Constructing a Balanced Homodyne Detector

For Low Quantum Noise Gravitational Wave Interferometry

John Martyn, LIGO SURF 2018
Mentors: Andrew Wade, Kevin Kuns, Aaron Markowitz, Rana Adhikari

Caltech, LIGO

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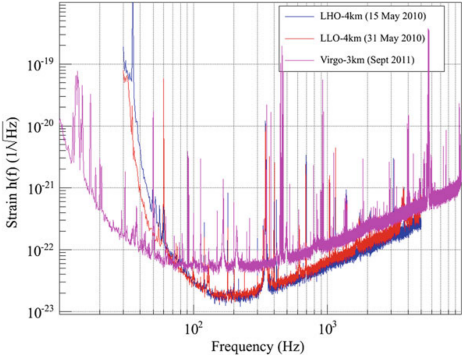
A Brief Discussion of Noise

- Given a signal, $y(t)$, as a function of time, the noise spectral density of the signal, $N_y(f)$, is defined by

$$N_y(f) := \lim_{T\to\infty} \frac{2}{T} \left| \int_{-T/2}^{T/2} dt \; (y(t) - \bar{y}) e^{2\pi i f t} \right|^2$$

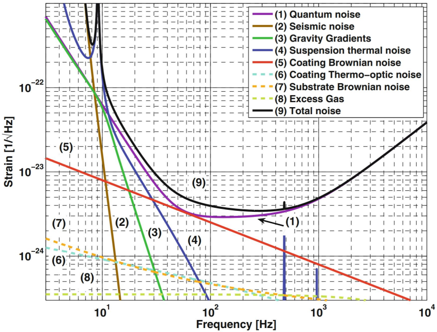
- This obeys $\int_0^\infty df \; N_y(f) = \sigma_y^2$, and allows one to examine what frequencies contribute to a signal's variance.



Sources of Noise

Sources of noise at LIGO:

- Extrinsic
  - Weather, human activity, electronic noise, etc.
  - Reduced by performing interferometry in vacuum chambers, vibration isolation systems, low noise circuits, etc.
- Intrinsic
  - Arises from the laws of quantum mechanics
  - Quite nontrivial to reduce



Quantization and Noise

A source of noise, known as quantum noise, contributes to intrinsic noise that LIGO must combat.

- Due to quantum mechanics
- Recall the quantization of a mechanical system:

$$[\hat{x}, \hat{p}] = i\hbar \Rightarrow \sigma_x \sigma_p \geq \hbar/2 \tag{1}$$

- Nonzero uncertainties introduce noise into x and p
  - For instance, $\sqrt{\int_0^\infty df \;\, N_x(f)} = \sigma_x \neq 0 \Rightarrow N_x(f) \not\equiv 0$

EM field

How does this affect LIGO? $\Rightarrow$ the light in the interferometer
First consider a monochromatic plane wave:

- Its electric field:

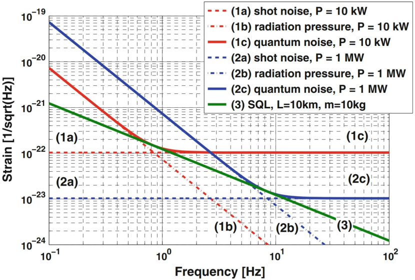
$$\hat{\mathbf{E}}(\mathbf{r}, t) = E_0\Big(\hat{X}_1 \cos(\omega t) - \hat{X}_2 \sin(\omega t)\Big)\mathbf{p}(\mathbf{r}, t)$$

$$E_0 = \text{amplitude}, \quad \mathbf{p}(\mathbf{r}, t) = \text{polarization}$$

- $\hat{X}_1$ and $\hat{X}_1$, the amplitude and phase quadratures, furnish a description of the wave.
- We wish to measure these quadratures to perform interferometry.

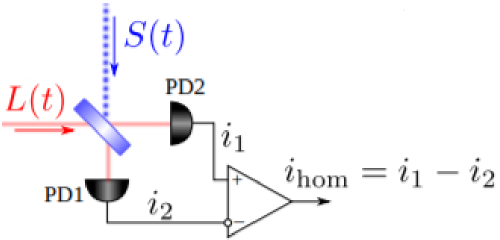
Quantum Noise

- Unfortunately, quantum noise introduces shot noise and radiation pressure noise into monochromatic plane waves (by quantizing EM field).
- Quadratures become
  $X_{1,2} = \text{classical field} + \text{noise} = X^0_{1,2} + x_{1,2}$
- This poses a serious difficulty for gravitational wave interferometers using monochromatic plane waves.



Balanced Homodyne Detection

- Luckily, balanced homodyne detection (BHD) can accurately measure an arbitrary quadrature of light.
- BHD works by mixing a strong source of light known as the local oscillator (LO), with a weak signal (modulated light), and sending the combined light through a beam splitter.
- The signals exiting the beamsplitter are then subtracted, producing the homodyne signal.



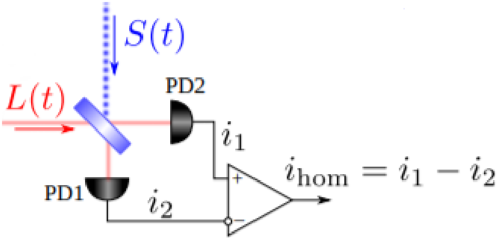
Balanced Homodyne Detection

- $S_{c,s}(t)$ and $L_{c,s}(t)$ (quadratures) contain effects due to quantum noise:

$$S_{c,s}(t) = S^0_{c,s}(t) + s_{c,s}(t), \qquad L_{c,s}(t) = L^0_{c,s}(t) + l_{c,s}(t)$$

- We assume the local oscillator (LO) is more intense than the other fields:

$$L^0_{c,s}(t) \gg S^0_{c,s}(t),\ s_{c,s}(t),\ l_{c,s}(t)$$



Balanced Homodyne Detection

- Local oscillator (LO) is more intense than the other fields:

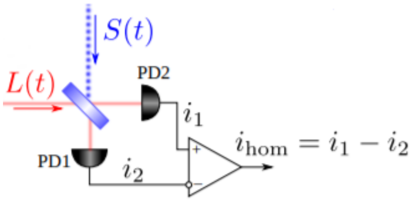
$$L^0_{c,s}(t) \gg S^0_{c,s}(t),\ s_{c,s}(t),\ l_{c,s}(t)$$

- Homodyne current: (Danilishin, Khalili, arXiv:1203.1706)

$$i_{\text{hom}} = i_1 - i_2 \propto L^0_c(S_c + s_c) + L^0_s(S_s + s_s)$$

- LO noise cancels out! i_{hom} depends only on signal noise.

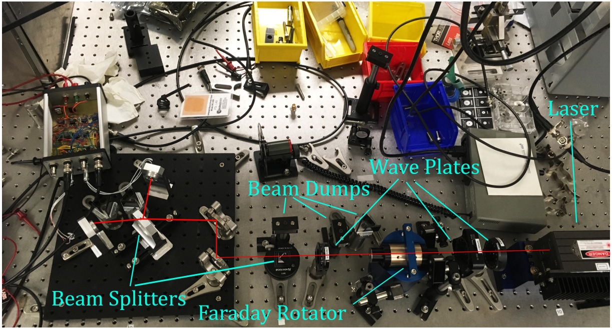
- Can measure arbitrary quadratures $\Rightarrow$ more information than LIGO's DC readout scheme
- Useful for experiments with squeezed light



The Goal

- The goal of this project is to construct the optical components and readout electronics for a balanced homodyne detector that may be used in various LIGO research labs performing experiments with non-classical light.

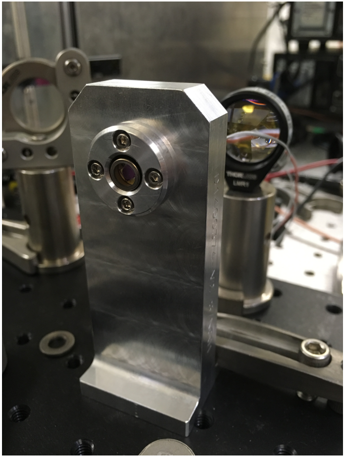
Optics



- Laser emits 1064 nm TEM_{00} Gaussian mode
- Wave plates and Faraday rotator for power control.
- Steering mirrors for proper alignment

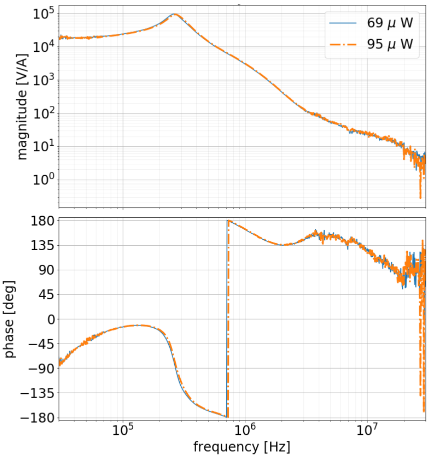
Photodiodes

- Our BHD readout uses Laser Components InGaAs PIN photodiodes.
  - Model Number: IG17X3000G1i
  - 3 mm diameter
  - 1.55 nF capacitance
- We must characterize these to ensure they will perform well in the detector.



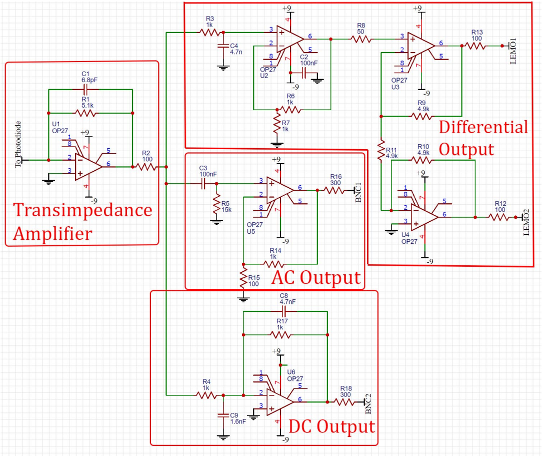
Photodiodes

- Measured current to voltage transfer function at two different powers.
- Large gain, independent of power, displays roll off with corner frequency $f_c \approx 300$ kHz.



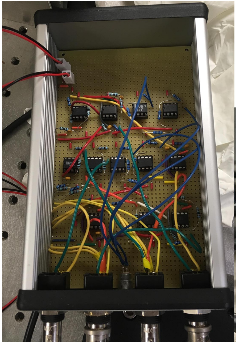
Circuit Design

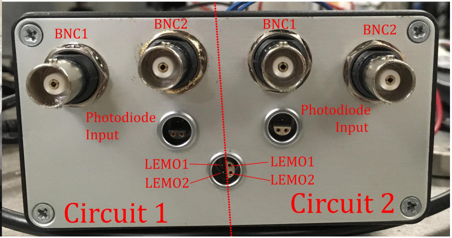
- Created two circuits (one for each photodiode), which feature buffers, AC and DC output, and differential output:



Circuit Design

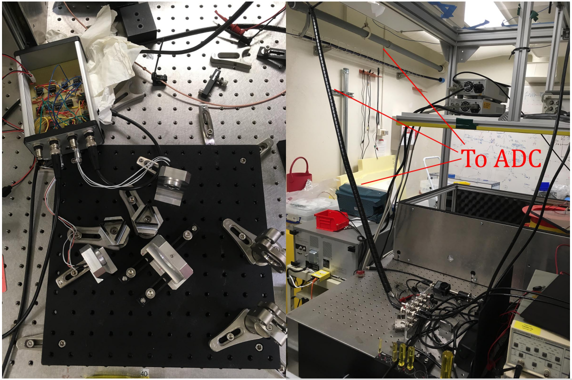
- Powered by 9V batteries
- Inputs from photodiode come from LEMO connectors that I attached to the photodiode
- Outputs are sent to BNC and LEMO connectors





ADC and Digital Subtraction

- Attached circuit inputs to photodiodes and performed subtraction via SR785 performed well
- Signals were discernible and noise reduced to noise floor
- Digital subtraction is more robust $\Rightarrow$ connected DC outputs to an analog-to-digital converter

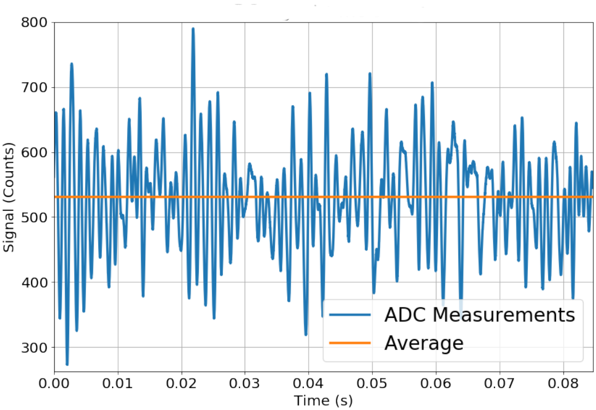


ADC and Digital Subtraction

- As a test, I sent in AC (amplitude modulated) and DC signals from the laser and collected data from the ADC with a python script
- Homodyne readout was achieved by subtracting the data from the two photodiodes in appropriate quantities via a Jupyter notebook:
  - homodyne signal $= H = \alpha(D_1 - \beta D_2)$
  - $\alpha =$ ADC counts to volts, $\beta =$ relative gain,
  - $D_{1,2} =$ photodiode data from ADC (measured in counts)

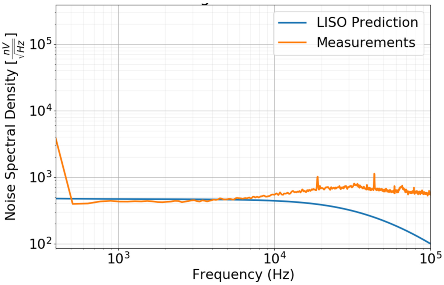
Measurements

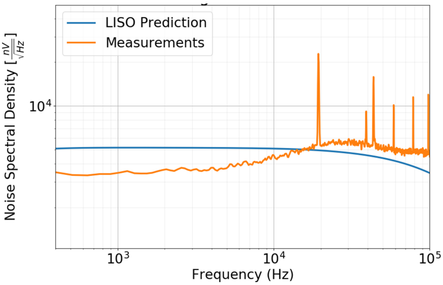
- ADC noise is high, making it hard to discern a signal
- Likely a transmission of configuration issue



Current Work

- Make changes to circuit to reduce noise (voltage regulators, shunt capacitors, new op amps)
- Some noise measurement agreement is fair, others is not
- Possible short circuit when changes were made?





Future Work

- Optimize noise
  - Use new op amps (OP37's in the mail!)
  - Reduce ADC noise (improve signal transmission to ADC (15m away), check configuration, use differential output)
- Use BHD setup in an interferometer or experiment

Thank You

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