# Modeling Interactions of Squeezing and the LIGO IFO at High Frequencies to Improve Sensitivity

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# Structure of Presentation

01
## Motivation
Why am I researching this?

02
## Process
How am I researching this?

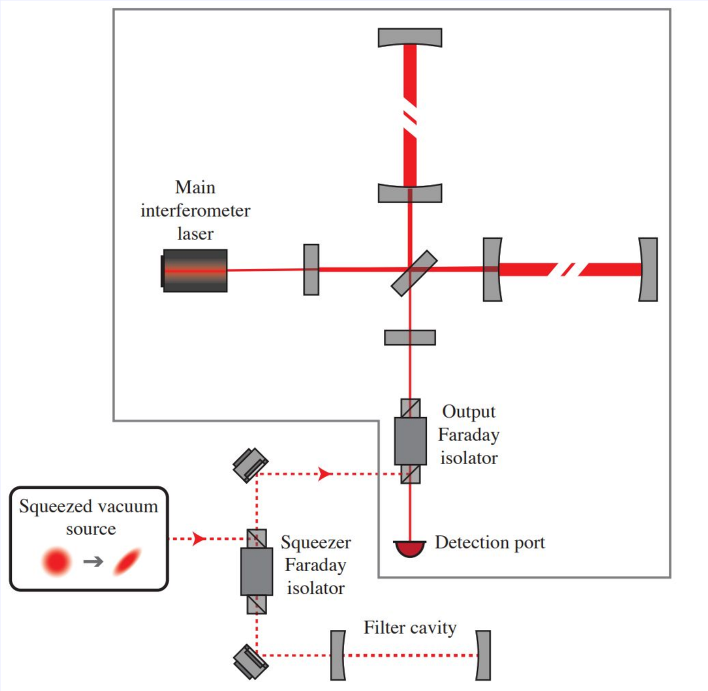
03
## Results
What have I found?

04
## Conclusions and Future
What have I learned?
What will I learn?

# 01 The Problem

LIGO uses squeezed light to improve measurement precision but squeezing interacts with the interferometer.

- Higher Order Mode Matching Effects are present at high frequencies.
- We can use finesse to simulate higher frequency effects



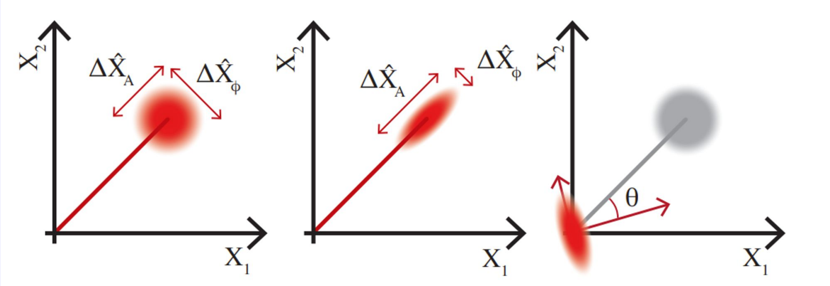

Dwyer & Mansell & McCuller, 2022

01

# The Approach

In LIGO, vacuum states are always incident on the interferometer-> causing shot noise effects

- With squeezed light -> reduce uncertainty below shot noise Poisson statistics




Dwyer & Mansell & McCuller, 2022

We represent squeezed states with non-vacuum sidebands. The part of squeezing we are interested in is rotations when interacting with the interferometer. This is related to differential phase effects that are present in squeezed light but not in vacuum states.

- Squeezed light has deterministic phase relations between positive and negative sidebands

02

# Building the Model

01

## Simple Michelson

2 mirrors and a beamsplitter

02

## Power Recycling

Added Power Recycling Mirror

03

## Fabry Perot Arm Cavity

Added Inner Mirrors

04

## Signal Recycling

Added a Signal Recycling Mirror

05

## Directional Beamsplitter

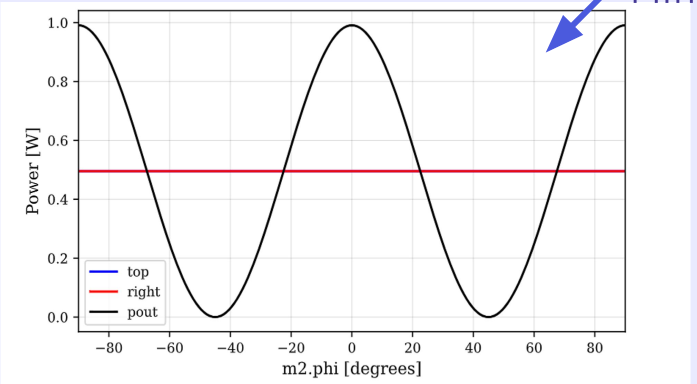
Add Modulated Field to Replicate Squeezing Effects

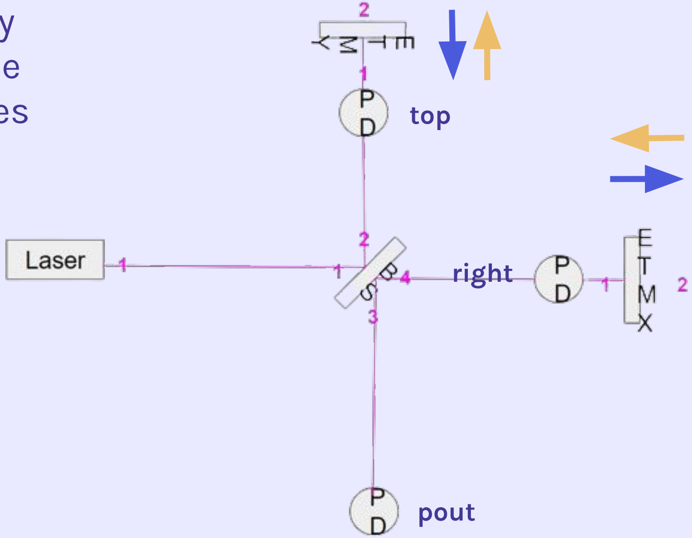
Add Higher Order Modes and Switch Over to Full LIGO Model

02

# Differential Motion

Differentially Modulate the Mirror Phases




$$r t E_{in} i e^{-2ikL} + r t E_{in} i e^{-2ikL} = E_{out}$$

$$E_{in} i (e^{-2ikL}) = E_{out}$$

$$|E_{out}|^2 = |E_{in}|^2$$

$$r t E_{in} i e^{-2ikL - \frac{i\pi}{2}} + r t E_{in} i e^{-2ikL + \frac{i\pi}{2}} = E_{out}$$

$$= E_{in} i e^{-2ikL} (e^{-i\pi/2} + e^{i\pi/2})$$

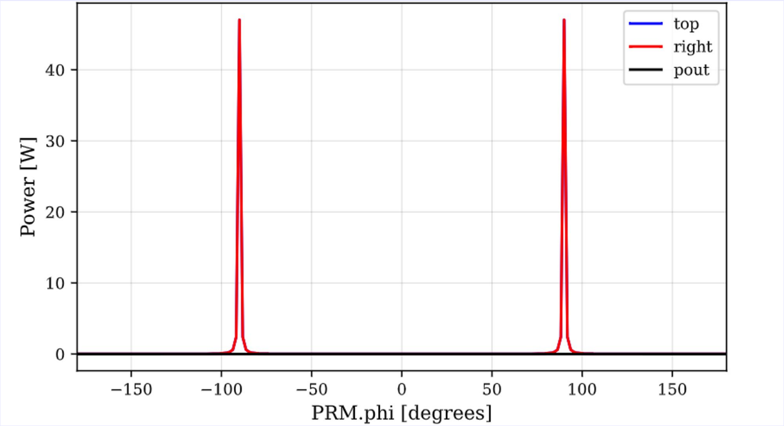
$$= E_{in} i e^{-2ikL} (\cos(\pi/2) - i\cancel{\sin(\pi/2)} + \cos(\pi/2) + i\cancel{\sin(\pi/2)})$$

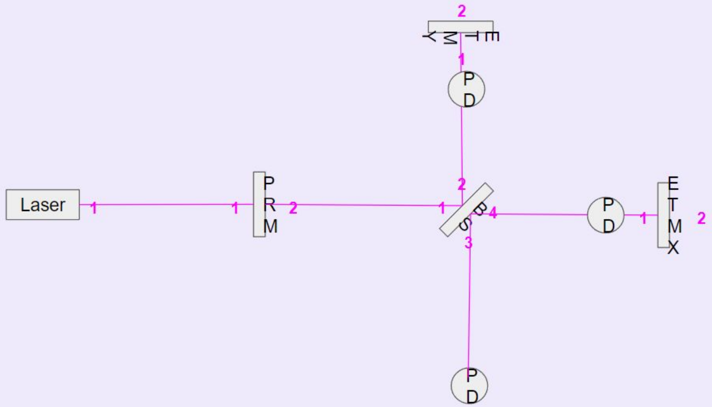
$$|E_{out}|^2 = 0$$

Full Power

Dark Fringe

# 02 Power Recycling Mirror

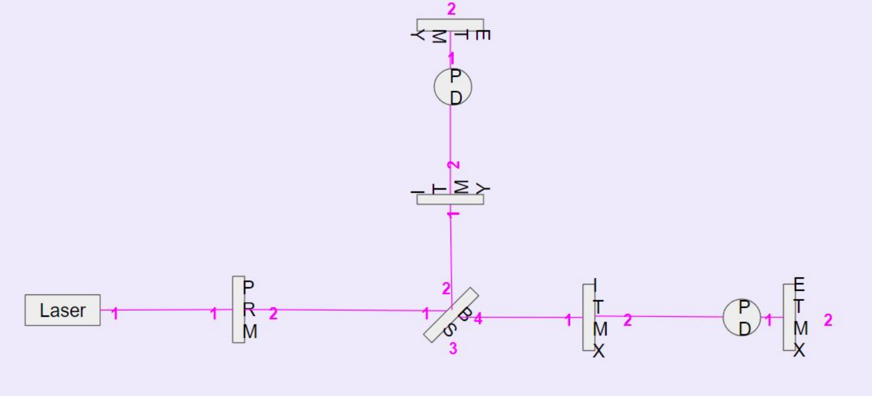


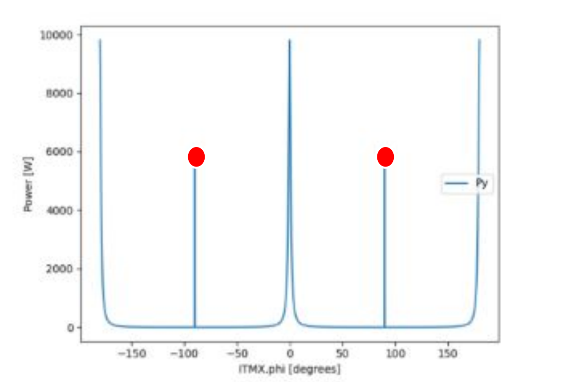



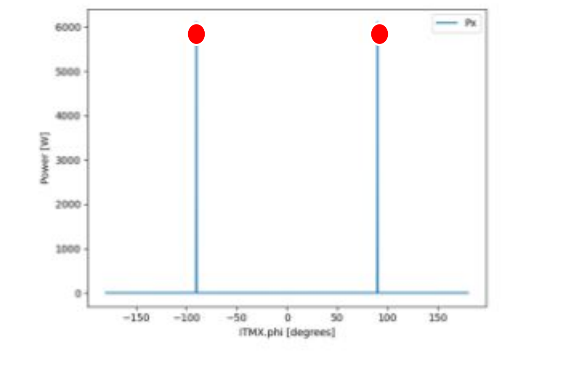

$$L_{\text{used}} = \lambda \left\lfloor \frac{L_{\text{input}}}{\lambda} \right\rfloor$$

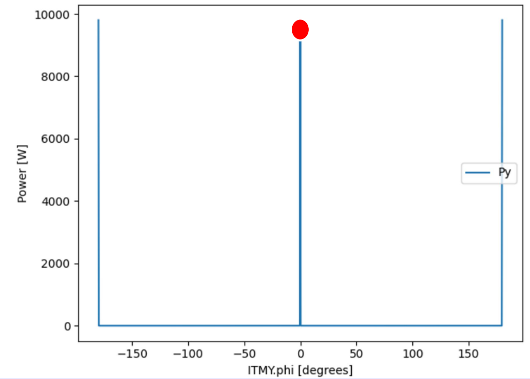
$$\Delta L = \frac{\phi}{360^\circ} \lambda$$

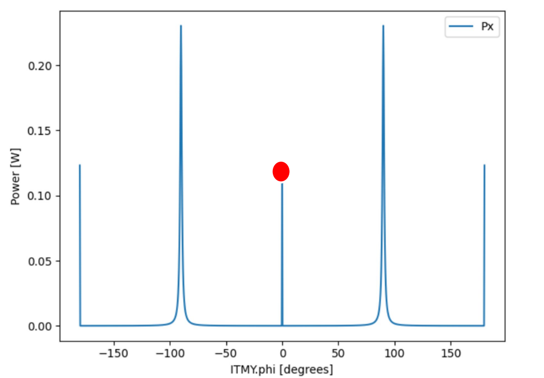
# 02 Arm Cavities - Finding the Operating Point



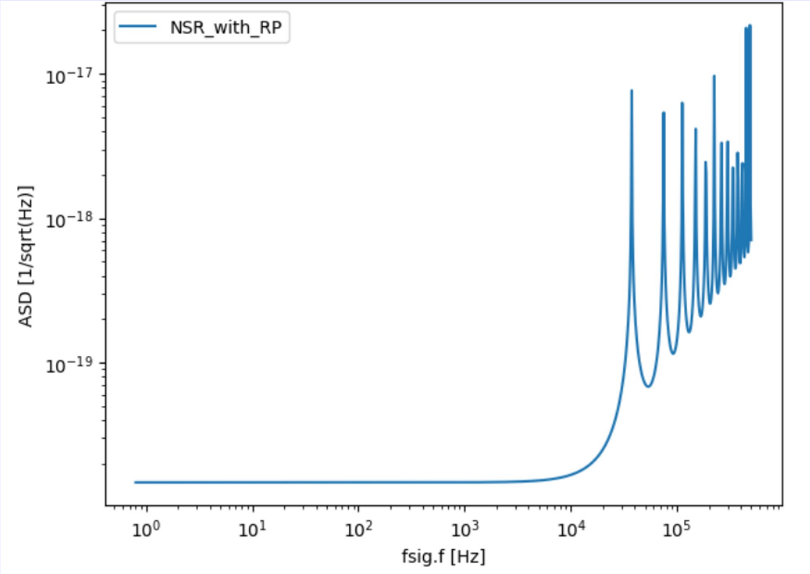



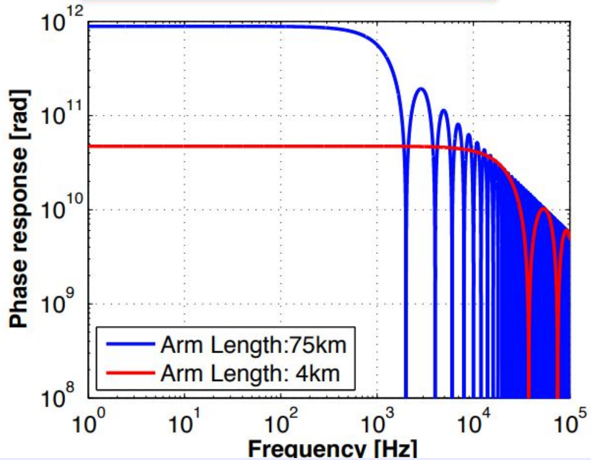
02

# Sensitivity Checks + Squeezing




DC Response longer -> larger

$$\Delta\phi = \boxed{\frac{2L\Omega}{c} e^{-iL\omega/c} \frac{\sin(L\omega/c)}{L\omega/c}} \cdot h_0 e^{i\omega t}$$

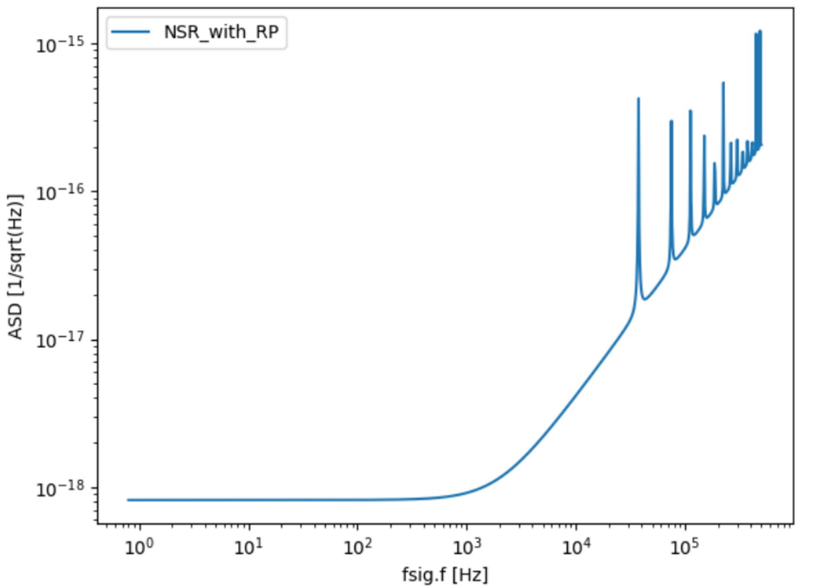


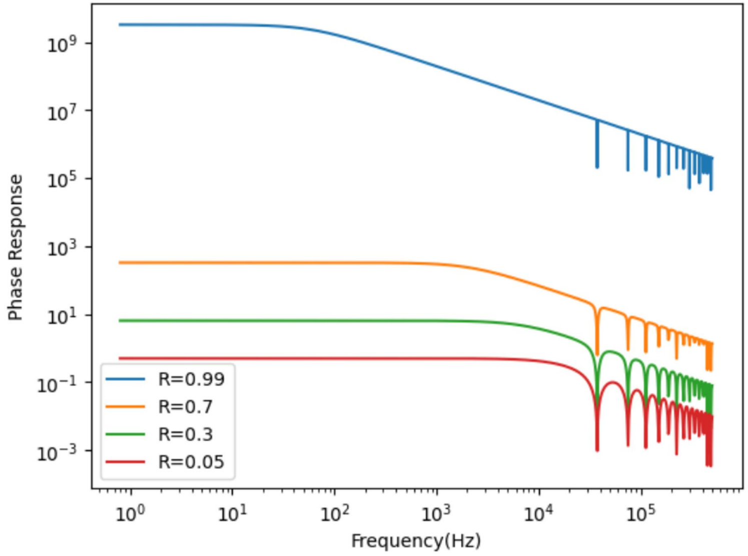

Cut off freq longer -> lower

Notch freq f = n c / (2 L)

Arai, 2016

## 02 Arm Cavities

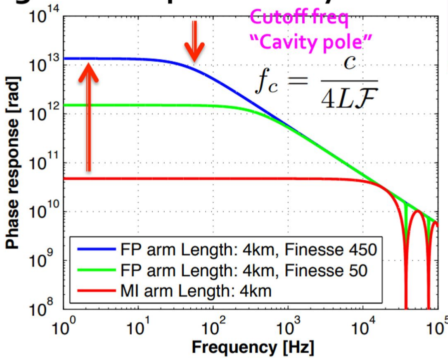



- **Storing light in an optical cavity**

DC Response amplification

$N = 2\mathcal{F}/\pi$




Finesse

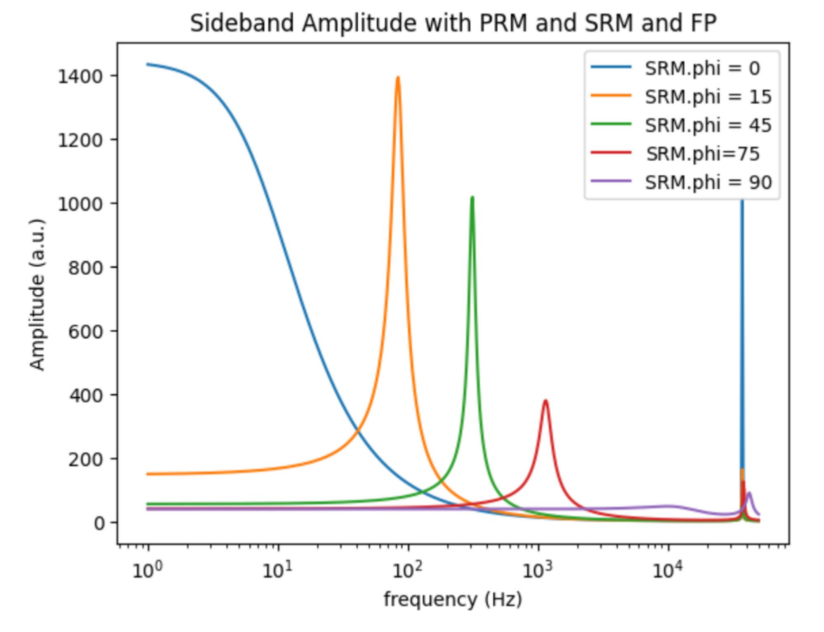
$$\mathcal{F} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}$$

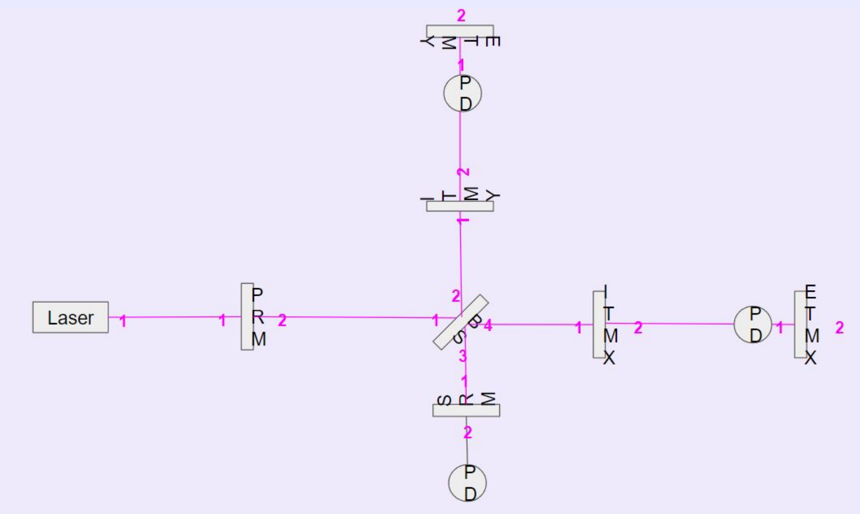
Arai, 2016

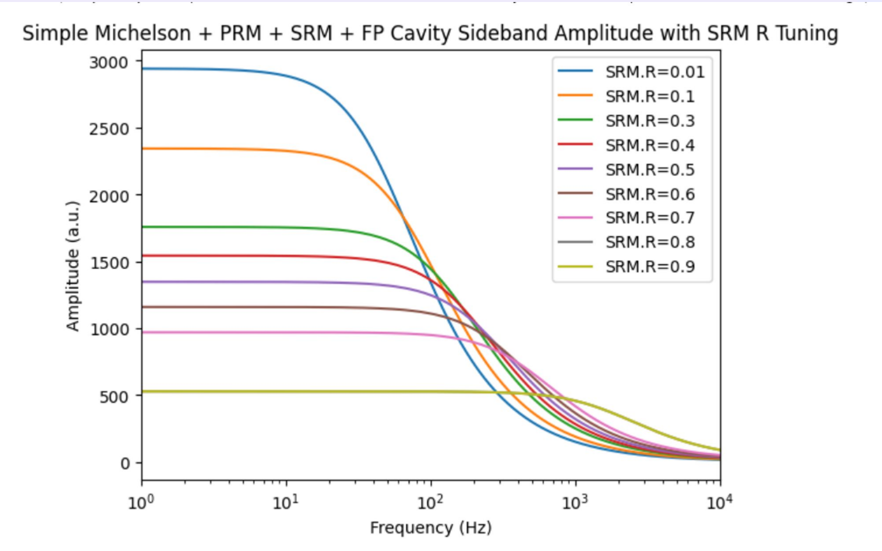
1. FP increases stored power in the arm
2. FP increases accumulation time of the signal

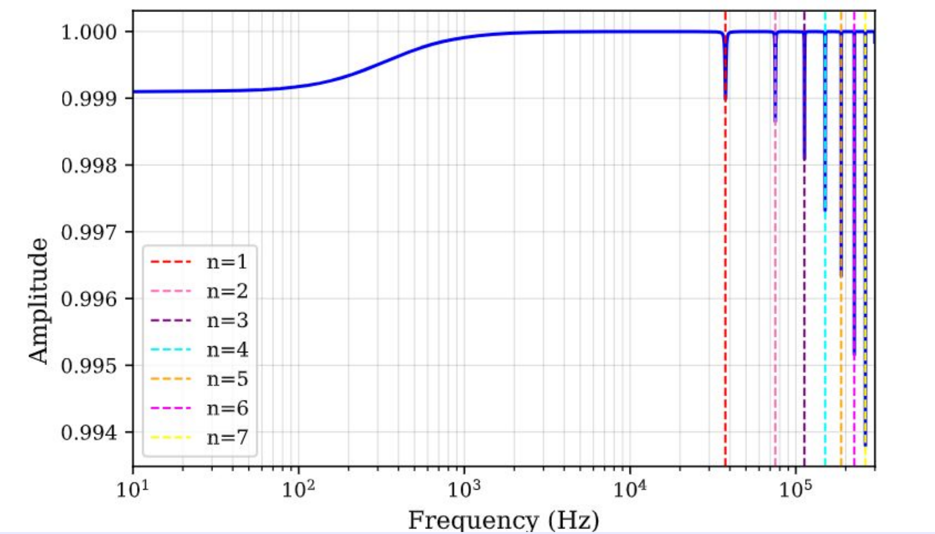
02

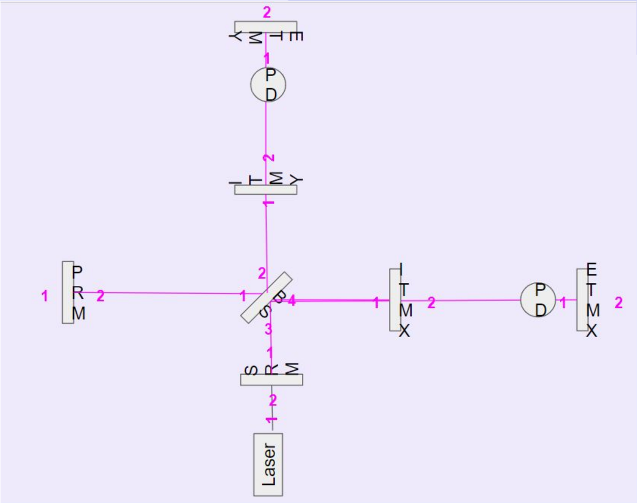
# Signal Recycling Mirror






$L_{arm} = 3995 \text{ m}$

$c = \lambda f$

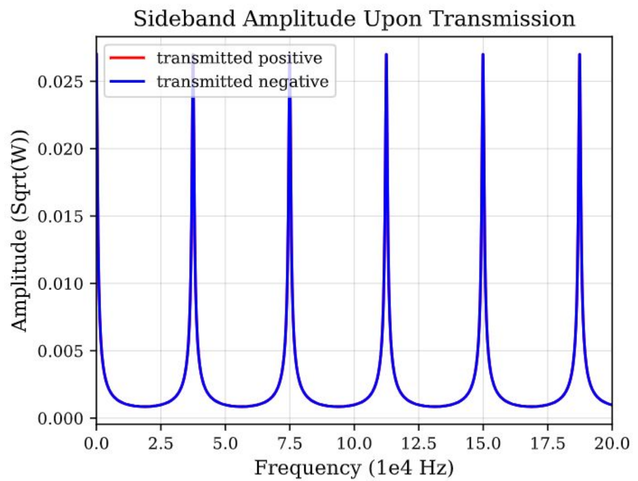
$f = \frac{c}{\lambda}$

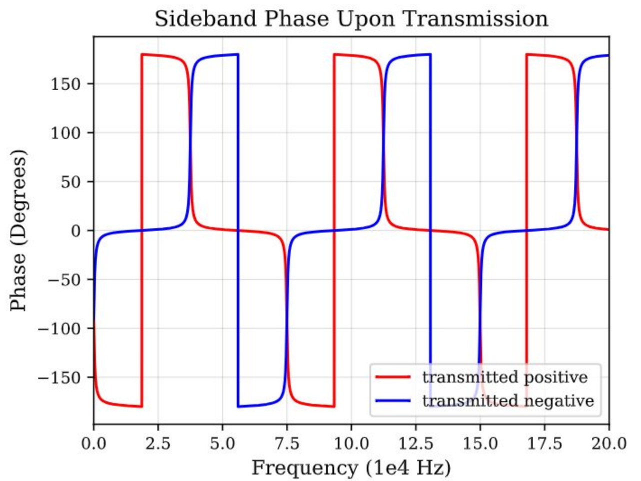
$L_{arm} = \frac{\lambda n}{2}$ → resonance condition

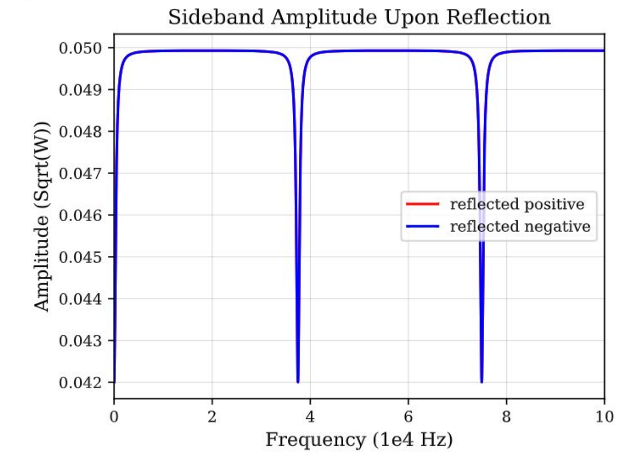
$f_{res} = \frac{cn}{2L_{arm}}$

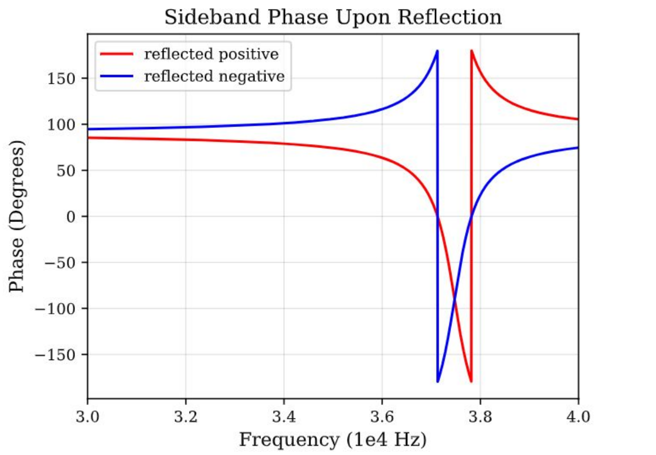
| n | FREQUENCY (HZ) |
|---|---|
| 1 | 37 547 |
| 2 | 75 094 |
| 3 | 112 641 |
| 4 | 150 188 |
| 5 | 187 735 |
| 6 | 225 282 |
| 7 | 262 829 |

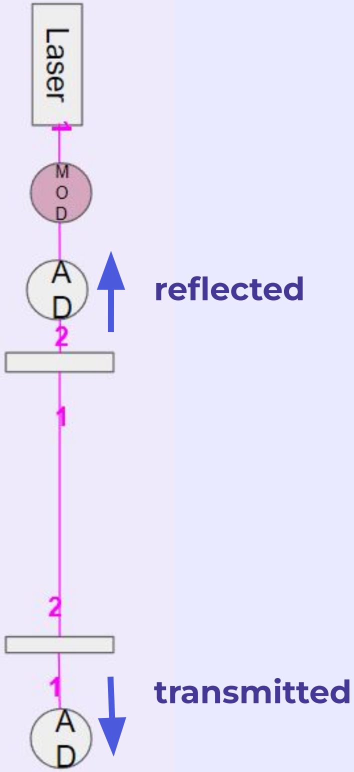
03


Sideband Amplitude Upon Transmission
transmitted positive
transmitted negative
Amplitude (Sqrt(W))
Frequency (1e4 Hz)


Sideband Phase Upon Transmission
transmitted positive
transmitted negative
Phase (Degrees)
Frequency (1e4 Hz)

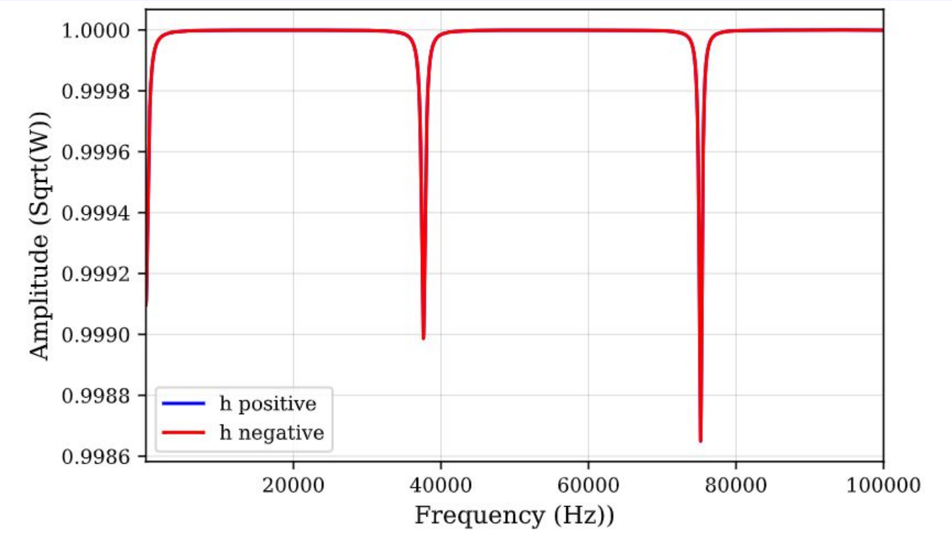

Sideband Amplitude Upon Reflection
reflected positive
reflected negative
Amplitude (Sqrt(W))
Frequency (1e4 Hz)

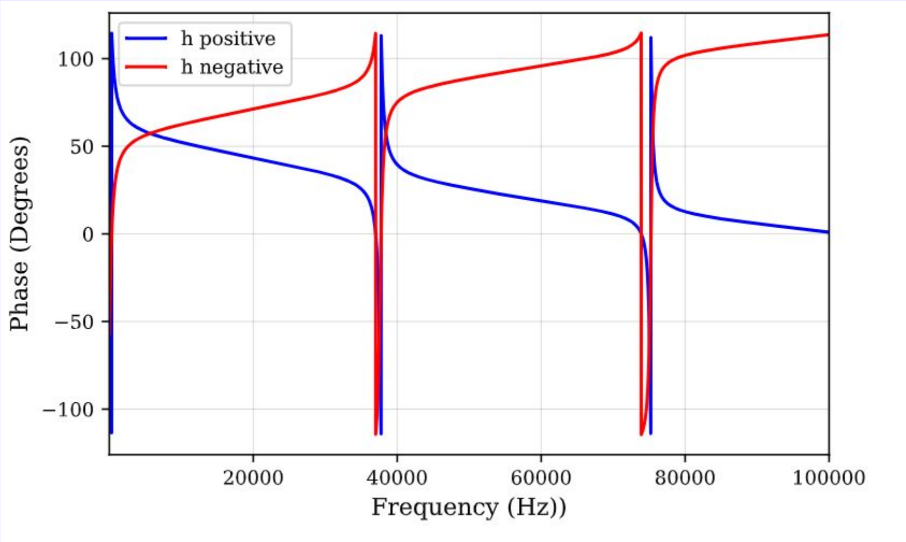

Sideband Phase Upon Reflection
reflected positive
reflected negative
Phase (Degrees)
Frequency (1e4 Hz)


Laser
MOD
AD
reflected
transmitted

03

# Transfer Function for the Sidebands



04

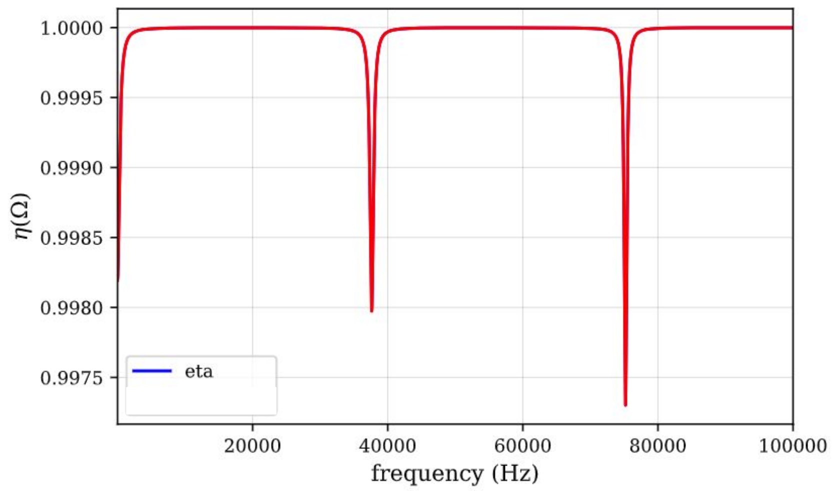
# Squeezing Parameters

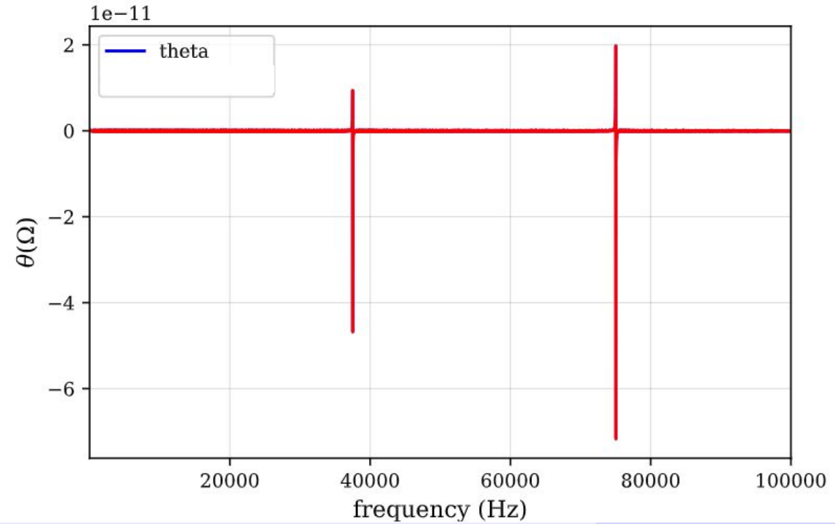
$$\theta(\Omega) = (\arg(\mathfrak{h}(+\Omega)) + \arg(\mathfrak{h}(-\Omega)))/2,$$

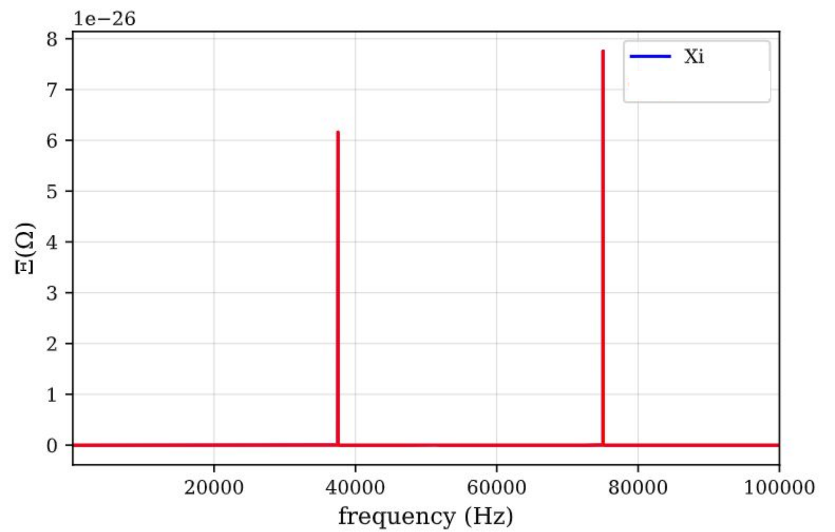
$$\eta(\Omega) = (|\mathfrak{h}(+\Omega)|^2 + |\mathfrak{h}(-\Omega)|^2)/2,$$

$$\Xi(\Omega) = (|\mathfrak{h}(+\Omega)| - |\mathfrak{h}(-\Omega)|)^2/4\eta.$$

McCuller et. al, 2021



04

# Future Steps

- Consider Gaussian beams and Higher Order Modes
  - Mode Matching Effects with Squeezing are what we are most interested in
- Switch over to Full LIGO Model (not that different from current advanced model)
- Compute additional squeezing parameters
- Compare with Experimental data

# Acknowledgements

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