Frequency Locking a Laser to Rb-87

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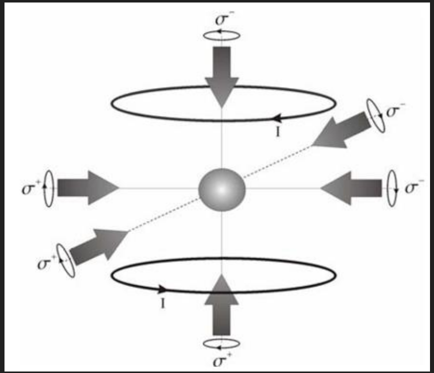
Why do we want to frequency-lock lasers?



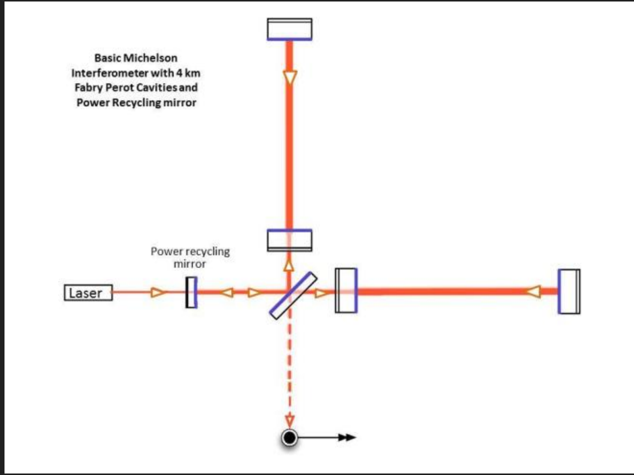
doi:10.12921/cmst.2010.SI.02.115-129

Laser frequency drifts due to different environmental effects.

Applications:

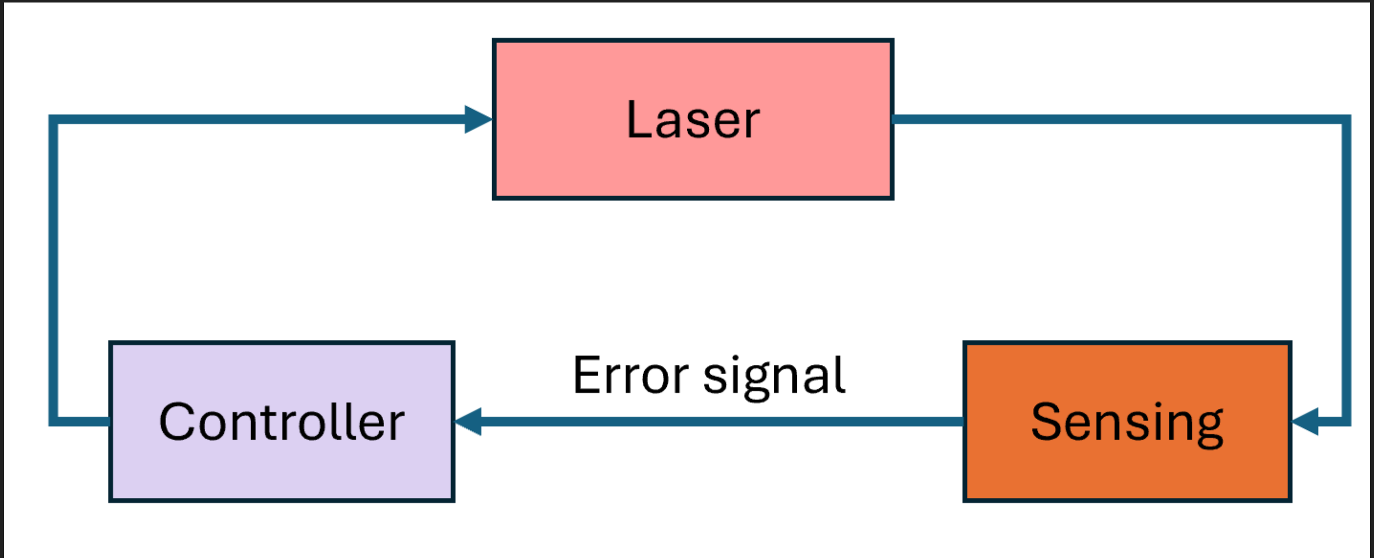
- LIGO: frequency lock using PDH locking
- GQuEST: Design filter cavities (MOT)

Ultimately, we want to frequency-lock the laser to reduce the degrees of freedom in and stabilize our experiments.



Credit: Caltech/MIT/LIGO Lab

How do we lock lasers?

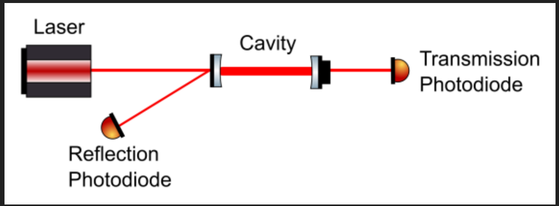


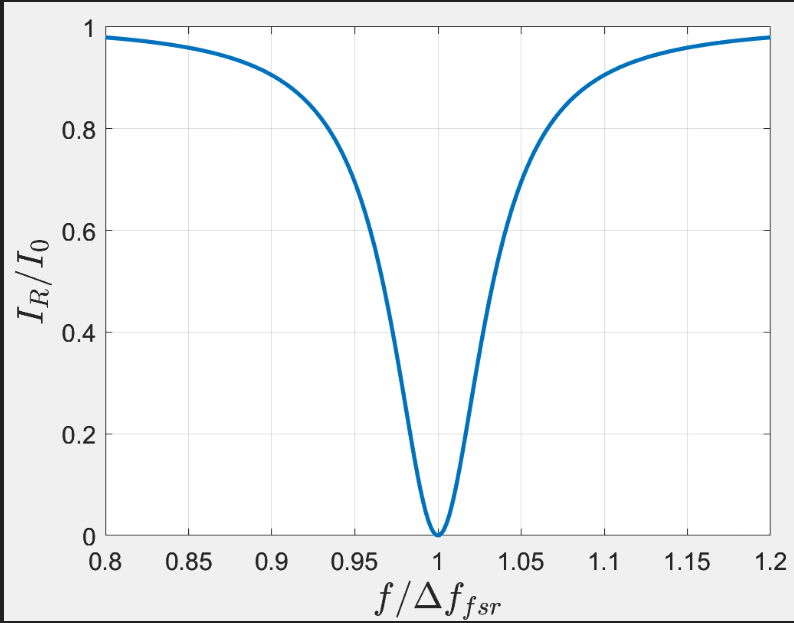
How do we lock lasers? Pound Drever Hall (PDH) technique

1). Mechanism

The PDH technique uses a cavity (two parallel mirrors) as a reference to lock the laser to.

If our laser is at the resonant frequency of the cavity, we achieve minimum reflectance and maximum transmittance.

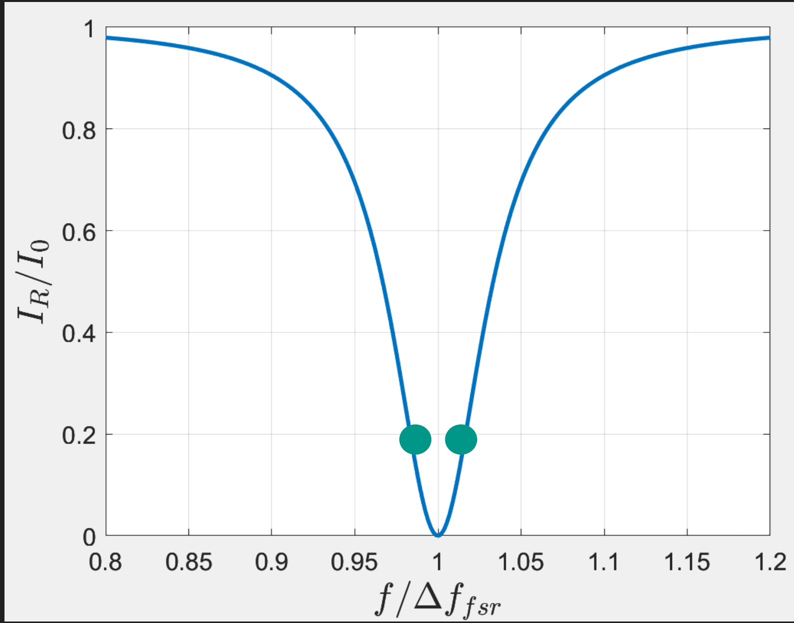




How do we lock lasers? Pound Drever Hall (PDH) technique

1). Mechanism

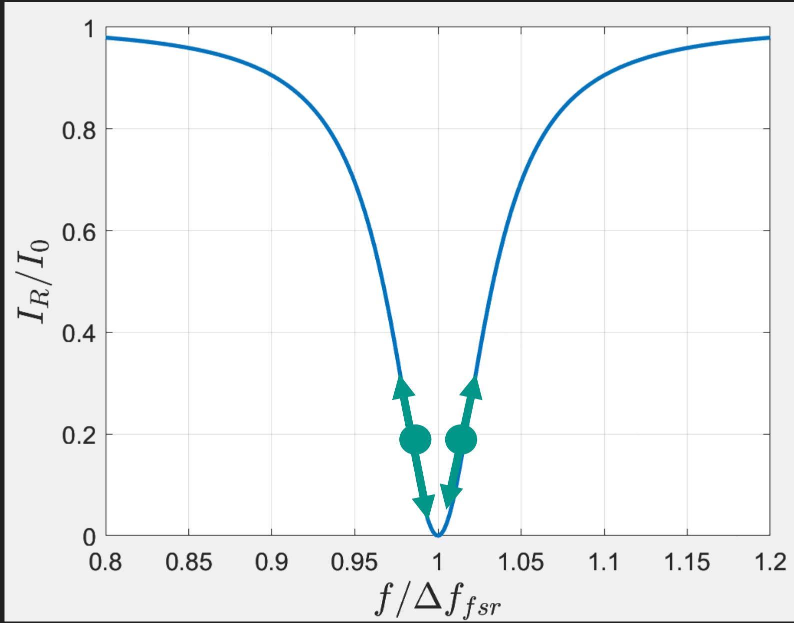
How do we distinguish between if we are above or below resonance?



How do we lock lasers? Pound Drever Hall (PDH) technique

2). Dithering

If we modulate the incoming light, we can determine if the “derivative” of the curve is positive or negative, which distinguishes whether we are above or below resonance.

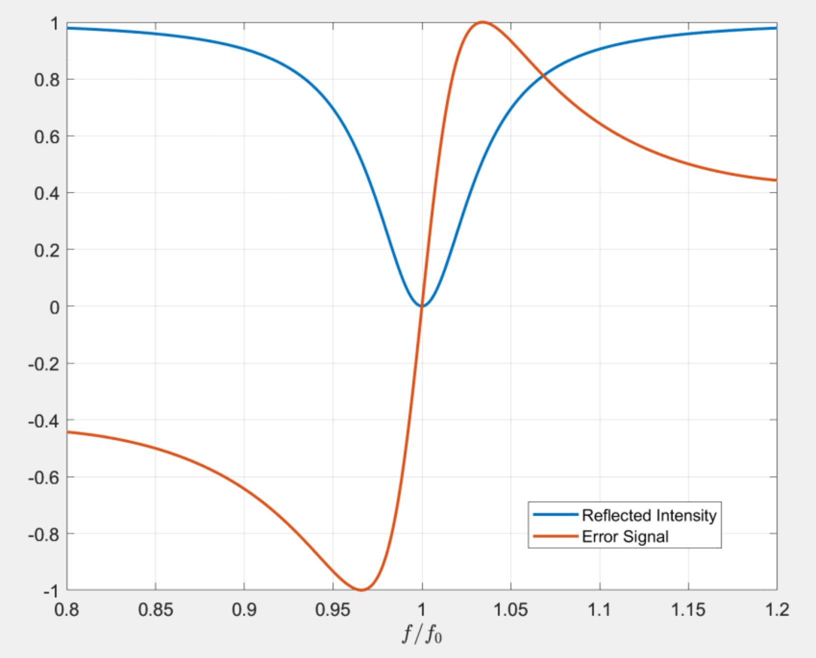


How do we lock lasers? Pound Drever Hall (PDH) technique

3). Demodulation

We extract the error signal by mixing then lowpass-filtering our measured signal.

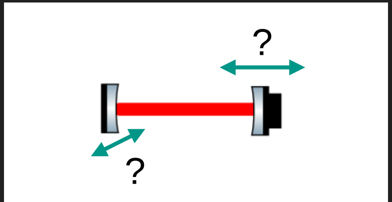
This asymmetric signal tells us which side of resonance we are on!



Vapor Cells: an absolute reference

Downfalls of cavities:

- Mirrors are prone to mechanical shifts, temperature expansions, etc.
- Relative reference.



Vapor Cells: an absolute reference

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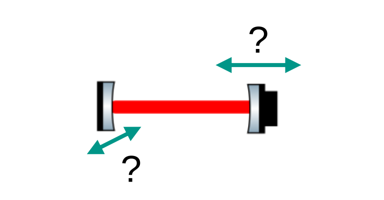
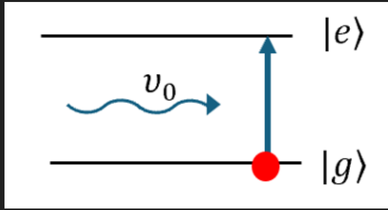
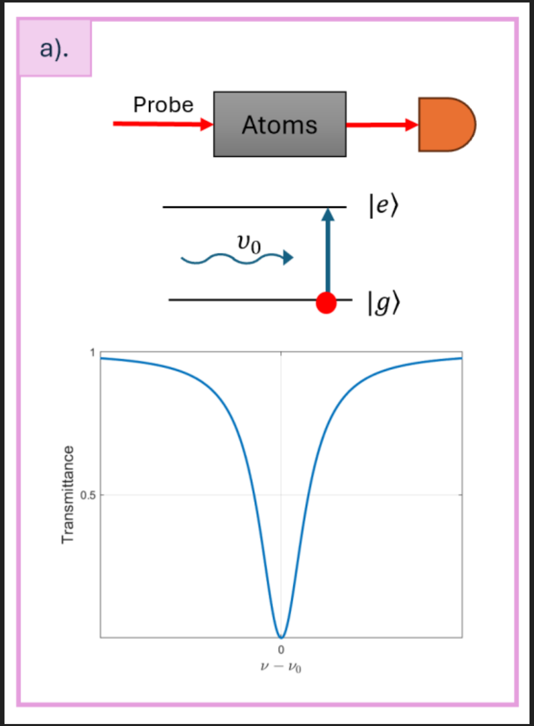


What about locking with a vapor cell?

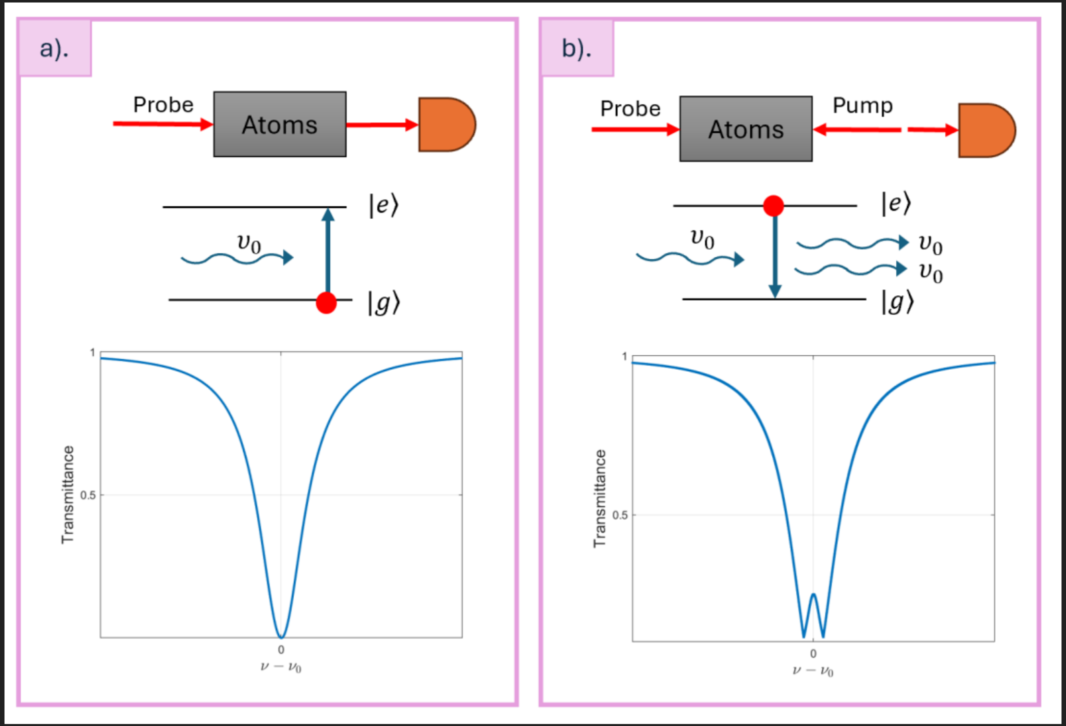
- Atomic transitions are an absolute reference.
- We can lock to an exact transition, which is useful when you are working with a laser of single frequency.
- Issues: they suffer from external fields, limited transitions and transition strength



How do we lock to a vapor cell?



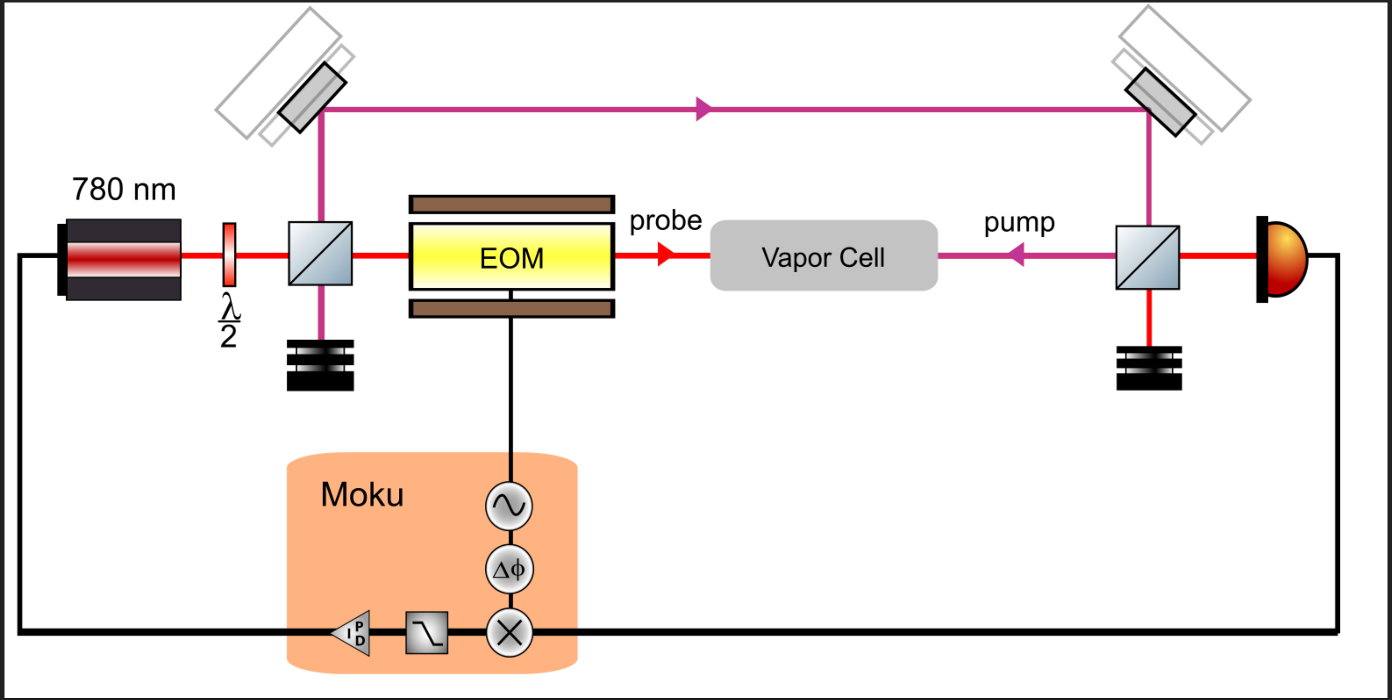
How do we lock to a vapor cell?

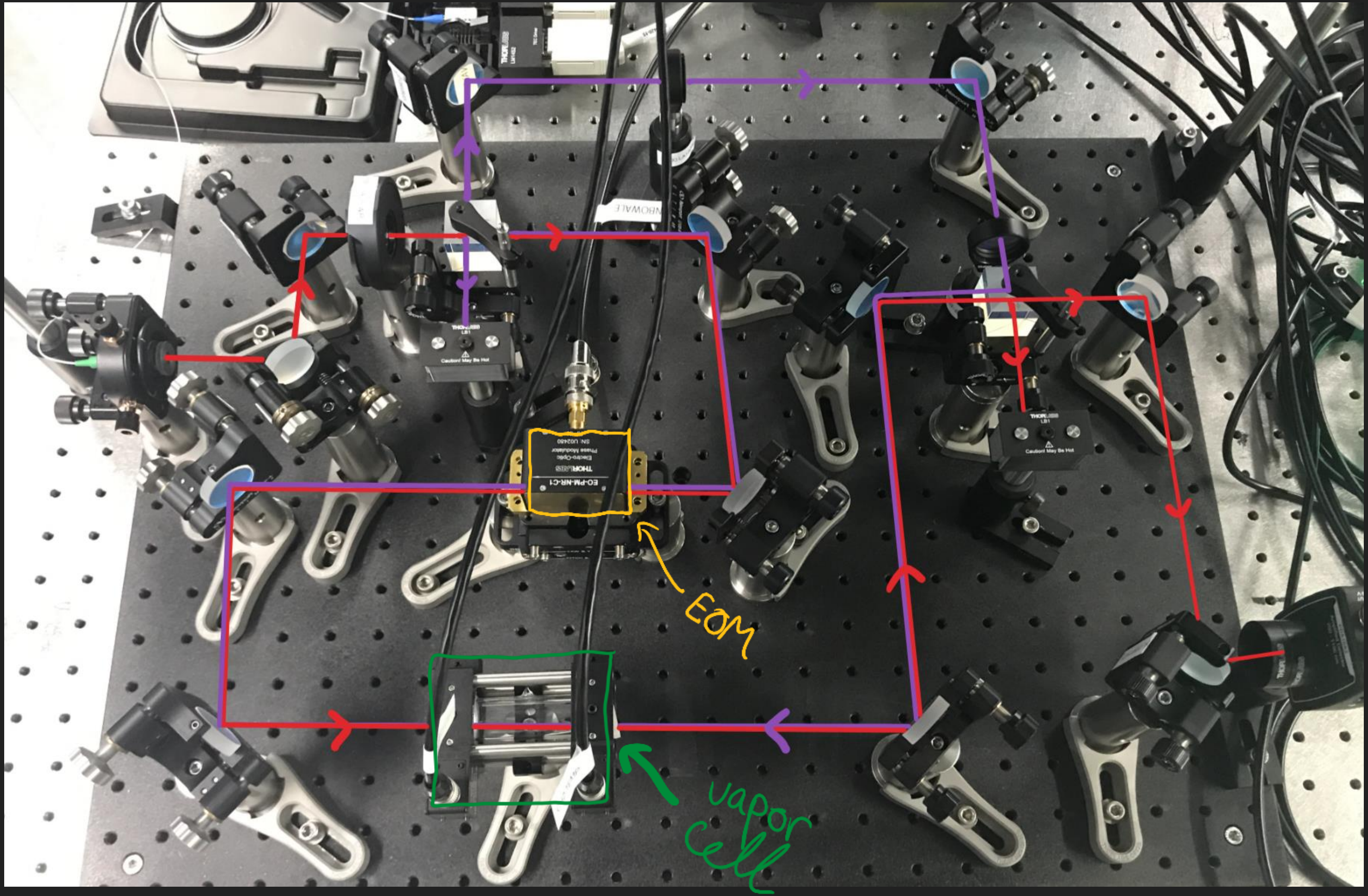


How can we achieve greater frequency discrimination?

Add a pump into the setup.

Method: Optical Setup

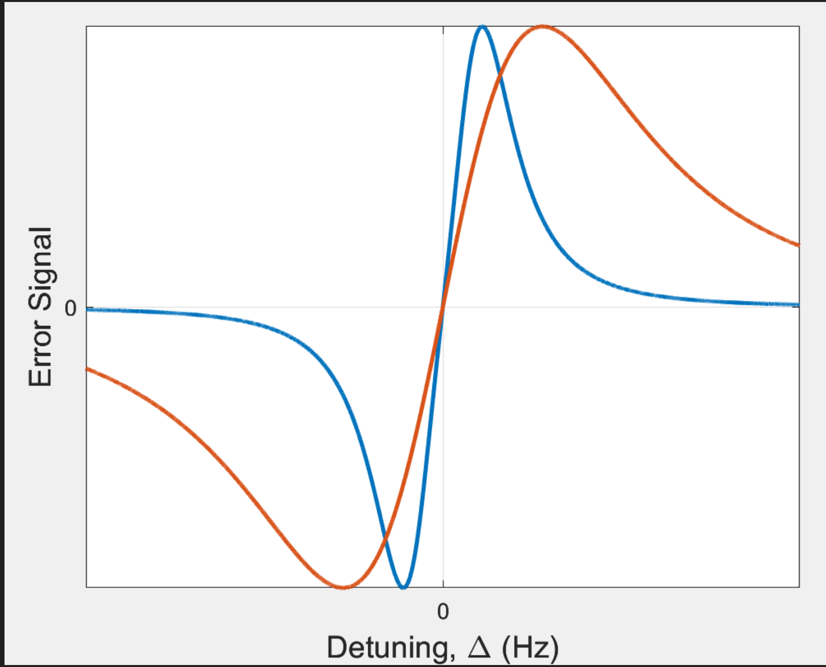



EOM
vapor
cell

Maximizing error signal

We want to maximize the error signal slope to get better frequency discrimination.

To maximize the slope, we want to maximize the absorption dip depth.

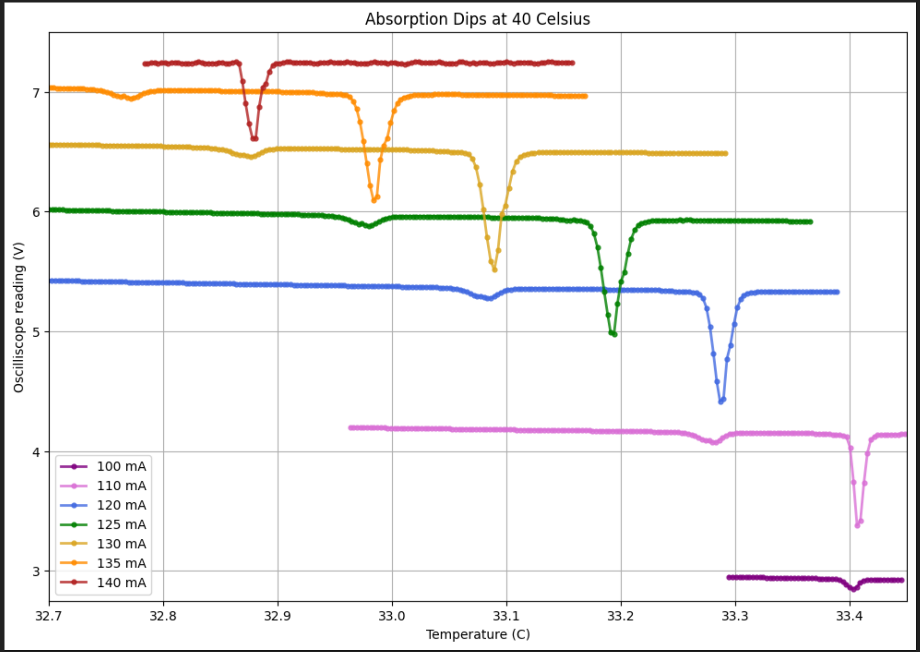


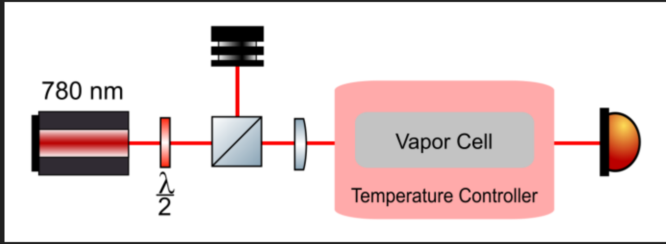
Maximizing error signal

How do…

- Beam size
- Vapor cell temperature
- Laser current
- Laser temperature
- Incident power on vapor cell

affect the depth of the absorption dip?

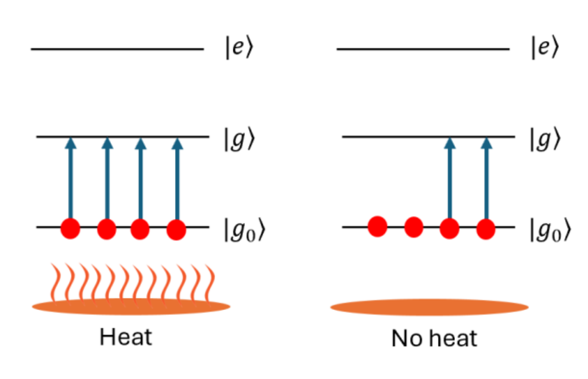


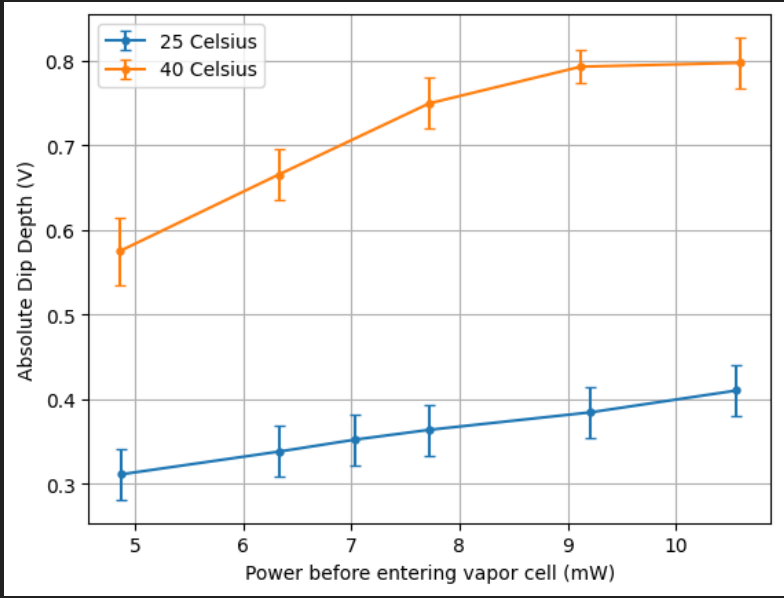


Effect of vapor cell temperature on dip depth

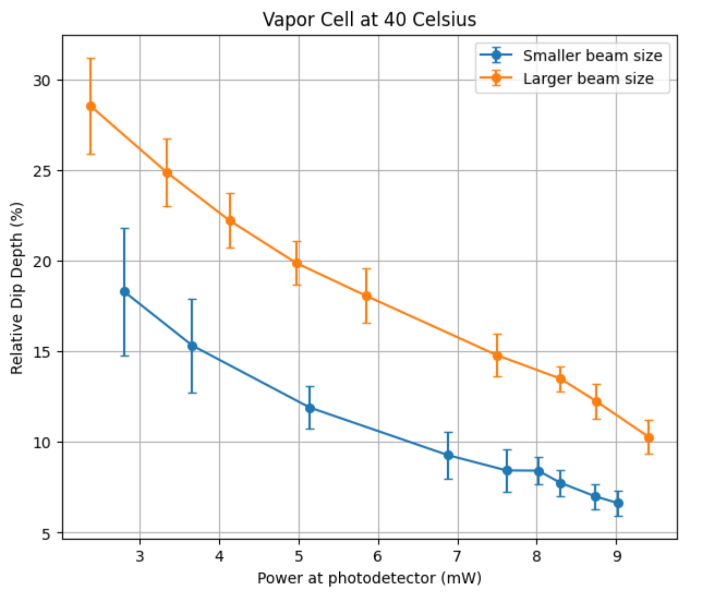
At higher temperatures…

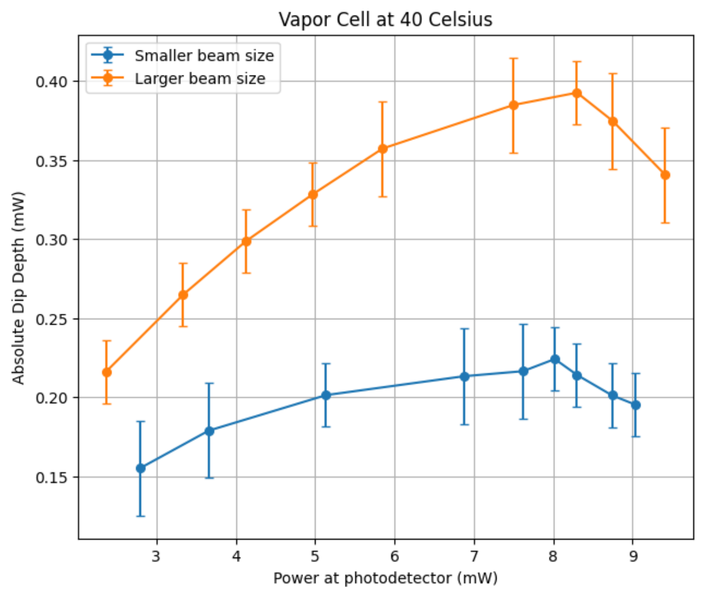
- We begin packing the states.
- We get a higher atomic density, which increases absorption.

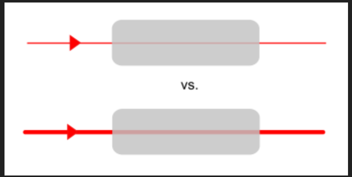




Effect of beam size on dip depth



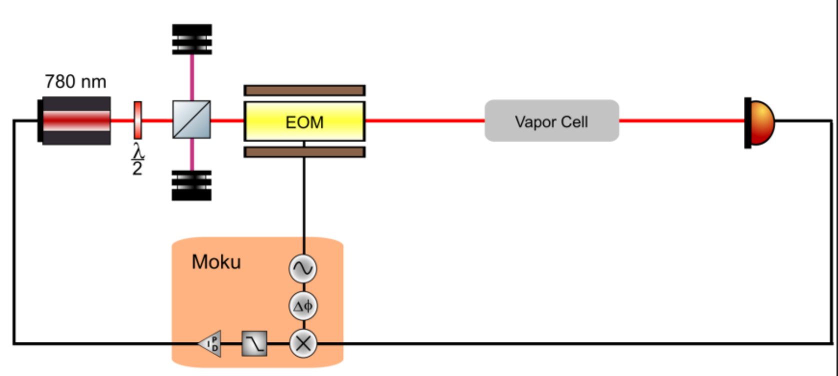


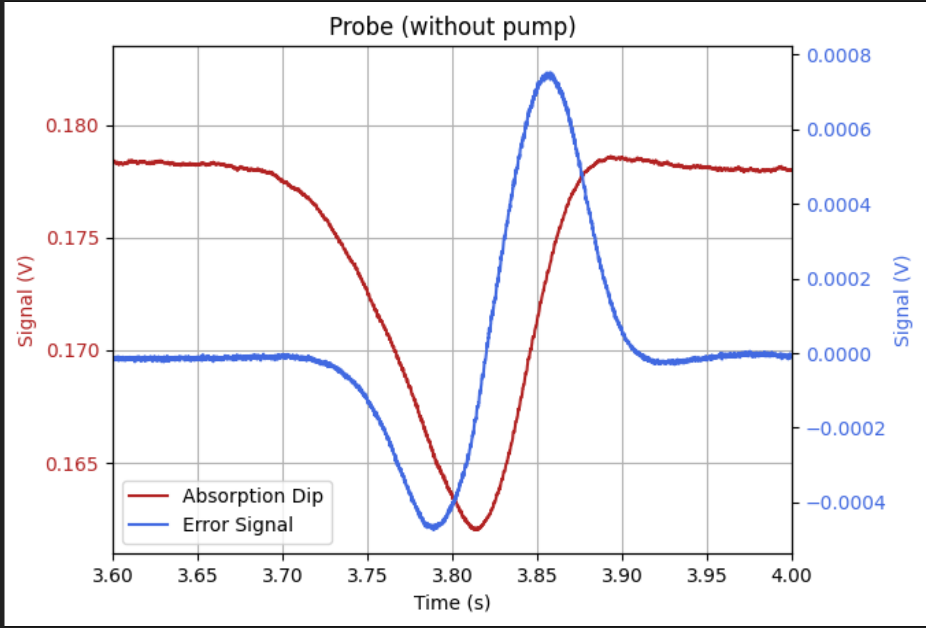


Main conclusions: A larger beam size and higher vapor cell temperature increases the absorption dip depth.

Locking to the single absorption dip

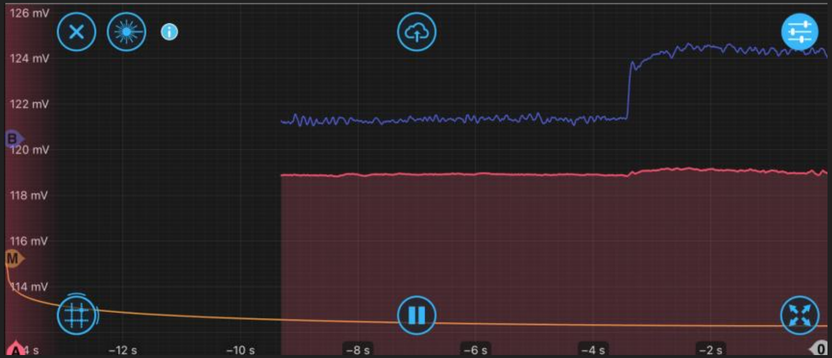
Send modulated light through the vapor cell and demodulate to get the error signal.



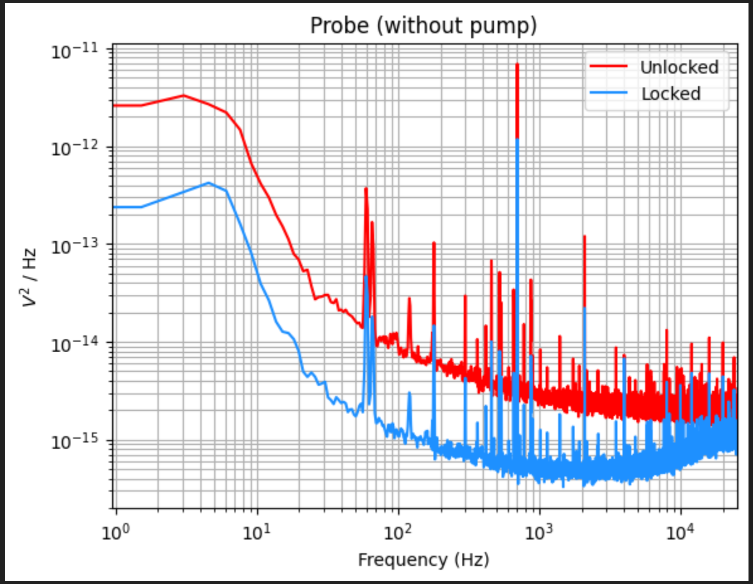


Locking to the single absorption dip

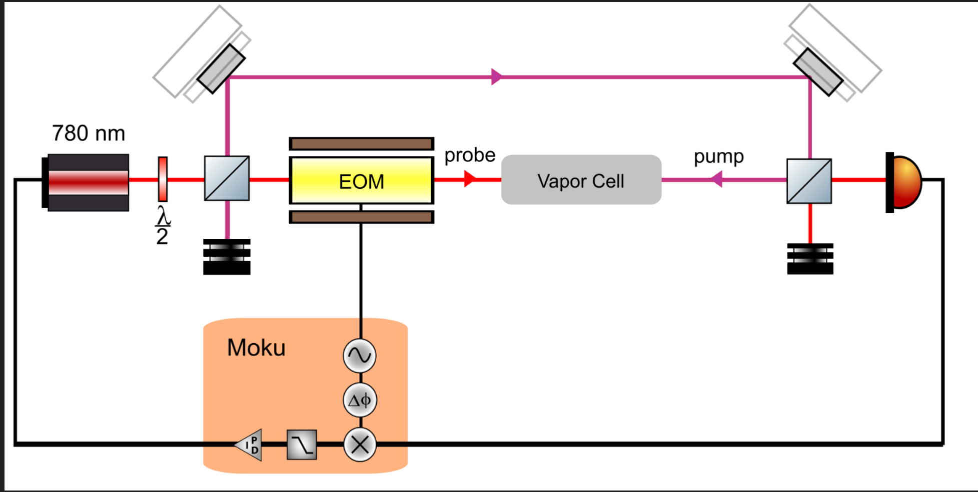
How do we know we're locked?

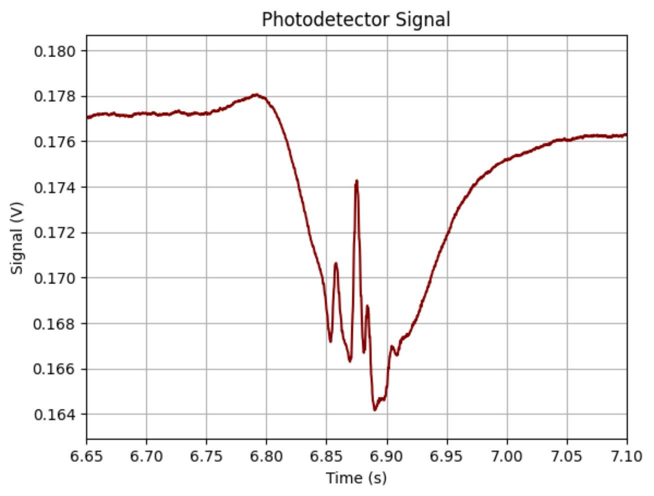


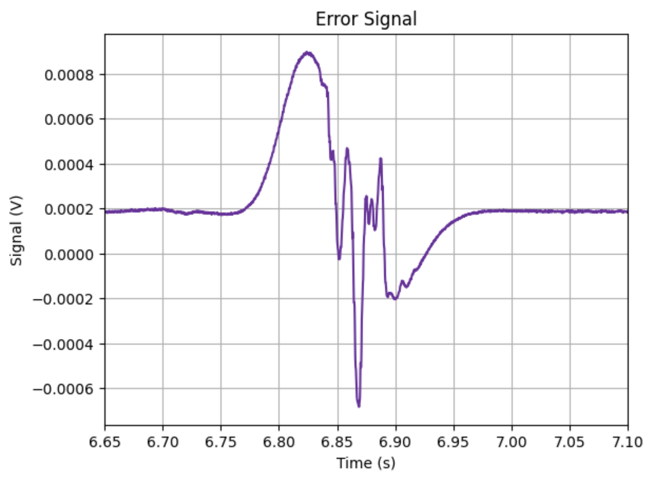
We take the power spectral density (PSD) of the error signal while locked and after breaking lock to obtain a measurement of noise.



Locking to the saturated absorption dip







Locking to the saturated absorption dip

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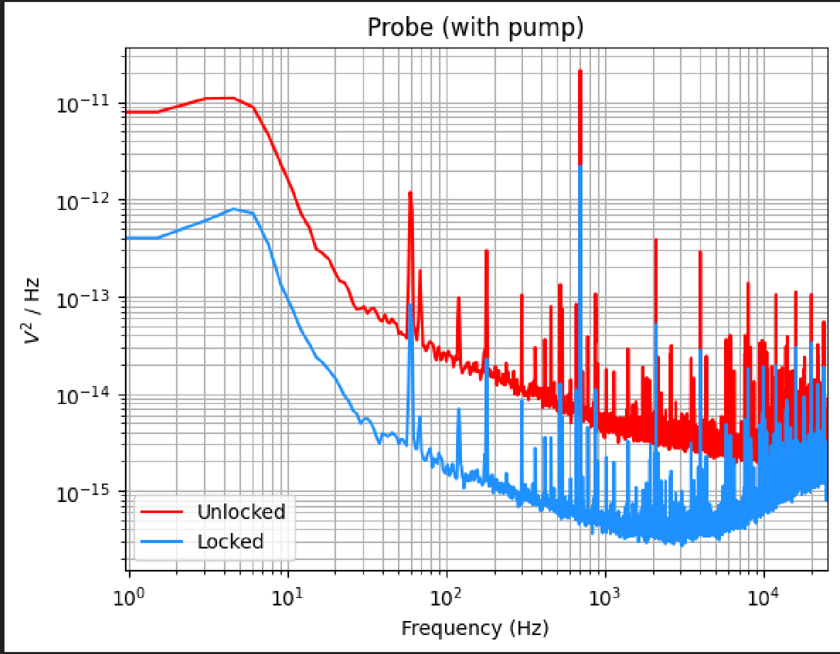
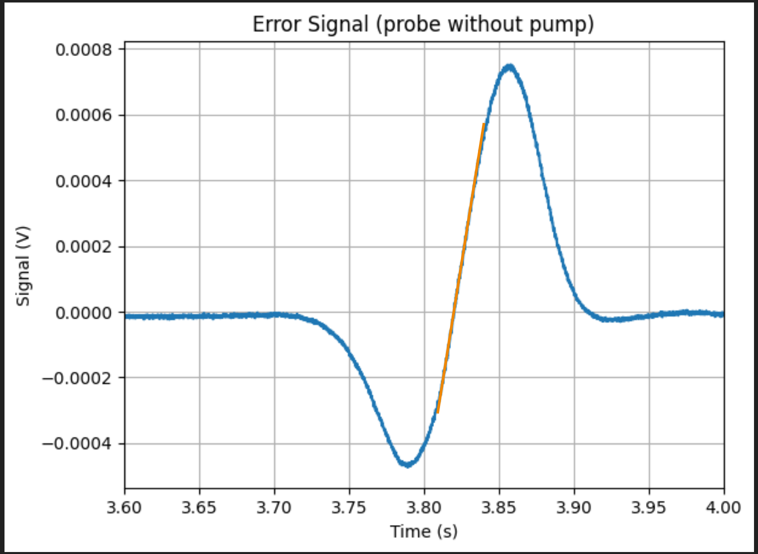
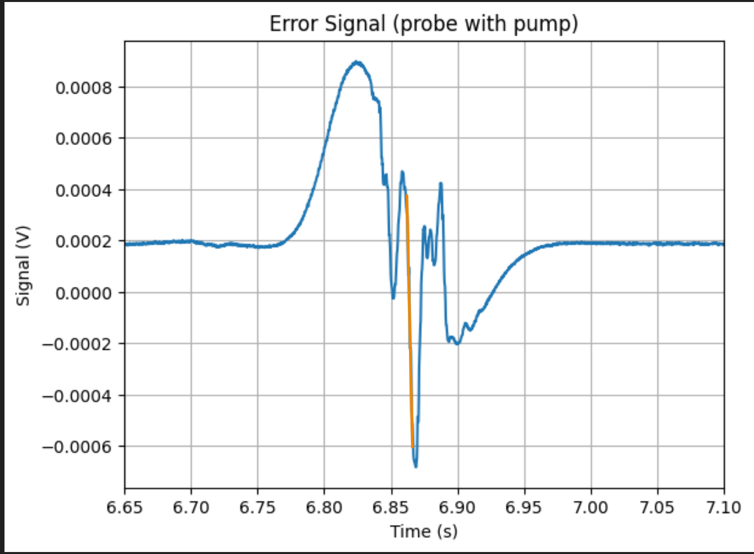


Frequency Discrimination Comparison

The magnitude of the slope of our error signal is approximately 3.4 V/THz.

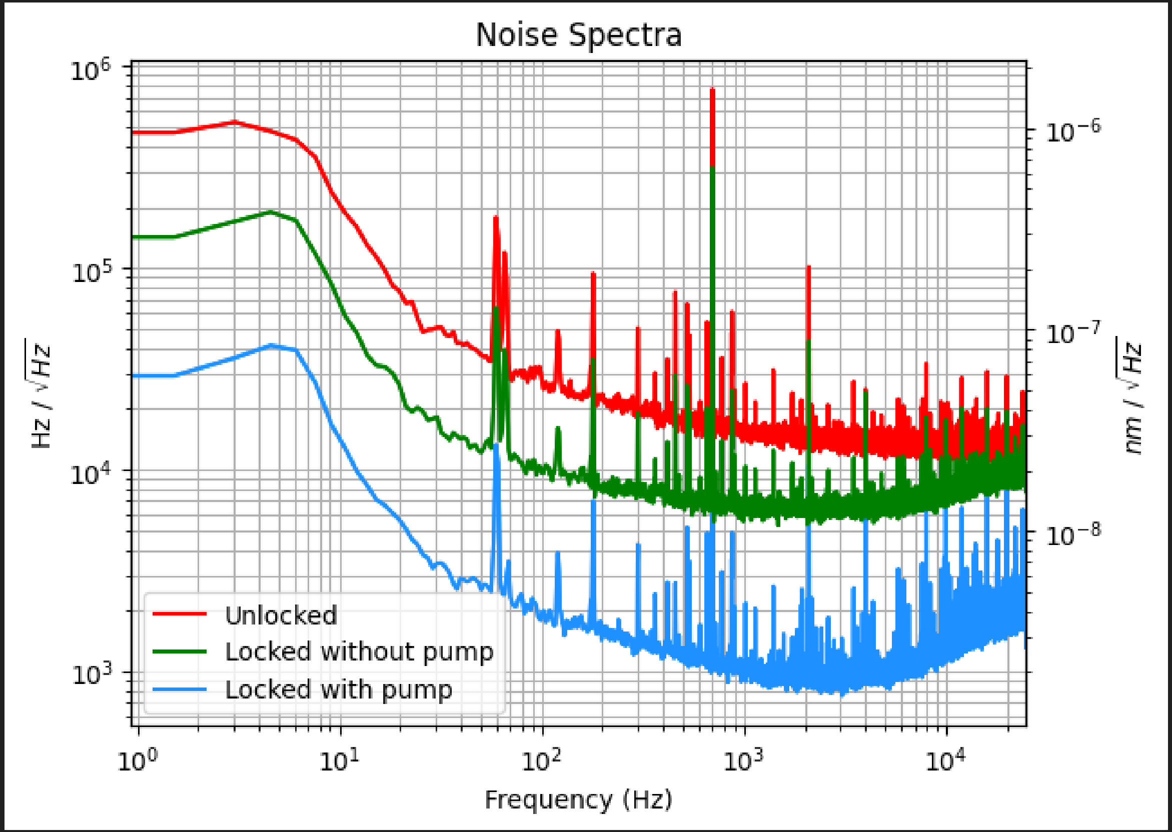


The magnitude of the slope of our error signal is approximately 21.6 V/THz.



Noise Spectra

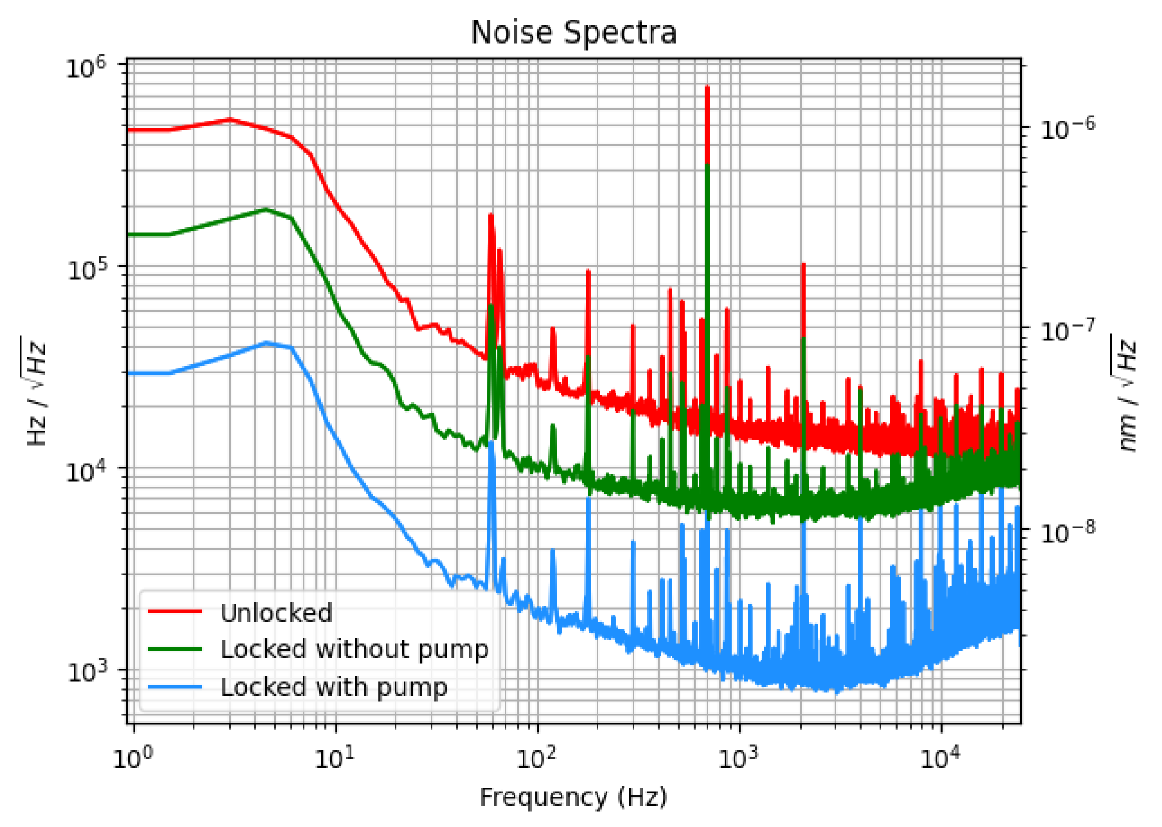
The probe and pump configuration produces the least amount of noise!



Noise Spectra

The probe and pump configuration produces the least amount of noise!

This is a good sanity check but more optimization and testing is necessary before we can fully trust these results.



Future Work

- Optimize the slow and fast controller.
  - Parameter adjustments like gain and corner frequencies can cause the locked laser to display greater noise than the free-running laser.
- Improve signal amplification with a low-noise amplifier and tank (resonance) circuit.
- Fix the laser’s power fluctuations.
- Improve calibration.
- Subtract out Doppler broadening effect to extract atom transitions.
- Add second harmonic generation to lock a 1560 nm laser rather than just a 780 nm laser.

Acknowledgements

Thanks to…

- Ian MacMillan and Lee McCuller
- Everyone in the McCuller lab (Alex, Daniel, Jeff, Sander, Torrey)
- Erin McGee, Umran Koca, Rafael Crespo, and everyone in the LIGO SURF program

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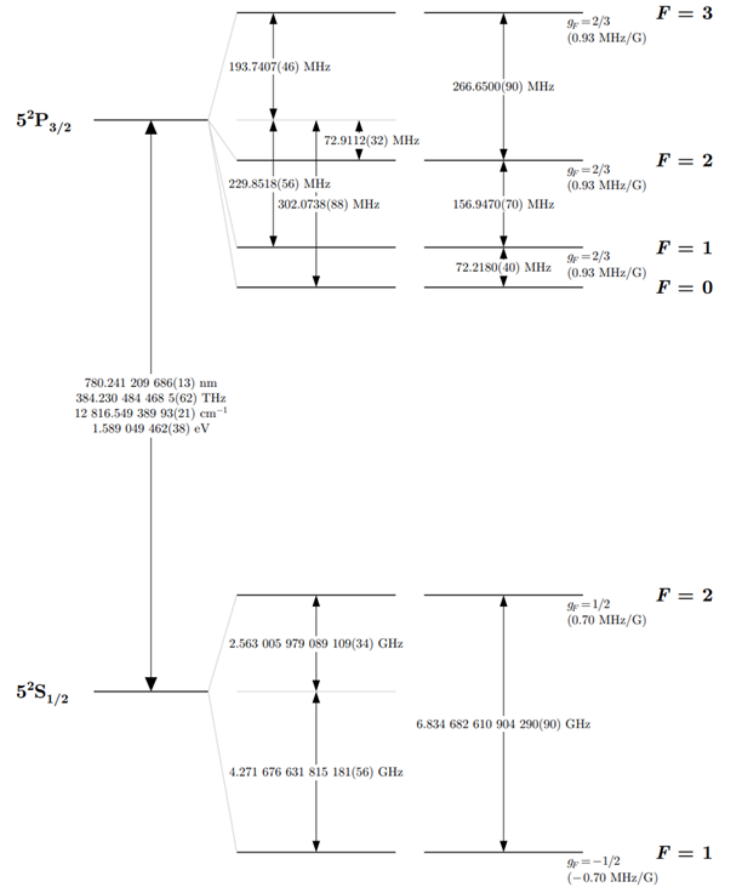
Rb 87 Structure

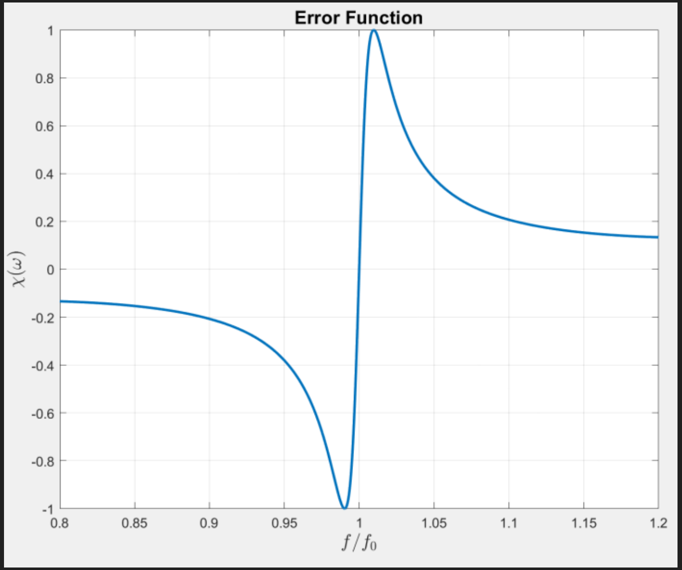
Table 3: ^{87}Rb D_2 ($5^2S_{1/2} \longrightarrow 5^2P_{3/2}$) Transition Optical Properties.

Frequency	ω_0	$2\pi \cdot 384.230\,484\,468\,5(62)$ THz	[6]
Transition Energy	$\hbar\omega_0$	1.589 049 439(58) eV	
Wavelength (Vacuum)	λ	780.241 209 686(13) nm	
Wavelength (Air)	λ_{air}	780.032 00 nm	
Wave Number (Vacuum)	$k_L/2\pi$	12 816.549 389 93(21) cm^{-1}	
Lifetime	τ	26.24(4) ns	[11]
Decay Rate/ Natural Line Width (FWHM)	Γ	$38.11(6) \times 10^6$ s^{-1} $2\pi \cdot 6.065(9)$ MHz	
Absorption oscillator strength	f	0.6956(15)	
Recoil Velocity	v_r	5.8845 mm/s	
Recoil Energy	ω_r	$2\pi \cdot 3.7710$ kHz	
Recoil Temperature	T_r	361.96 nK	
Doppler Shift ($v_{atom} = v_r$)	$\Delta\omega_d(v_{atom} = v_r)$	$2\pi \cdot 7.5419$ kHz	
Doppler Temperature	T_D	146 μK	
Frequency shift for standing wave moving with $v_{sw} = v_r$	$\Delta\omega_{sw}(v_{sw} = v_r)$	$2\pi \cdot 15.084$ kHz	

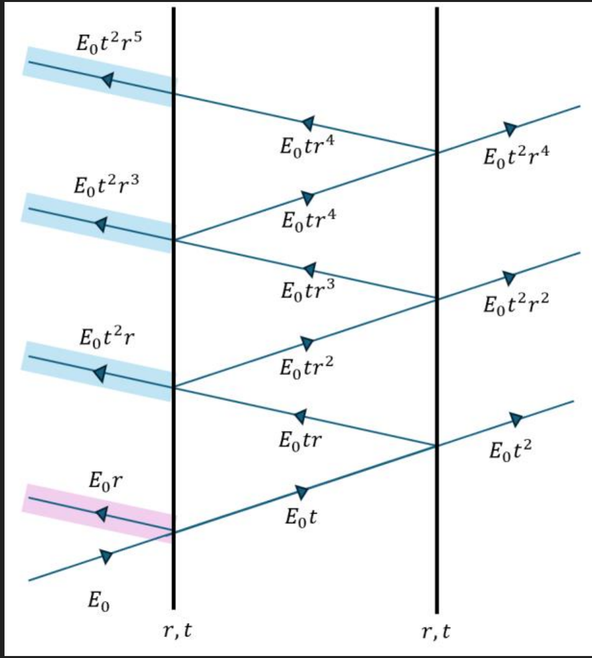


D. A. Steck, Rubidium 87 d line data, available online at http://steck.us/alkalidata. (revision 2.1.4, 23 December 2010

PDH cont.

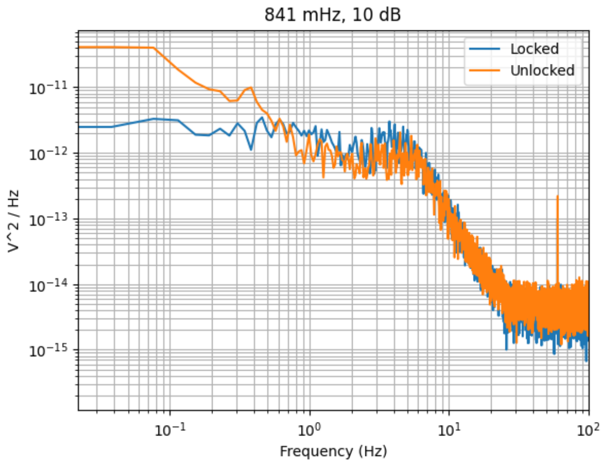


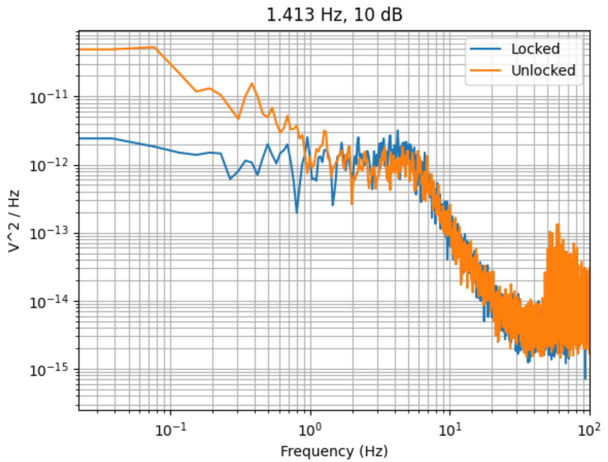
Error Function
$\chi(\omega)$
f/f_0
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0.8
0.85
0.9
0.95
1
1.05
1.1
1.15
1.2

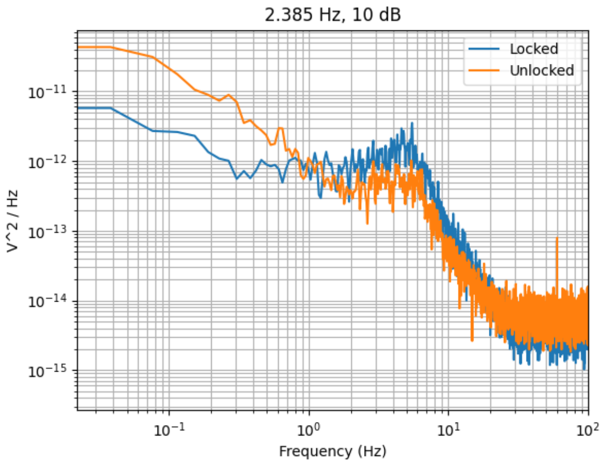


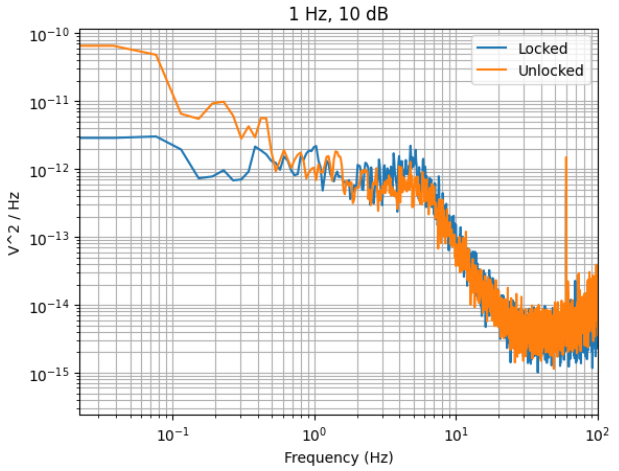
$E_0t^2r^5$
E_0tr^4
$E_0t^2r^4$
$E_0t^2r^3$
E_0tr^4
E_0tr^3
$E_0t^2r^2$
E_0t^2r
E_0tr^2
E_0tr
E_0t^2
E_0r
E_0t
E_0
r, t
r, t

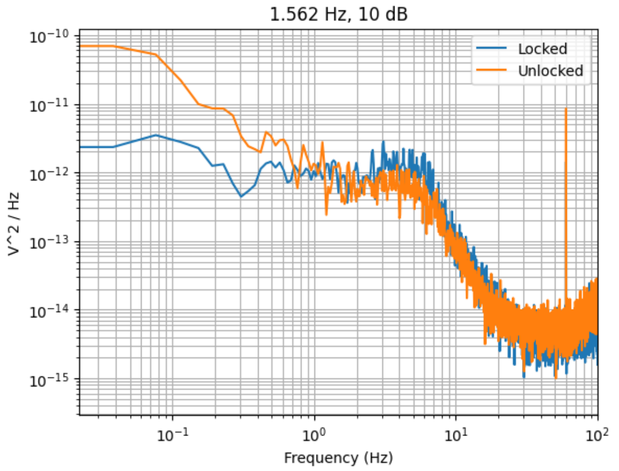
Slow Controller Tuning

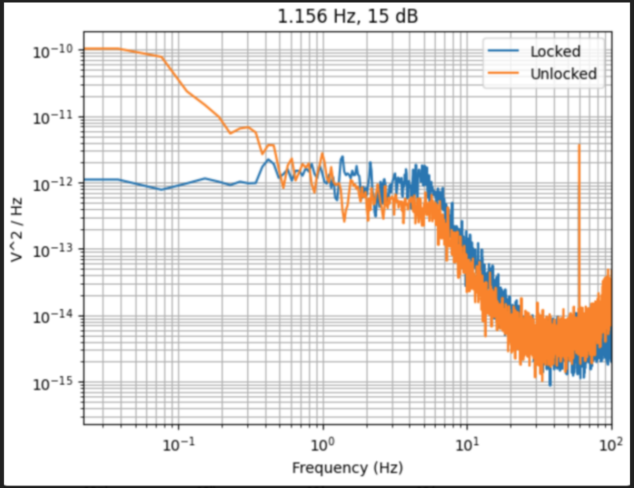


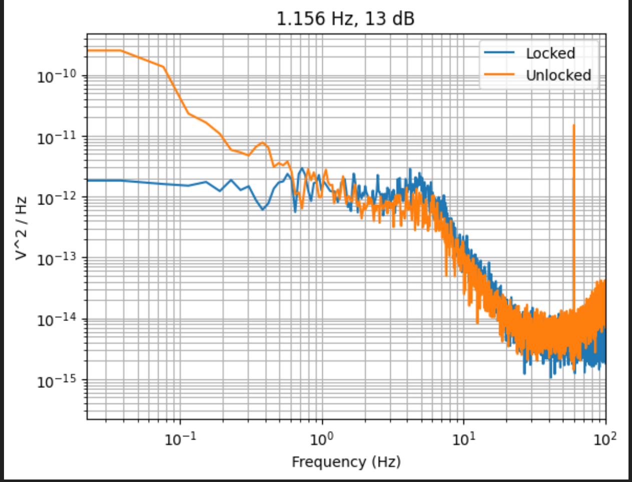


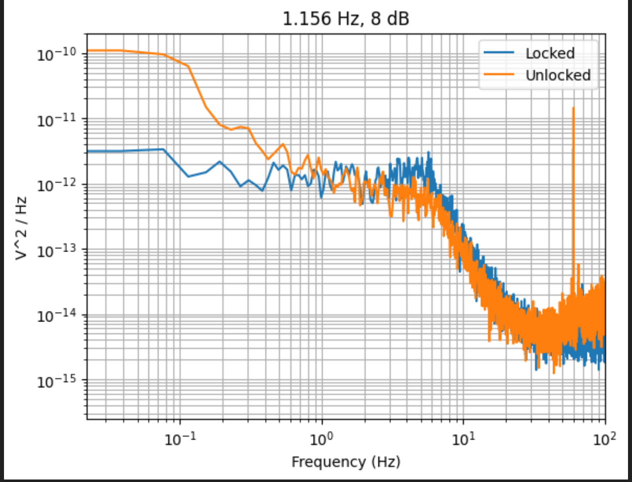


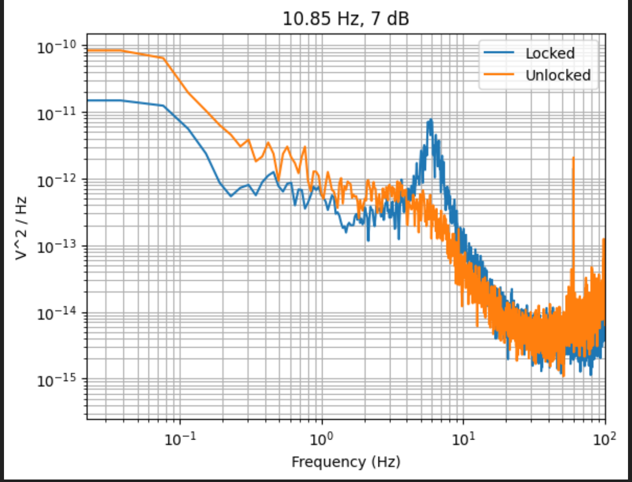


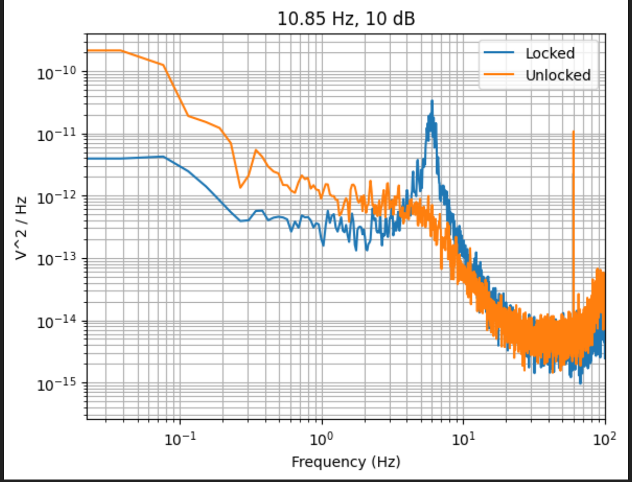


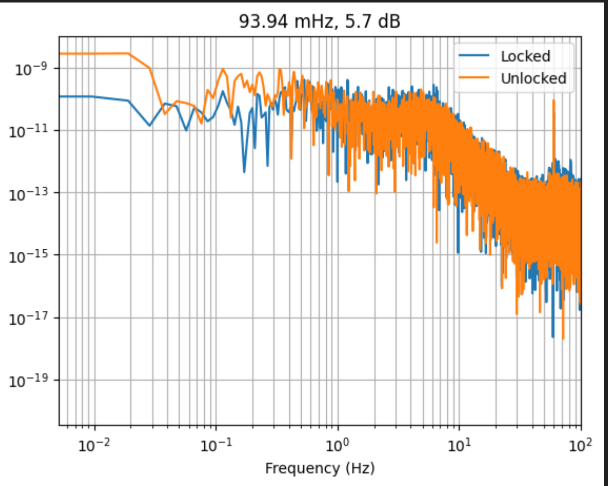

1.156 Hz, 15 dB
Locked
Unlocked
V^2 / Hz
Frequency (Hz)

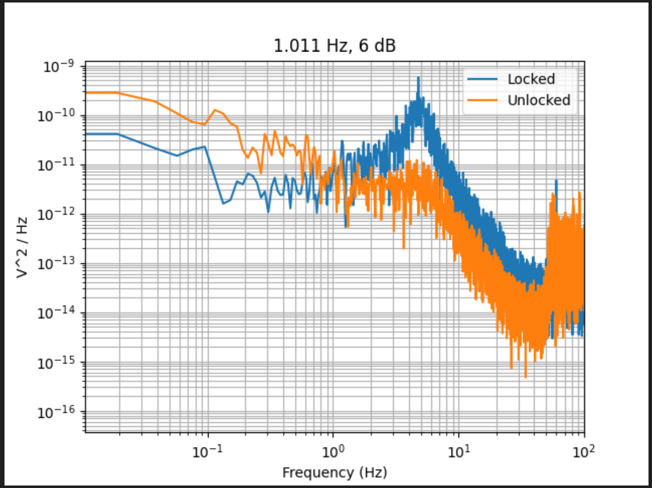

1.156 Hz, 13 dB
Locked
Unlocked
V^2 / Hz
Frequency (Hz)

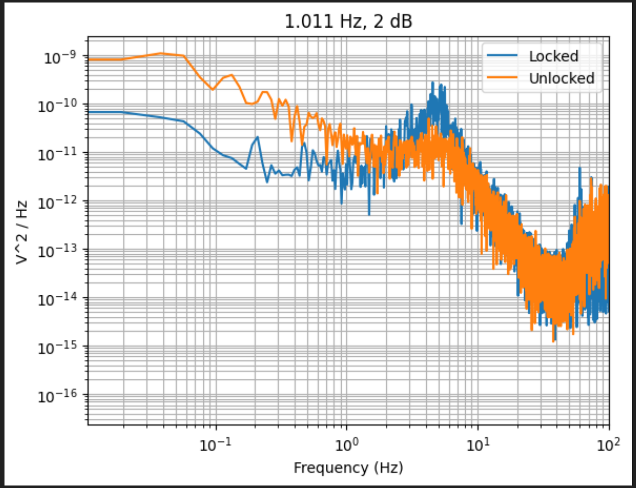

1.156 Hz, 8 dB
Locked
Unlocked
V^2 / Hz
Frequency (Hz)


10.85 Hz, 7 dB
Locked
Unlocked
V^2 / Hz
Frequency (Hz)

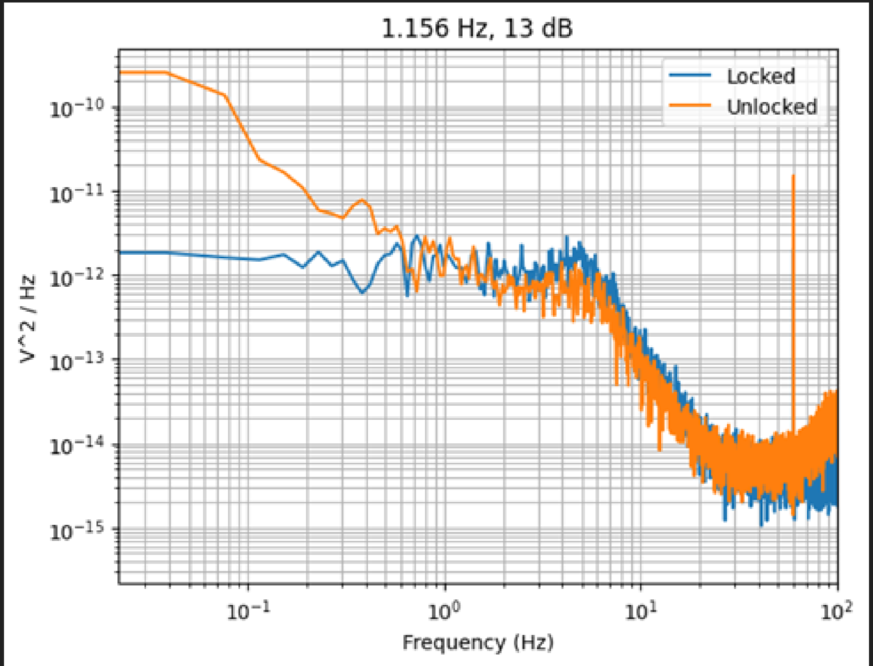

10.85 Hz, 10 dB
Locked
Unlocked
V^2 / Hz
Frequency (Hz)

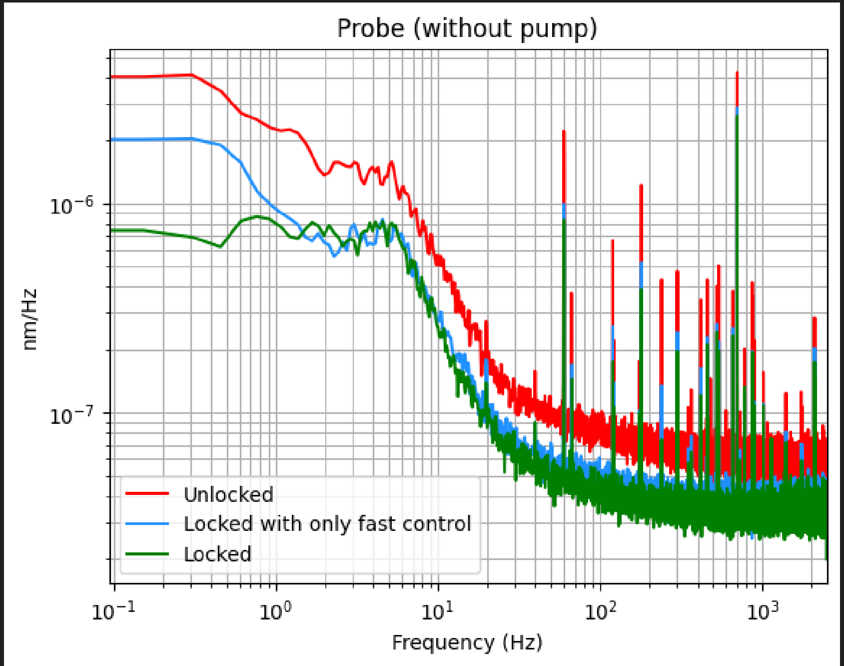

93.94 mHz, 5.7 dB
Locked
Unlocked
Frequency (Hz)


1.011 Hz, 6 dB
Locked
Unlocked
V^2 / Hz
Frequency (Hz)

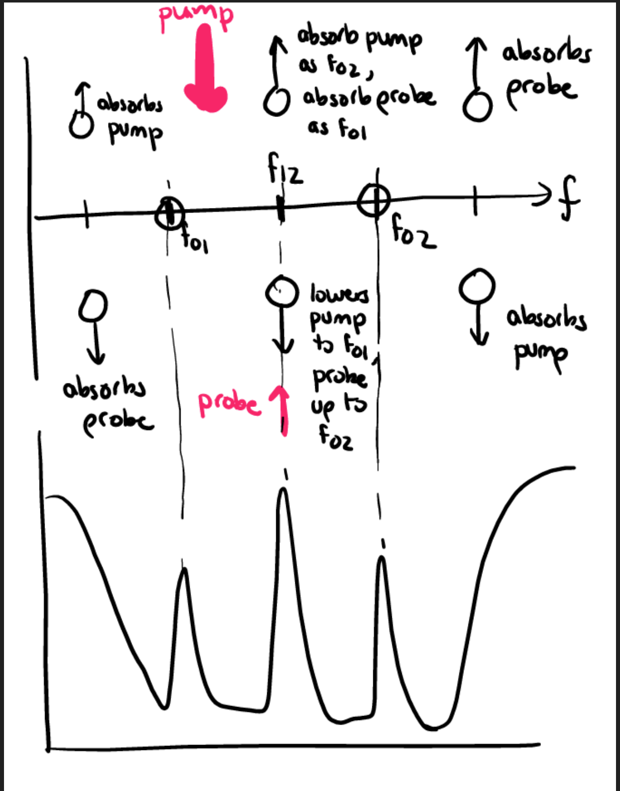

1.011 Hz, 2 dB
Locked
Unlocked
V^2 / Hz
Frequency (Hz)

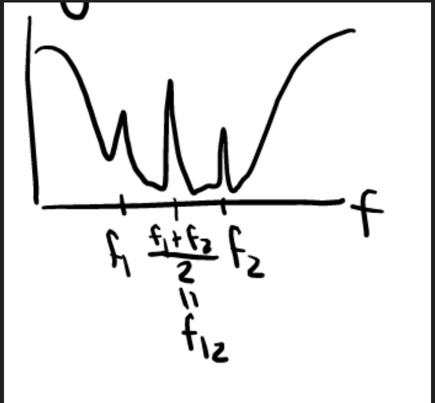
Slow Controller Effect (Without Pump)

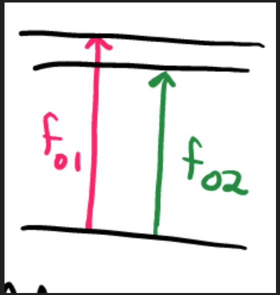




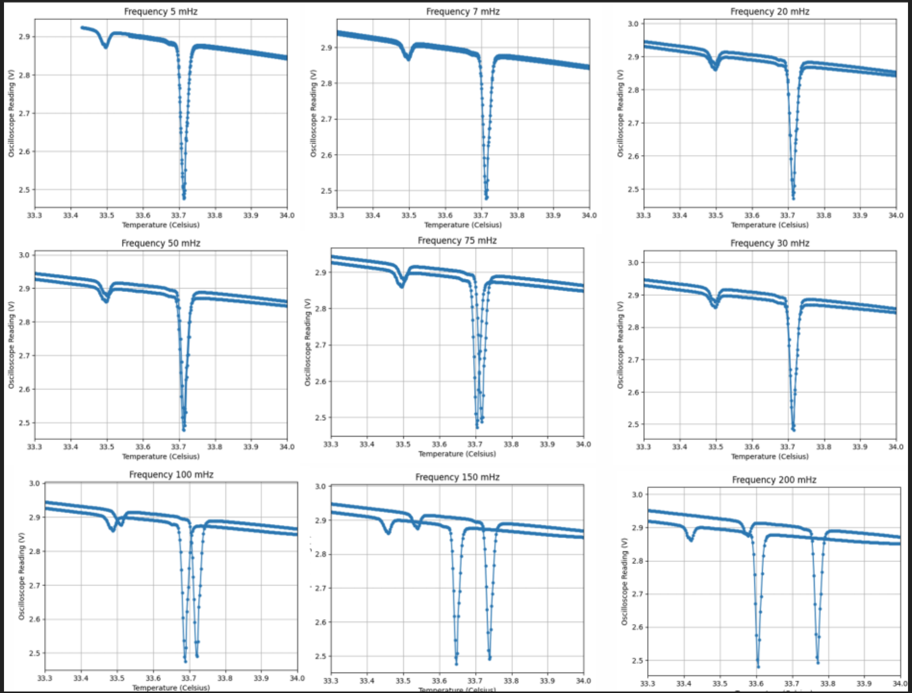
Crossover Resonances







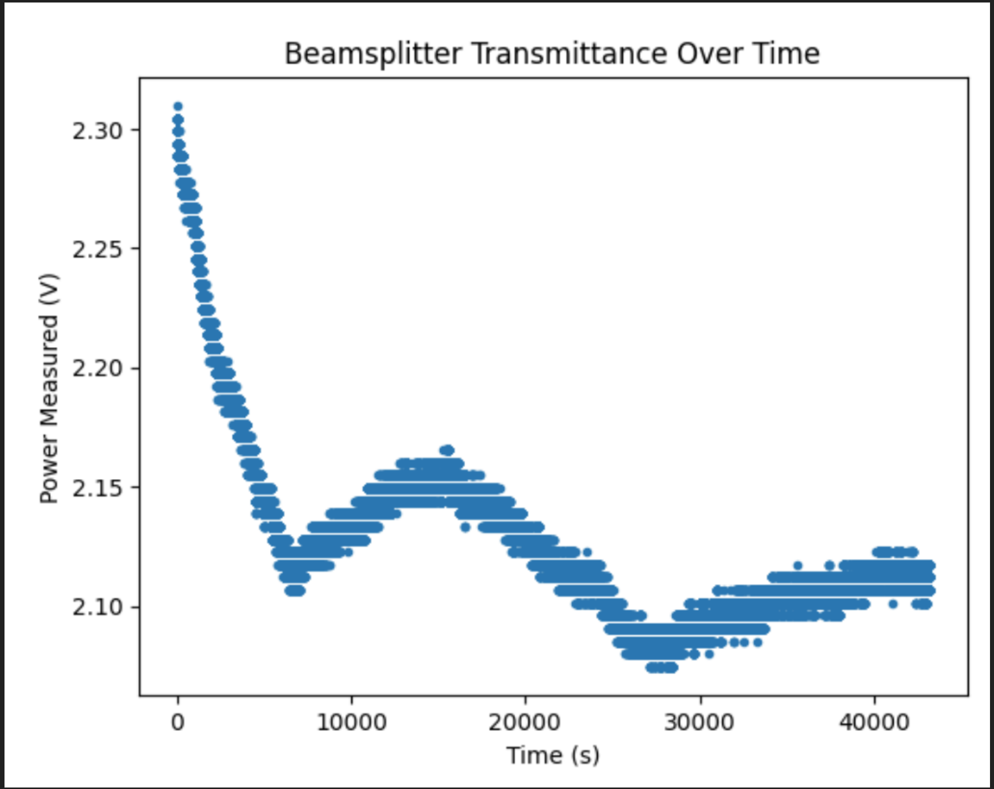
Scan Offset



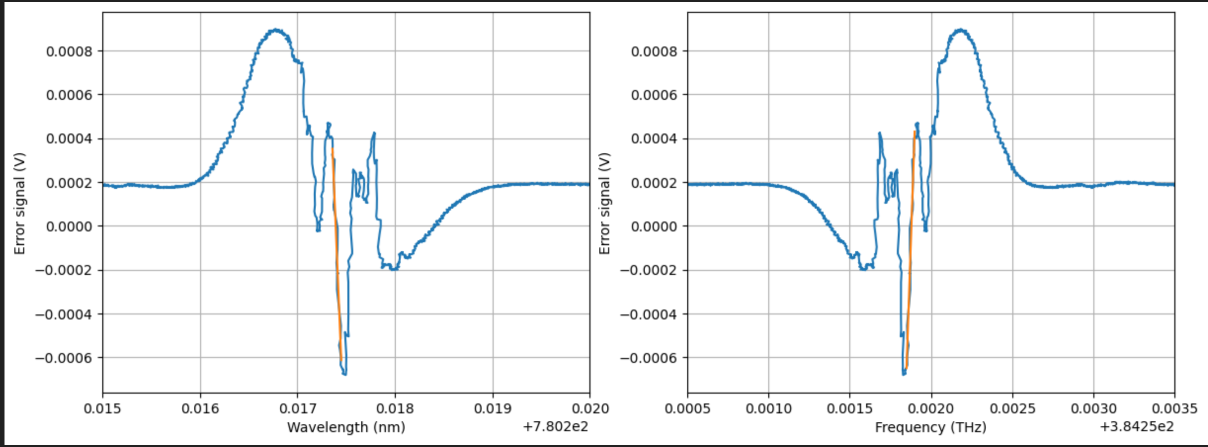
Frequency 5 mHz
Frequency 7 mHz
Frequency 20 mHz
Frequency 50 mHz
Frequency 75 mHz
Frequency 30 mHz
Frequency 100 mHz
Frequency 150 mHz
Frequency 200 mHz
Oscilloscope Reading (V)
Temperature (Celsius)

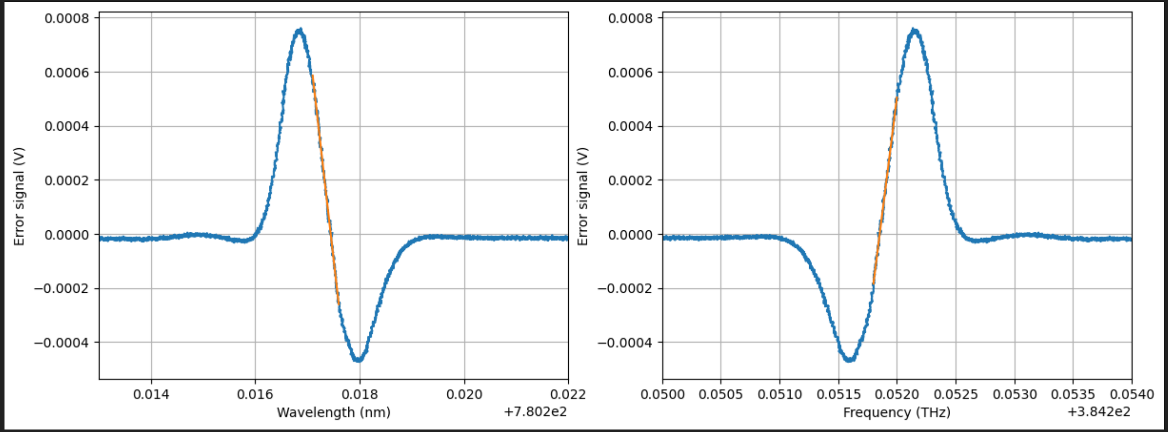
59.38 mV
55.14 mV
51.88 mV
48.10 mV
60 mV
58 mV
56 mV
54 mV
52 mV
50 mV
48 mV
46 mV
44 mV
42 mV
40 mV
−12 s
−10 s
−8 s
−6 s
−4 s
−2 s

Power Fluctuations



Calibrated error signals





This used lock-in amplifier.

Locking to two different transitions (red is the D2).

Comparison with PDH cavity?