Building Blocks of a PT-Symmetric Interferometer

Kagan Yanik
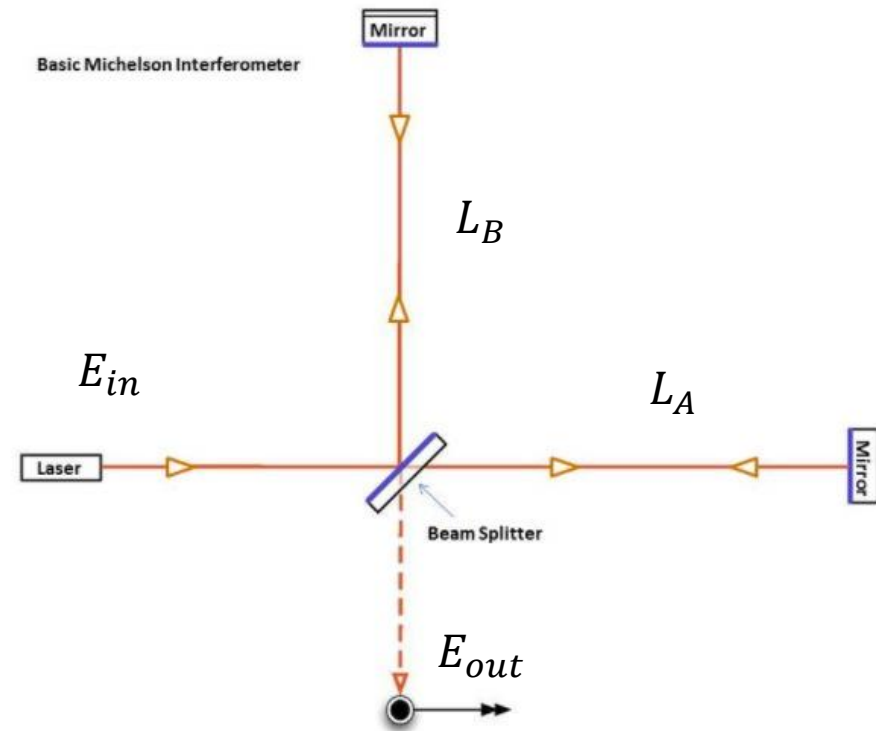
Mentors: Xiang Li, Shruti Jose Maliakal, Yanbei Chen, Rana Adhikari

Contents

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Conventional LIGO

- Michelson interferometer
- Differential path length change due to GW
- $\varphi_A = 2kL_A$
- $\varphi_B = 2kL_B$
- $P_{out} = (1 - \cos(\varphi_A - \varphi_B))\frac{P_{in}}{2}$

Basic Michelson Interferometer

Mirror

L_B

E_{in}

L_A

Laser

Beam Splitter

Mirror

E_{out}

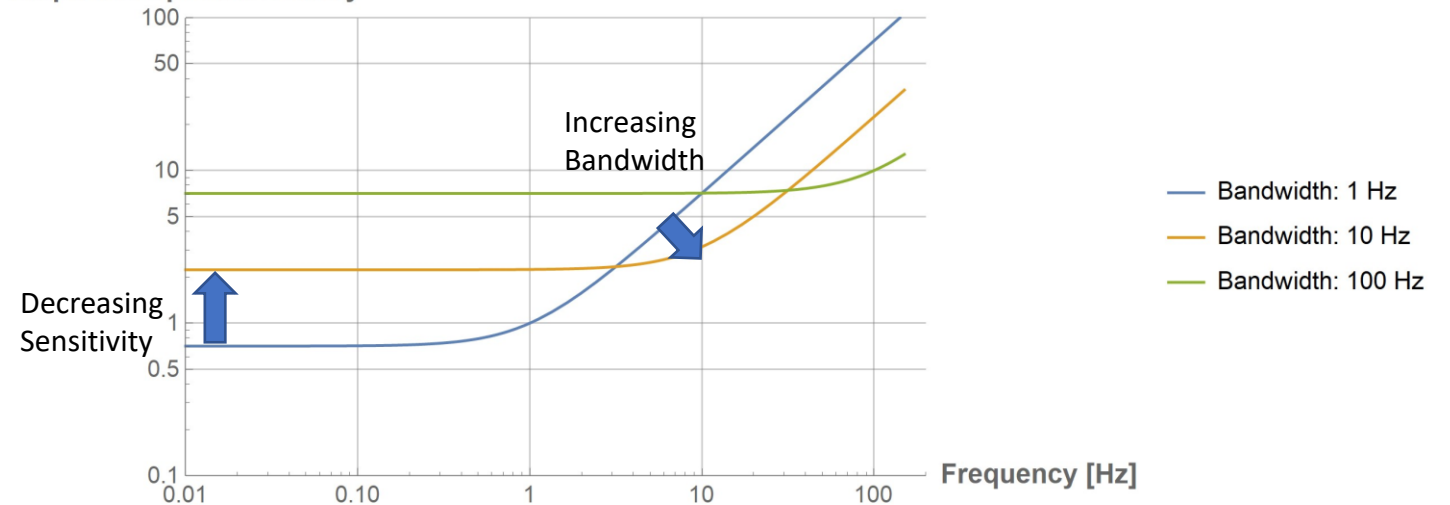Image from https://www.ligo.caltech.edu/page/ligos-ifo

Bandwidth vs Sensitivity

- Energetic Quantum Limit (EQL)

- We want to increase the bandwidth without sacrificing the sensitivity

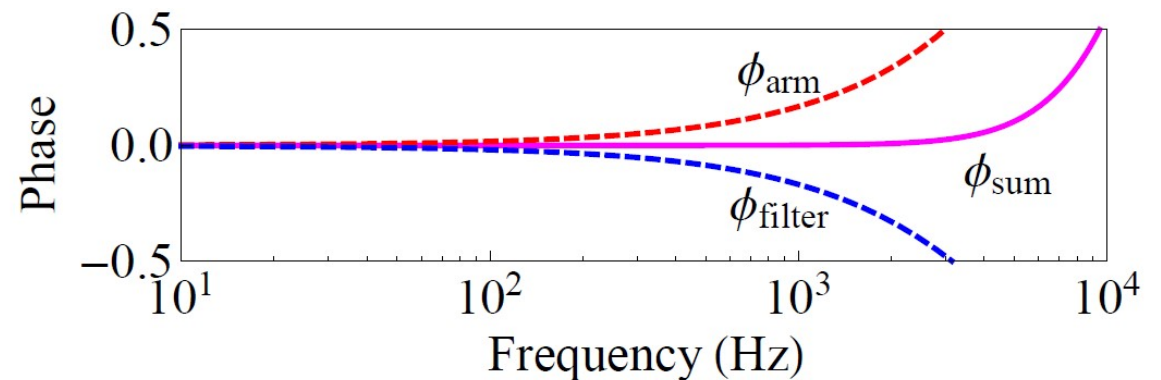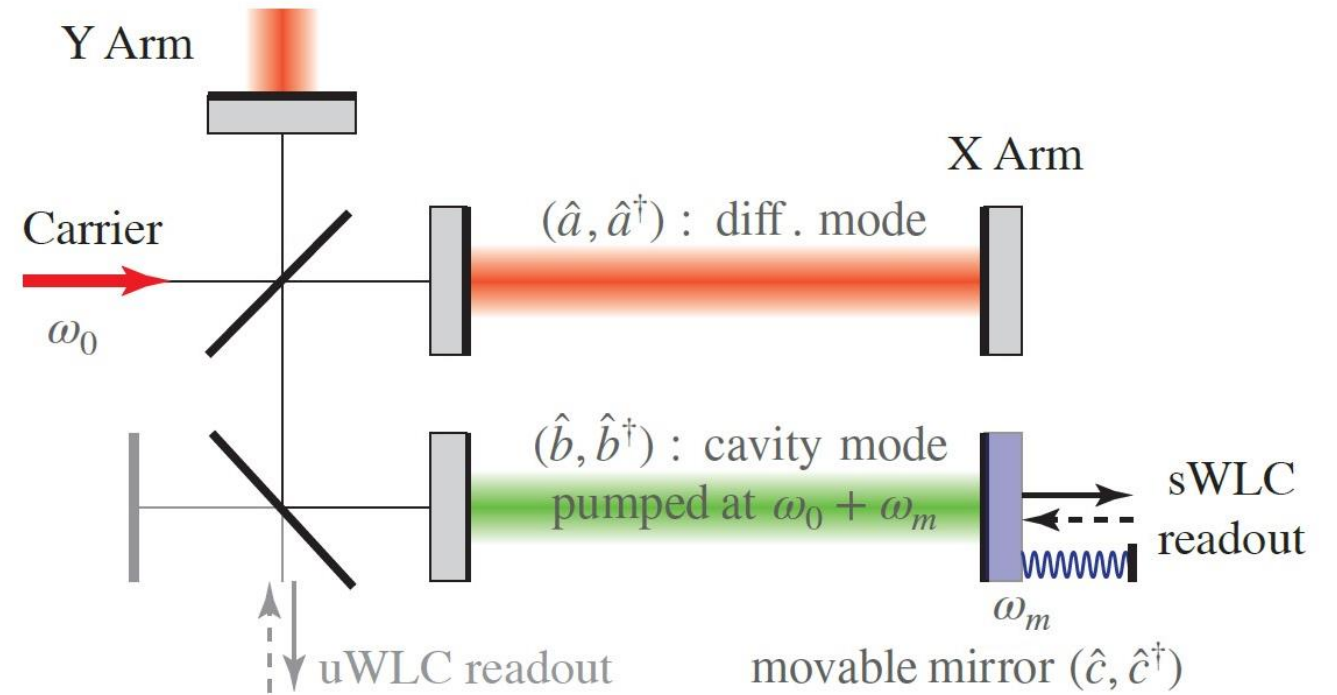- Overcoming the trade-off: Higher sensitivity in the entire frequency range

$$\int_0^{+\infty} d\Omega/(2\pi) S_h^{-1}(\Omega) \leq \Delta\mathcal{E}^2/(4\hbar)^2$$
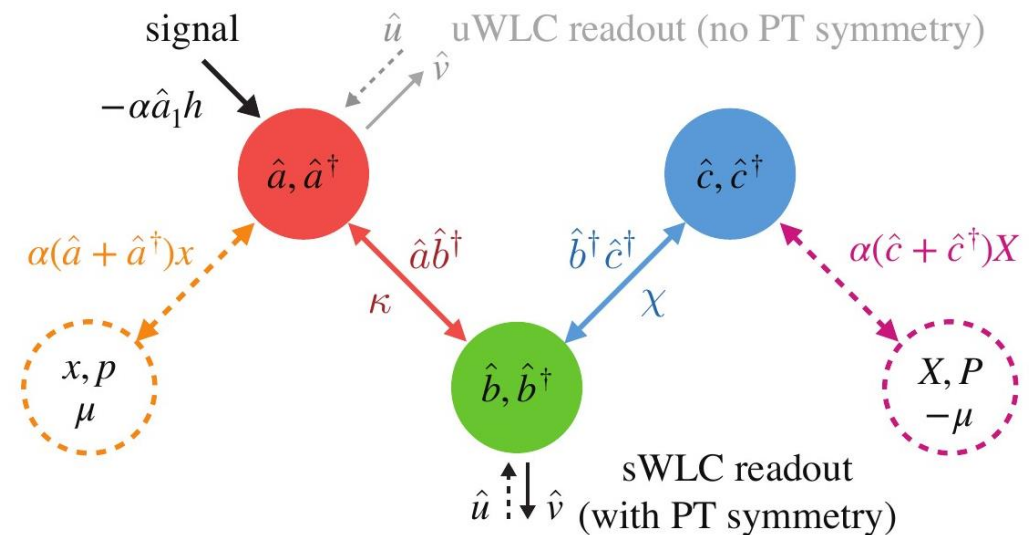
Amplitude Spectral Density

Increasing Bandwidth

Decreasing Sensitivity

Frequency [Hz]

— Bandwidth: 1 Hz
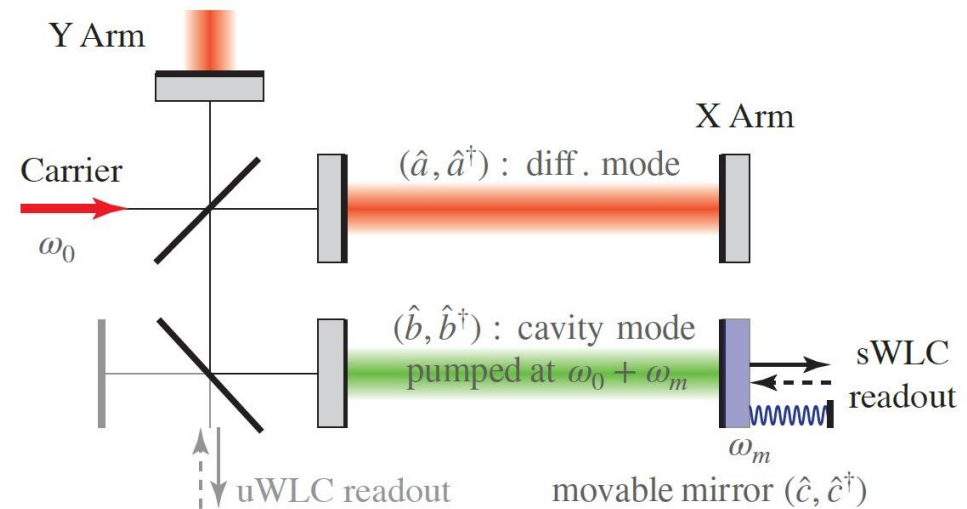— Bandwidth: 10 Hz
— Bandwidth: 100 Hz

Setup of the System

- Arm cavity - $\hat{a}$ (optical mode)

- Filter cavity - $\hat{b}$ (optical mode)

- Mechanical mode - $\hat{c}$ (attached to filter cavity)

Li, Xiang, et al. "Broadband sensitivity improvement via coherent quantum feedback with PT symmetry." *arXiv preprint arXiv:2012.00836* (2020), p2.
Miao, Haixing, et al. "Enhancing the bandwidth of gravitational-wave detectors with unstable optomechanical filters." *Physical review letters* 115.21 (2015): 211104, p2.
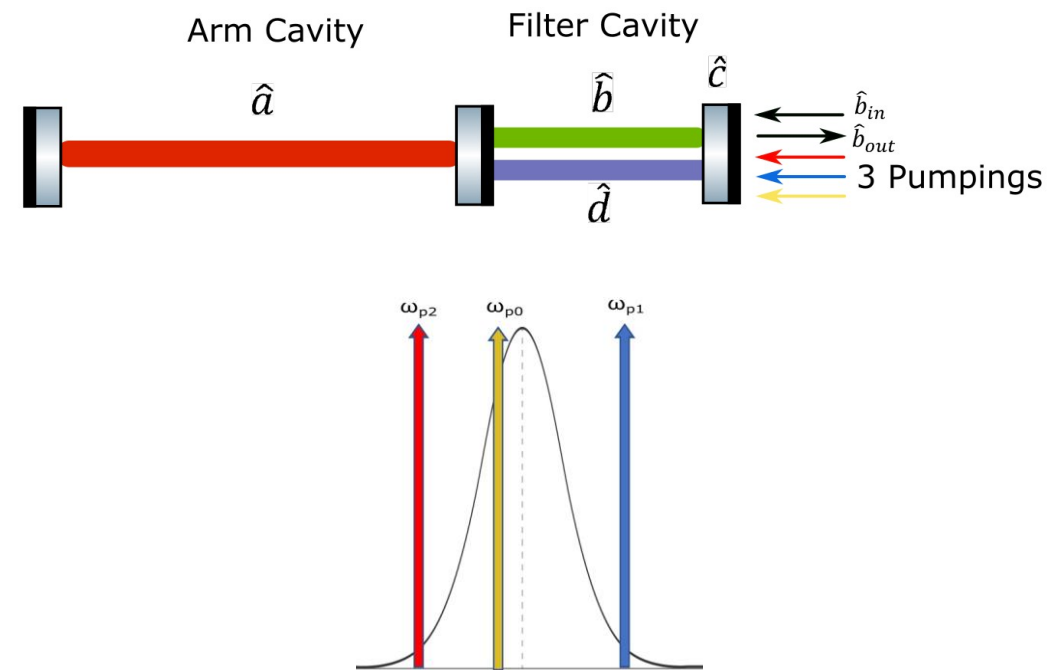
PT-symmetric Interferometer

- White Light Cavity can improve the sensitivity while sacrificing less of the bandwidth

Li, Xiang, et al. "Broadband sensitivity improvement via coherent quantum feedback with PT symmetry." *arXiv preprint arXiv:2012.00836* (2020), p2.

Negative Mass

- Optical mode - $\hat{d}$
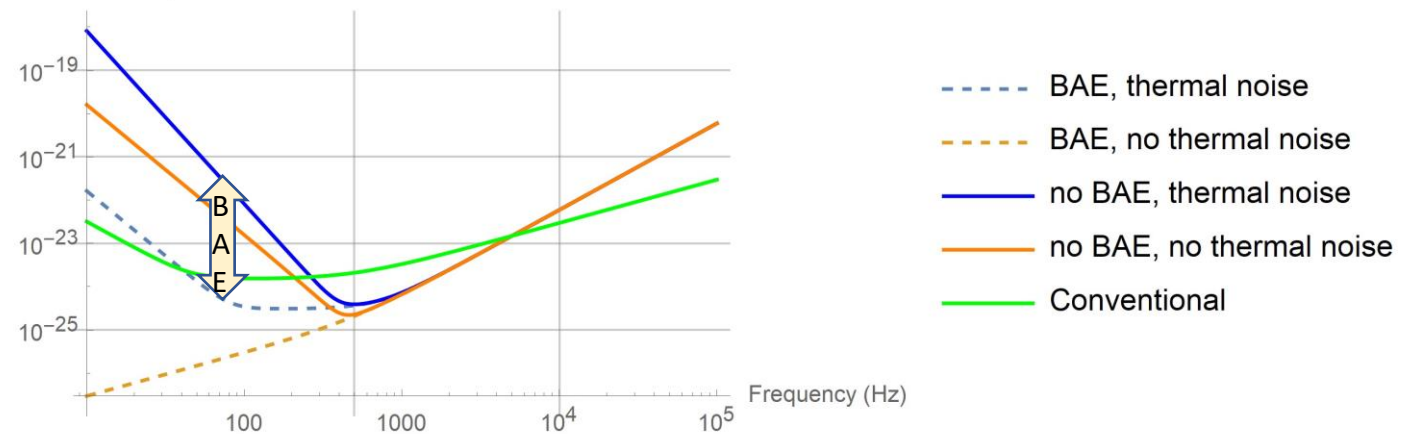- $\hat{V}_{aux} = -\hbar\alpha_d\hat{c}_1\hat{d}_1 - \hbar\omega_d\,\hat{d}^\dagger\hat{d}$

Li, Xiang, et al. "Broadband sensitivity improvement via coherent quantum feedback with PT symmetry." *arXiv preprint arXiv:2012.00836* (2020), p2.
Figures from http://www.gwoptics.org/ComponentLibrary/

Mathematica Simulations

GW Noise Spectra with backaction

- GW Noise Spectra normalized for signal

Parameter	Value
γ_R	$(2\pi)500$ Hz
γ_m	0.0000001 Hz
κ	$(2\pi)5000$ Hz
χ	$(2\pi)5000$ Hz
k_B	1.38065×10^{-23} m^{2}s^{-2}kgK^{-1}
T	4 K
μ	50 kg
μc	-50 kg
ω_m	$(2\pi)10$ kHz
ω_0	$(2\pi)299792458$ ms^{-1}/2μm
$\hbar$	$1.054571628\times10^{-34}$ Js
L	4000 m
c	299792458 ms^{-1}
P_c	3×10^6 Watt

GW Noise Spectral Density $\sqrt{S_h}$ (Hz$^{-1/2}$)

- - - BAE, thermal noise
- - - BAE, no thermal noise
—— no BAE, thermal noise
—— no BAE, no thermal noise
—— Conventional

Filter Cavity in FINESSE

Filter Cavity

- Blue detuned pumping
- FP cavity with movable end mirror (mechanical oscillator)

laser
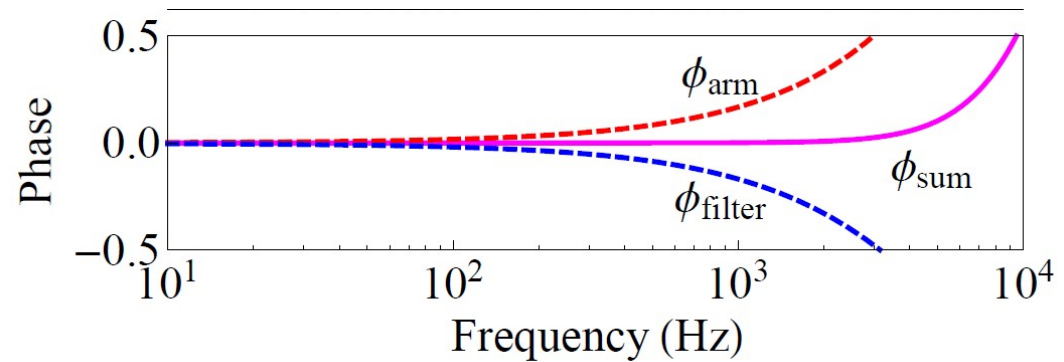$\omega_p = \omega_0 + \omega_m$

cavity mode
$(\hat{b}, \hat{b}^\dagger)$

b_{out}

b_{in}

ω_0

ω_m
movable mirror
$(\hat{c}, \hat{c}^\dagger)$

$\hat{c}$

$\hat{b}$

ω_0 $\omega_0 + \omega_m$

Figure from http://www.gwoptics.org/ComponentLibrary/
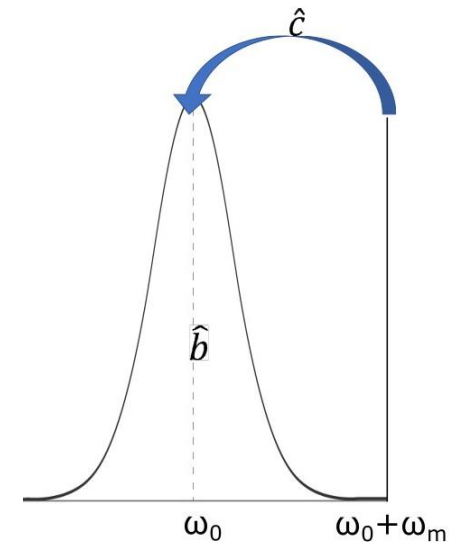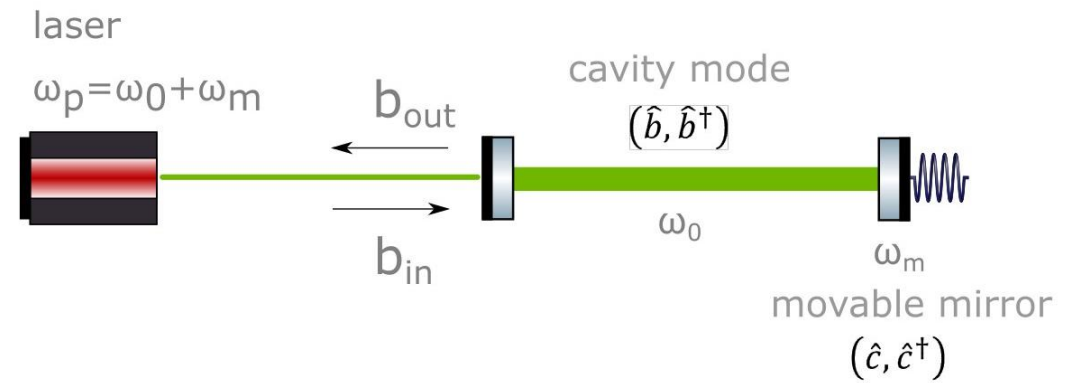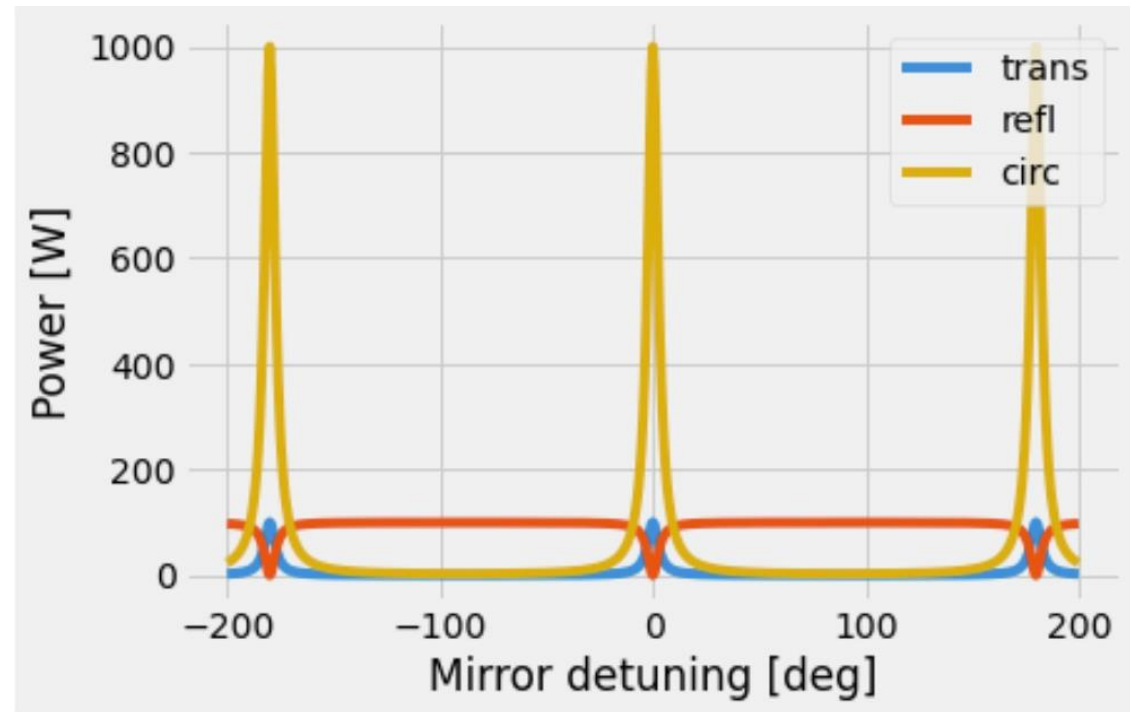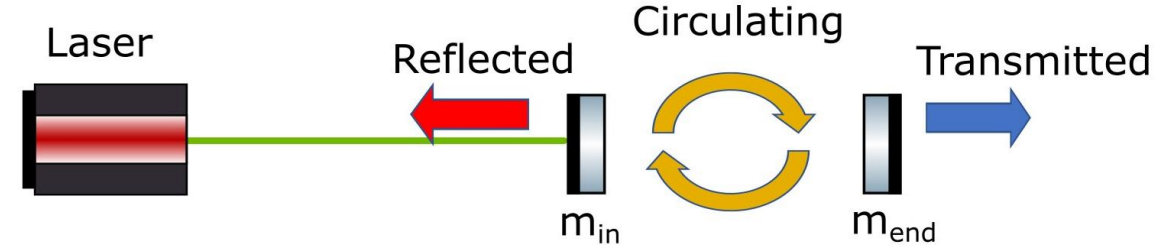
Filter Cavity

- Anomalous Dispersion

- $\hat{b}_{out}(\Omega) \approx \dfrac{\Omega + i\gamma_{opt}}{\Omega - i\gamma_{opt}}\hat{b}_{in}(\Omega)$
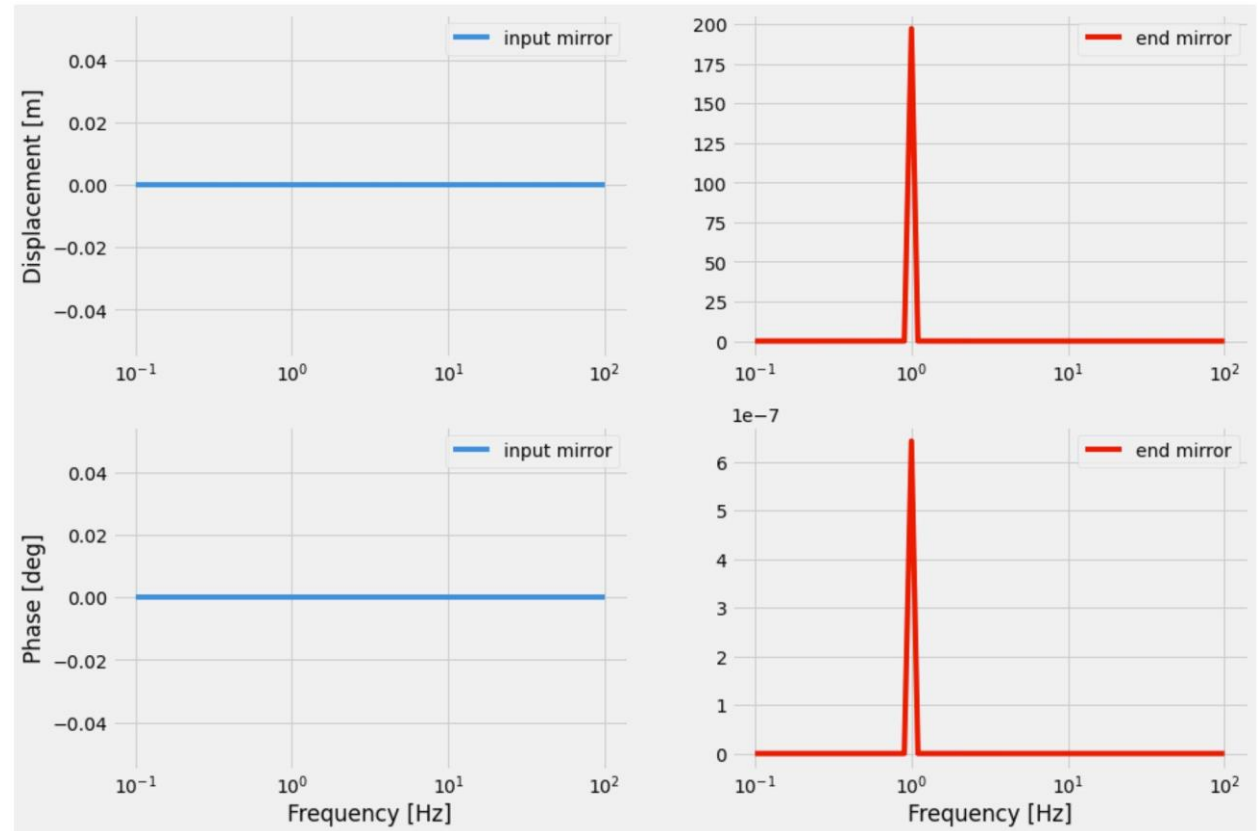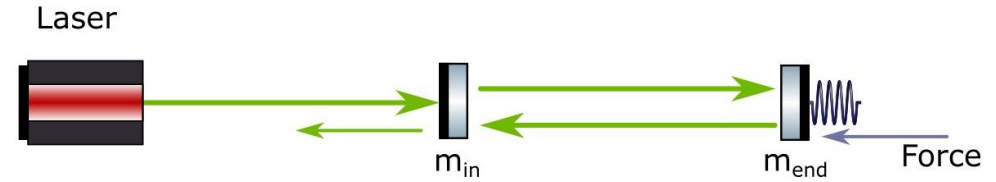 $(\gamma_{opt} \gg \gamma_m)$

Miao, Haixing, et al. "Enhancing the bandwidth of gravitational-wave detectors with unstable optomechanical filters." *Physical review letters* 115.21 (2015): 211104, p2.

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Fabry Perot Cavity

- Resonance
- P = 100W
- L = 4m
- Tin = Tend = 0.1
- Lin = Lend = 0

The top figure is constructed from http://www.gwoptics.org/ComponentLibrary/

Fabry Perot Cavity

- Mechanics without detuning
- P = 3100 W
- L = 50 m
- ωm = (2π)1 Hz
- Δ = 0 Hz
- m = 1 kg
- Qm = 8 x 10^5

The top figure is constructed from http://www.gwoptics.org/ComponentLibrary/

Fabry Perot Cavity

- Optical Spring Effect
- P = 3100 W
- L = 50 m
- $\omega m = (2\pi)1$ Hz
- $\Delta = (2\pi)300$ Hz
- m = 1 kg
- Qm = 8×10^5

$$\omega_{os} = \frac{2P_c}{\lambda_0 L}\left(\frac{\Delta}{\Delta^2 + \gamma^2}\right)$$

$$\omega = \sqrt{\omega_m{}^2 + \omega_{os}{}^2}$$

The top figure is constructed from http://www.gwoptics.org/ComponentLibrary/
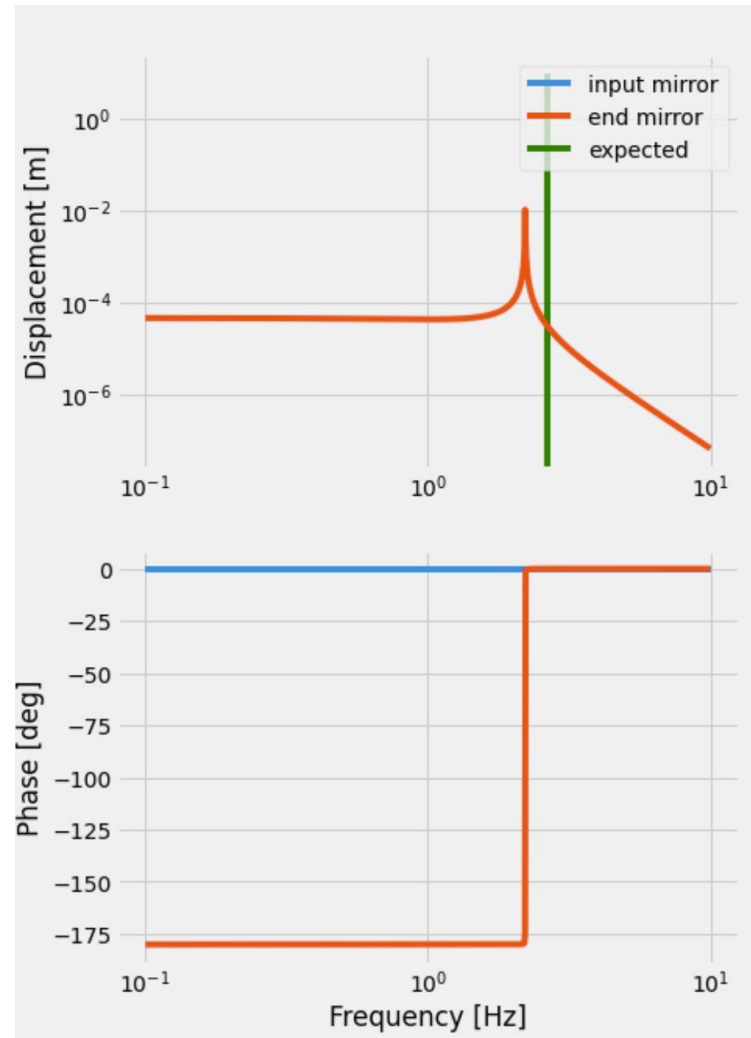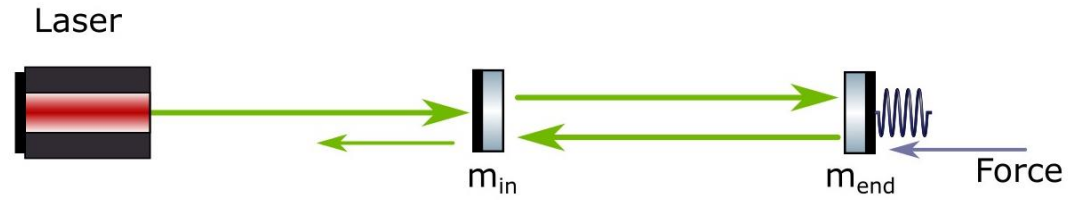
Future Directions

- Realize anomalous dispersion for filter cavity
- Add the rest of the building blocks of the system (arm cavity, negative mass)
- Evaluate losses at different parts of the system

References

[1] Li, Xiang, et al. "Broadband sensitivity improvement via coherent quantum feedback with PT symmetry." *arXiv preprint arXiv:2012.00836* (2020).

[2] Miao, Haixing, et al. "Enhancing the bandwidth of gravitational-wave detectors with unstable optomechanical filters." *Physical review letters* 115.21 (2015): 211104.