Stabilization of a $2\mu m$ Laser using an all fiber delay-line Mach-Zehnder Interferometer

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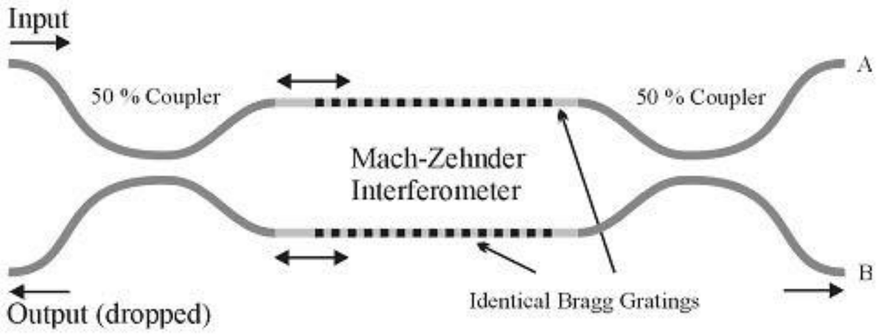
Motivations

- Current stage of LIGO Voyager R&D
- Not much is known about the effectiveness of a $2\mu m$ laser in this interferometric context

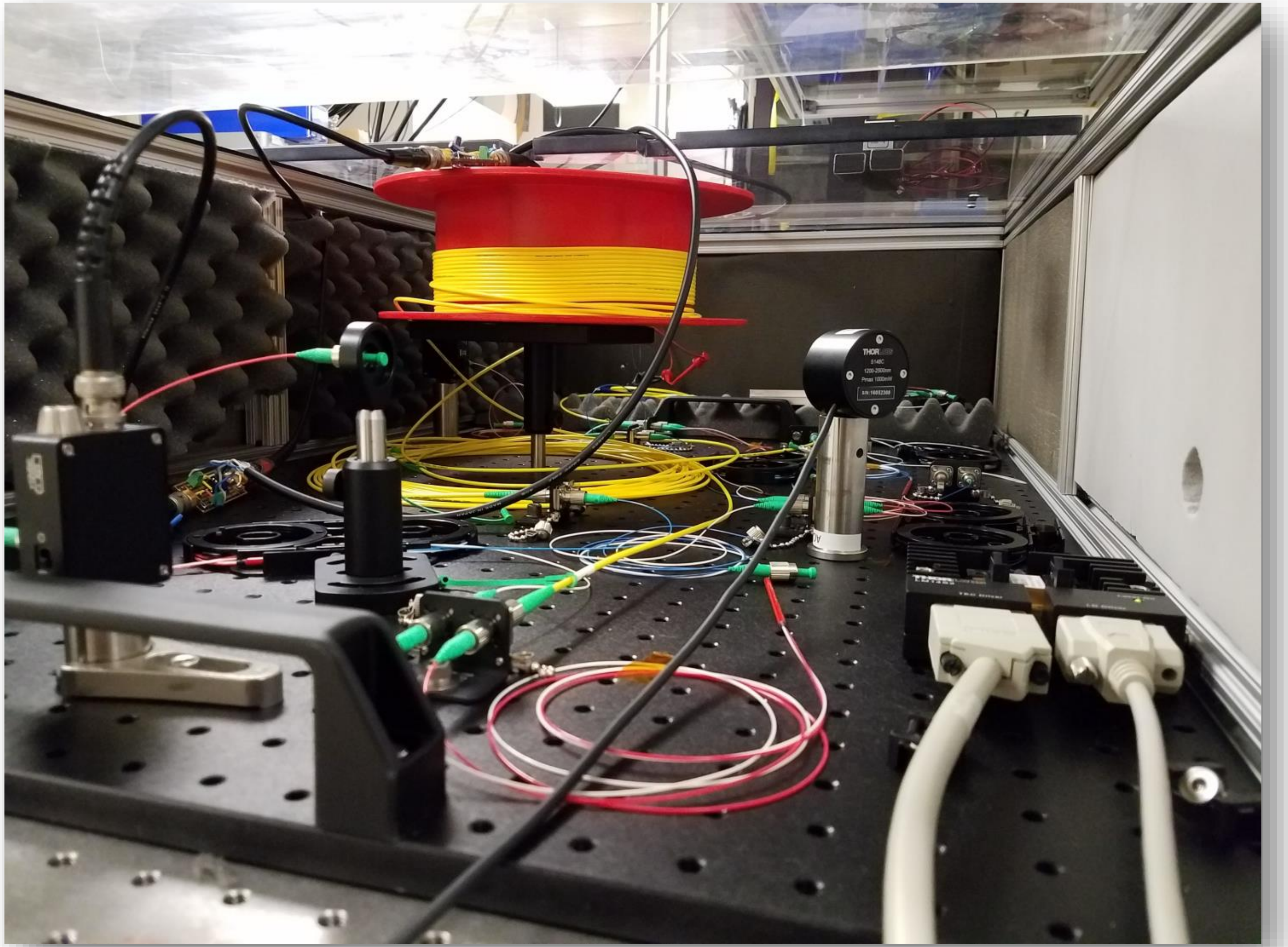
LIGO

The Experiment

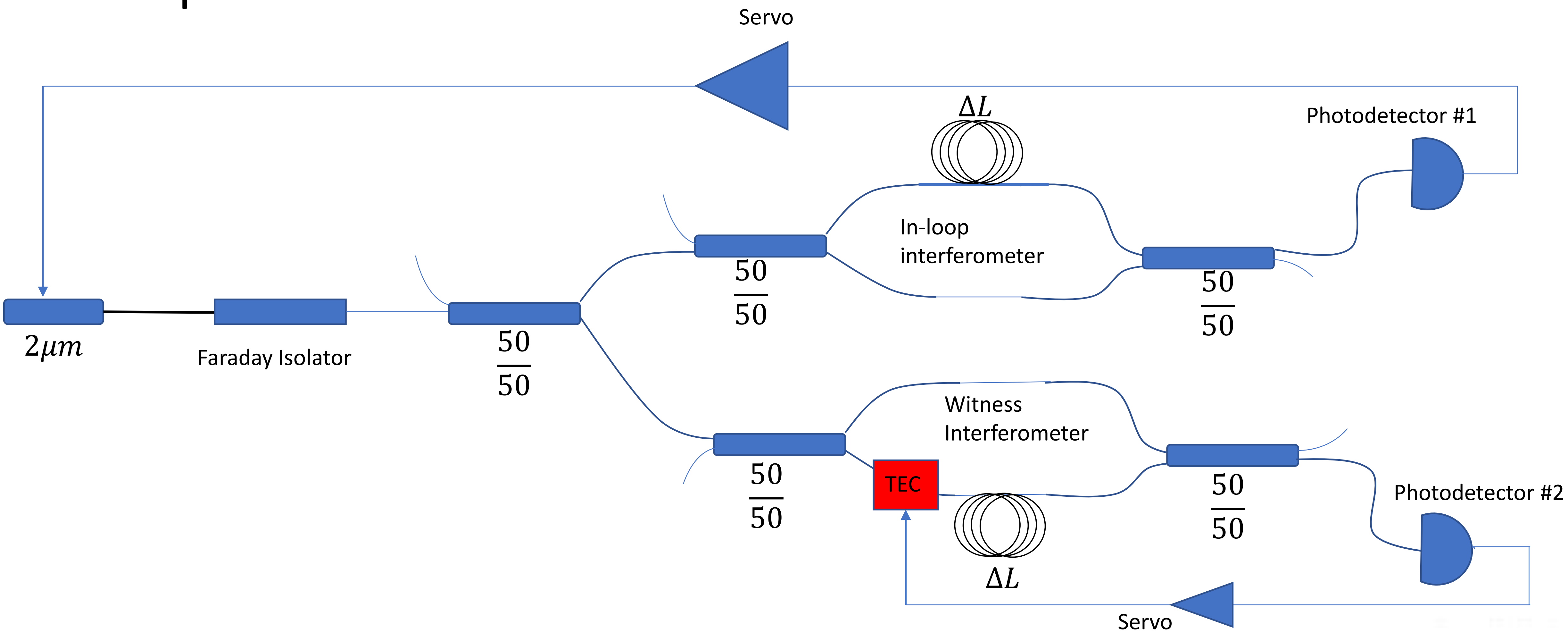
- Fibered Mach-Zehnder Interferometer (MZI)
  - Fibered set-up provides greater flexibility in experiment adjustments
- The delay-line, arm length mismatch
  - Frequency Discriminator
- The nearby “Witness” Interferometer
  - Provide a reference for the purpose of prolonged stability

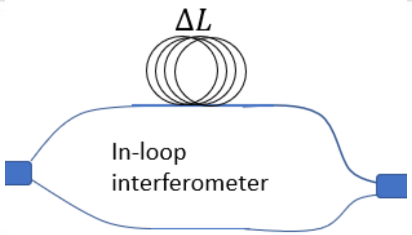


The Experiment



The Experiment

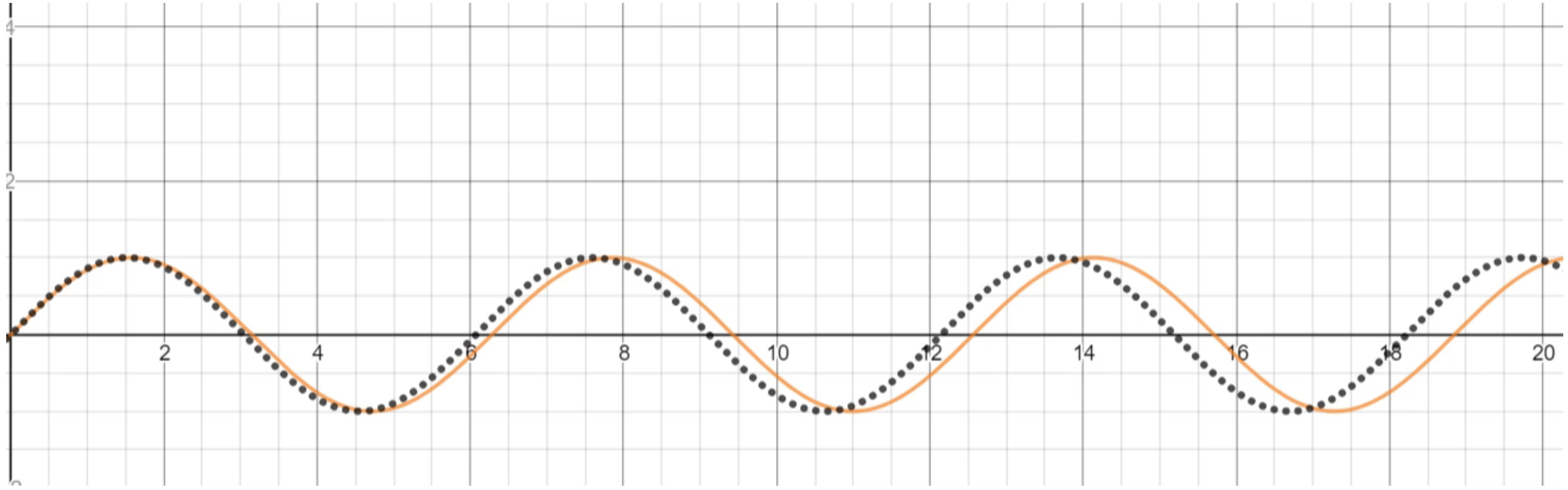


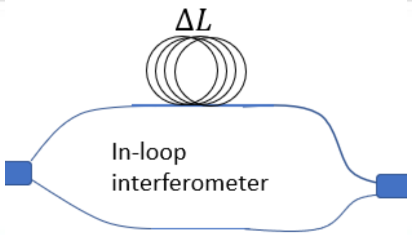


Frequency Noise

- Random fluctuations in the instantaneous frequency of an oscillating signal.
  - Where *instantaneous frequency is expressed as:*
    - $\nu(t) = \frac{\Delta\phi}{2\pi\Delta t}$

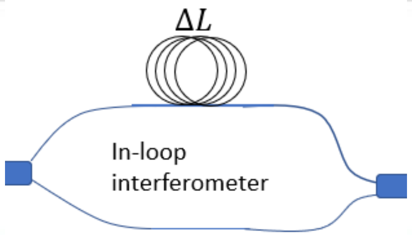
$$\Delta\phi = 2\pi\left(\frac{n\Delta L}{c}\right)\nu(t)$$





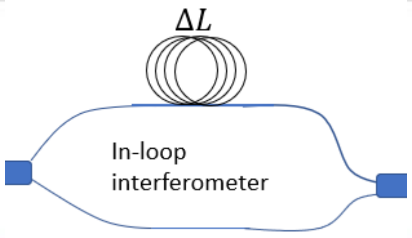
Frequency Noise

- Frequency noise is directly related to the change and, in our delay line, the accumulation of phase.
- That $\Delta\phi$ will ultimately be read as fluctuations in intensity (signal amplitude) in our oscilloscope.



Delay Line

- Manifested through the MZI arm-mismatch.
- Phase accumulation in longer arm is converted to power fluctuations.
- The longer arm acts as a frequency discriminator.

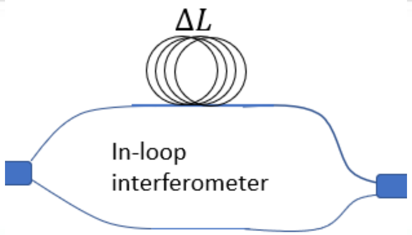


Delay Line, the ΔL

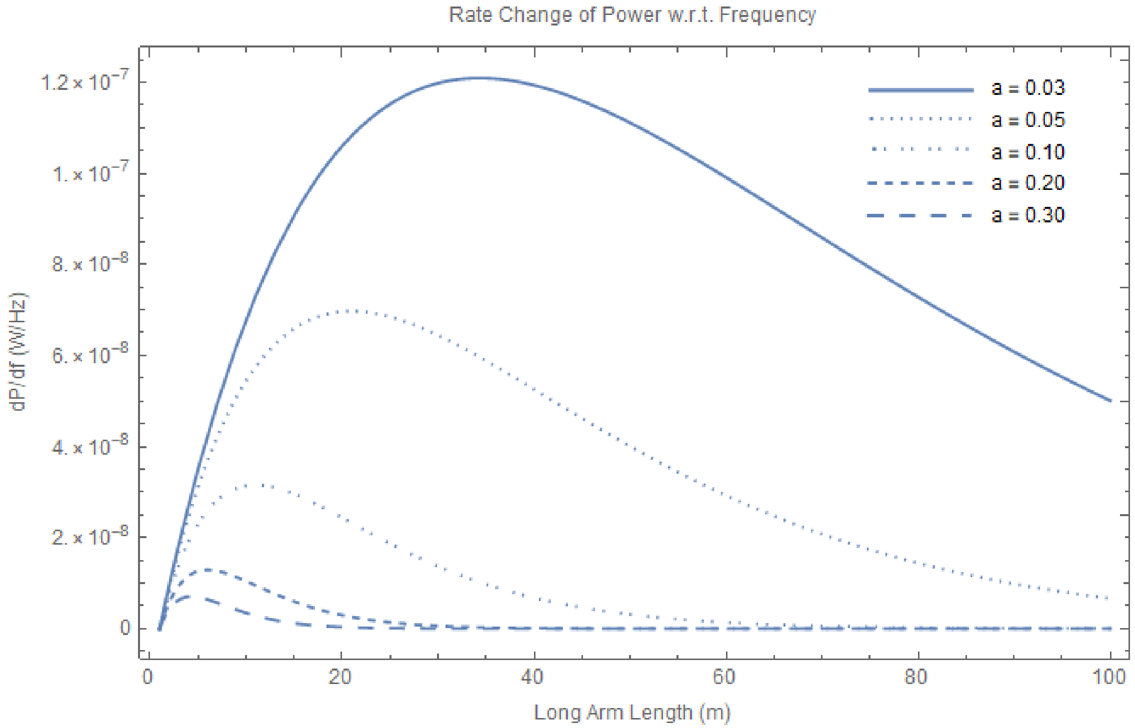
- Various routes of optimization exist when choosing the ideal path length difference:
  - Acoustic sensitivity
  - Power loss*

$$E_{inc}(t) = E_0 \cos(kx - \omega t)\, \mathrm{e}^{-\alpha L_1}$$

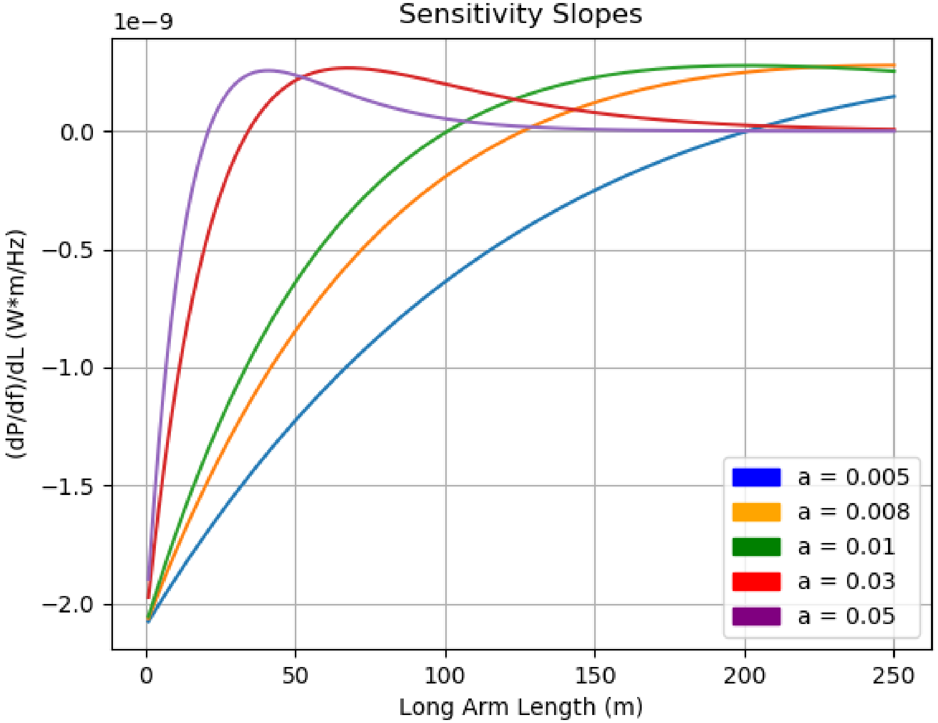
$$P_{out} = \frac{P_{in}}{4}(e^{-2L_1\alpha} + e^{-2L_2\alpha} + 2e^{-(L_1+L_2)\alpha} \cos(\frac{2f(L_2 - L_1)\pi}{c}))$$



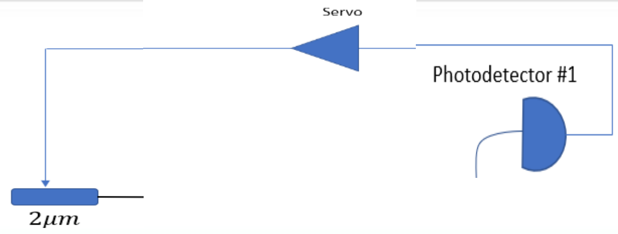
$$\frac{dP_{out}}{df}$$



$$\frac{dP_{out}}{df}/dL_2$$

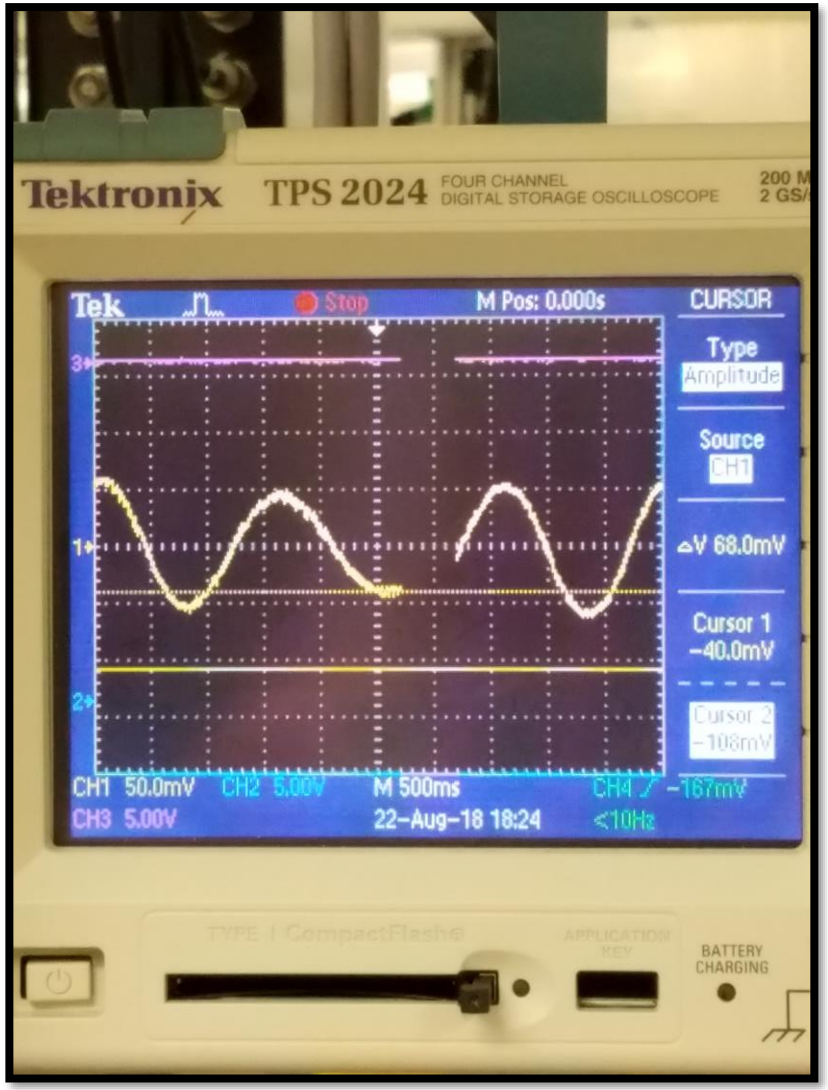


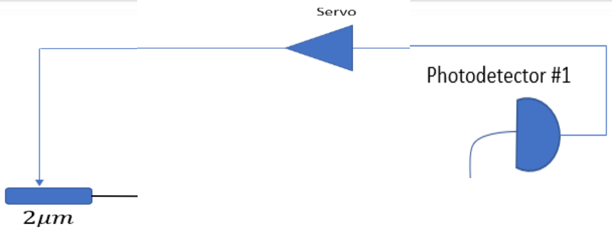
Given this optimization, ideal path length would be roughly 136m.



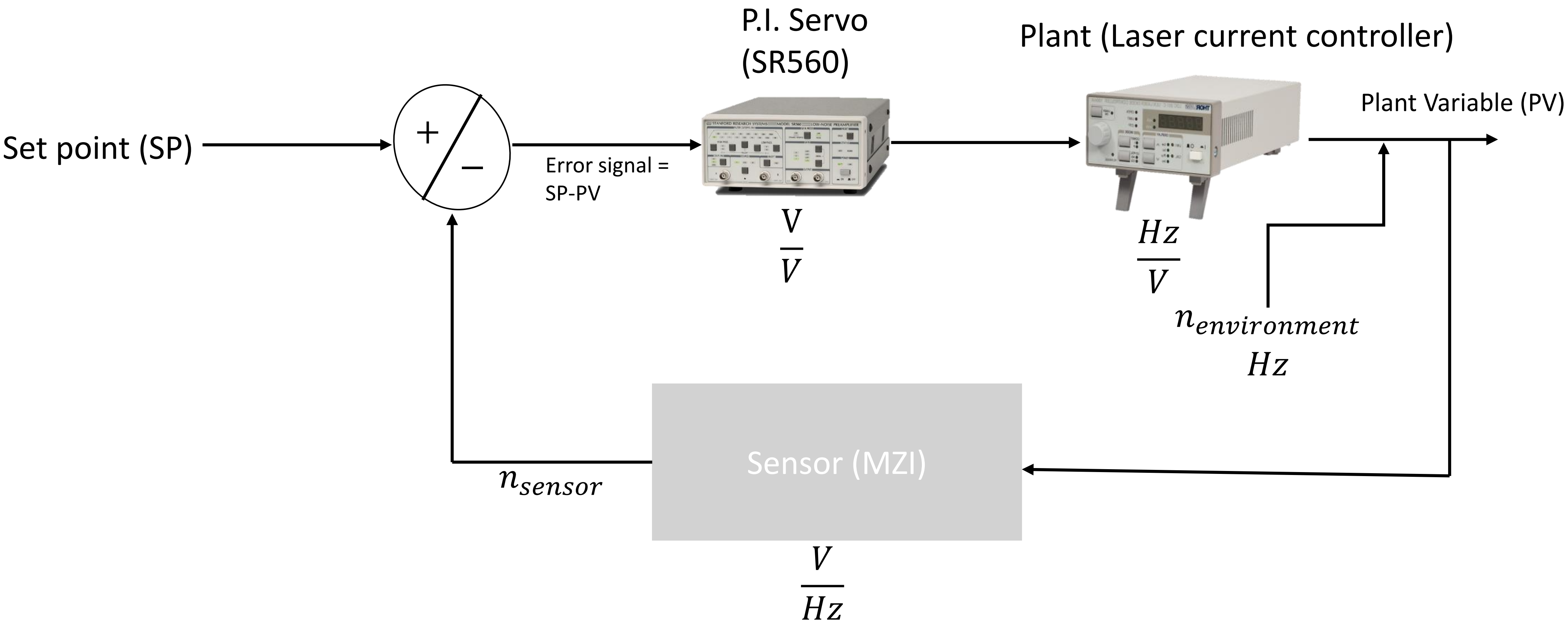
Stabilization, *How?*

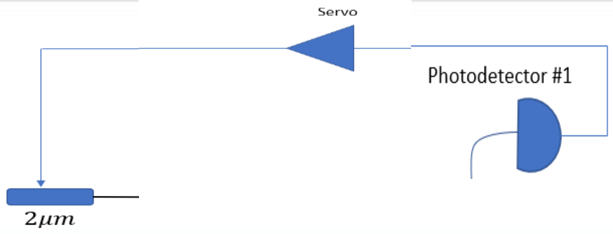
- Achieved by *locking* the photodetector’s output to mid-fringe, and subsequently creating a closed feedback loop with its current controller.
- The feedback loop is a PI (Proportional – Integration) control system because of its servo’s integer gain and bandpass filter capabilities, respectively.





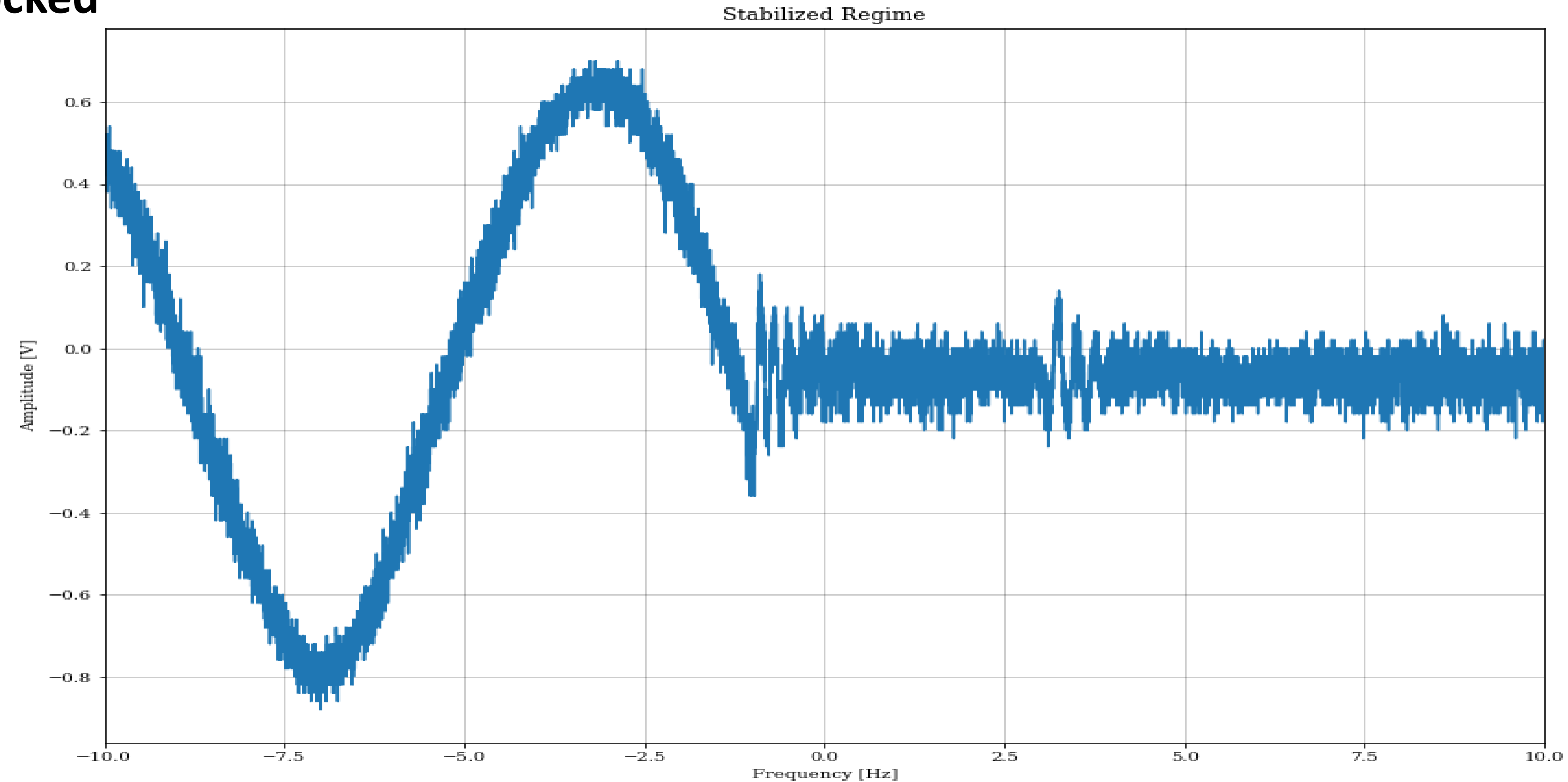
Stabilization, *How?*





Open loop signal output, mid-fringe locked

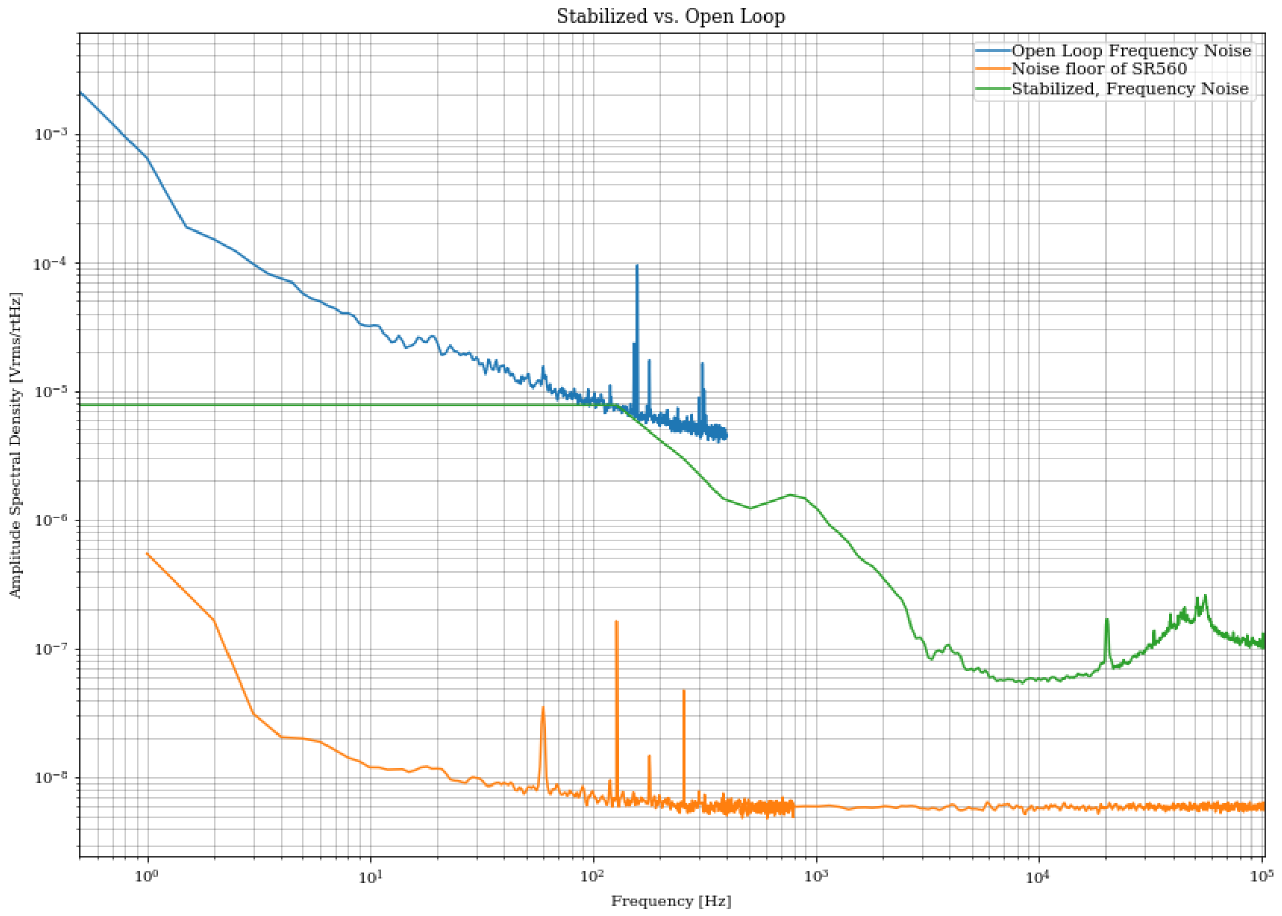
Closed loop stability regime



Stabilization, *Why?*

- Stabilization is crucial in the characterization of our $\mathbf{2}\boldsymbol{\mu m}$ laser.
  - Observing residual fluctuations inherent within the laser under testing.
- Witness interferometer acts as a reference to in-loop interferometer.
  - It has its own closed feedback loop with a thermally actuating pair of plates.

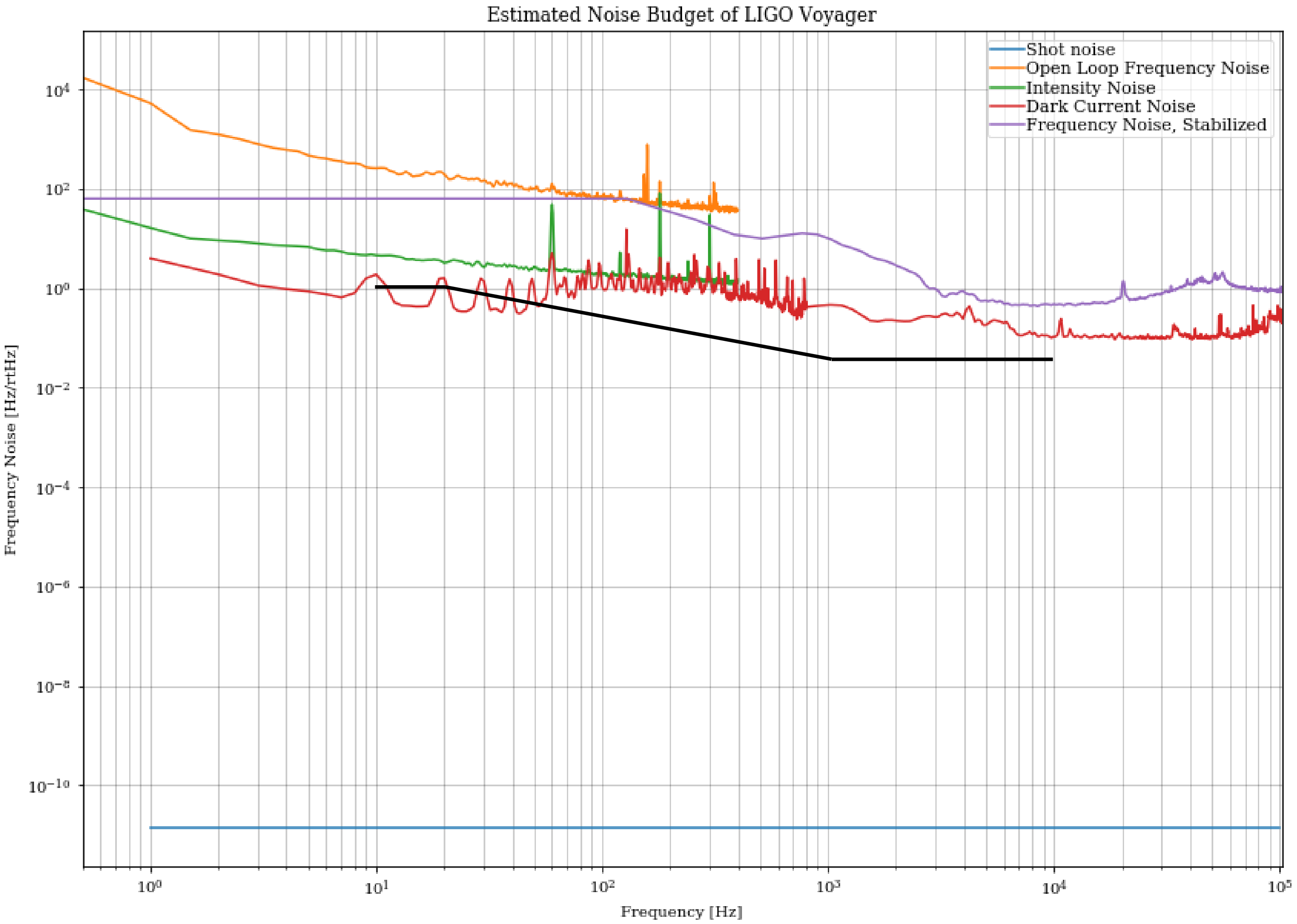
Stabilization



Noise Budget

- Shot noise
  - Fundamental limit to optical intensity noise.
- Open loop frequency noise
  - No feedback
- Intensity noise
  - One arm signal, including electronics noise
- Dark current Noise
  - From powered photodetector
- Frequency Noise of stabilized laser

Speculated LIGO Voyager requirement (based of Advanced LIGO's)



Further work

- Acoustic sensitivity measurements within optic fibers
- Incorporate thermal sensors within and around TMTF

- Characterize potential sources of noise in stabilized laser

Acknowledgements

Andrew Wade, Aidan Brooks

LIGO, Caltech SFP

Laser Safety Guidelines

SURFers