Building Blocks of a PT-Symmetric Interferometer

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Contents

Conventional LIGO

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

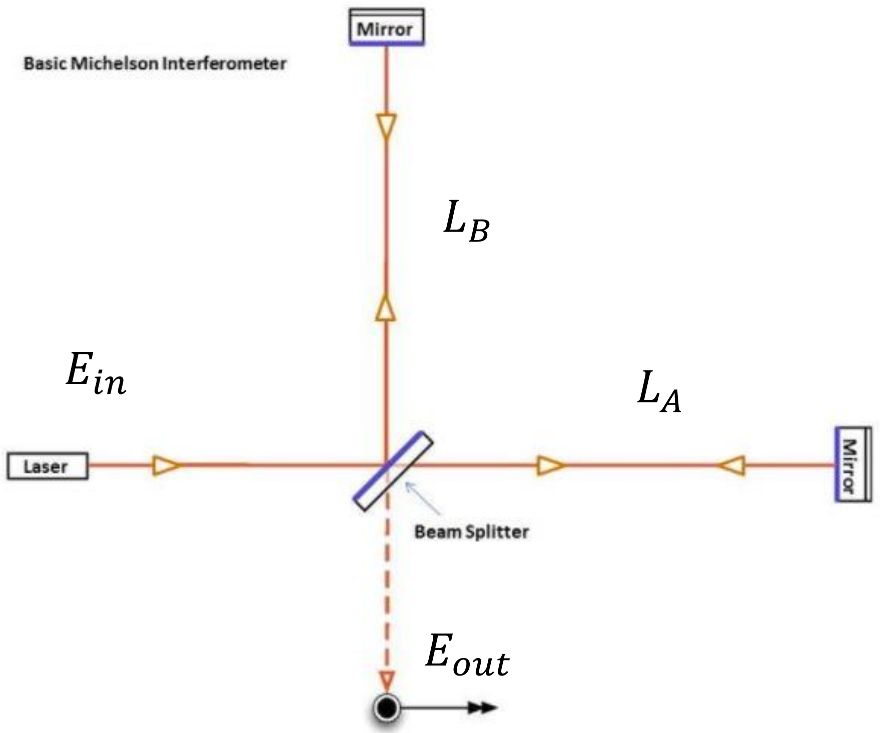
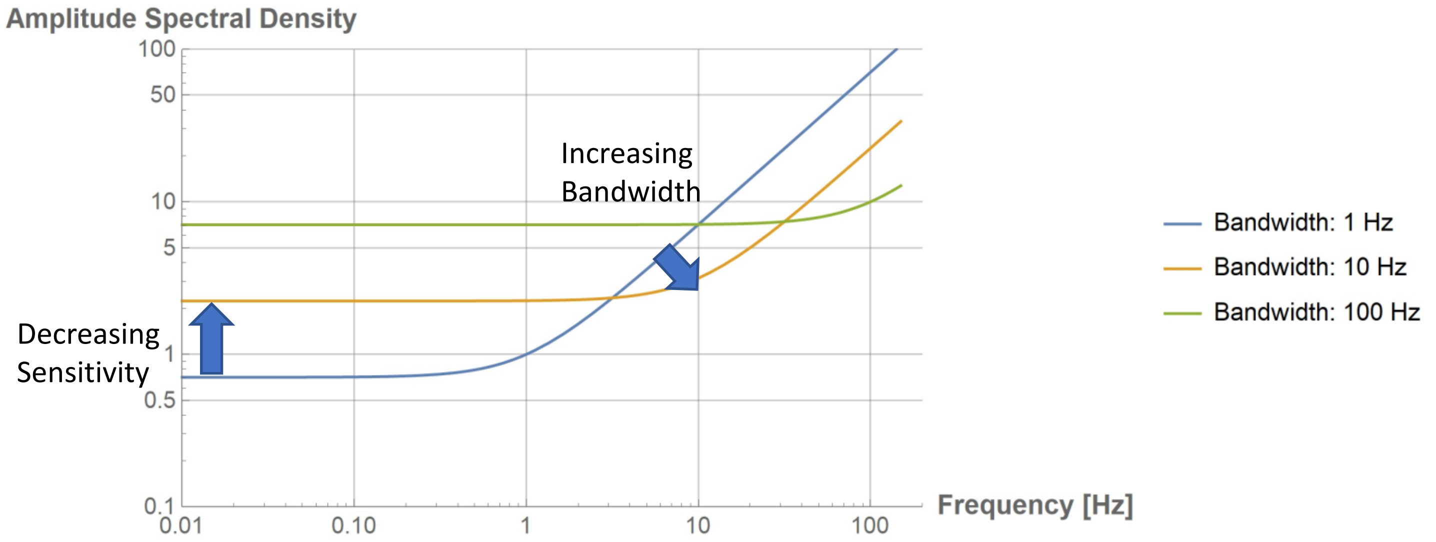


Image from https://www.ligo.caltech.edu/page/ligos-ifo

Bandwidth vs Sensitivity

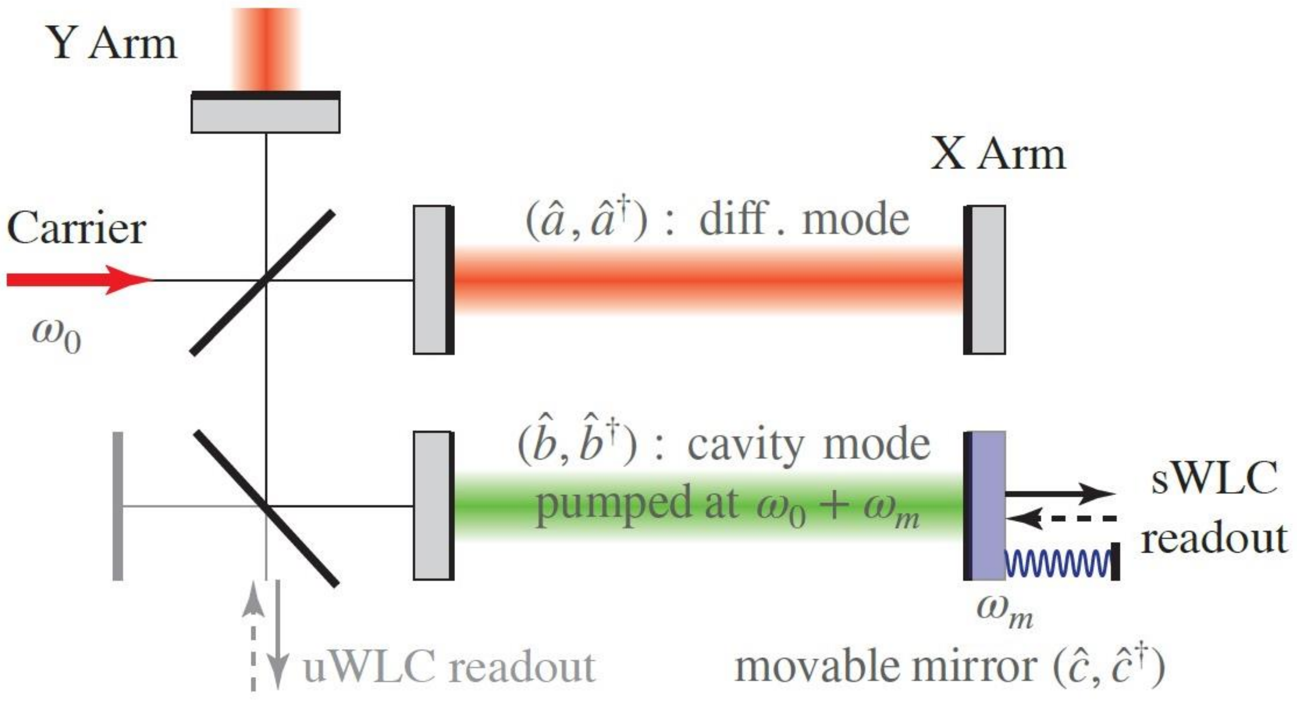
- Energetic Quantum Limit (EQL)
- We want to increase the bandwidth without sacrificing the sensitivity
- Overcoming the trade-off: Higher sensitivity in the entire frequency range

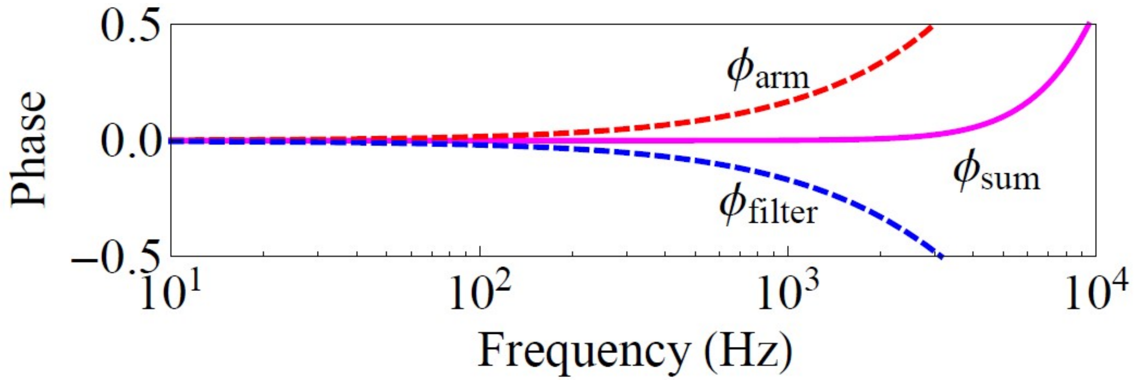
$$\int_0^{+\infty} d\Omega/(2\pi) S_h^{-1}(\Omega) \leq \Delta\mathcal{E}^2/(4\hbar)^2$$



Setup of the System

- Arm cavity - $\hat{a}$ (optical mode)
- Filter cavity - $\hat{b}$ (optical mode)
- Mechanical mode - $\hat{c}$ (attached to filter cavity)

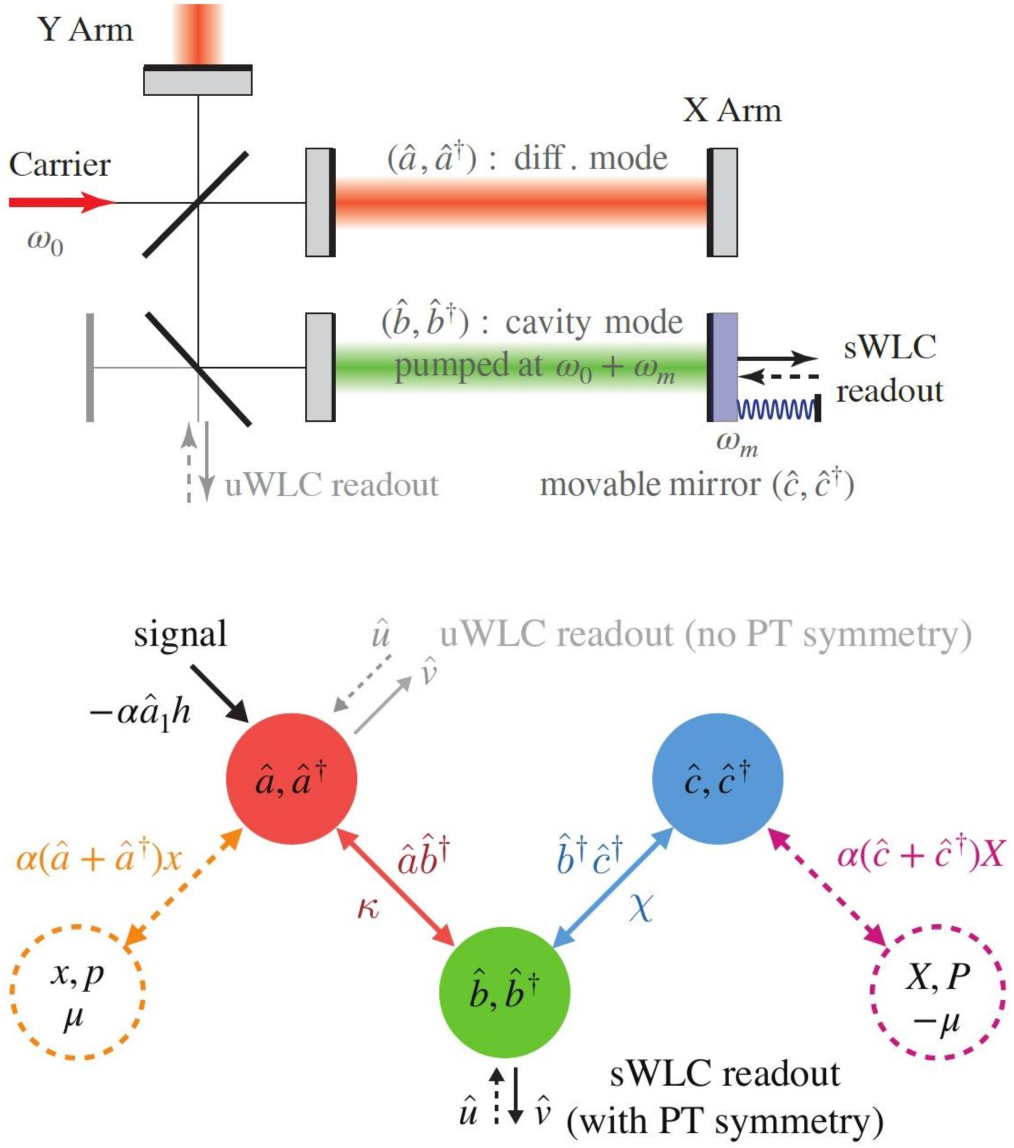




Li, Xiang, et al. "Broadband sensitivity improvement via coherent quantum feedback with PT symmetry." *arXiv preprint arXiv:2012.00836* (2020), p2.
Miao, Haixing, et al. "Enhancing the bandwidth of gravitational-wave detectors with unstable optomechanical filters." *Physical review letters* 115.21 (2015):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

PT-symmetric Interferometer

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



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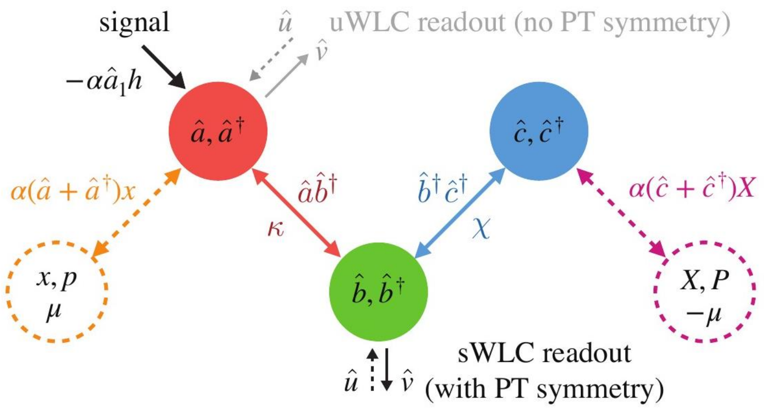
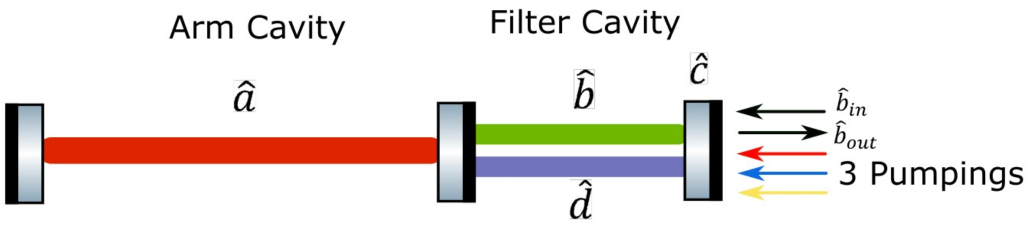
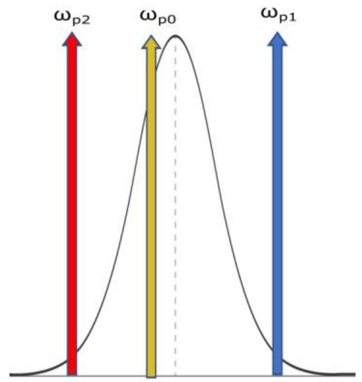
Negative Mass

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







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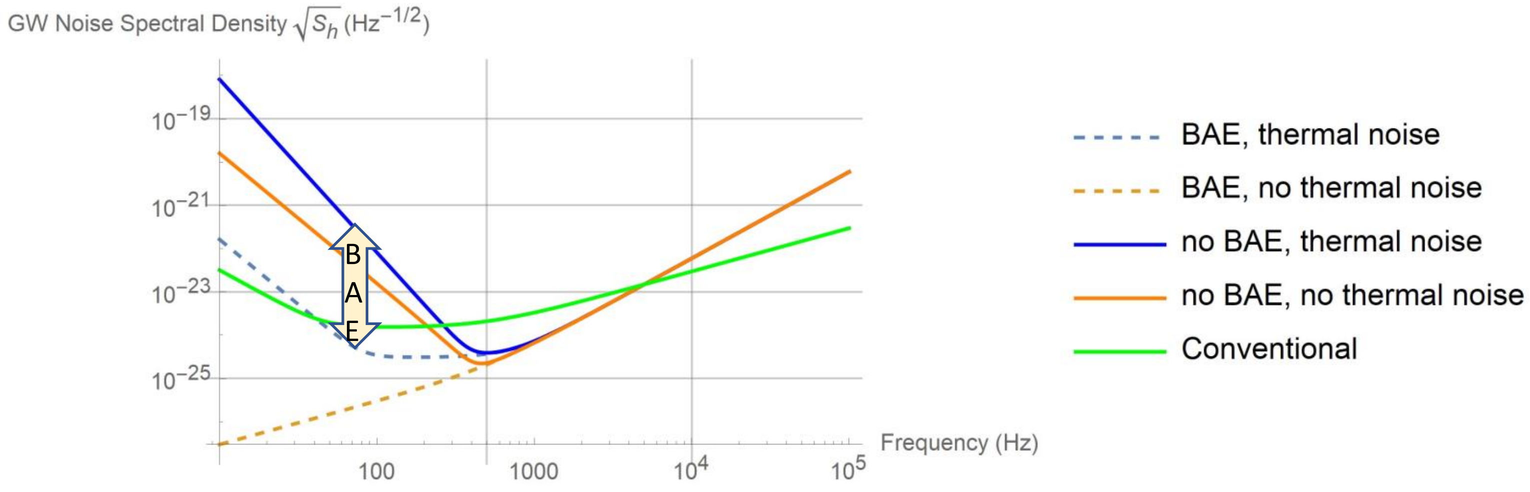
Figures from http://www.gwoptics.org/ComponentLibrary/

Mathematica Simulations

GW Noise Spectra with backaction

- GW Noise Spectra normalized for signal

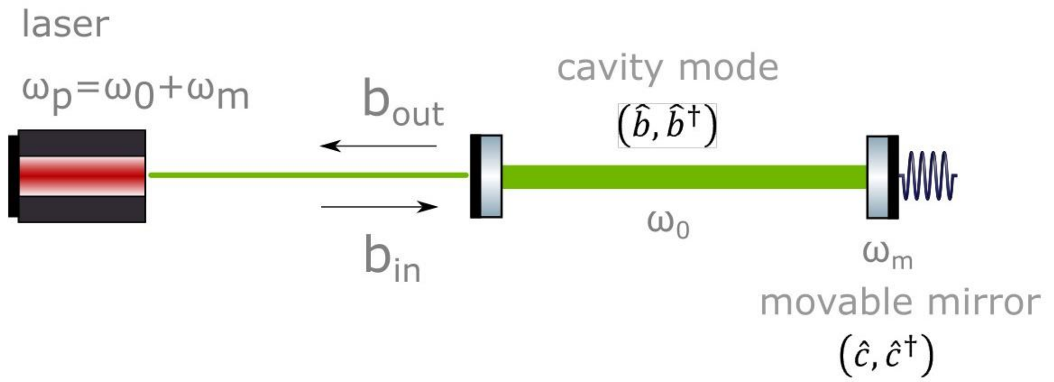
Parameter	Value
γ_R	$(2\pi)500$ Hz
γ_m	0.0000001 Hz
κ	$(2\pi)5000$ Hz
χ	$(2\pi)5000$ Hz
k_B	$1.38065\times10^{-23}\ m^2s^{-2}kgK^{-1}$
T	4 K
μ	50 kg
μ_C	-50 kg
ω_m	$(2\pi)10$ kHz
ω_0	$(2\pi)299792458\ ms^{-1}/2\mu m$
$\hbar$	$1.054571628\times10^{-34}$ Js
L	4000 m
c	$299792458\ ms^{-1}$
P_c	3×10^6 Watt



Filter Cavity in FINESSE

Filter Cavity

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



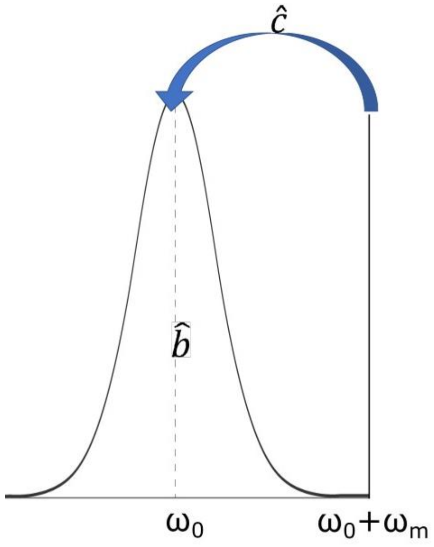
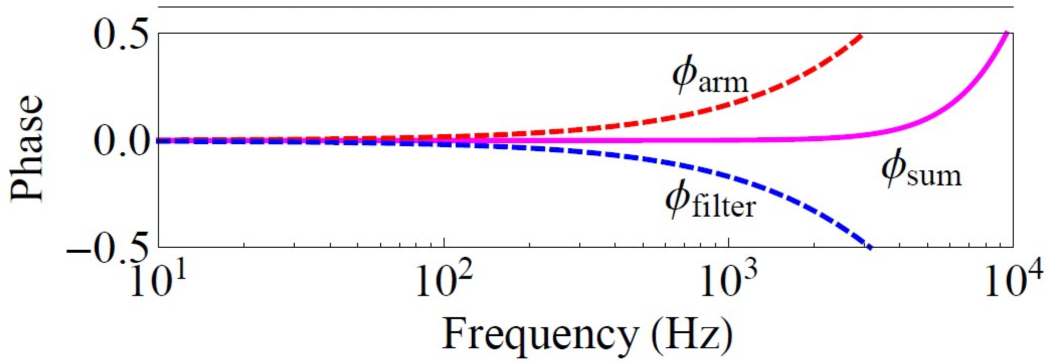


Figure from http://www.gwoptics.org/ComponentLibrary/

Filter Cavity

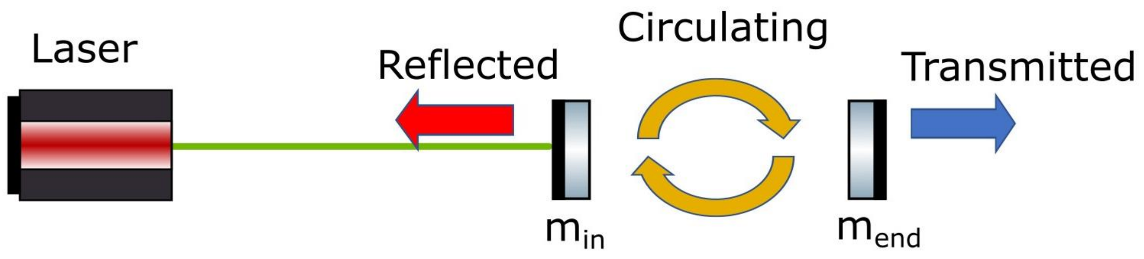
- Anomalous Dispersion
- $\hat{b}_{out}(\Omega) \approx \frac{\Omega + i\gamma_{opt}}{\Omega - i\gamma_{opt}} \hat{b}_{in}(\Omega)$ $(\gamma_{opt} \gg \gamma_m)$

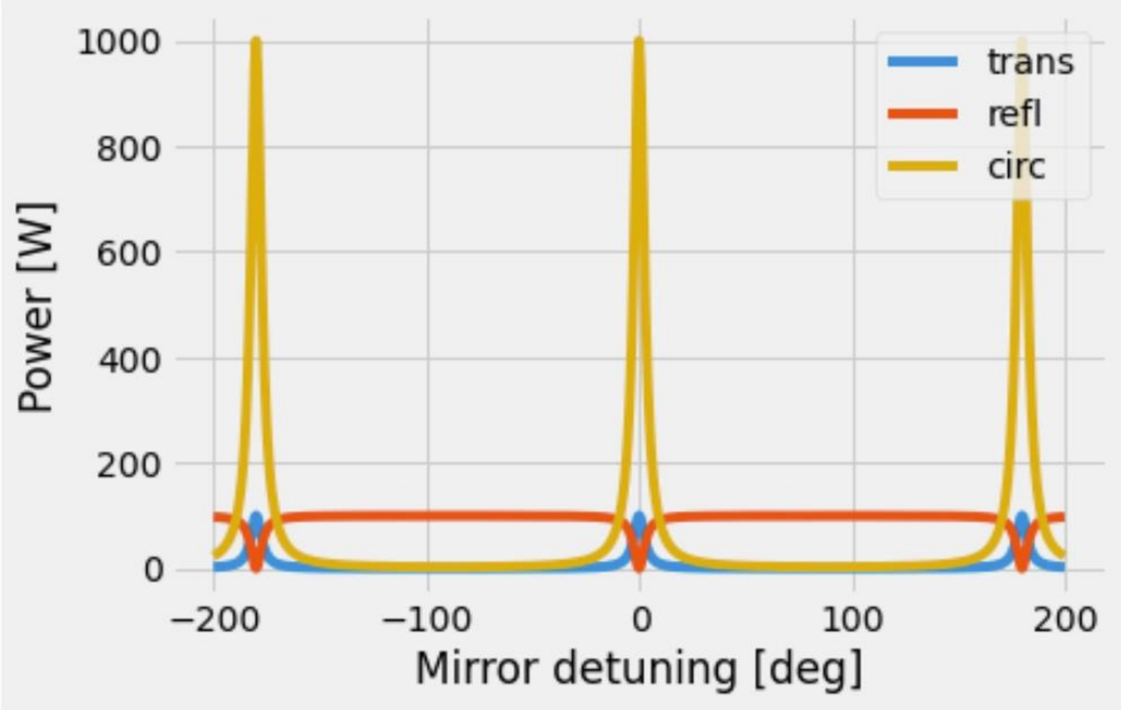


Miao, Haixing, et al. "Enhancing the bandwidth of gravitational-wave detectors with unstable optomechanical filters." *Physical review letters* 115.21 (2015): 211104, p2.

Fabry Perot Cavity

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

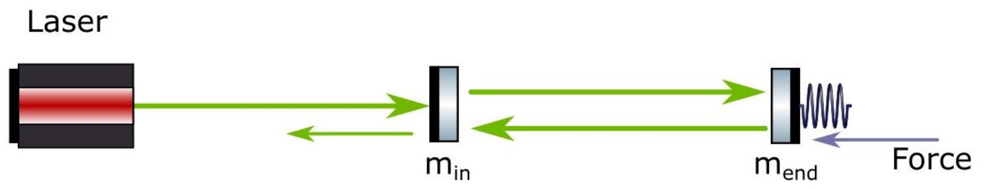


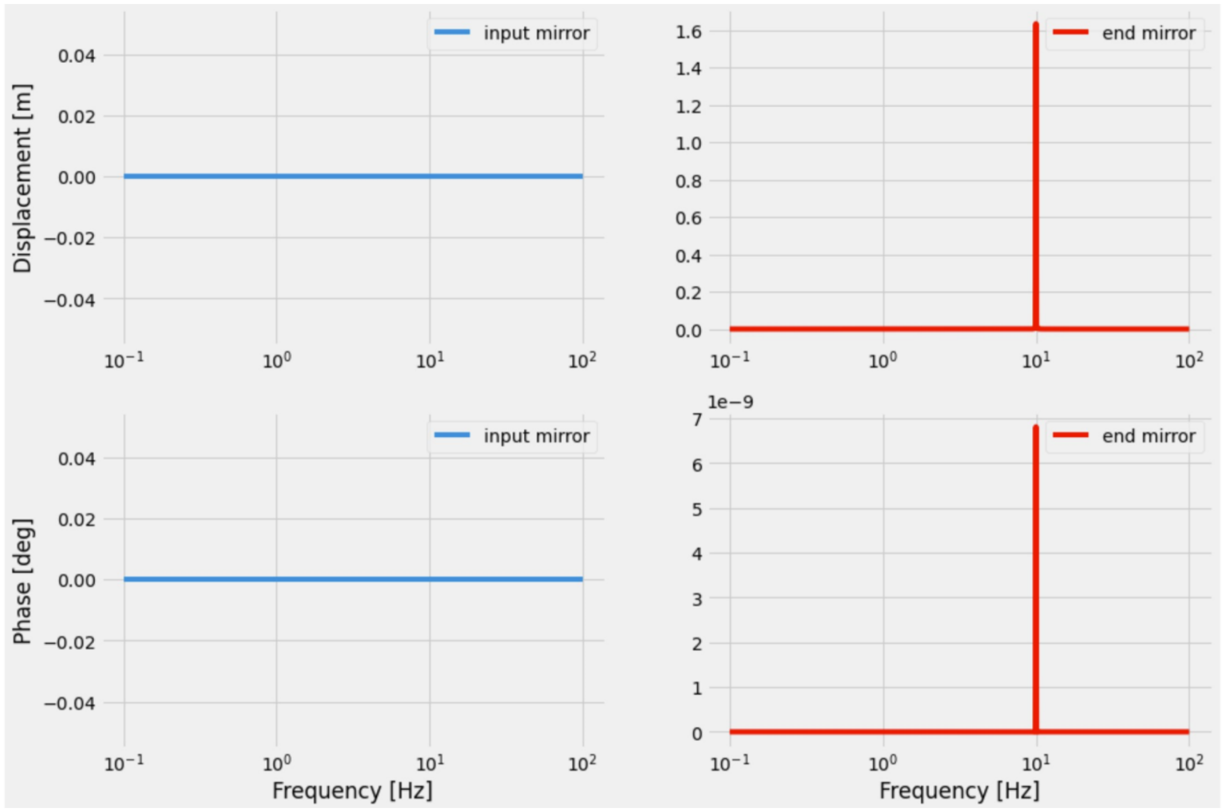


The top figure is constructed from http://www.gwoptics.org/ComponentLibrary/

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

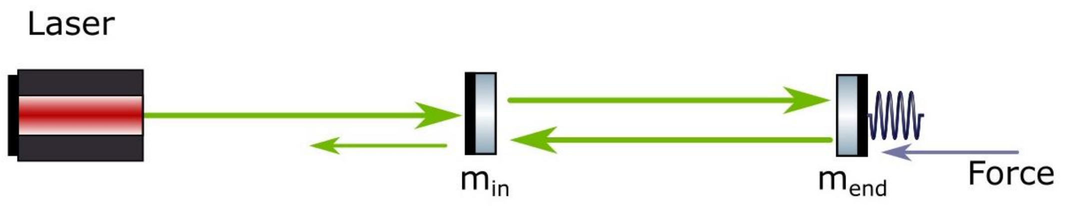


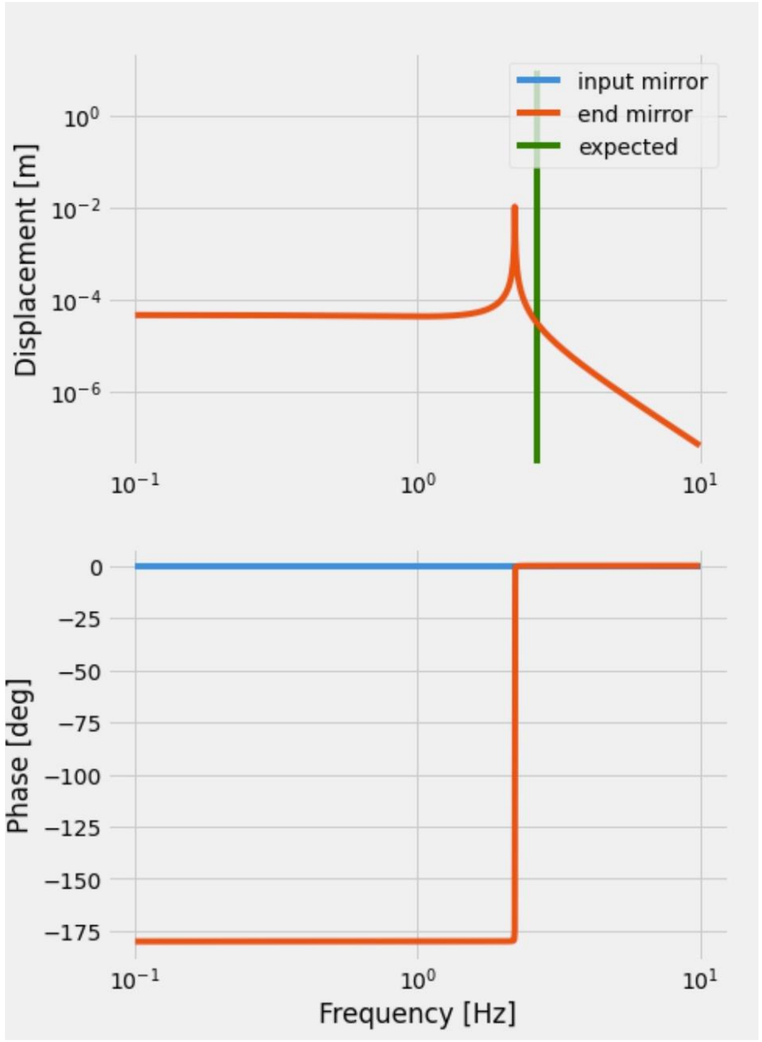


The top figure is constructed from http://www.gwoptics.org/ComponentLibrary/

Fabry Perot Cavity

- Optical Spring Effect
- P = 3100 W
- L = 50 m
- ωm = (2π)1 Hz
- Δ = (2π)300 Hz
- m = 1 kg
- Qm = 8 x 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.