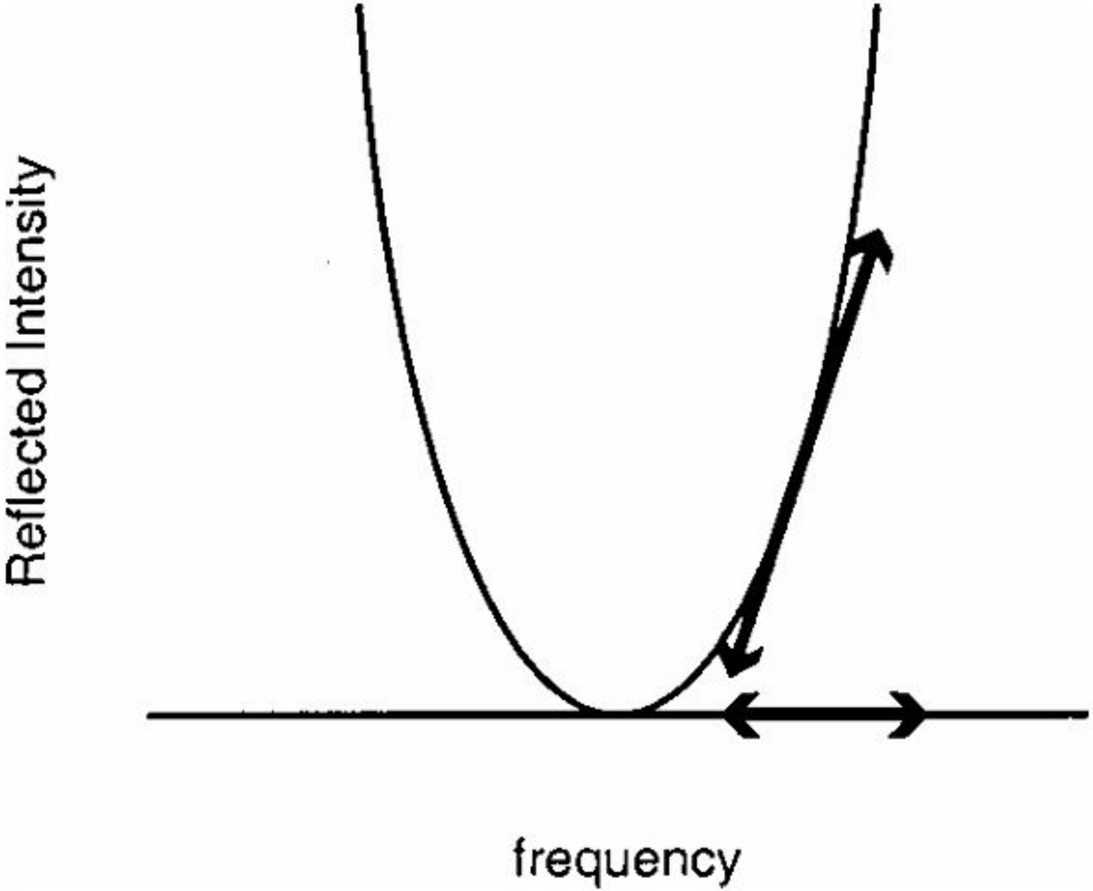




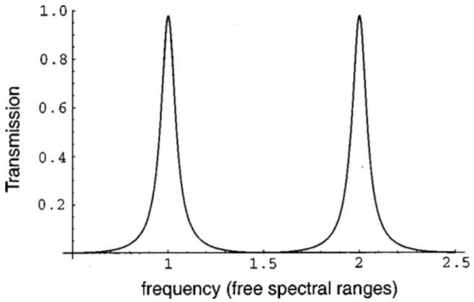




Indirect (Forbidden) Bandgap
FFT Ge1
FFT Ge2
FFT Ge3
Intersection
Intersection
(5.213, 7.952)
(3.887, 6.068)
$(a\ hv)^{1/3}$
hv/eV
10
9
8
7
6
5
4
3
2
2.5
3
3.5
4
4.5
5
5.5
6


Reflected Intensity
frequency

PDH motivations



- Need an accurate way to measure the laser's frequency

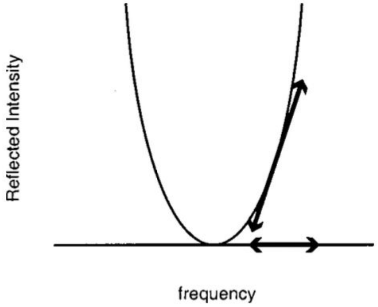
  - Send to cavity, check **transmitted** (or reflected)

  - fsr: free spectral range of cavity $\Delta \nu_{\text{fsr}} \equiv c/2L$

- Cannot distinguish between **fluctuations in the frequency** (that affects transmitted intensity) and **fluctuations in the intensity** of the laser itself
- Measure **reflected intensity** (and hold that at zero) to decouple intensity and frequency noise

Error signal

- ?: Reflected intensity is **symmetric about resonance**
- The **derivative** of it is **antisymmetric** about resonance
- Measure the **error signal** of the derivative by **varying the frequency**



- Above resonance: sinusoidal - **sinusoidal**

- Below resonance: sinusoidal - **180 degrees out of phase**

- At resonance: **no change** in the reflected intensity

How to measure the error signal?

- The reflected beam is sent into a (ms) **photodetector**
- The product of the **output of the photodetector** and the **local oscillator's signal** is generated via a mixer (which will contain signals with **low frequency** and **twice the modulation frequency**)
- The low frequency error signal is isolated from the combined output by the **low-pass filter**

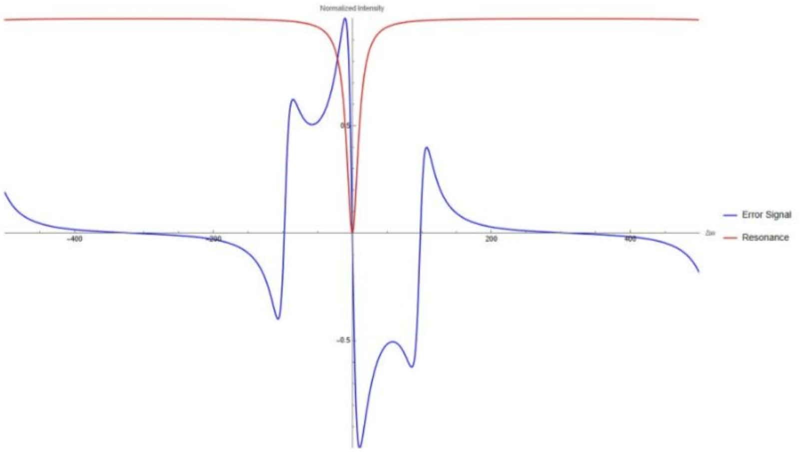


Figure 7: Calculated normalized resonance transmission signal and imaginary part of the error signal as a function of the deviation from the resonance frequency δw [1]. This should be experimentally observed on the oscilloscope.

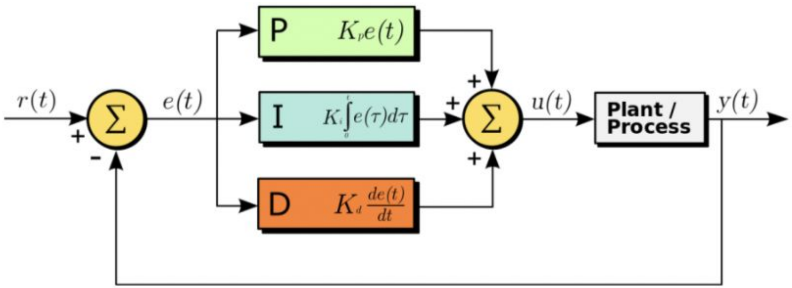
PID

- Proportional-Integral-Derivative algorithm
- **u(t)** (controlled input): **voltage** to the piezo in the laser cavity
- **e(t)**: error between the measured output and the desired output
- P, I, D account for

  - P: magnitude

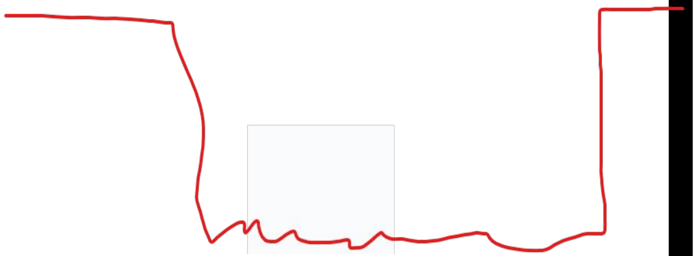
  - I: magnitude and time (reduce the error during a period of time)

  - D: Predicting future behavior using derivative (reduce the magnitude of overshoot)

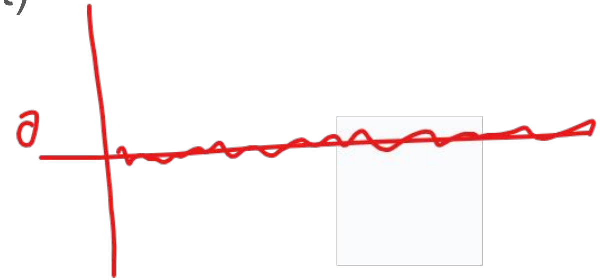


Result

Long term Trans
psi(t)

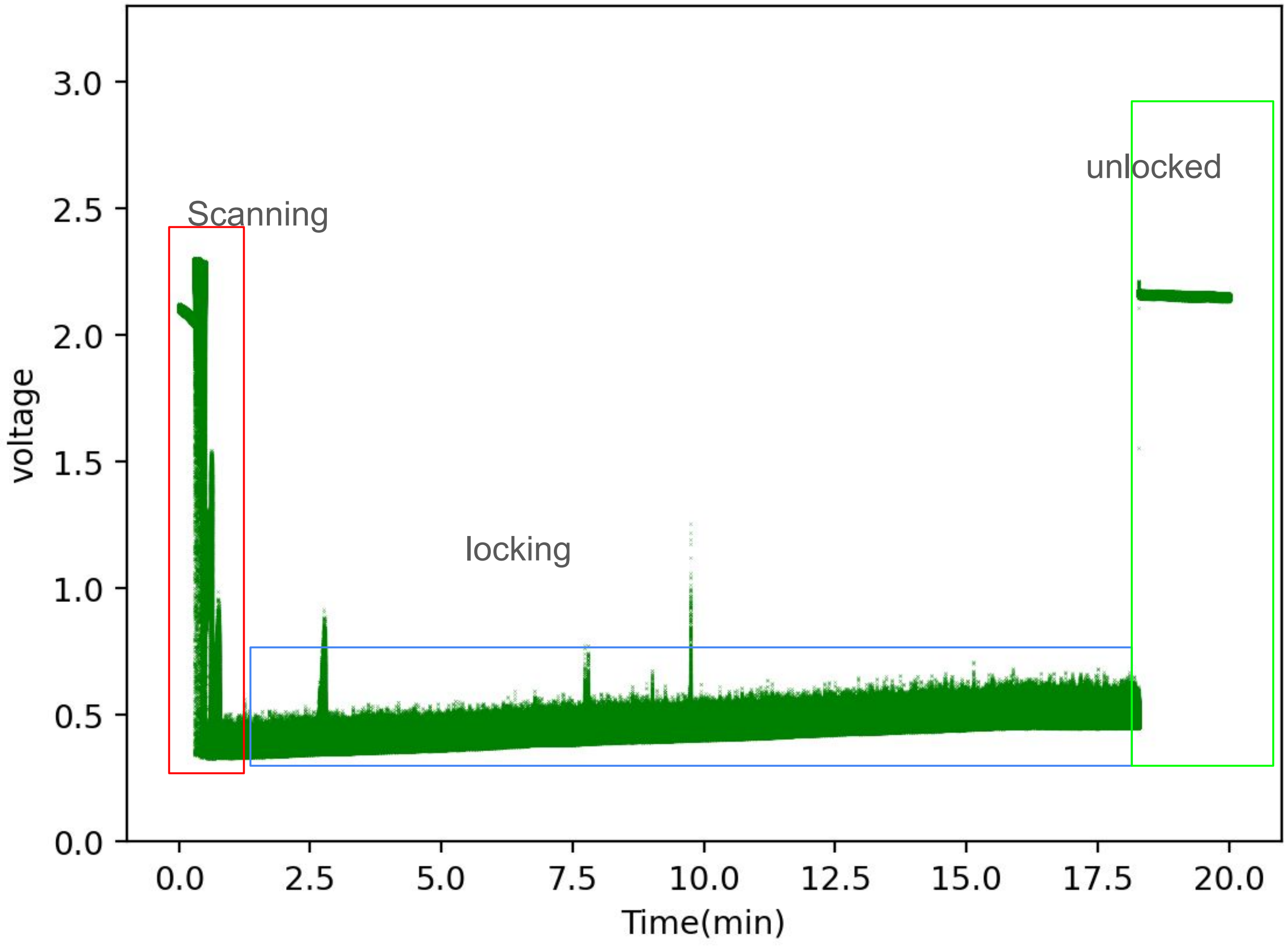


Long term error
psi(t)



Long term Trans
phi(f)

Long term error
phi(f)



Scanning

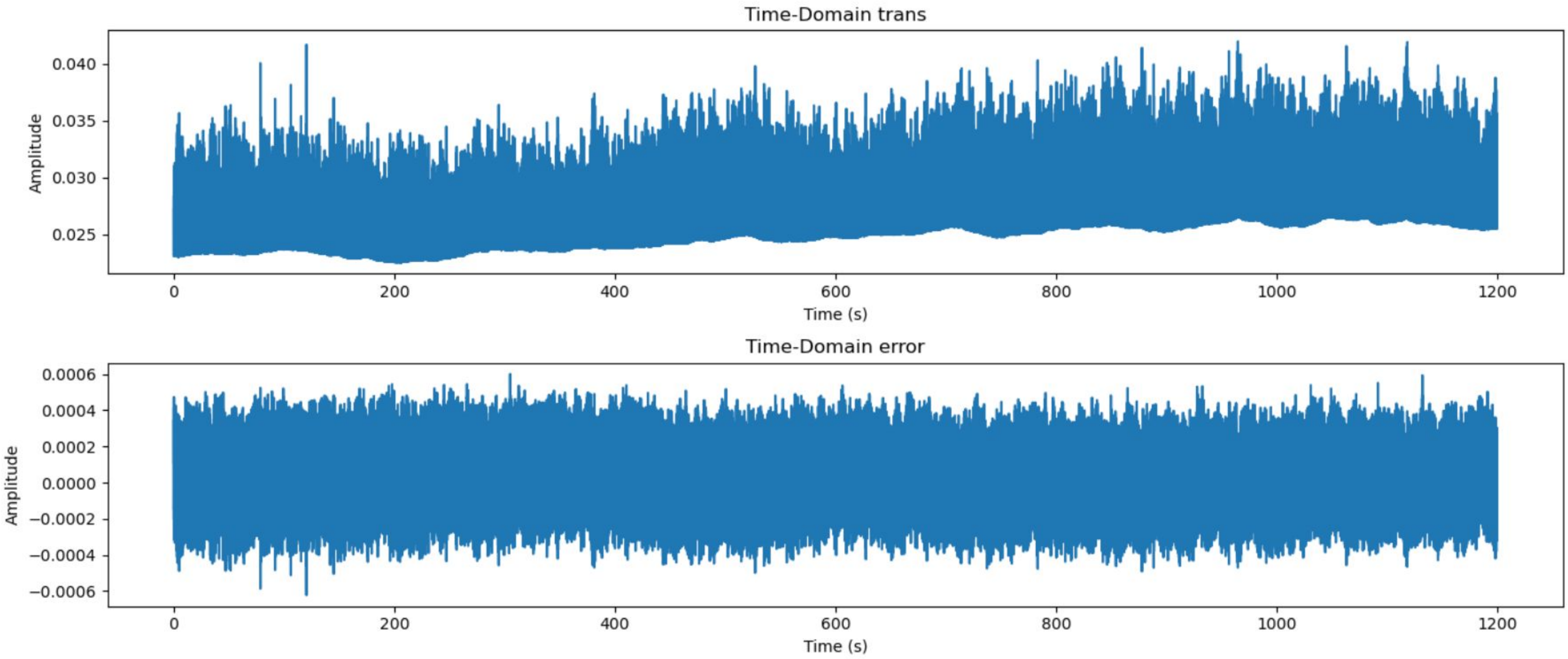
Locking

Unlocked

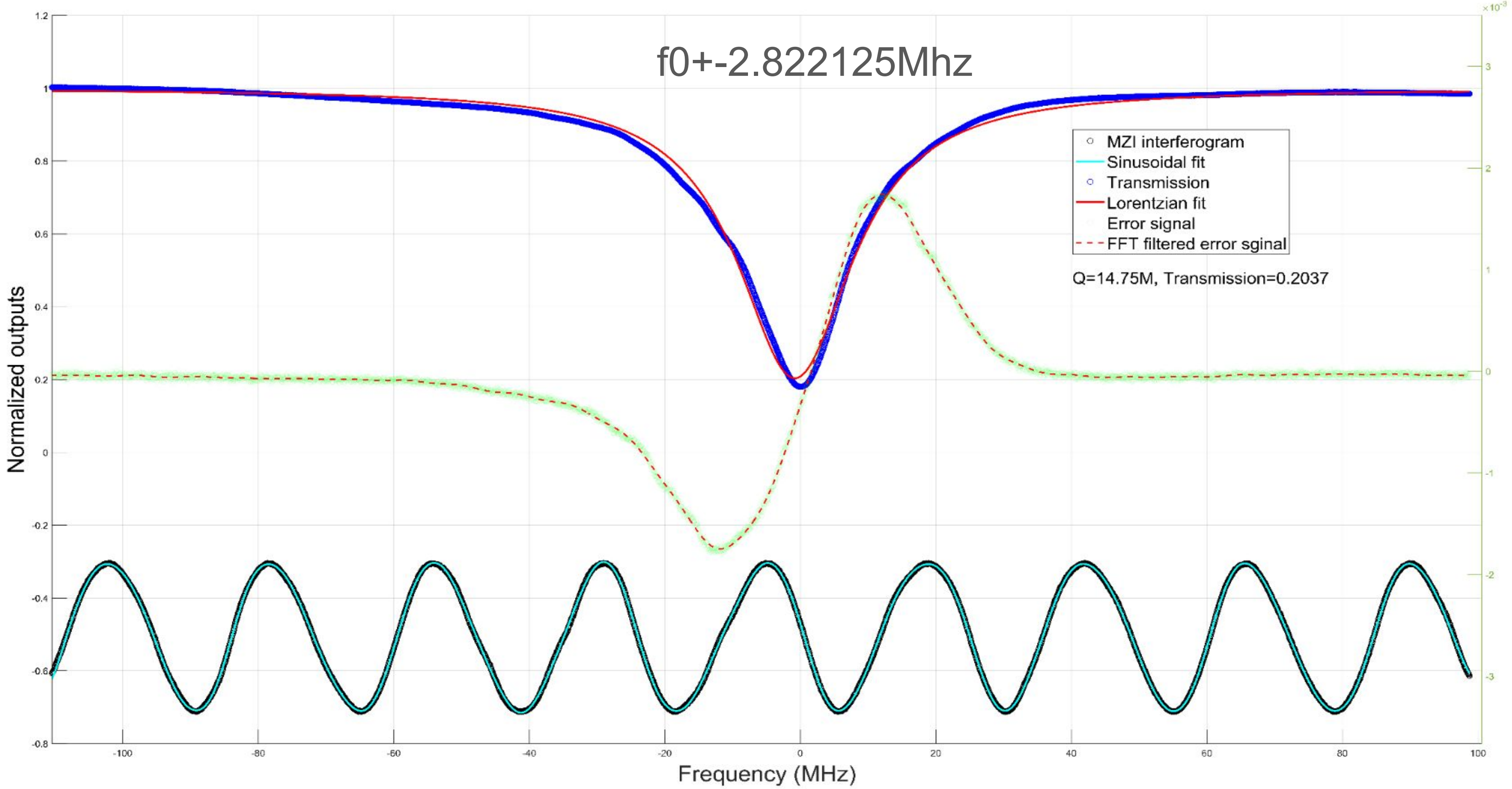
The reason it gradually lifts up is the change in polarization as time proceeds. This change the peak transmission

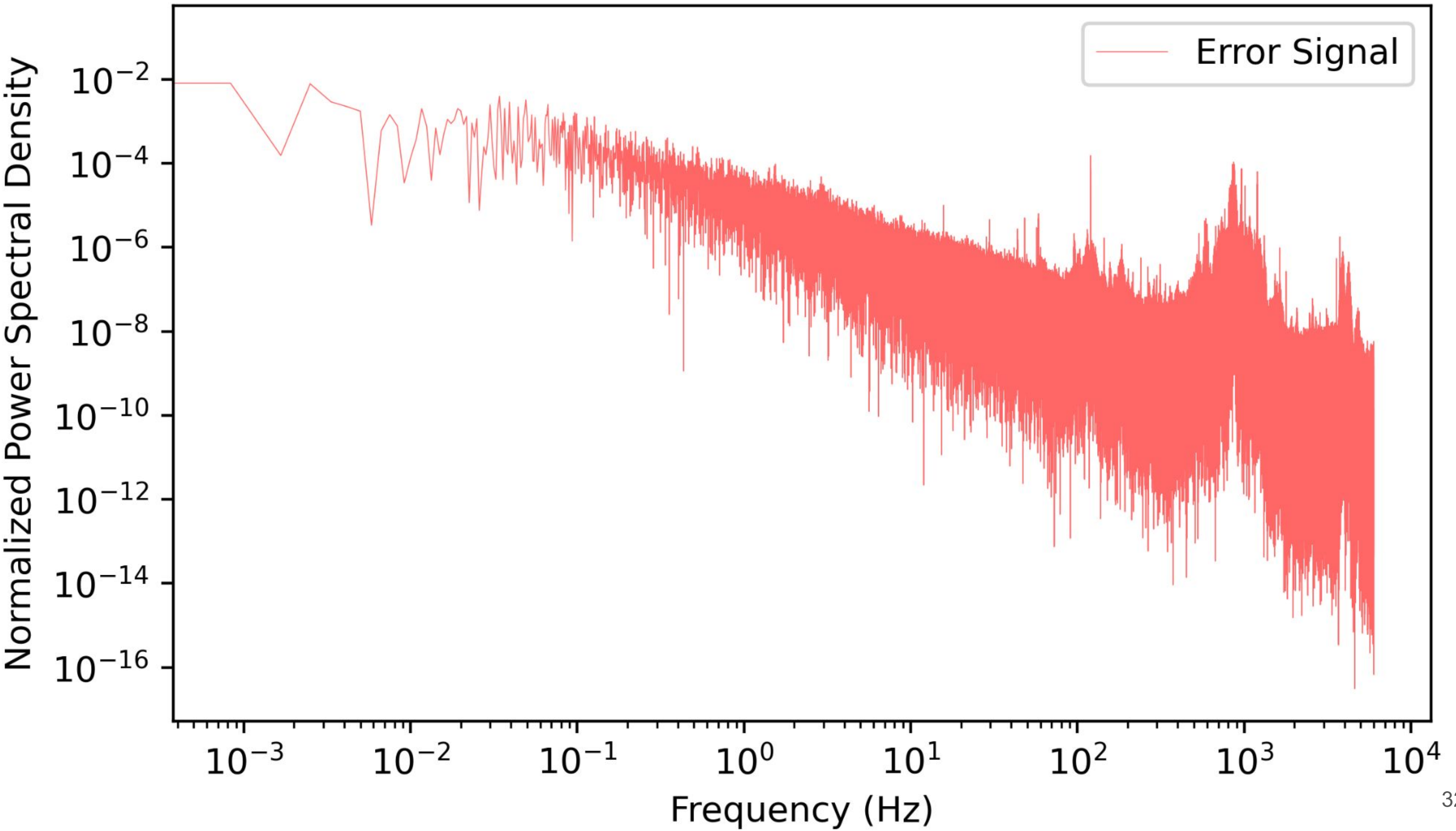
For this one(package1), it has a error in short term, and a long term transmission measurement

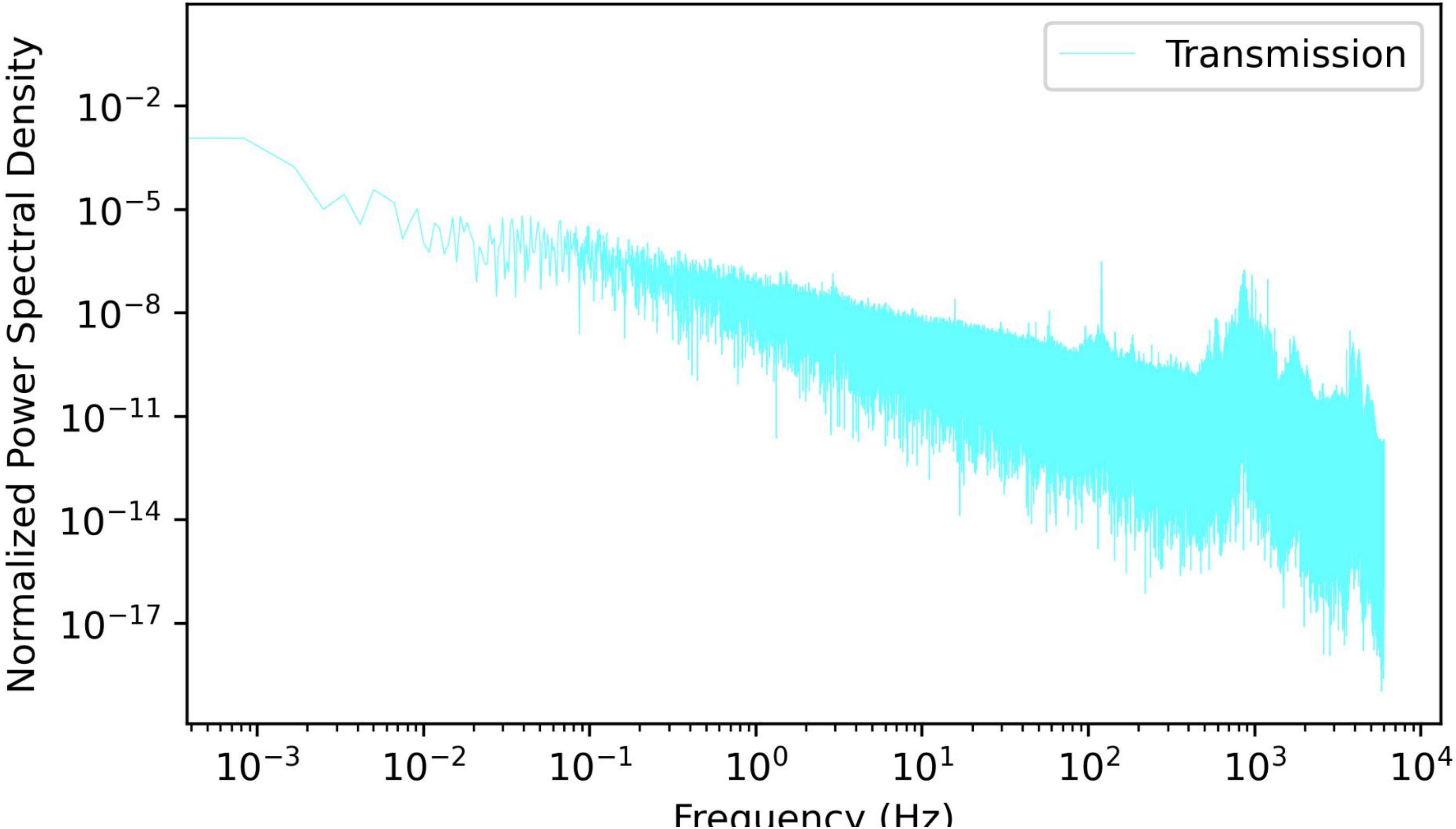
f0+-2.822125Mhz, Replace these two with alpha

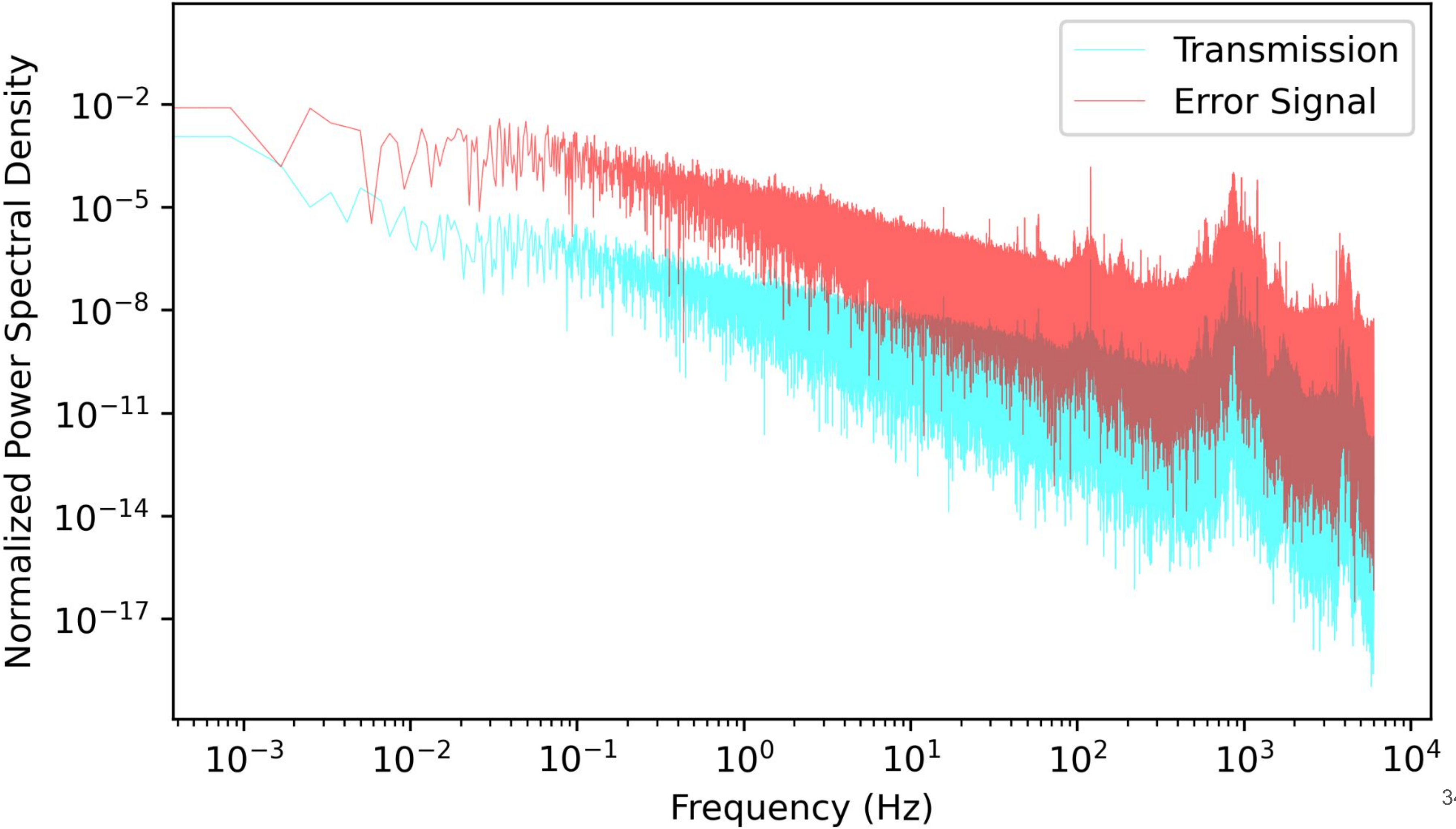


f0+-2.822125Mhz




Error Signal
Normalized Power Spectral Density
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency (Hz)


Transmission
Normalized Power Spectral Density
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency (Hz)


Transmission
Error Signal
Normalized Power Spectral Density
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency (Hz)

Compare the two measurements