Frequency Stabilization of 2 Micron Lasers Using Optical Delay Self-Heterodyne Interferometry

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Motivation

- Current LIGO:
  - 1064 nm
  - Fused Silica Test Masses
- Silicon:
  - Cryogenic Compatible
  - Less Mechanical Loss / Thermal Noise
  - Opaque at 1064 nm

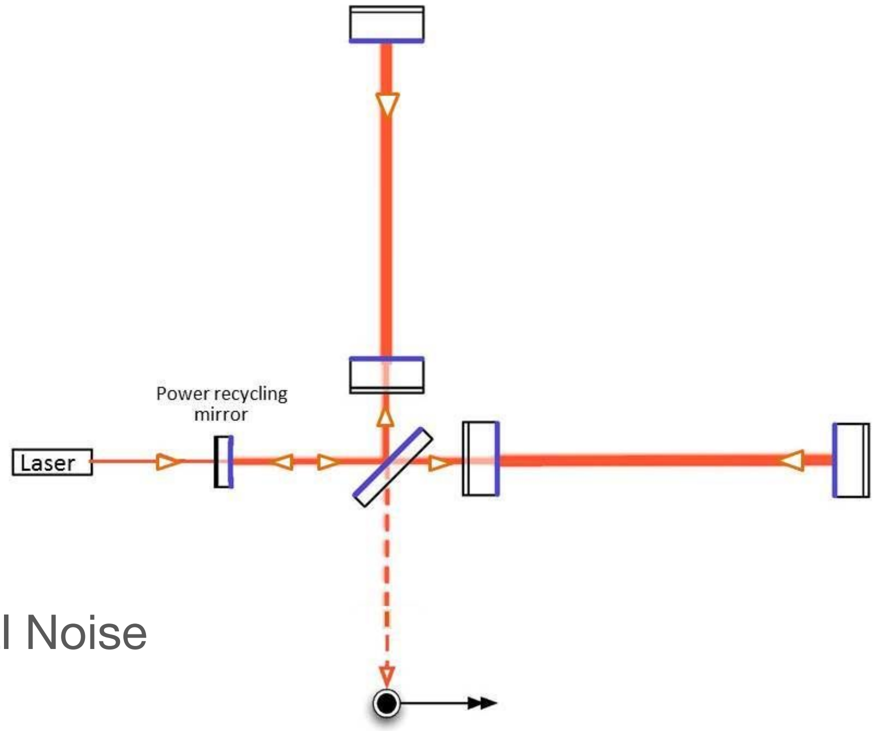

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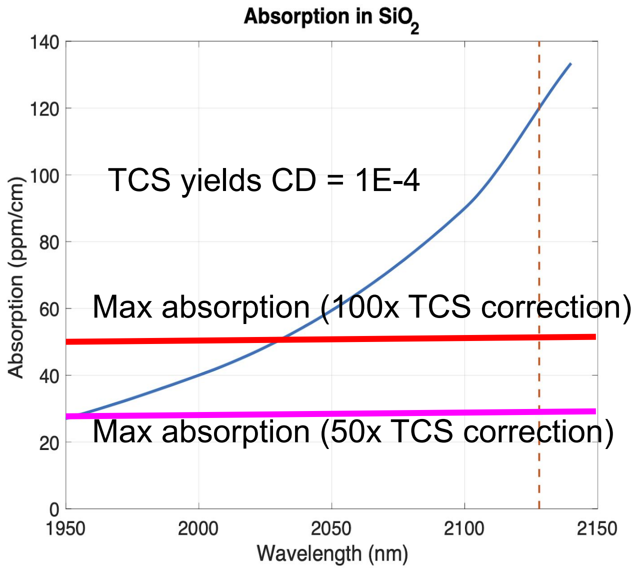
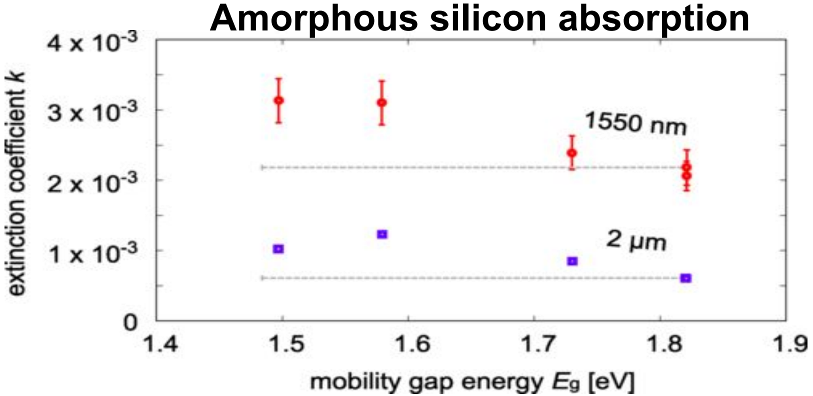
Image credit: LIGO Caltech

New Wavelength

- Low Si Absorption at 1400 - 2100 nm
- Current Laser Options:
  - 1550 nm
  - 1800 - 2100 nm
- Absorption Considerations:
  - Si has less absorption at longer wavelengths





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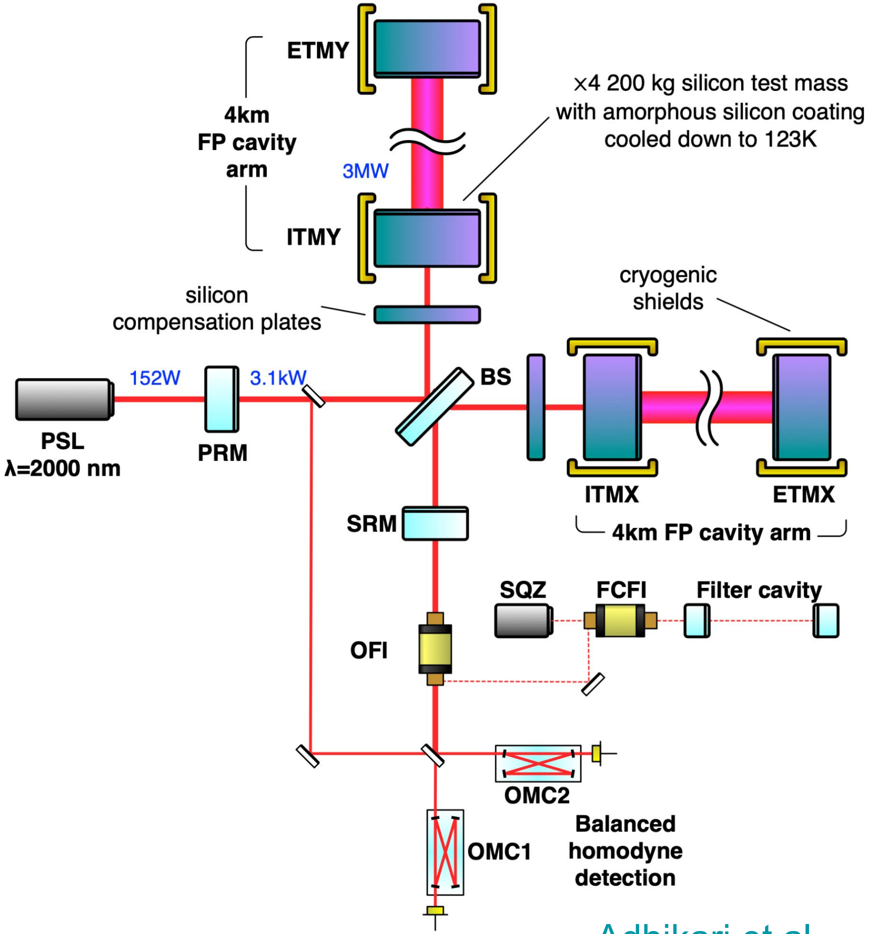
LIGO Voyager

- Potential Post-O5 upgrade:
- Cryogenic Silicon Test Masses
- 2050 nm Wavelength
- Requires Stable 2050 nm Source



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Laser Frequency Noise

- Measure via Phase Noise:

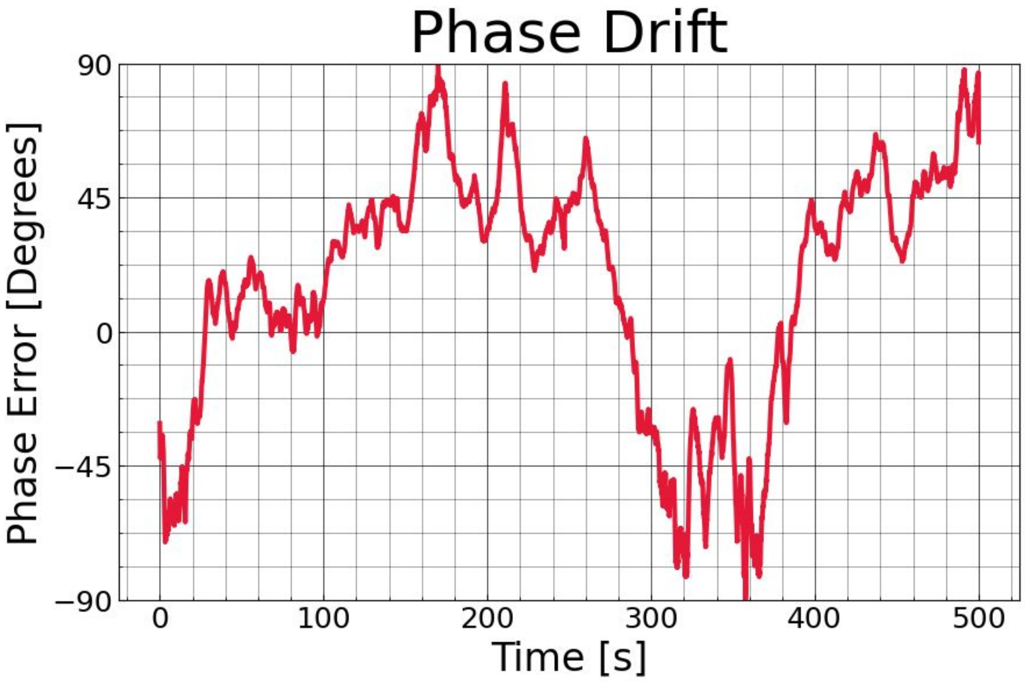
$$2\pi f(t) = \omega(t) = \frac{d}{dt}\phi(t)$$

$$E(t) = Ae^{i(\omega_0 t + \phi_n(t))}$$

- Phase Forms a Random Walk

- Within Interferometer

$$\phi_n(t) = 2\pi f_n(t)\Delta t$$

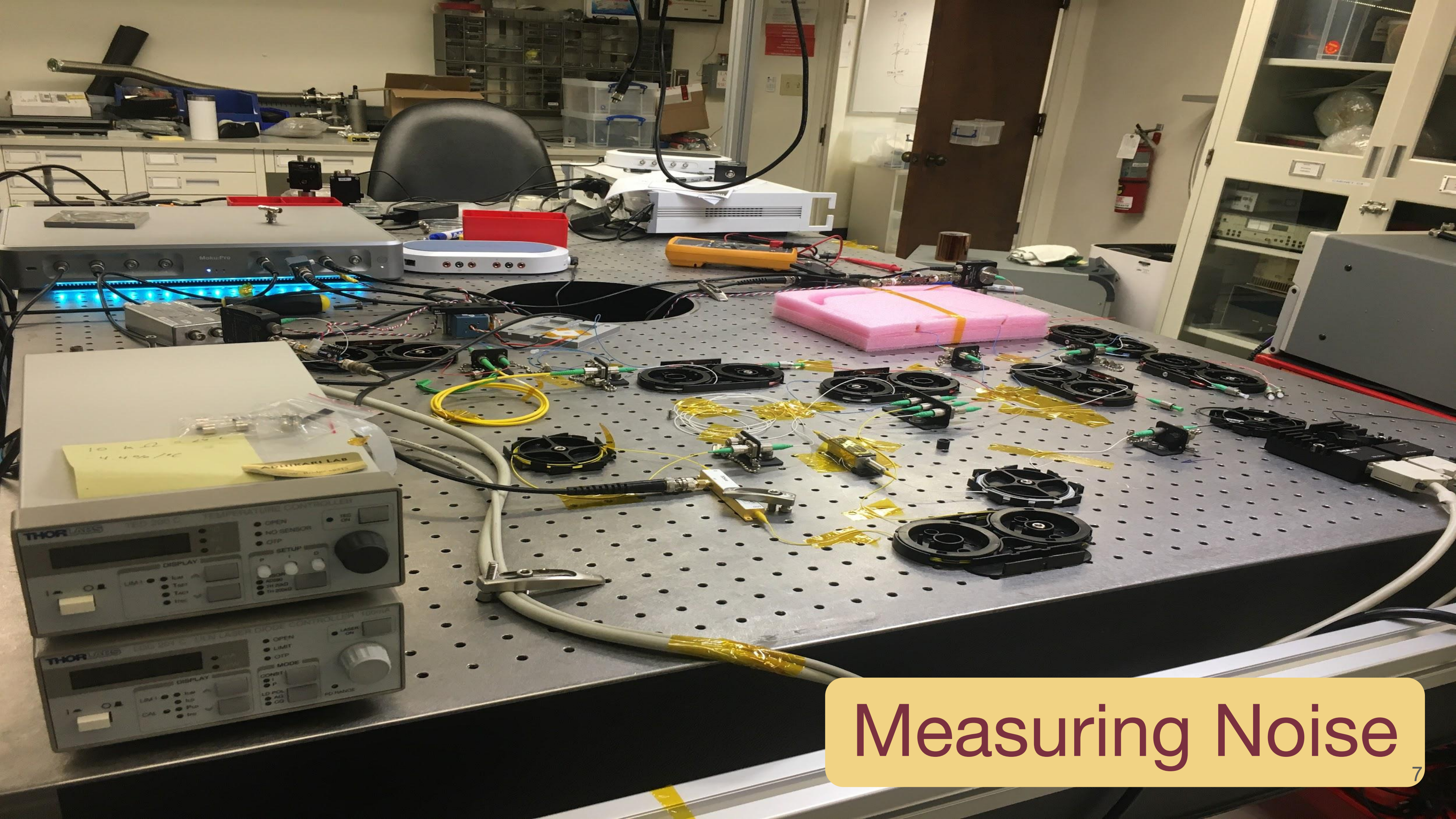


Our Goals

Measure Phase Error via Mach - Zehnder (MZ) Interferometer

Correct for Error via Feed Forward

Measure Corrected Signal via Second MZ interferometer

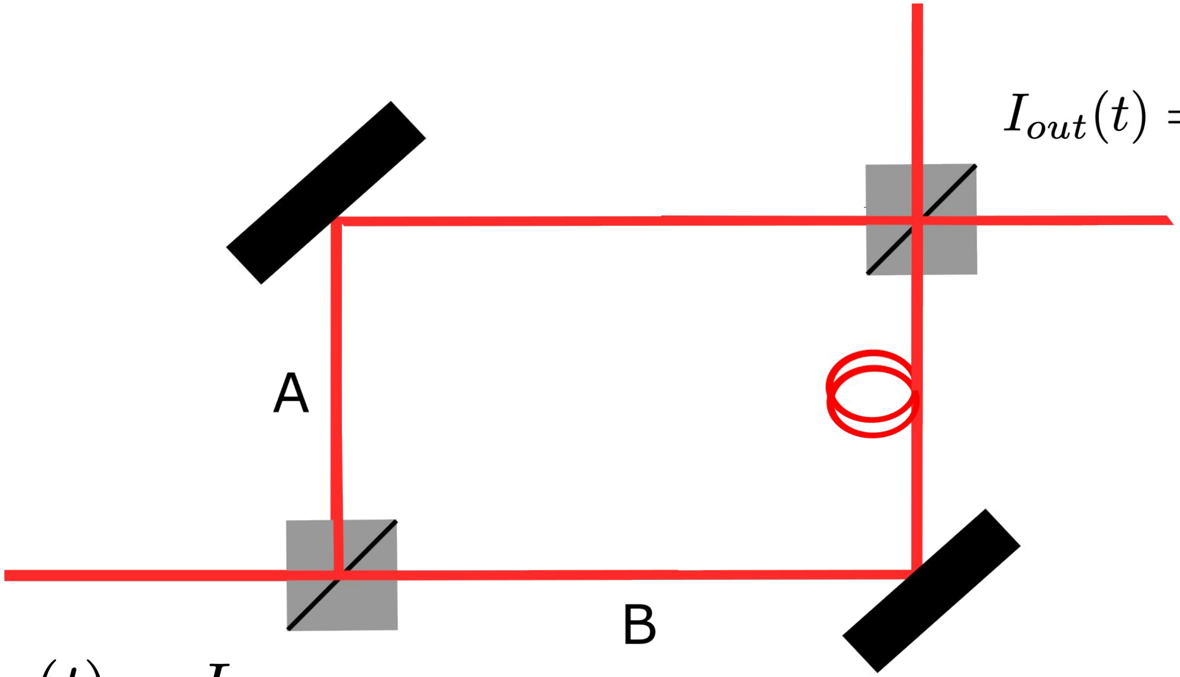


Measuring Noise

Mach-Zehnder Interferometer

- Interferometer Arms Differ in Time Delay by τ.

$$I_{out}(t) = \frac{I_0}{2} + \frac{I_0}{2} sin(2\pi \underline{f_n(t)\tau} + \phi_0)$$



$$I_{in}(t) = I_0$$

Fiber Stretcher Interferometer

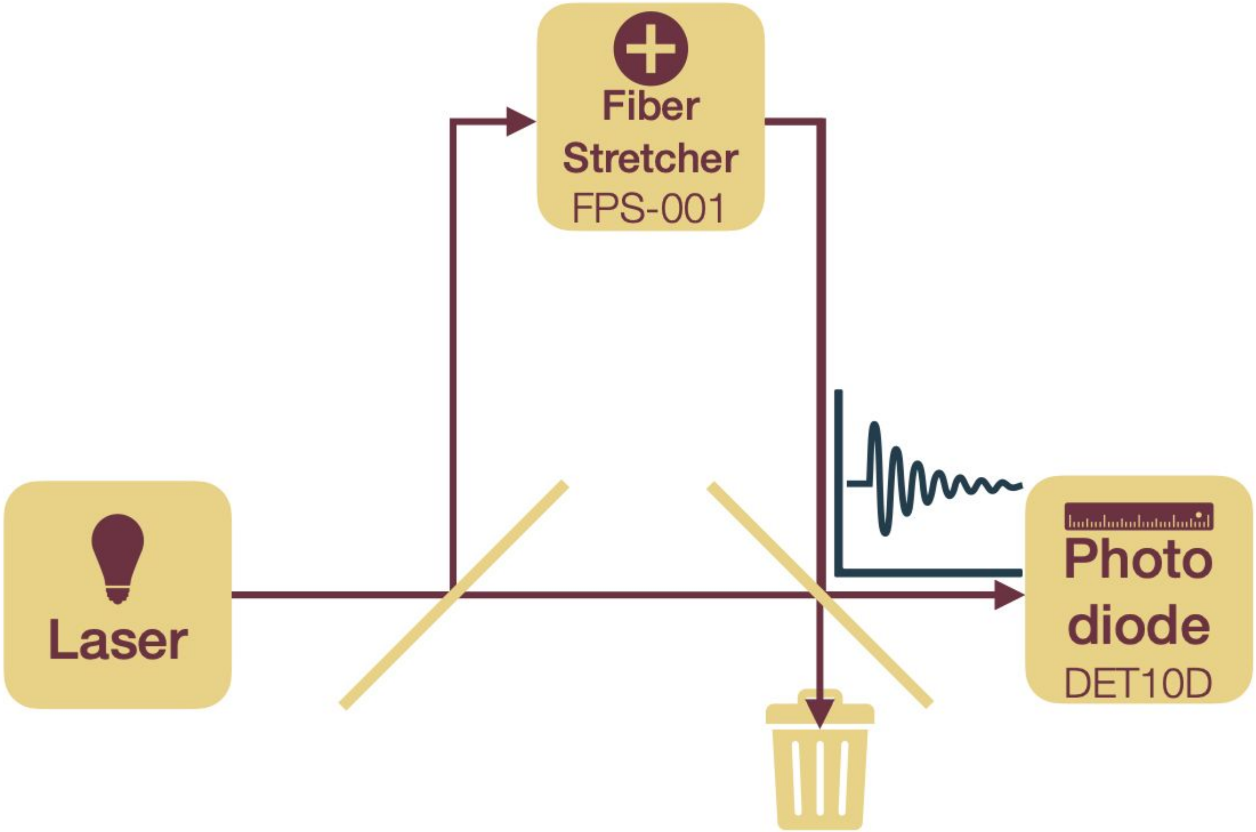
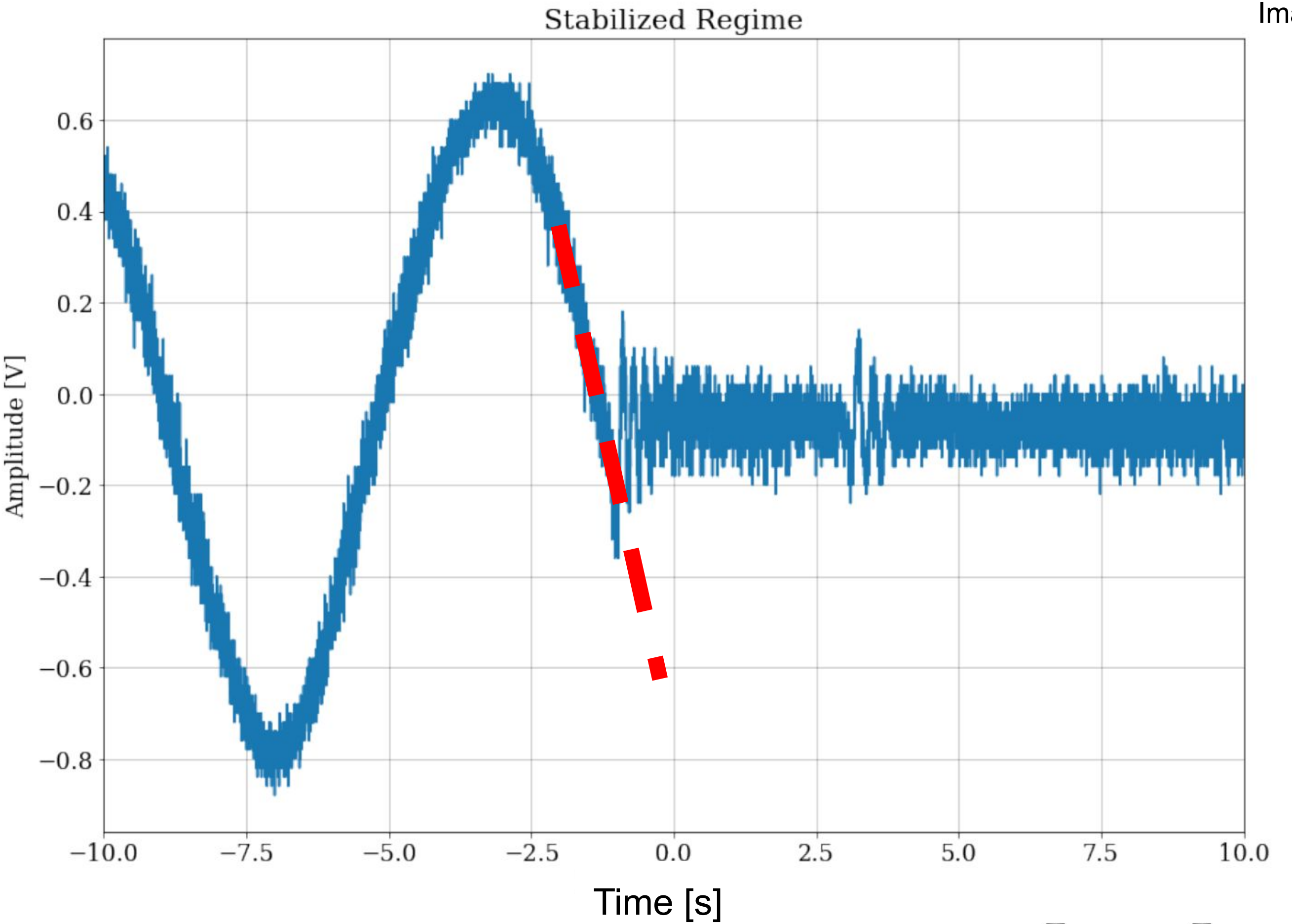
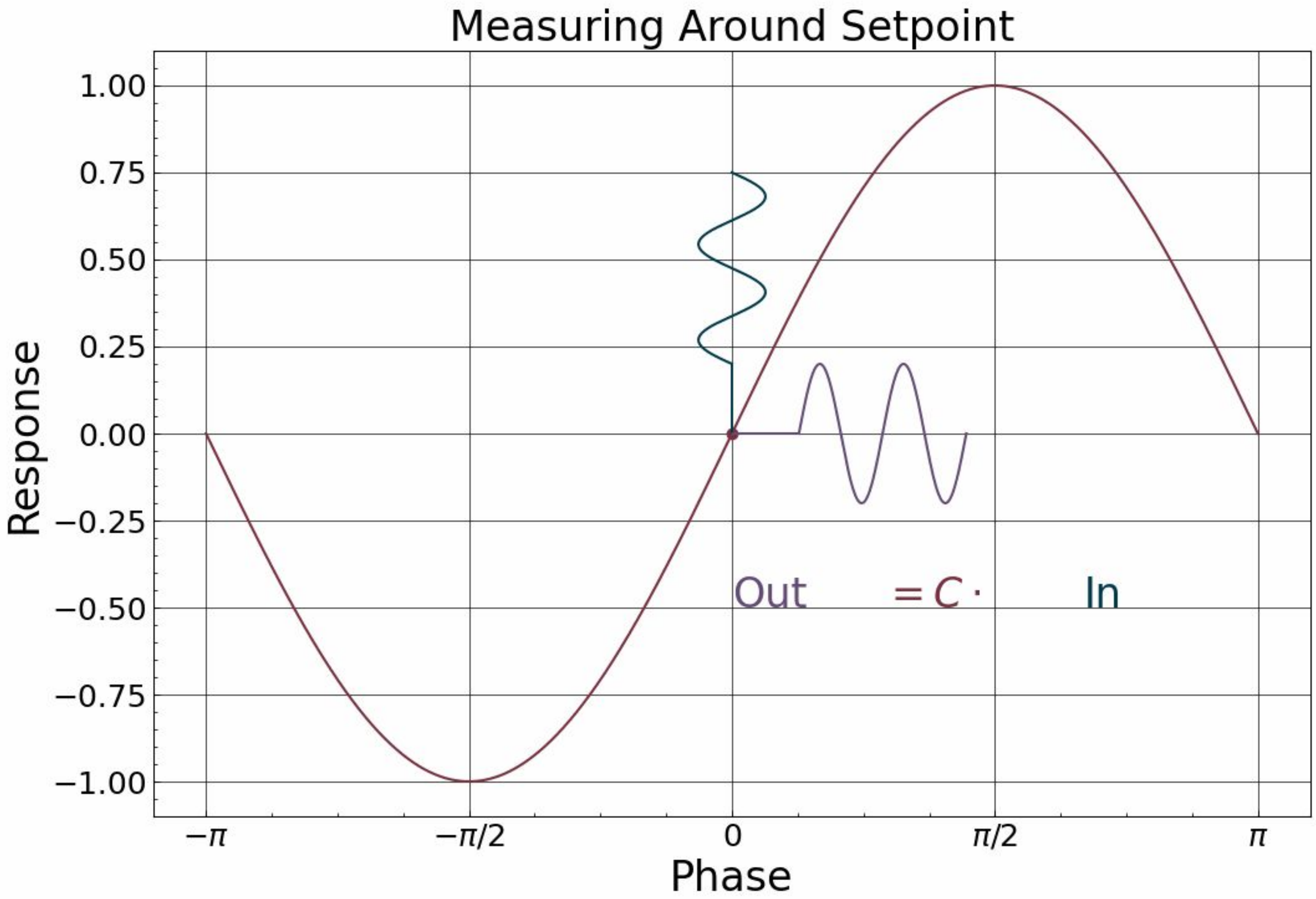


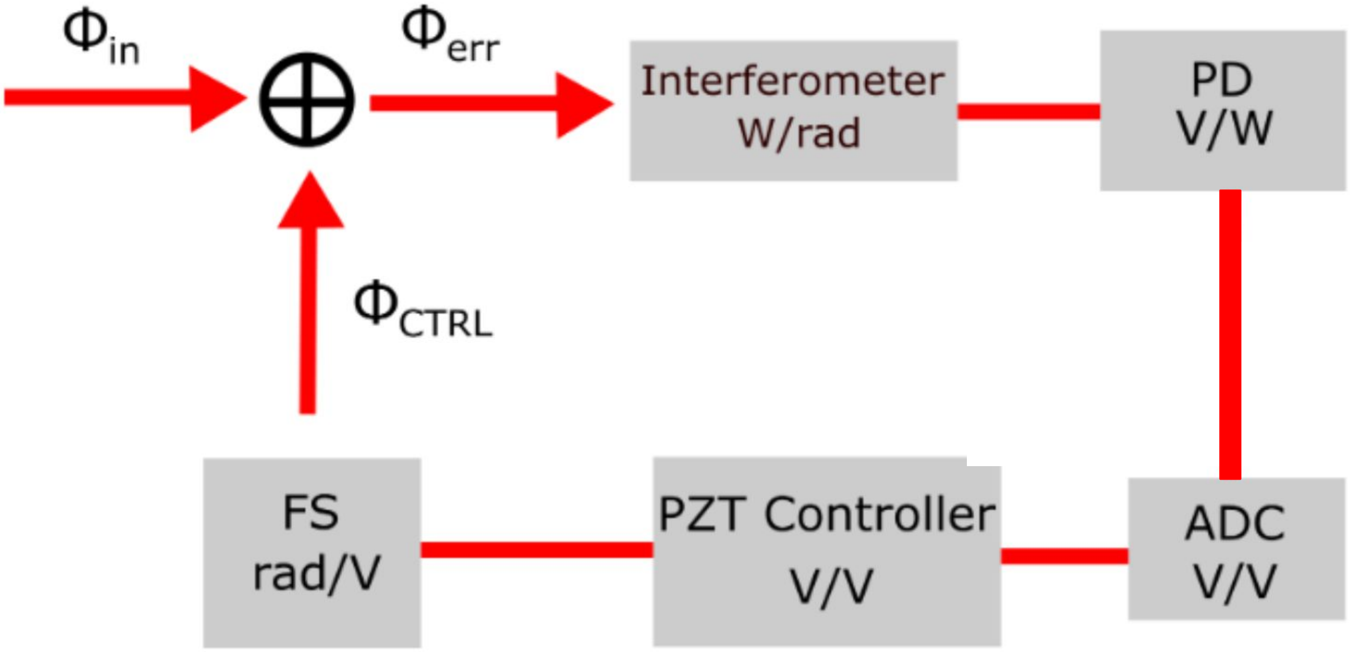
Image credit: [Wagner, et. al]()



$$I_{out}(t) = \frac{I_0}{2} + \frac{I_0}{2} sin(2\pi f_n(t)\tau + \phi_0) \rightarrow I_{out}(t) = \frac{I_0}{2} + \frac{I_0}{2} 2\pi f_n(t)\tau$$


Measuring Around Setpoint
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
Response
Out
= C ·
In
−π
−π/2
0
π/2
π
Phase

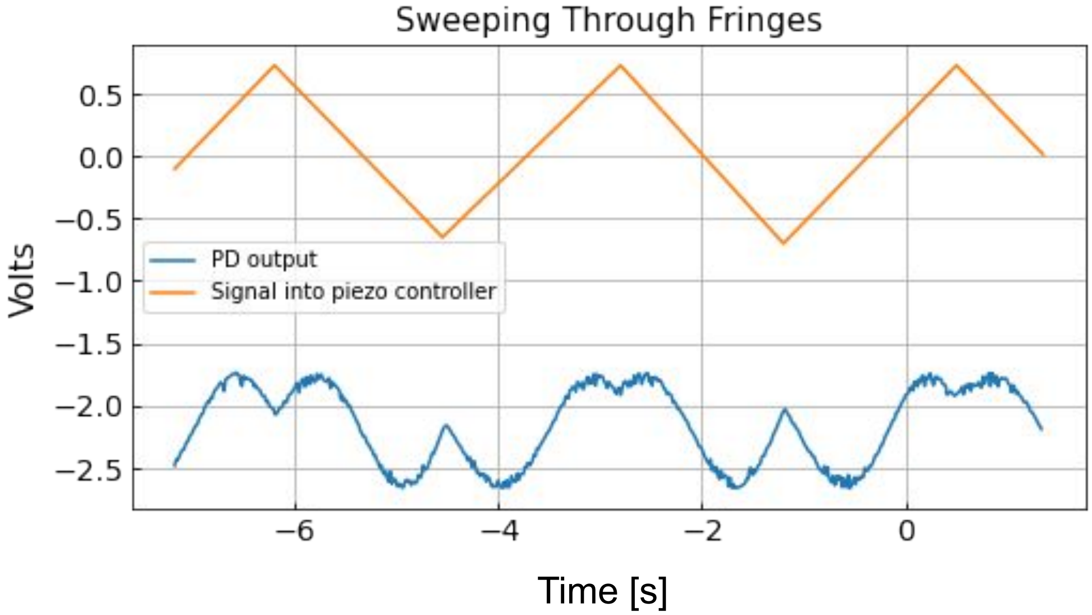
Locking the Loop



Calibrating Noise

- Sweep through fringes with fiber stretcher to correlate input voltage out of PD with radian change $\frac{radians}{volt}$
- Radian change and frequency drift related by

$$f(t) = V_{out}(t)\frac{radians}{volt}\frac{1}{2\pi\tau}$$



Calibrating the Photodiode (PD)

- Correspond PD Voltage to Laser Power
- Low Frequencies:

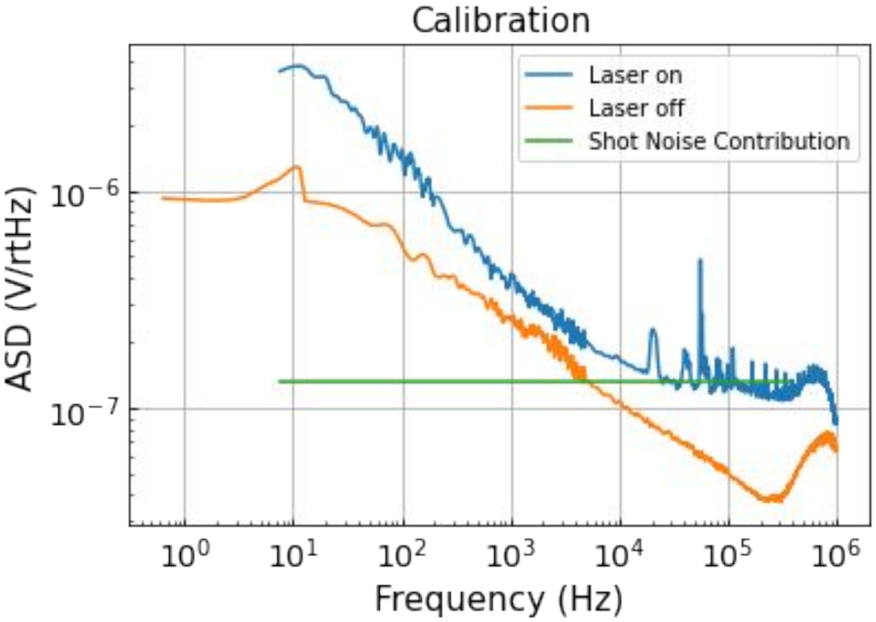
  1/f Intensity Noise Dominates

- High Frequencies:

  Shot Noise Dominates

- Variations in Electron Flow

- ASD of Shot Noise in amps/rtHz Given by $\delta n_{shot} = \sqrt{2q|\bar{I}|}$



Noise Sources

- Moku Input Noise floor
- Shot noise
- Photodiode Dark Noise
- Relative Intensity Noise
- Frequency Noise
- Piezo Controller Noise
- Moku Output Noise

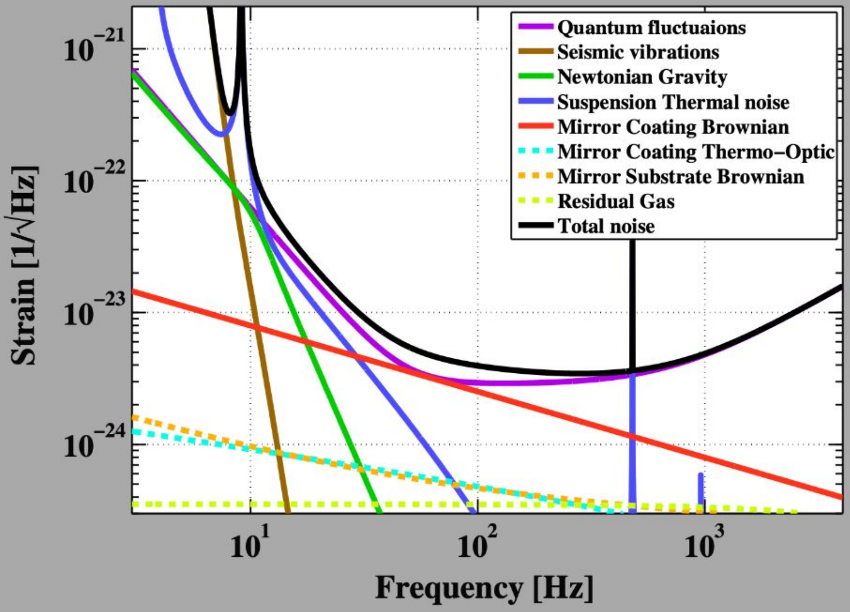
Image credit:
[Photonics Media]

Image credit:
[Thorlabs]

Image credit:
[Thorlabs]

LIGO Noise Budget

Theoretical Noise Budget



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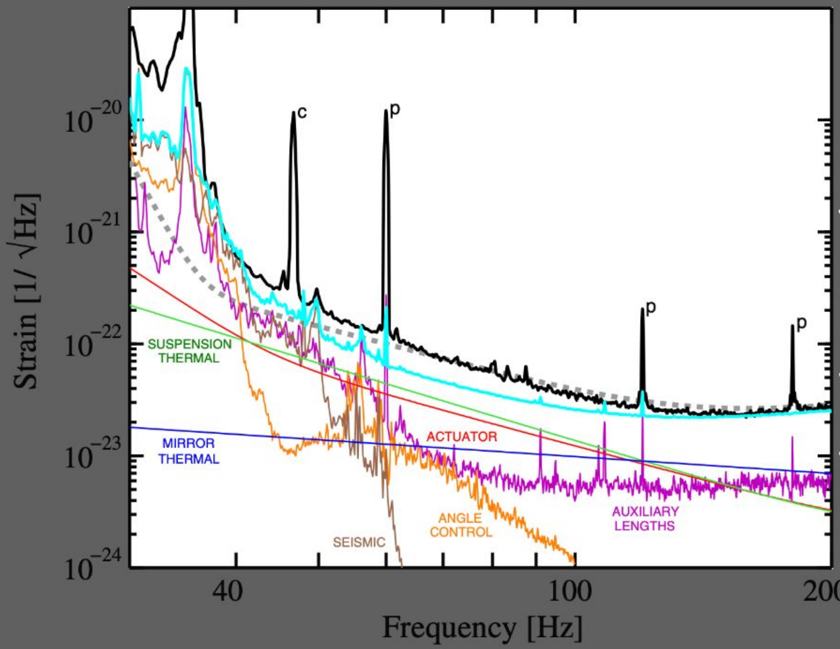
Realistic Noise Budget



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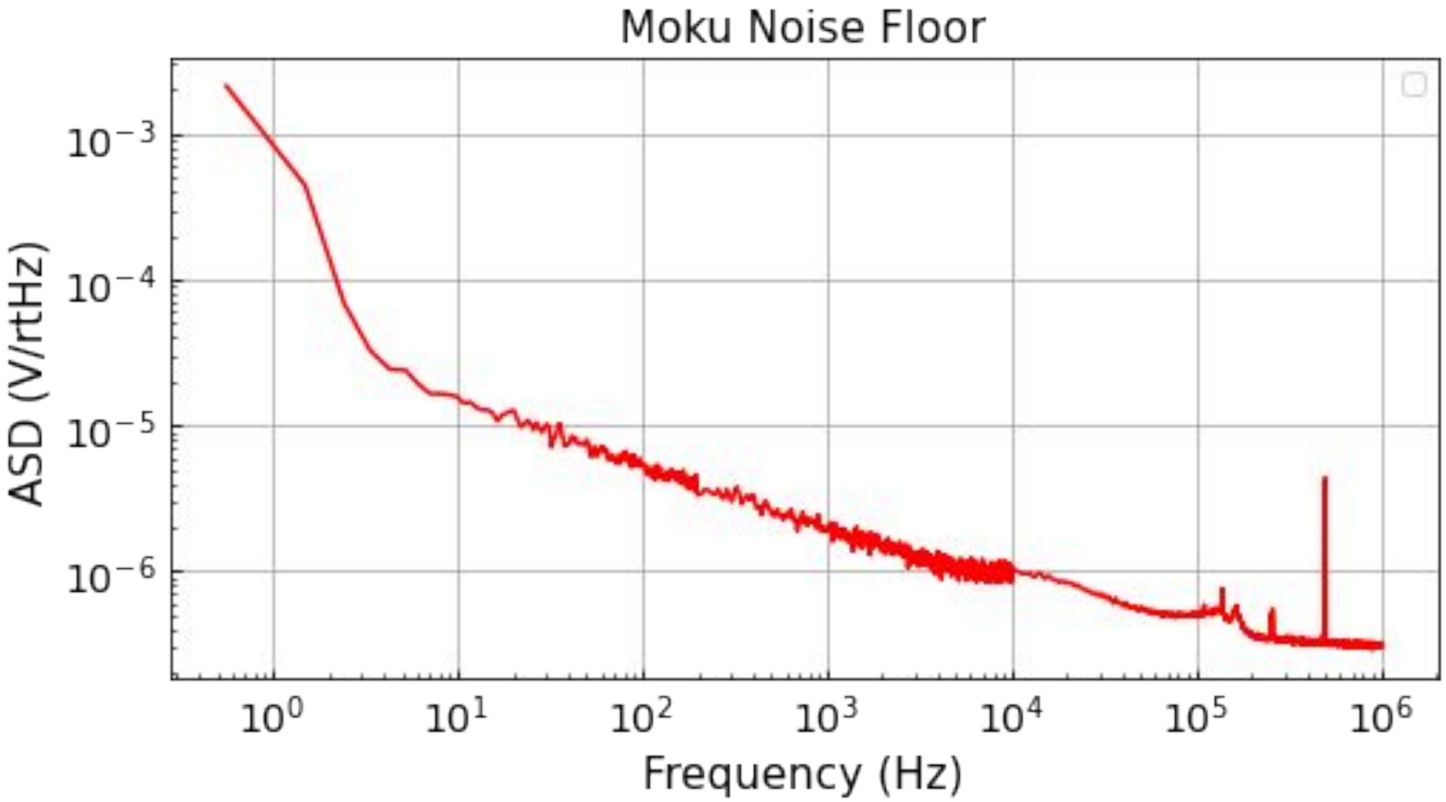
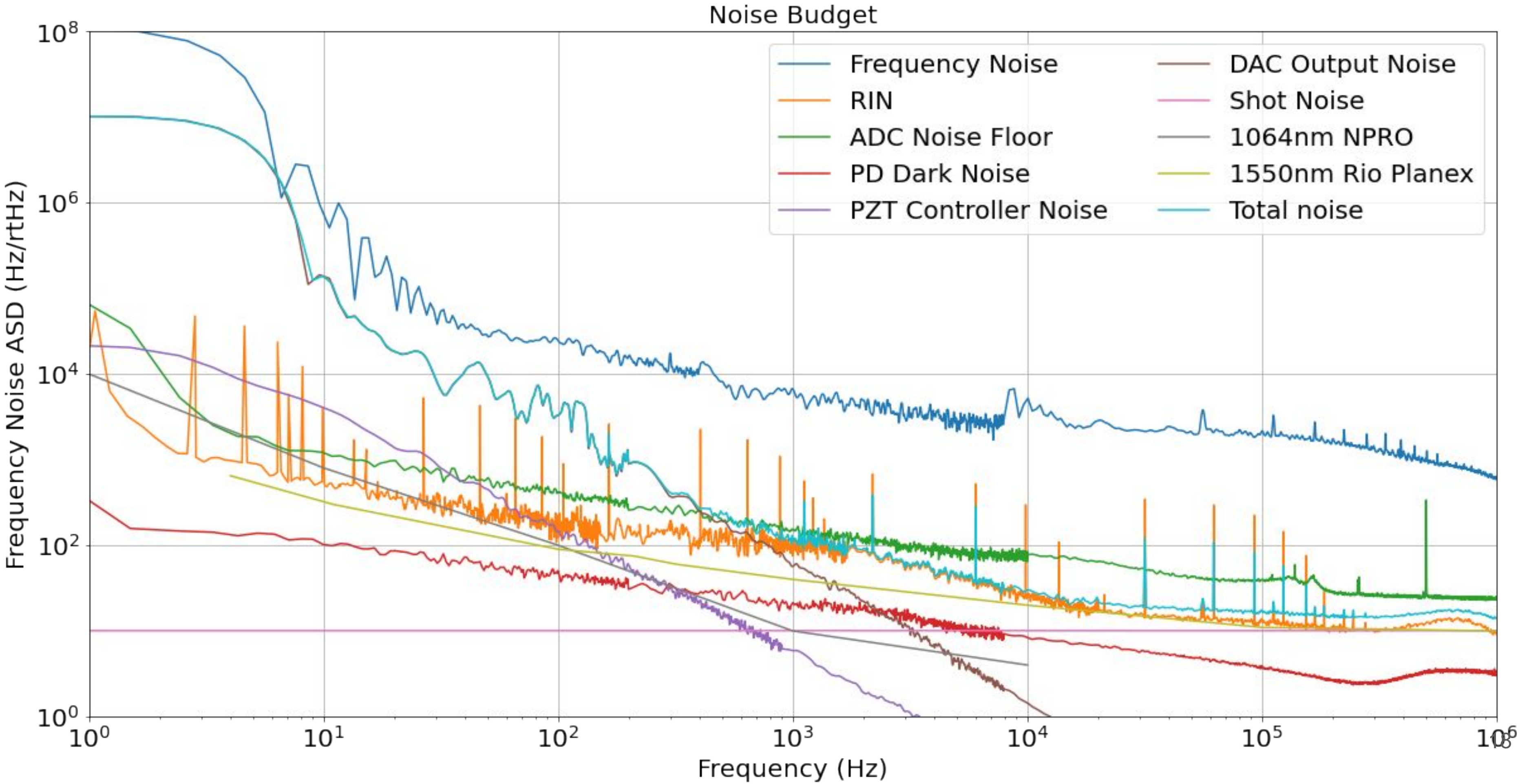
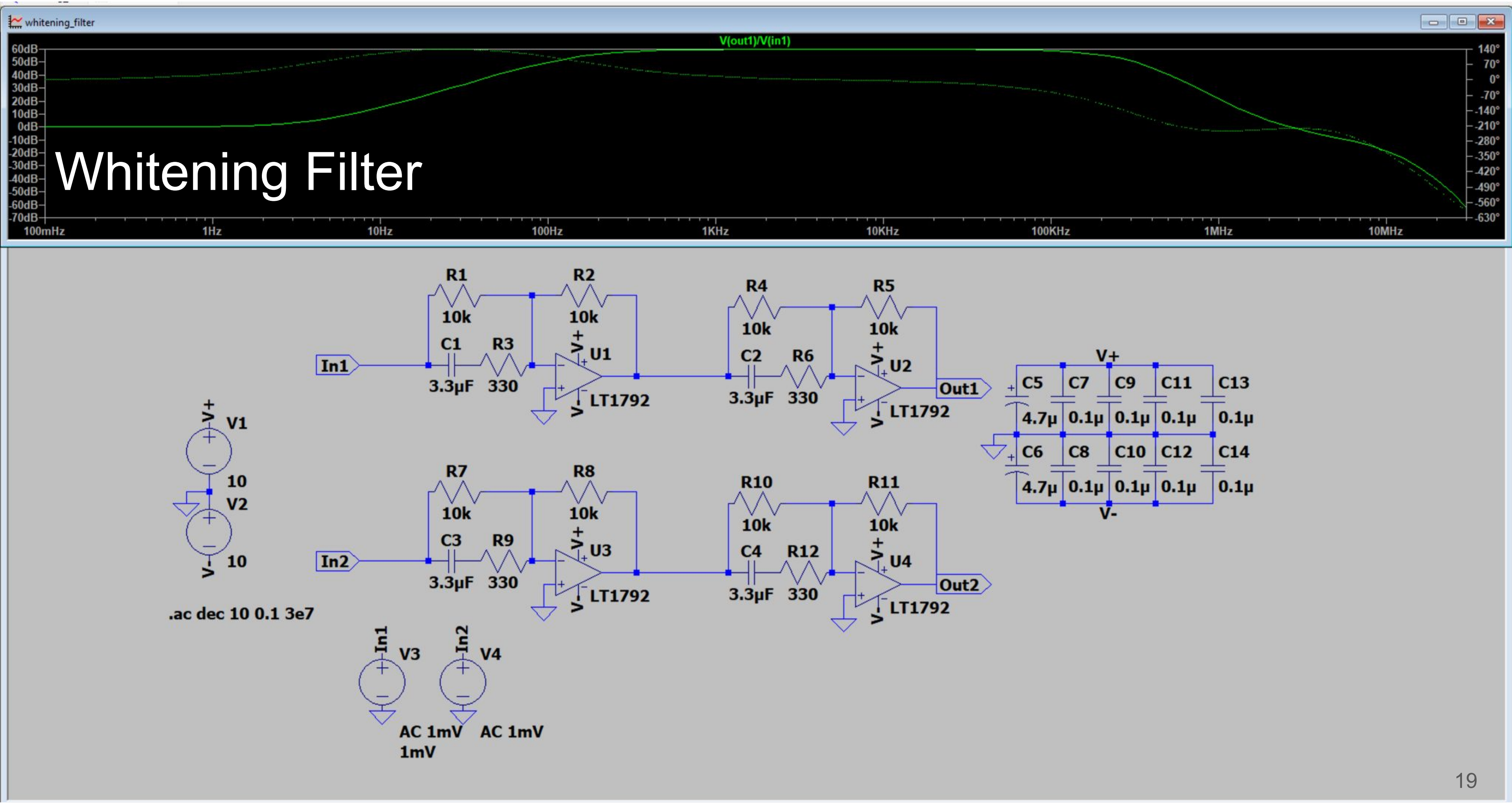
Moku Input Noise Floor



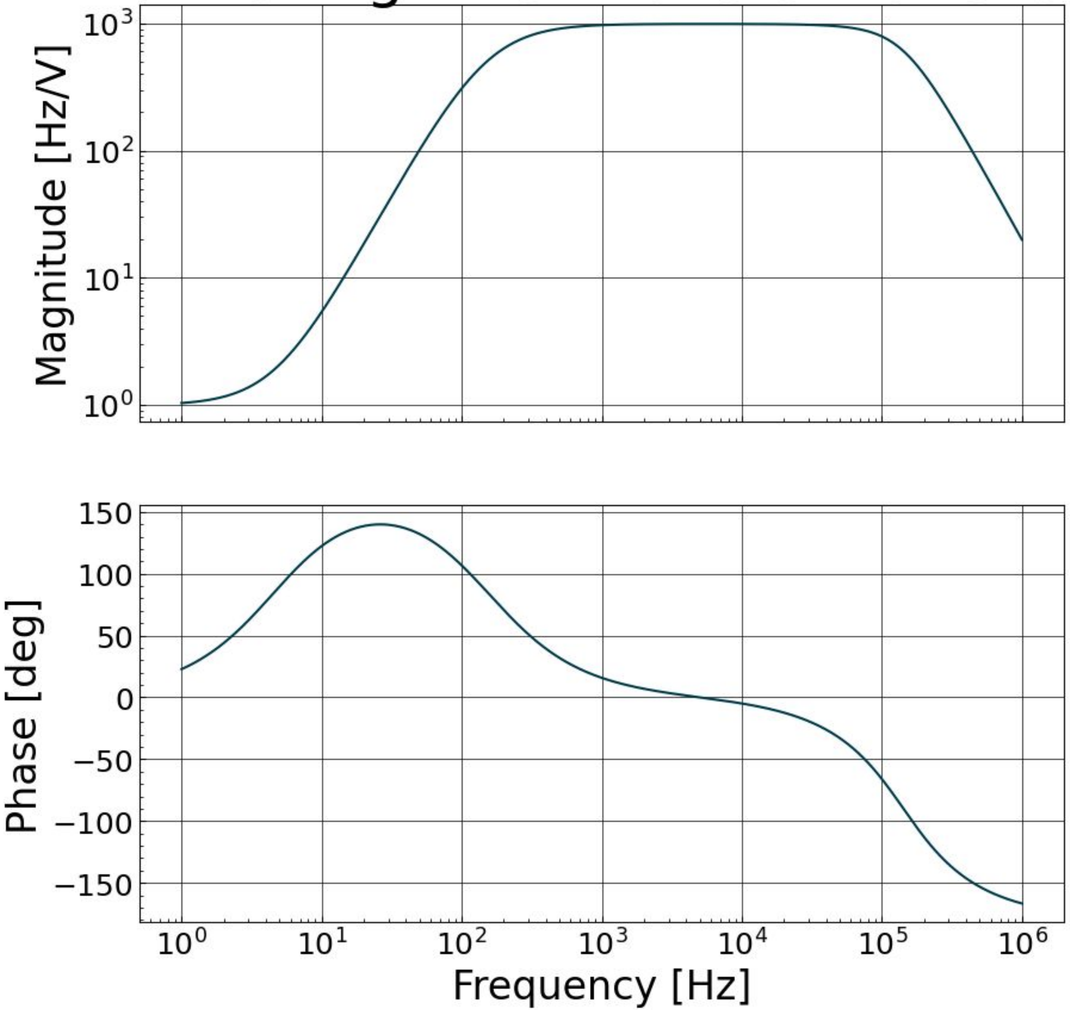
Noise Budget Before Whitening



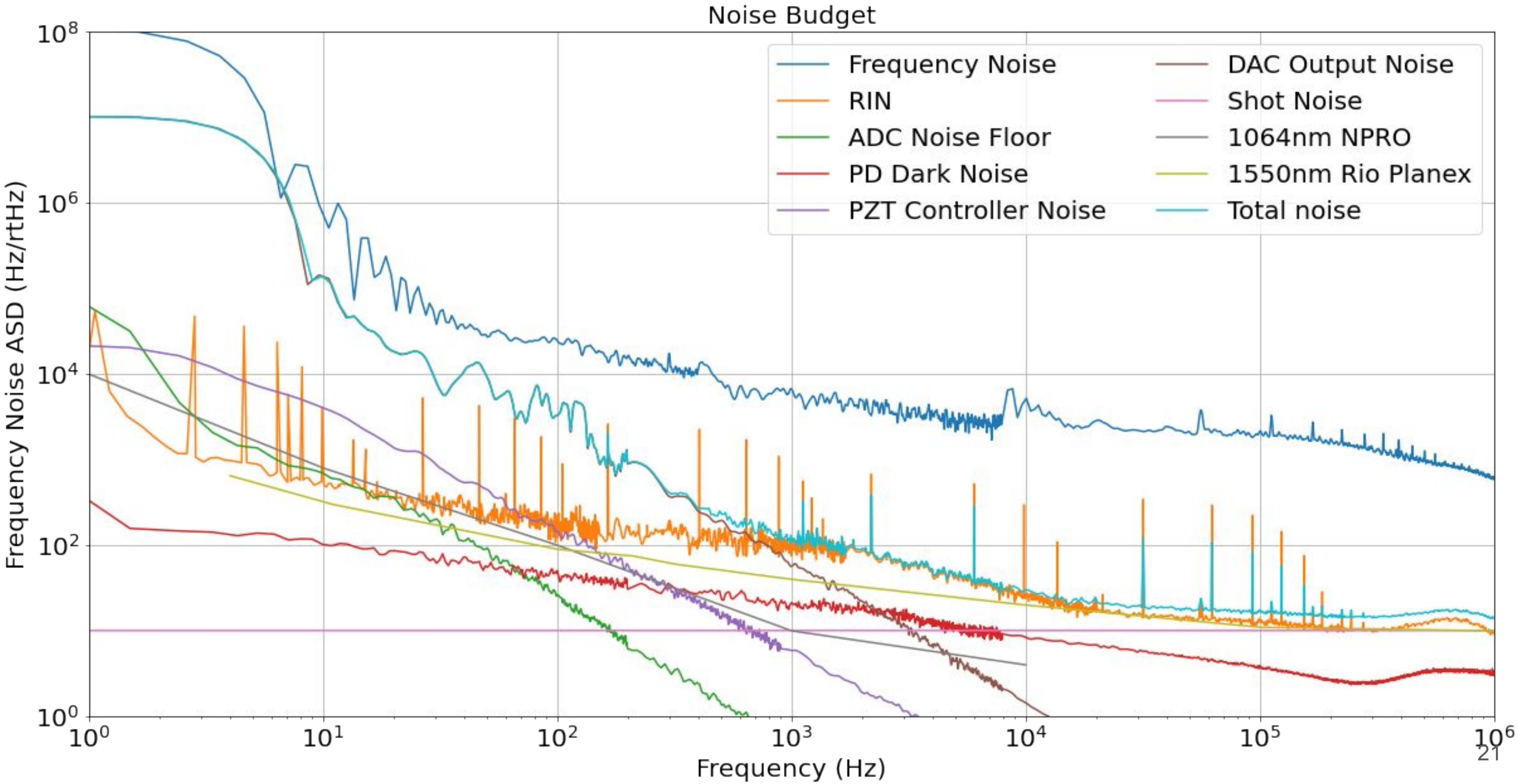
Whitening Filter



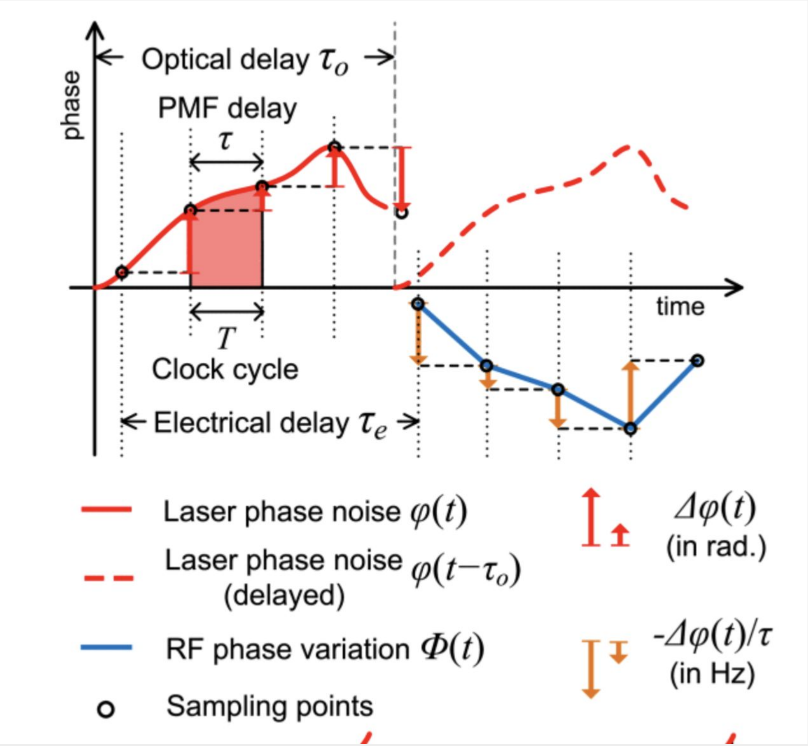
Whitening Filter Transfer Function



Noise Budget After Whitening



Performing the Feedforward



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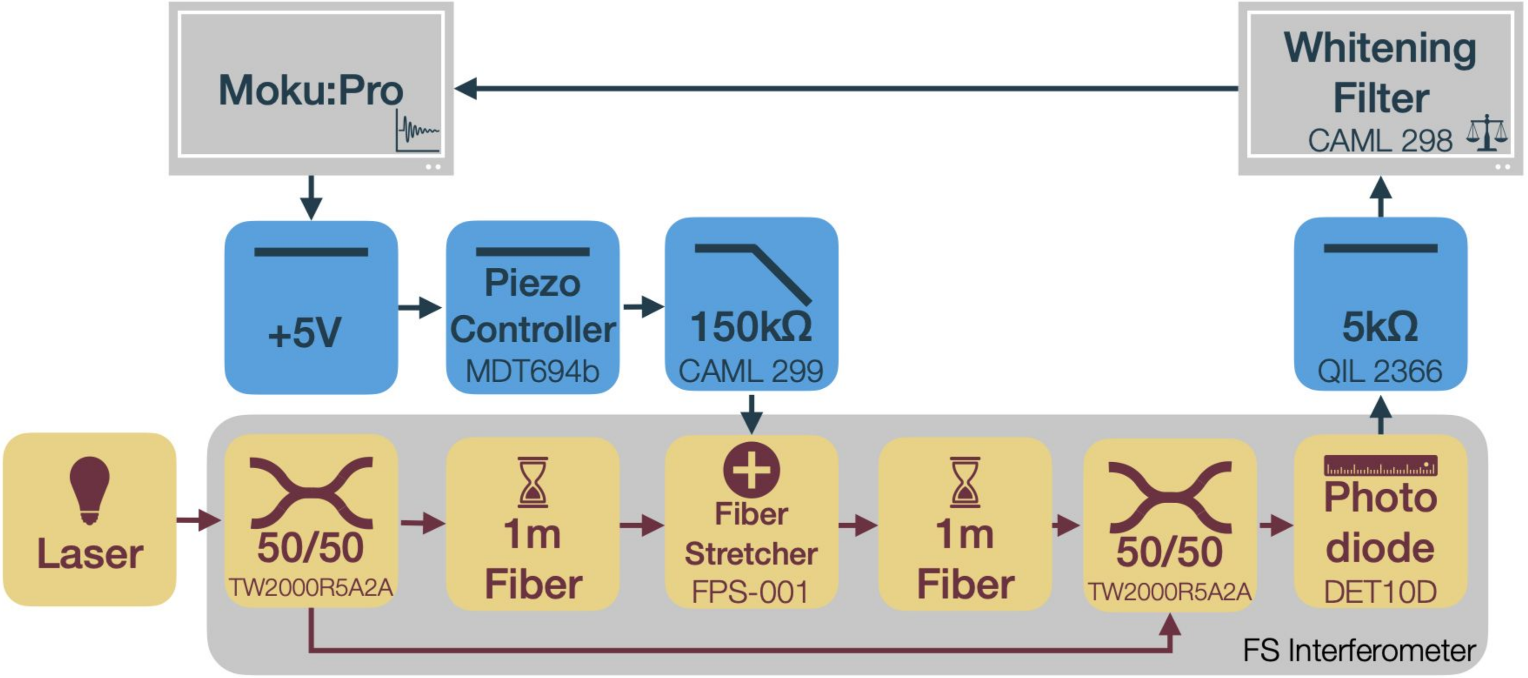
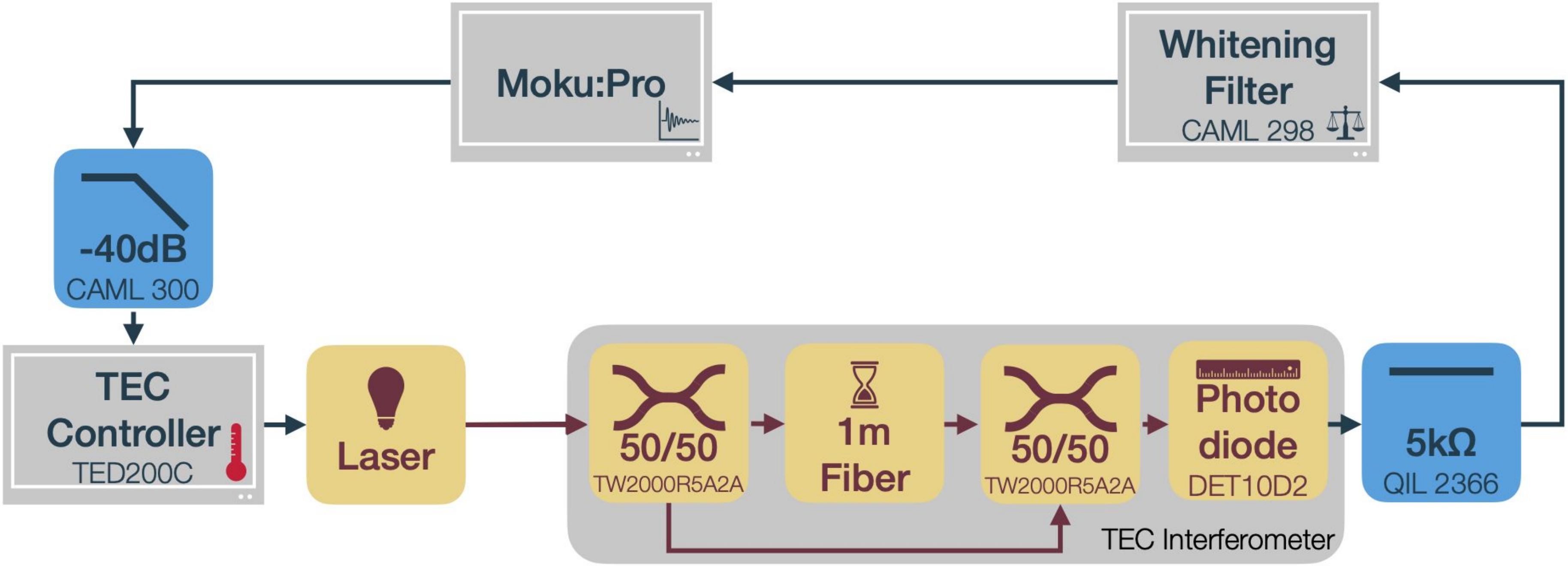
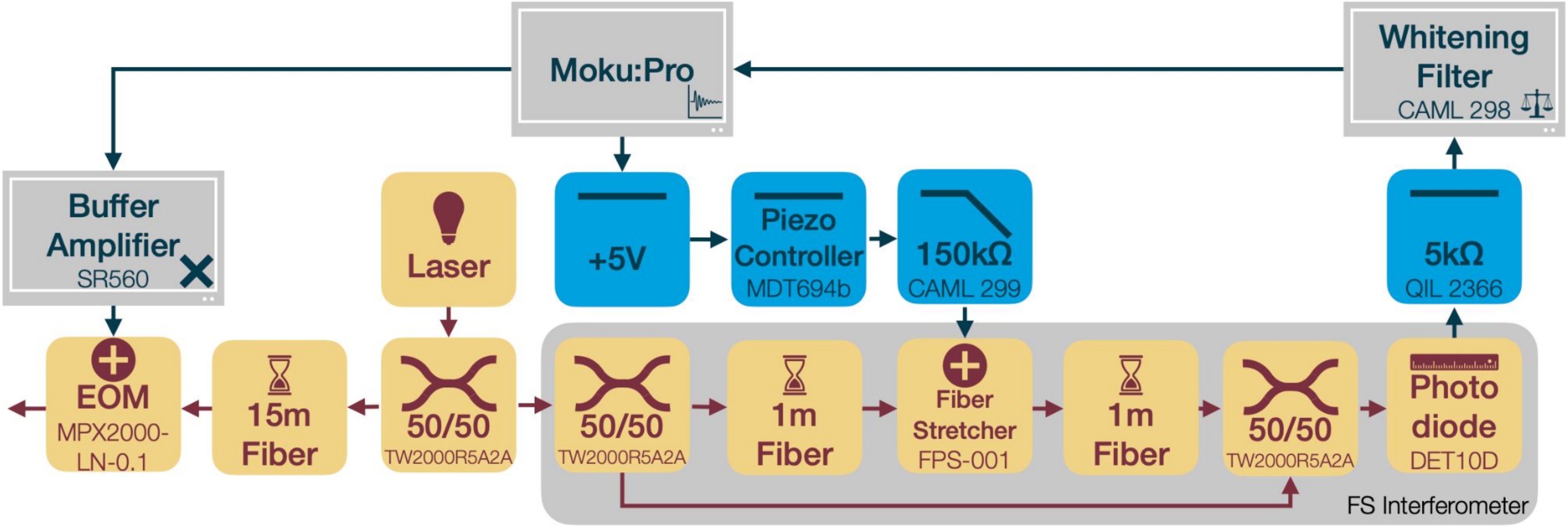
Block Diagram



Block Diagram



Block Diagram



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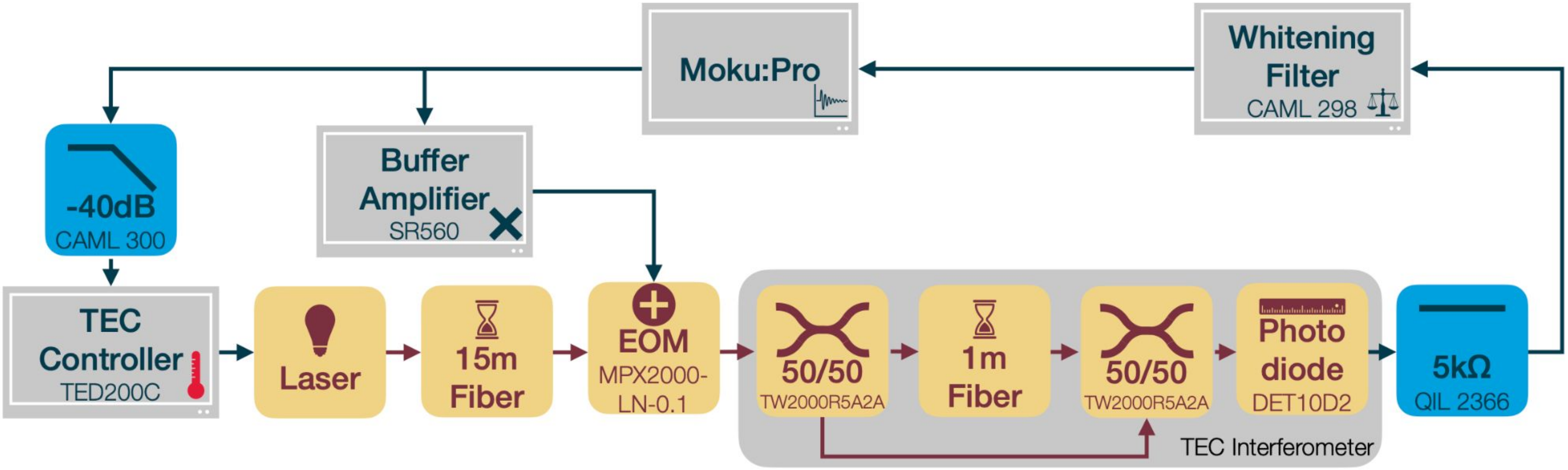
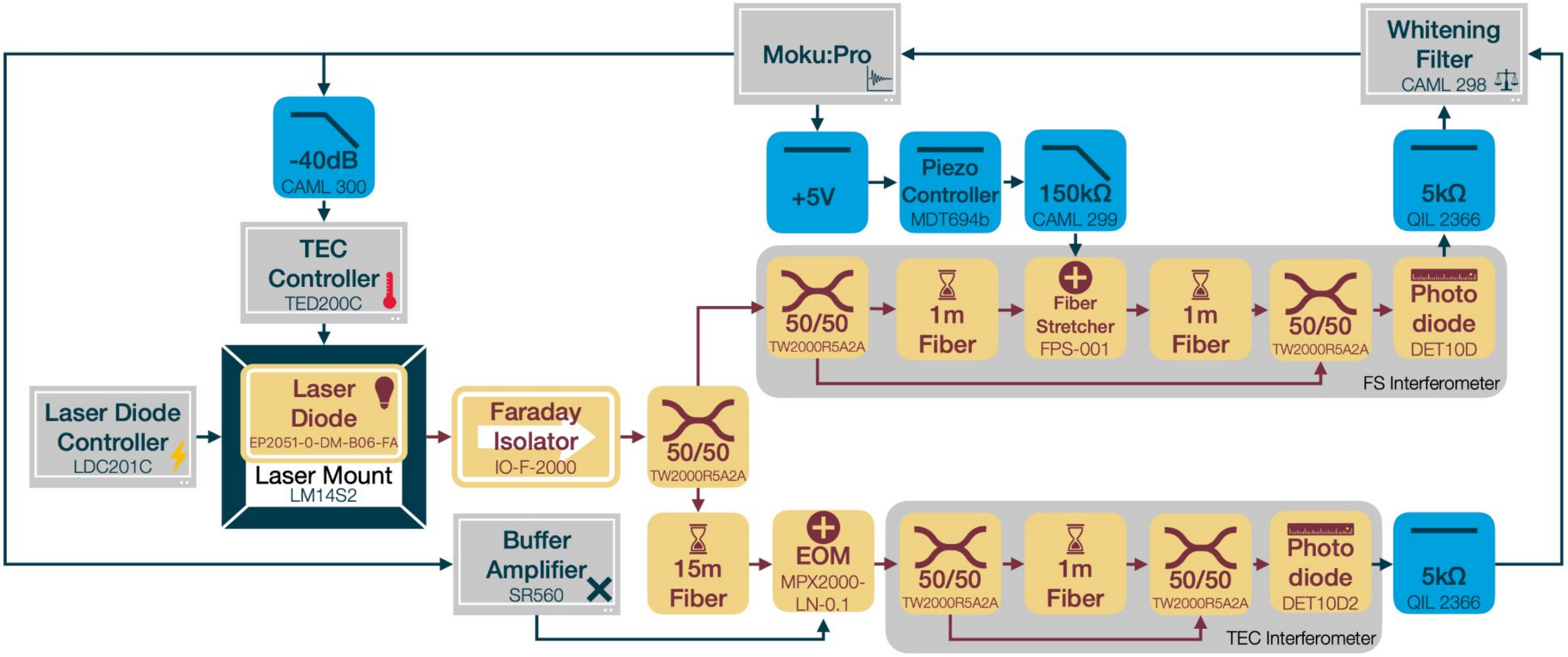
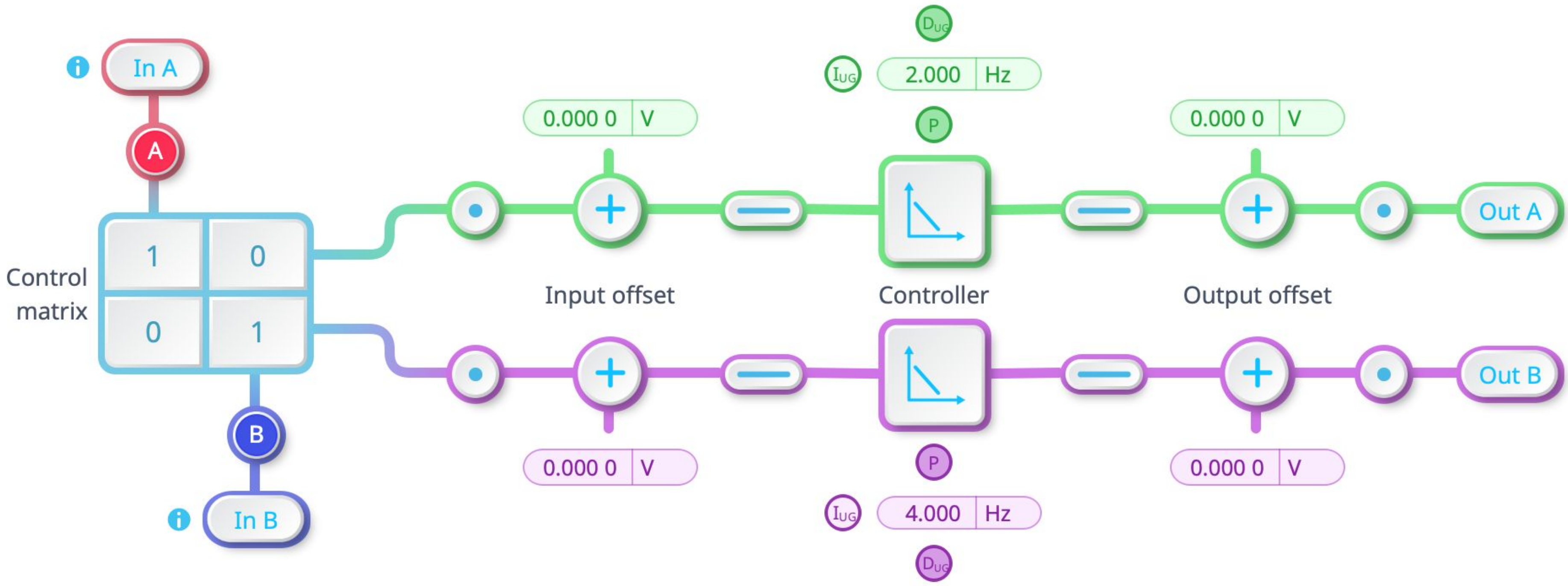


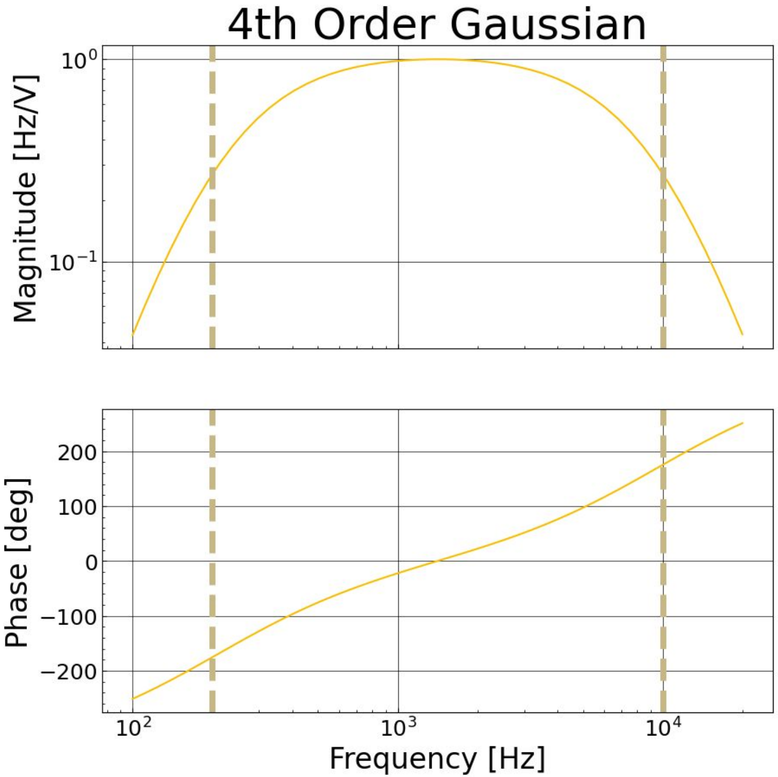
Block Diagram

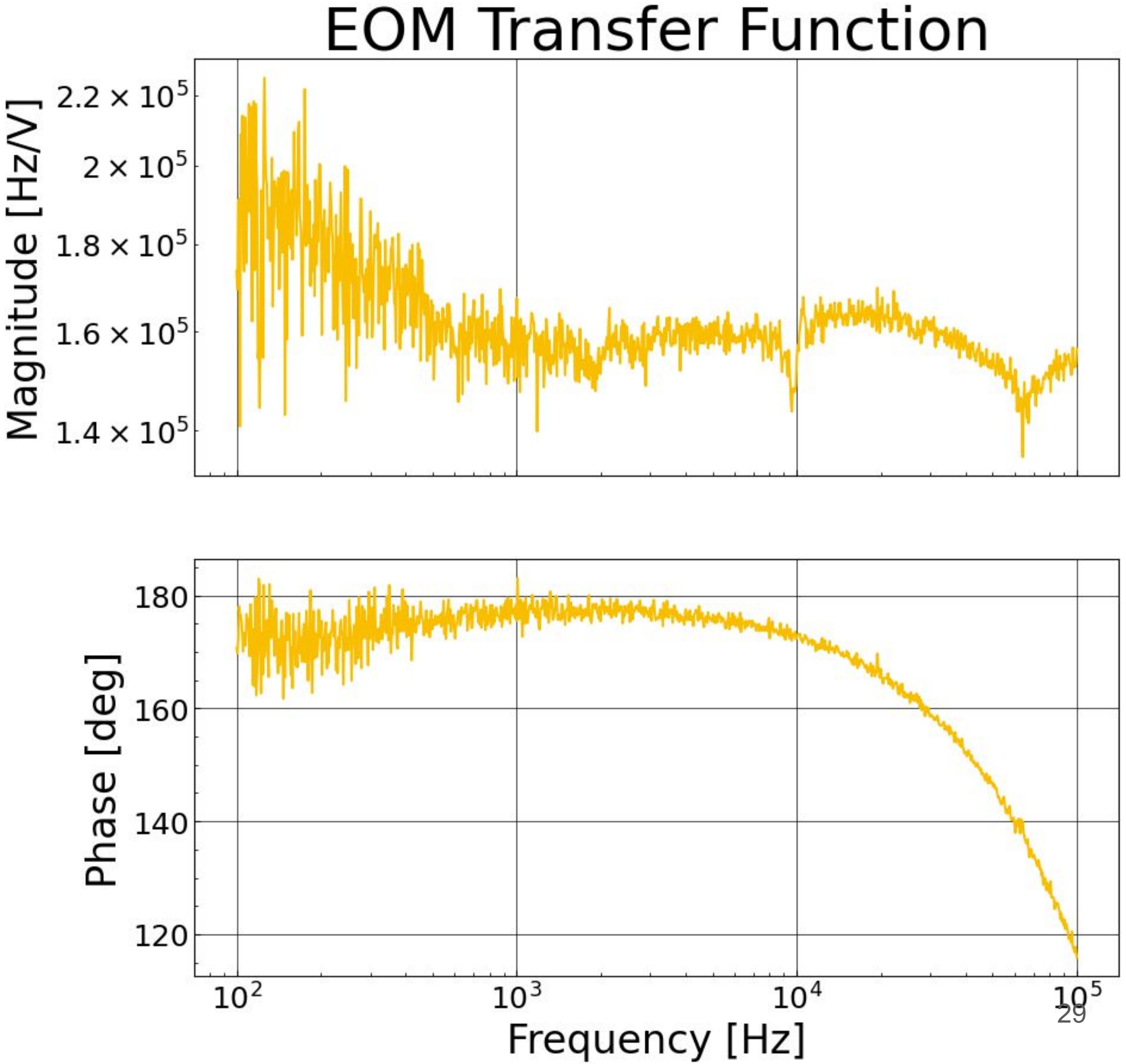


Locking Both Interferometers

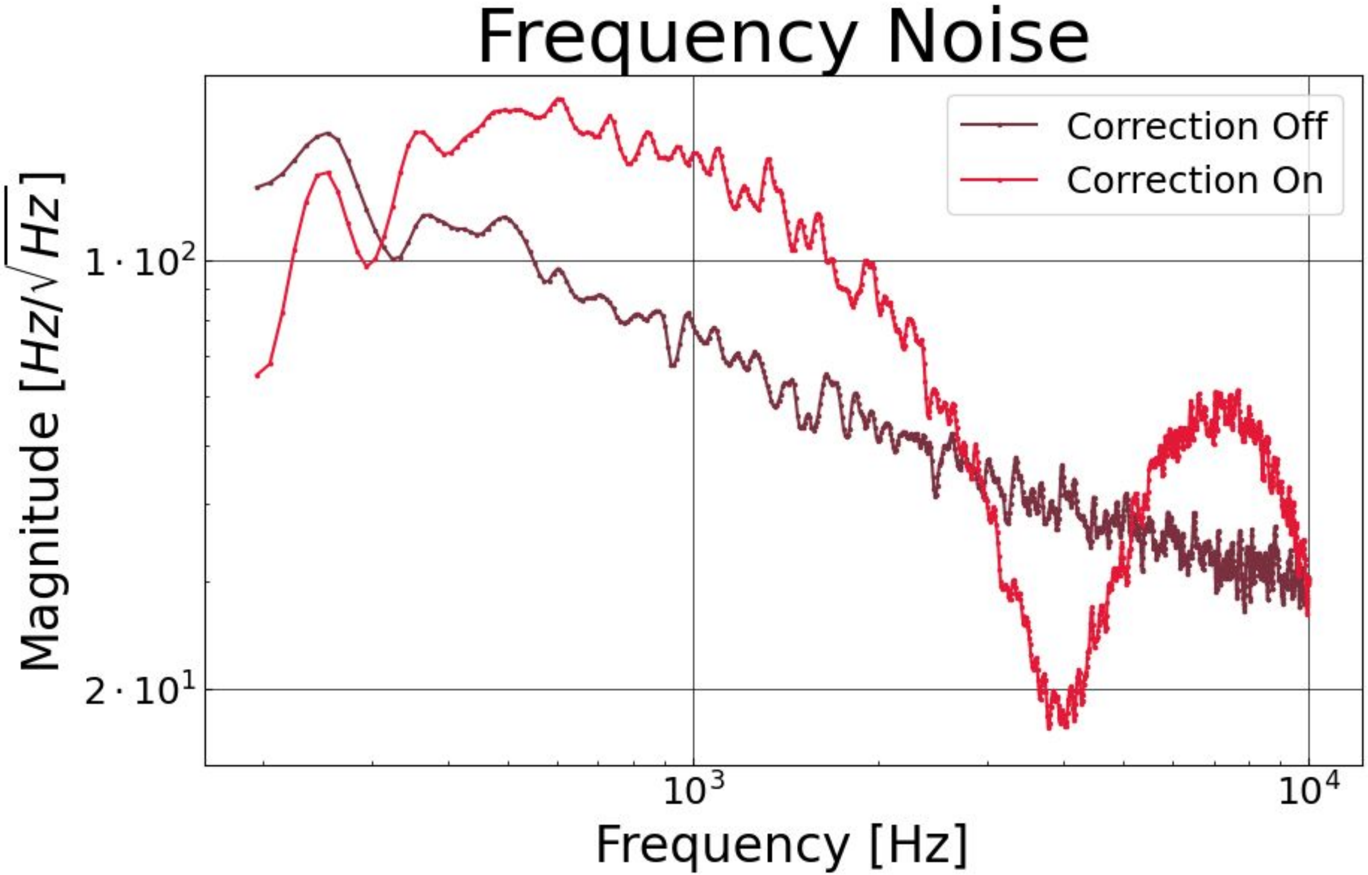


Controlling EOM





Demonstration of Noise Reduction



Conclusions

Successes:

- Two Interferometers
- Analysis of Noise in Measurement
- Demonstration of Noise Reduction

Future Work:

- Continue Modeling System
  - Analytic Ideal Cancellation
- Extend Cancellation Range
- Match Electrical & Optical Delay

Acknowledgements

Aidan Brooks, Rana Adhikari

LIGO, Caltech

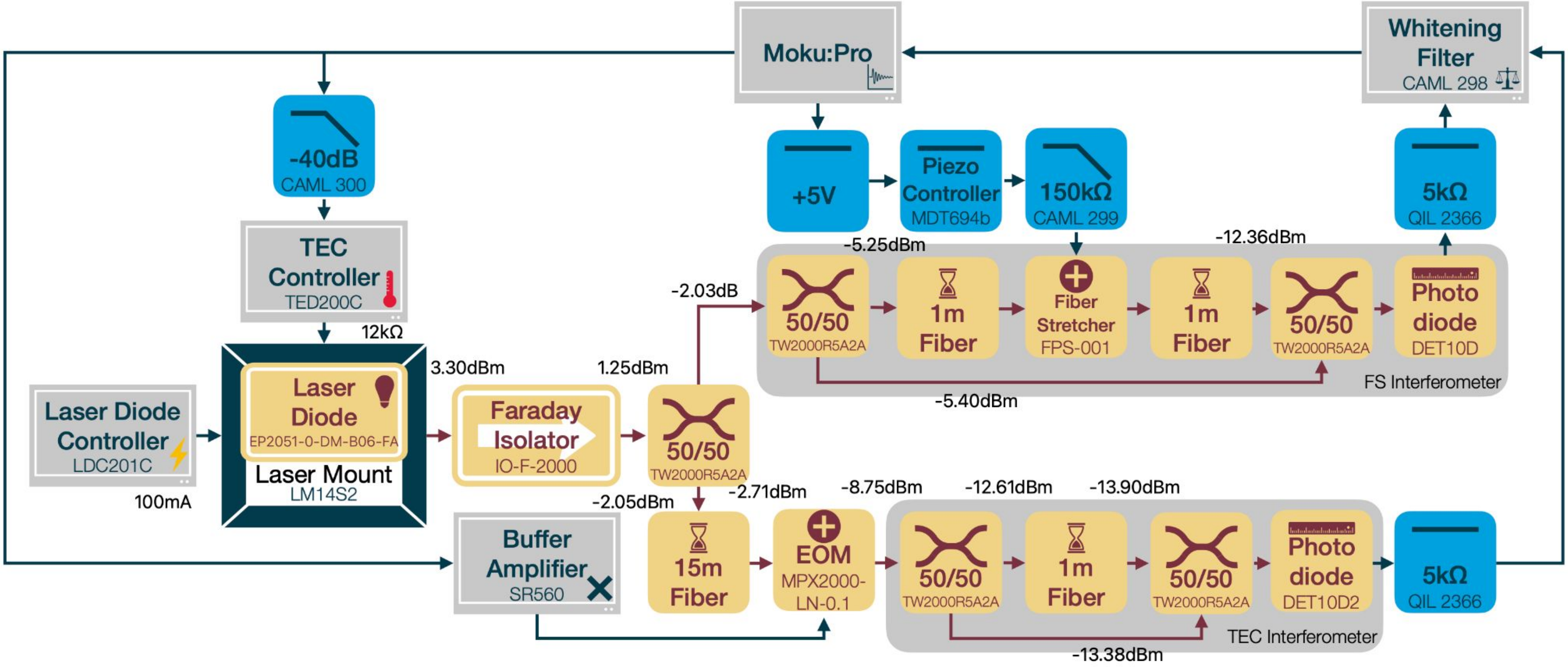
National Science Foundation

Caltech Class of ‘52 Named SURF

Caltech SFP Office

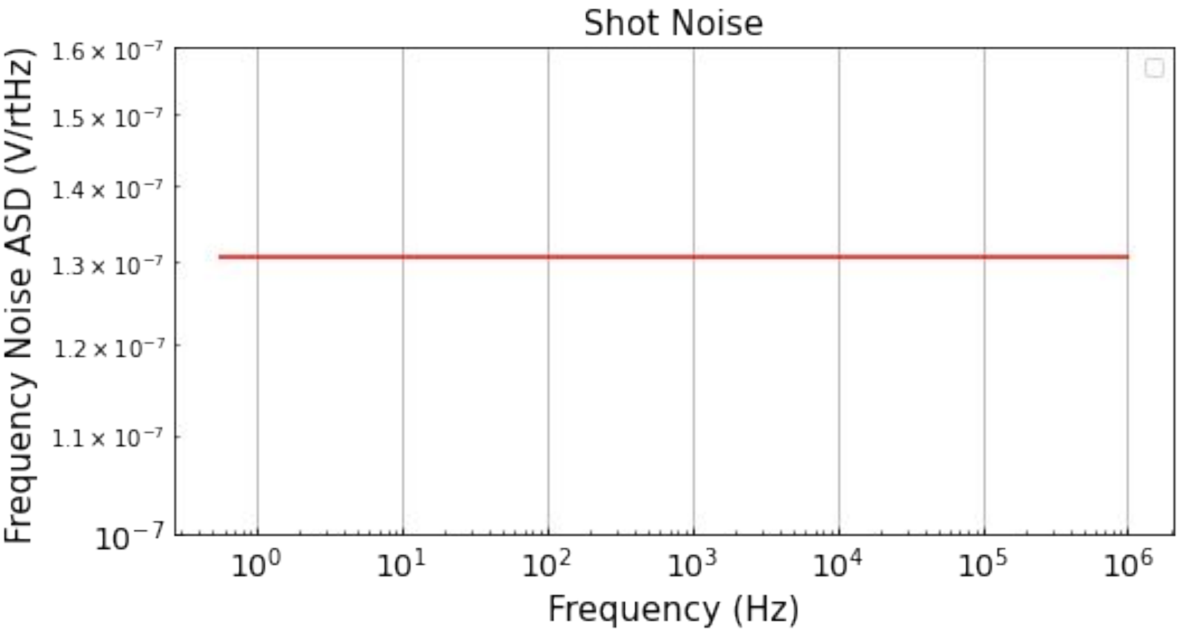
All the LIGO SURF students!

Extra Slides



Moku:Pro
Whitening Filter
CAML 298
-40dB
CAML 300
TEC Controller
TED200C
12kΩ
+5V
Piezo Controller
MDT694b
150kΩ
CAML 299
5kΩ
QIL 2366
-5.25dBm
-12.36dBm
-2.03dB
50/50
TW2000R5A2A
1m Fiber
Fiber Stretcher
FPS-001
1m Fiber
50/50
TW2000R5A2A
Photo diode
DET10D
FS Interferometer
-5.40dBm
3.30dBm
1.25dBm
Laser Diode Controller
LDC201C
Laser Diode
EP2051-0-DM-B06-FA
Laser Mount
LM14S2
Faraday Isolator
IO-F-2000
50/50
TW2000R5A2A
100mA
-2.05dBm
-2.71dBm
-8.75dBm
-12.61dBm
-13.90dBm
Buffer Amplifier
SR560
15m Fiber
EOM
MPX2000-LN-0.1
50/50
TW2000R5A2A
1m Fiber
50/50
TW2000R5A2A
Photo diode
DET10D2
5kΩ
QIL 2366
TEC Interferometer
-13.38dBm

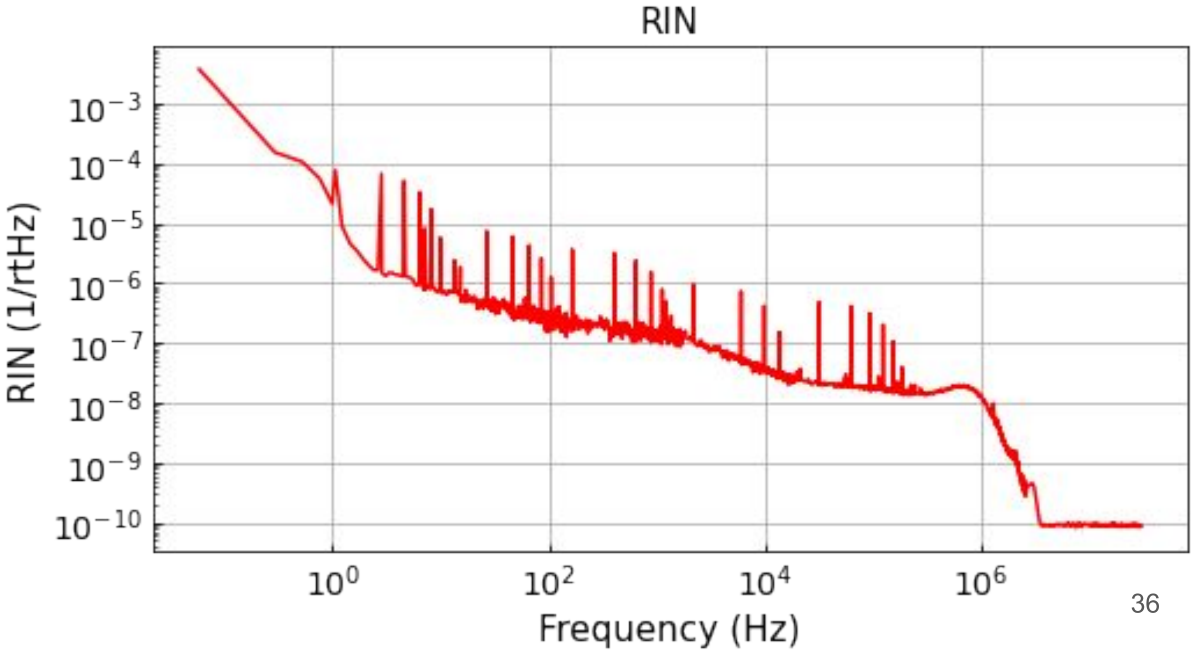
Shot Noise



- Noise due to the fact that photocurrent is a discrete flow of electrons
- There are variations in electron flow, as governed by Poisson statistics
- ASD of shot noise in amps/rtHz given by $\delta n_{shot} = \sqrt{2q|\bar{I}|}$
  - q : charge of electron
  - $|\bar{I}|$: absolute value of average current

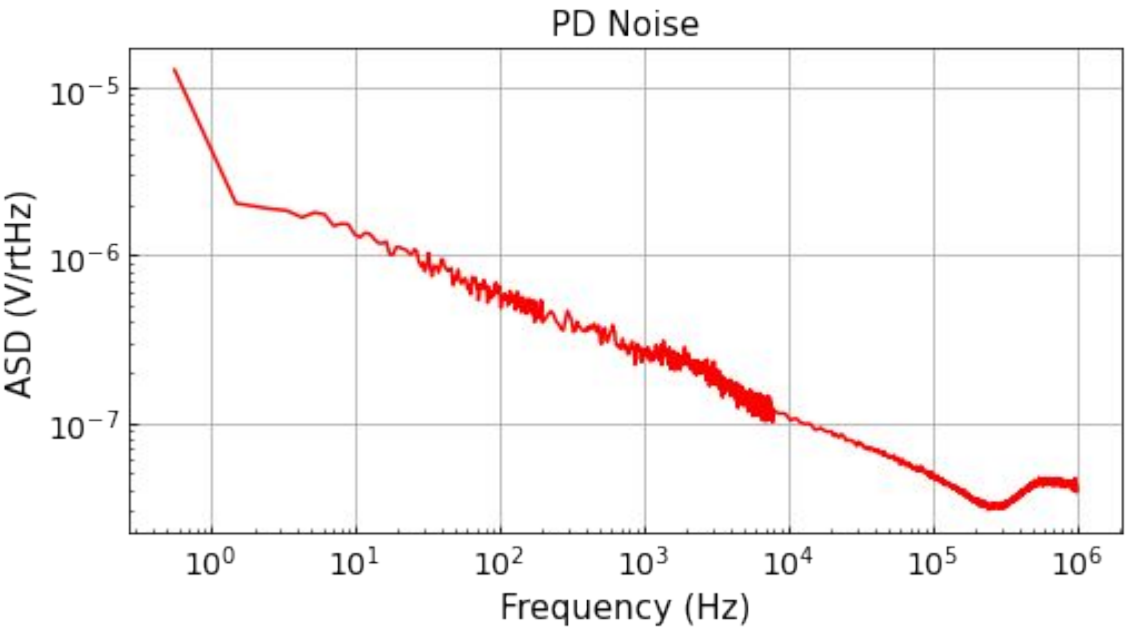
Relative Intensity Noise

- Fluctuations in intensity of laser output
- Measured without interferometer
- Convert input wattage of measured signal into DC output voltage, divide spectrum by this DC value



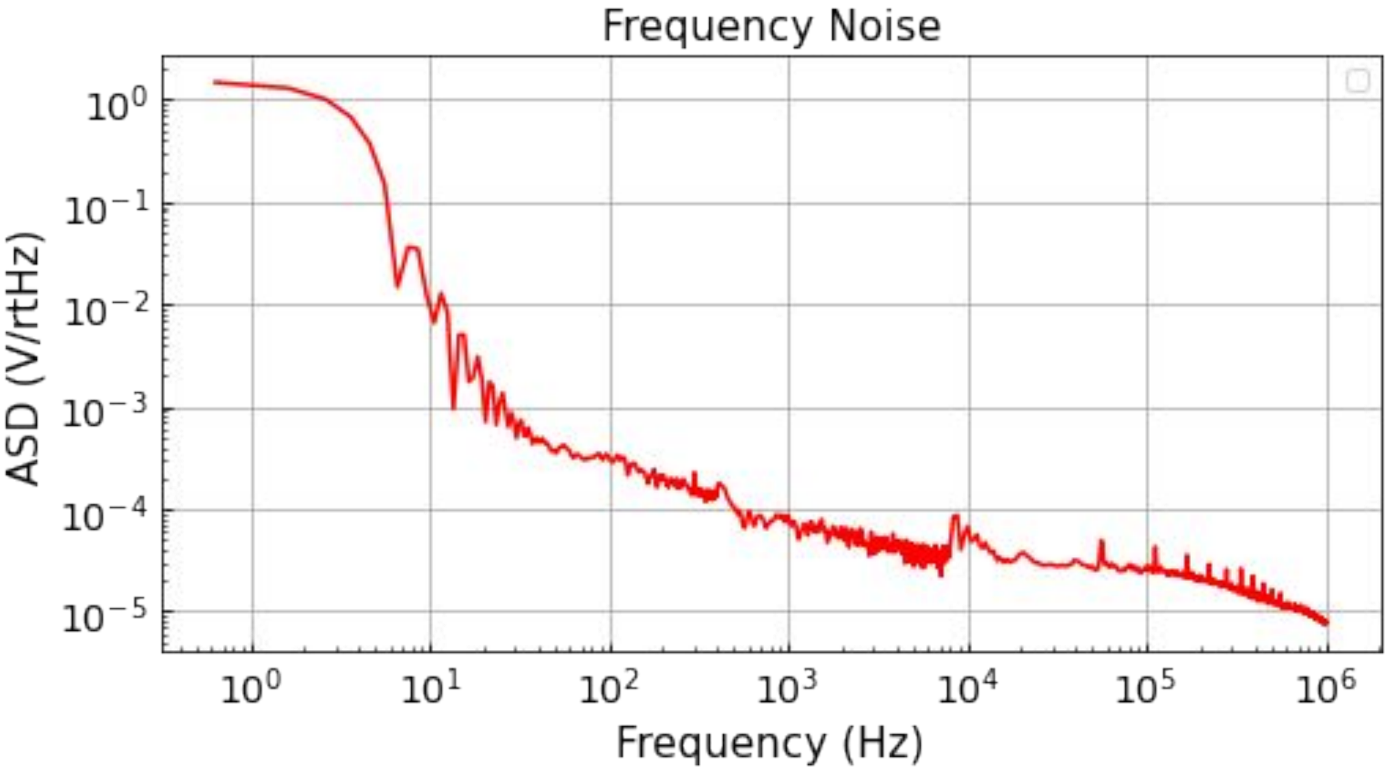
Photodiode Noise

- “Dark noise” from applying DC bias to diode
- Present whether laser is on or off
- Can’t just measure signal out of PD since it is below ADC noise floor
- Measured with signal amplified, then undid the amplification in our analysis



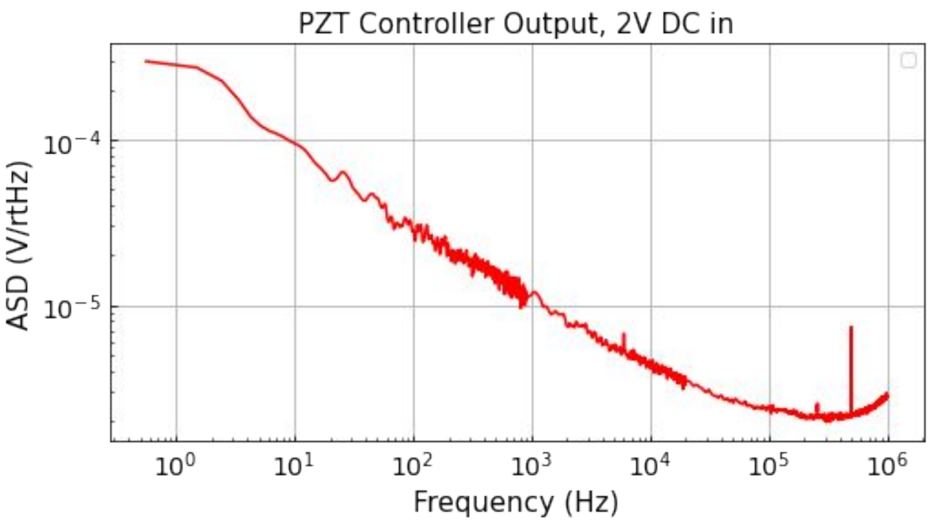
Frequency Noise

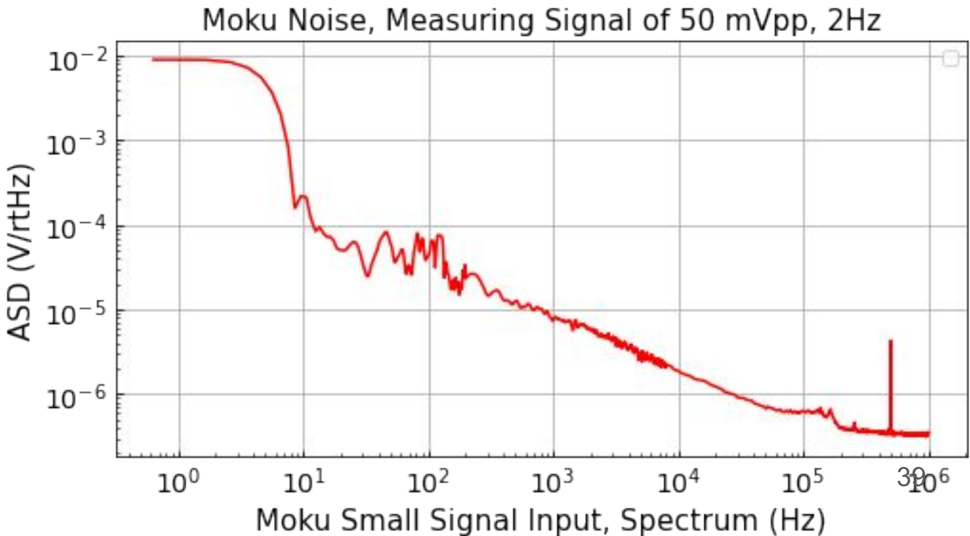
- Measured spectrum while laser was locked



Loop-Locking Noise

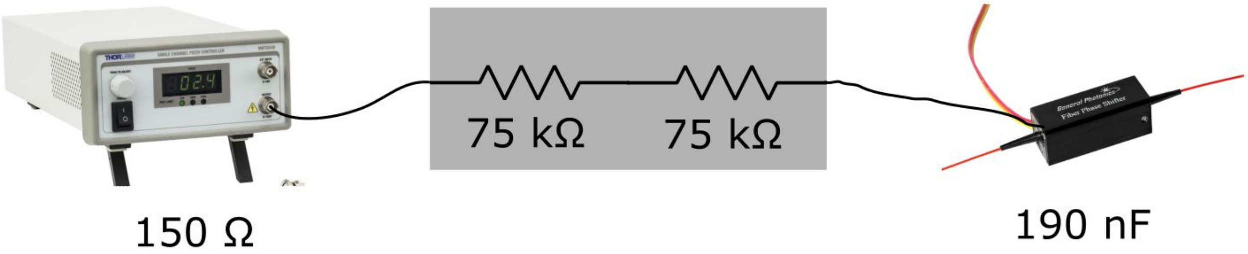
- There is noise associated with outputting a signal on the Moku and from using a piezo controller to amplify our signal
- Measured piezo controller output spectrum with a DC voltage input
- Set Moku to output a sine wave with a small amplitude and measured spectrum of the output

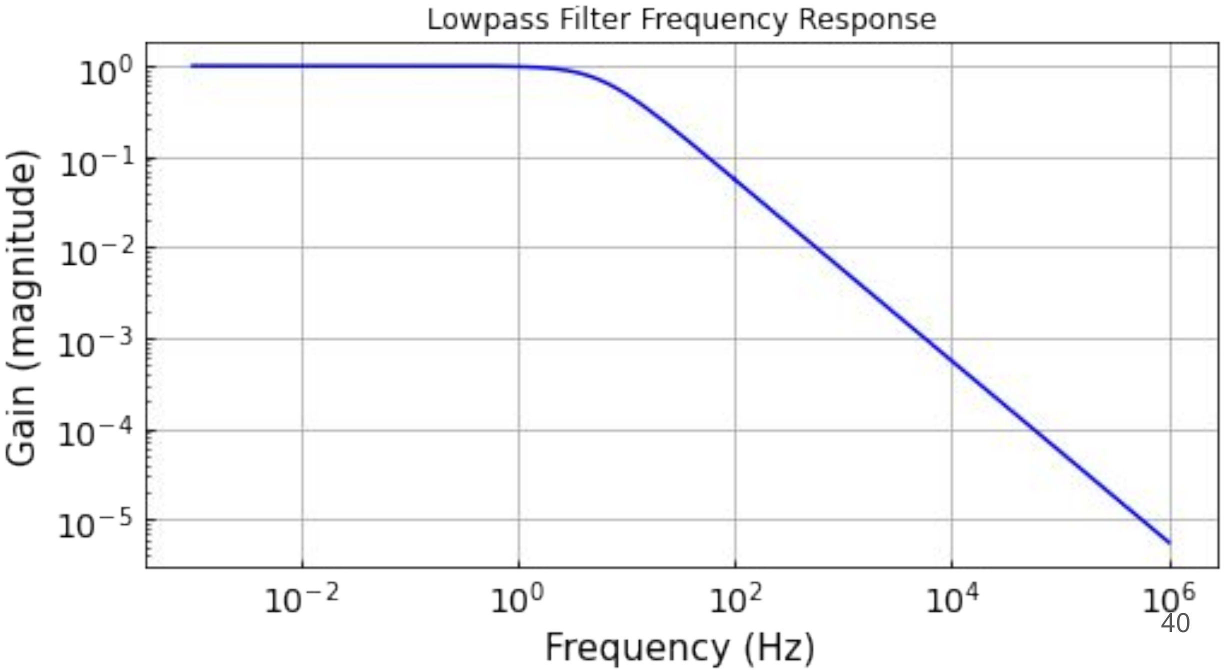


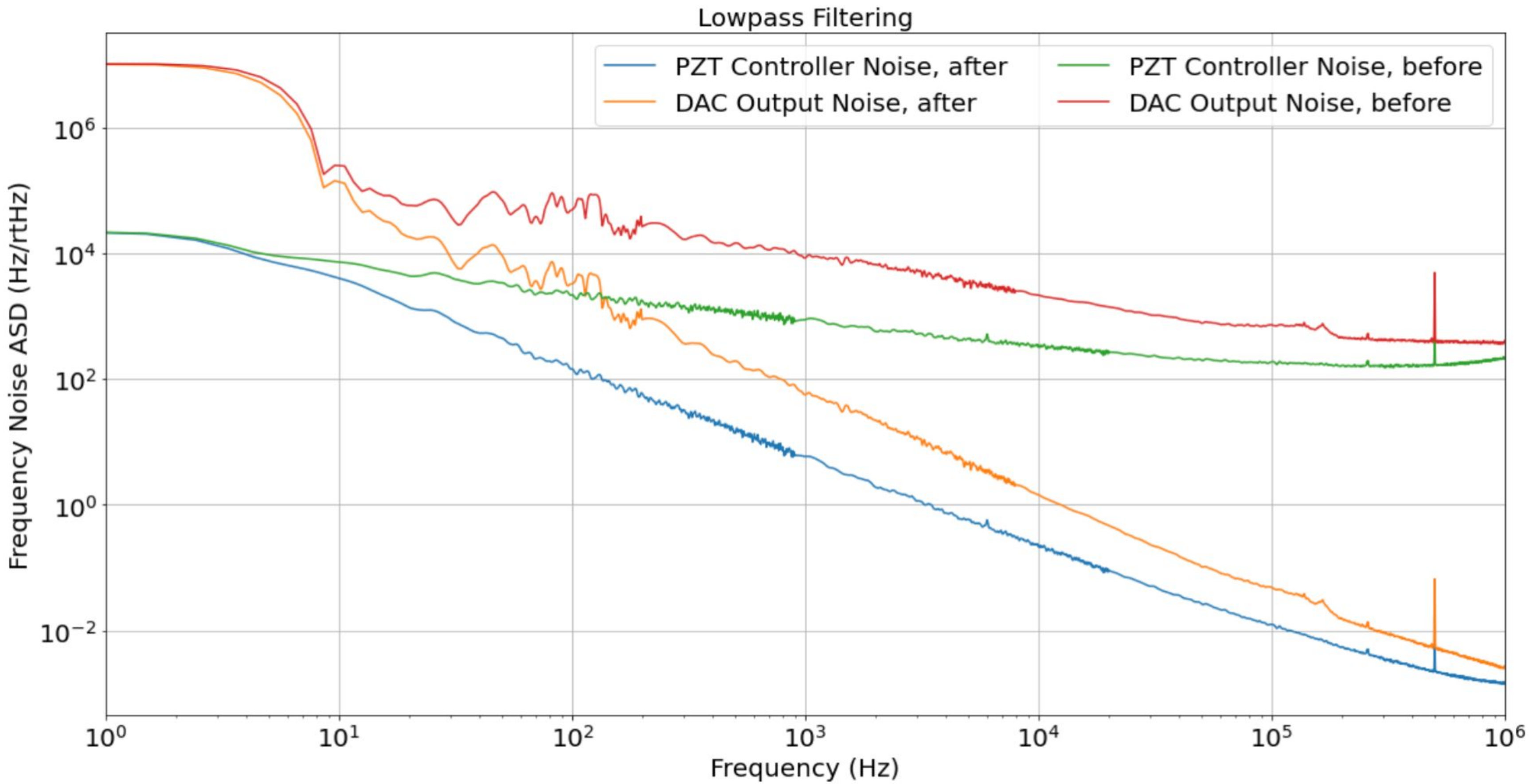


Low-pass Filter

- Suppress noise from fiber stretcher controls at high frequencies
- Use capacitance of fiber stretcher as our capacitor






Lowpass Filtering
PZT Controller Noise, after
DAC Output Noise, after
PZT Controller Noise, before
DAC Output Noise, before
Frequency Noise ASD (Hz/rtHz)
10^6
10^4
10^2
10^0
10^{-2}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Frequency (Hz)