Active media and unstable filters: Commonalities and difference

GWADW
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(also presenting slides by H.Miao)

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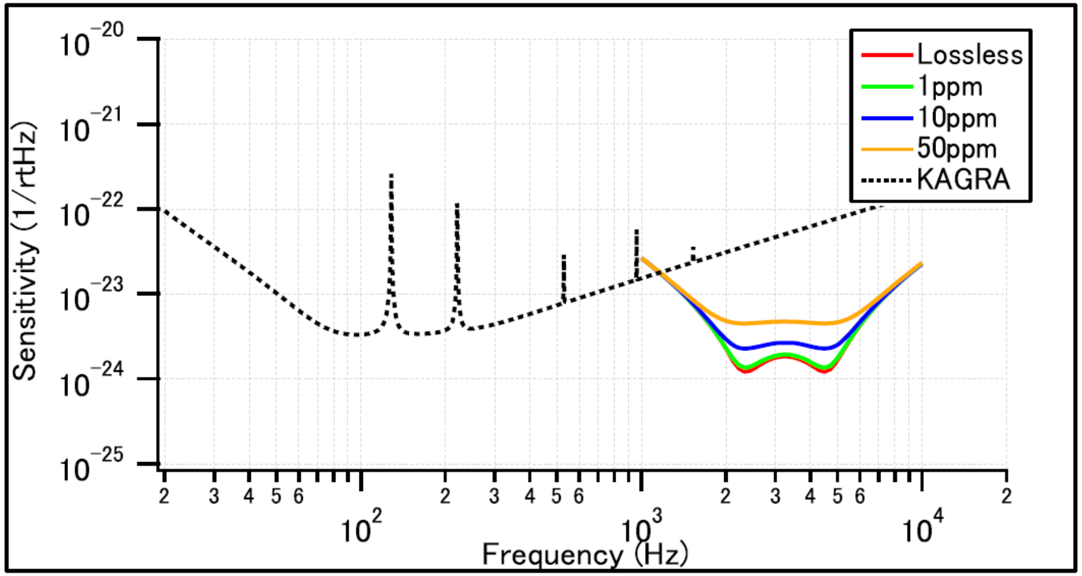
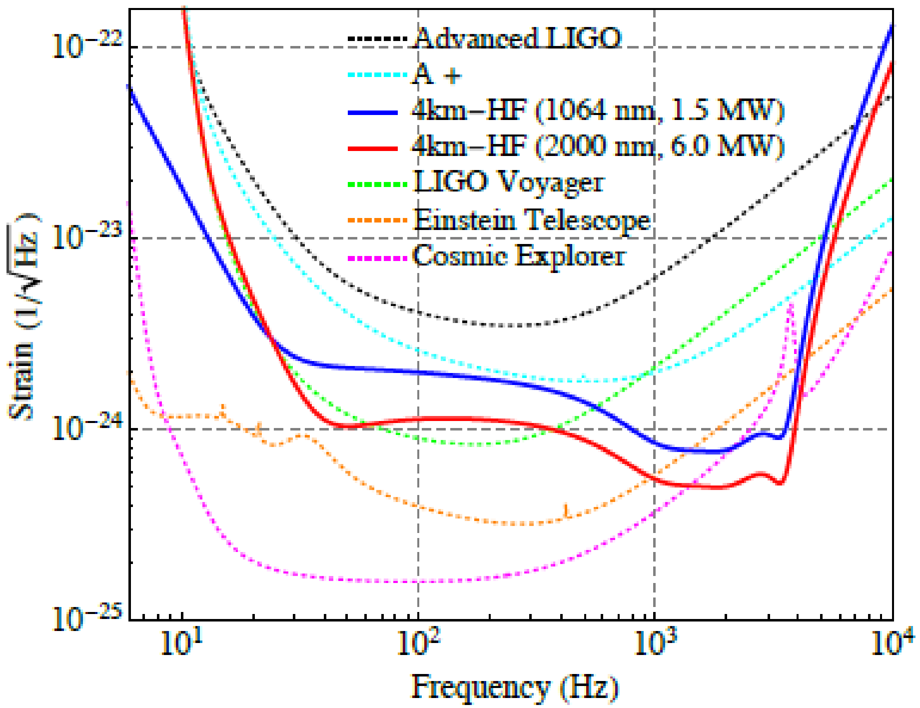
Introduction



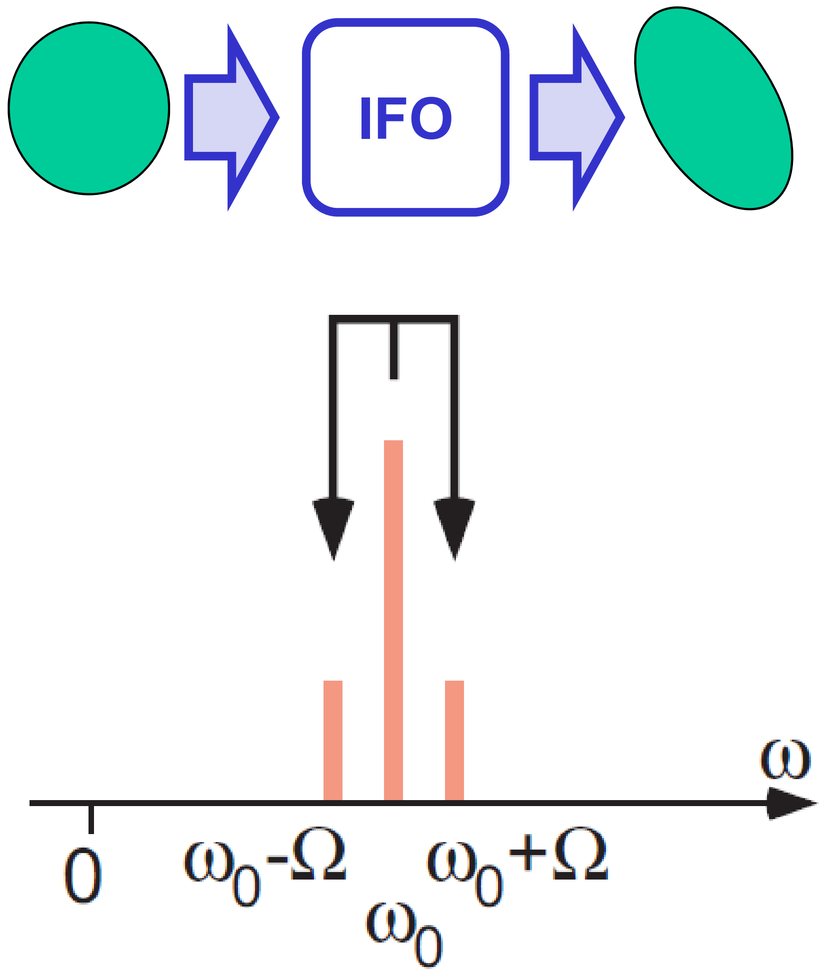
My plot for GEO-HF upgrade.



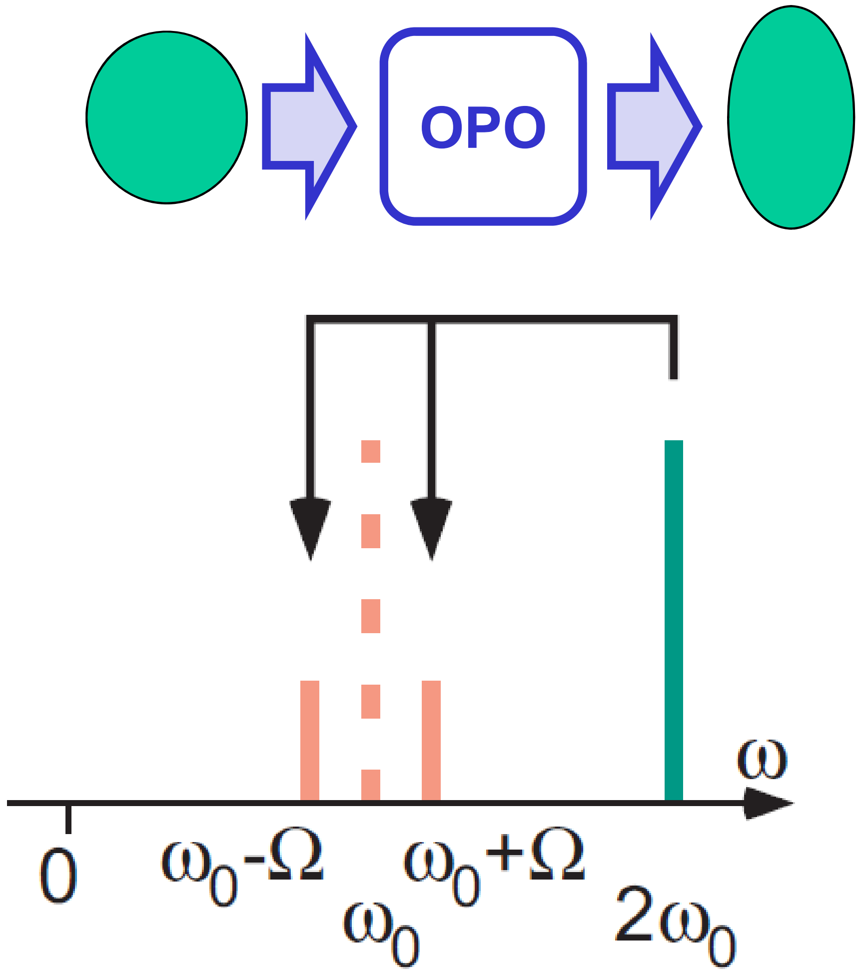
Haixing's plot for aLIGO upgrade.

Both are with an active device in the SR cavity.
I will show you,
(i) Commonality of the schemes
(ii) Current status of Haixing's scheme
(iii) Current status of Our scheme.

Ponderomotive and OPO squeezings

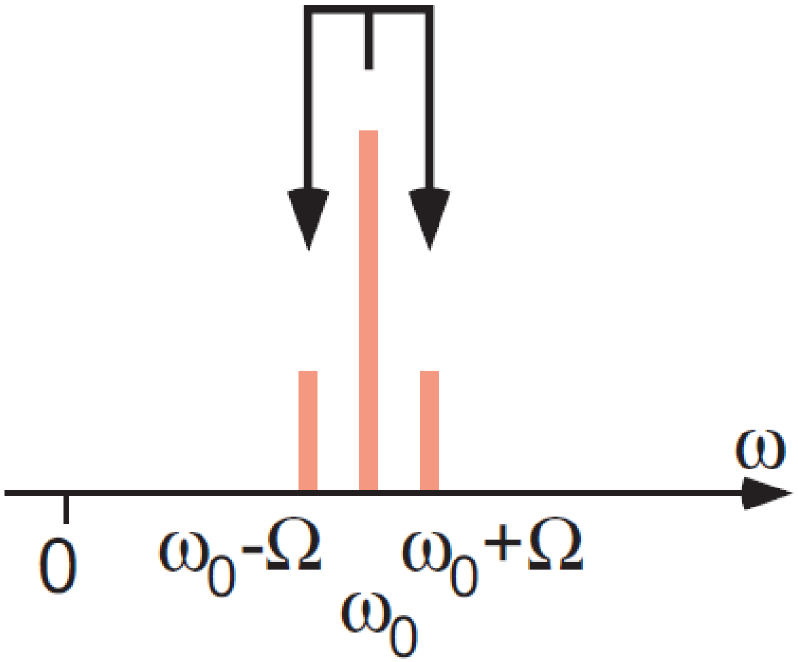


Amplitude-to-phase conversion (free-mass)



Upper-to-lower and lower-to-upper conversions

Ponderomotive and OPO squeezings

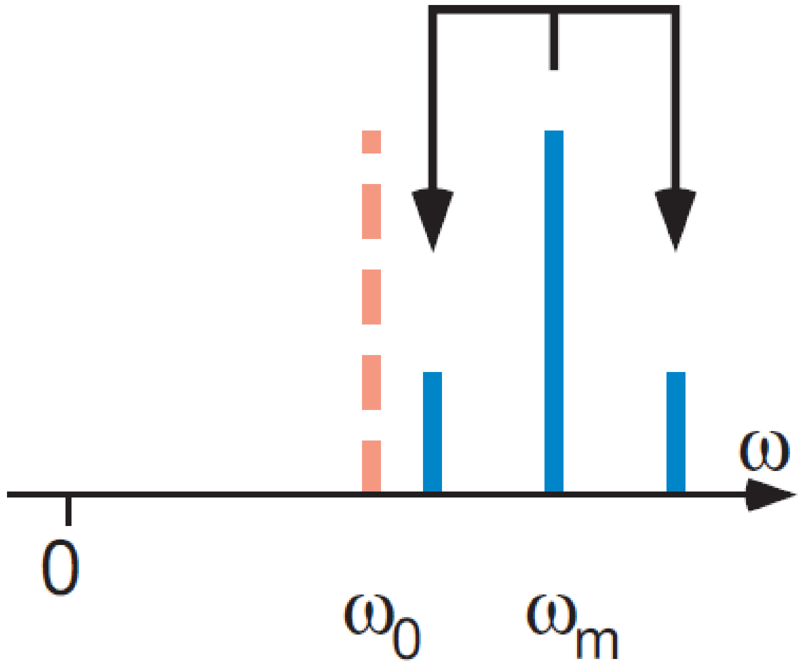


Amplitude-to-phase conversion (free-mass)

An optomechanical filter is based on this concept.

Optomechanical filter

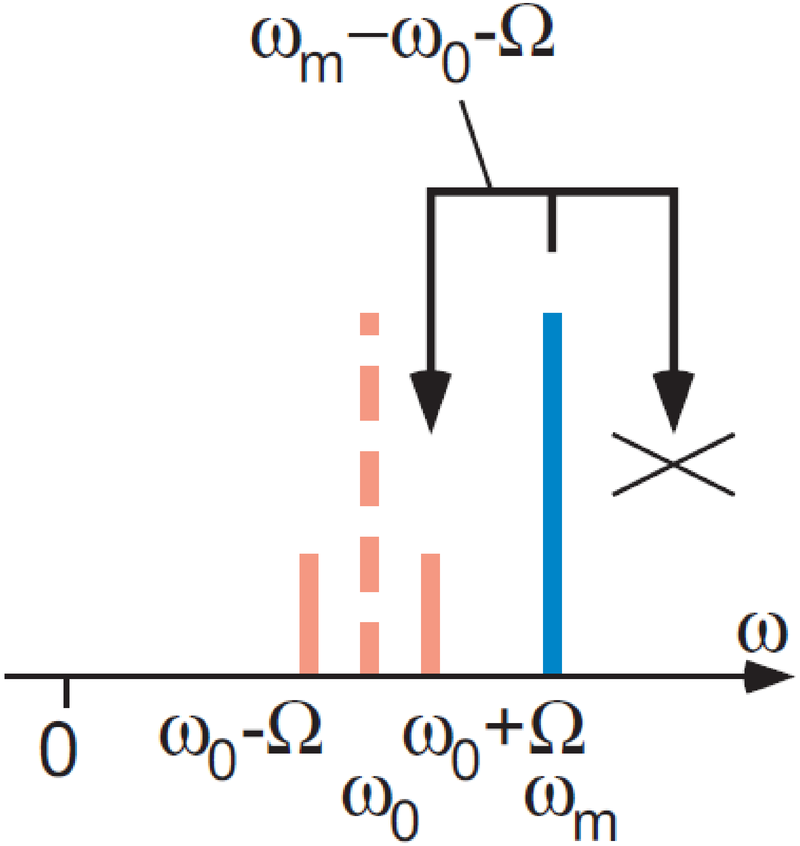
First, we shift the frequency of the beam that pumps the mechanical motion of an oscillator.



Ponderomotive coupling

(mechanical oscillator at ω_m)

Optomechanical filter



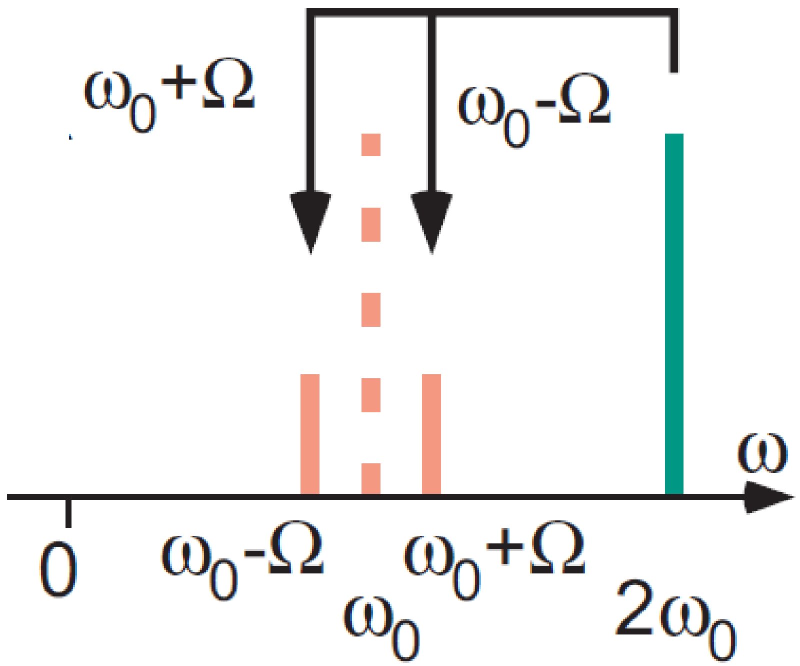
Ponderomotive coupling
(mechanical oscillator at ω_m)

Main signal is then injected to the system.

This realizes a negative dispersion of the optical field, i.e.
compensation of phase delay.

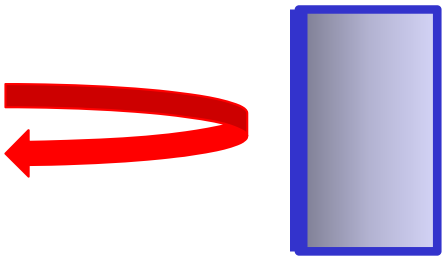
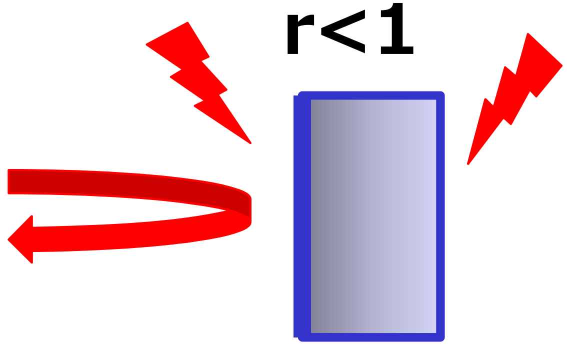
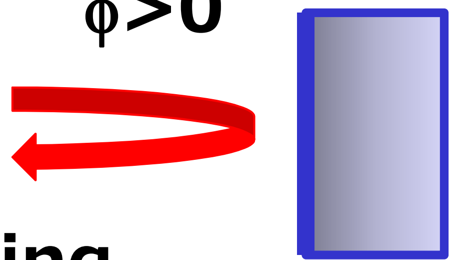
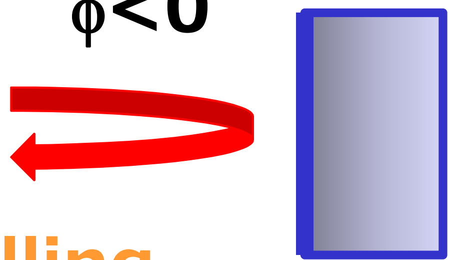
Ponderomotive and OPO squeezings

This is rather simple.
Main signal will be increased
("anti-squeezing").



Upper-to-lower
and Lower-to-upper
conversions

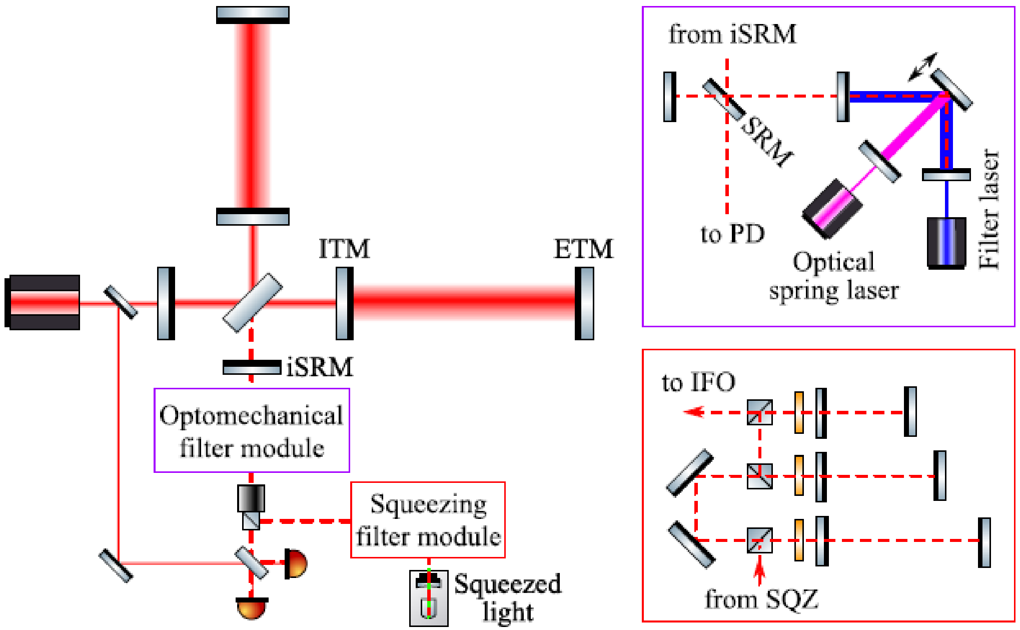
Usage as a mirror

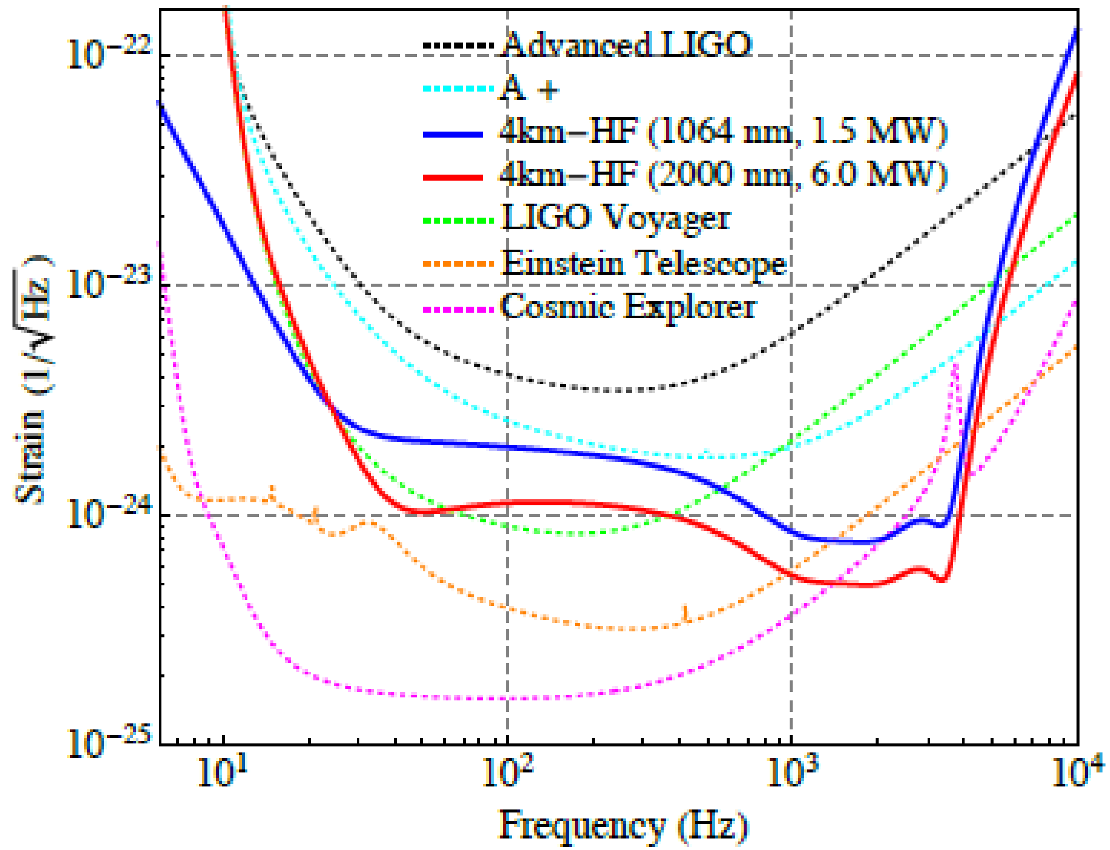
	positive	negative
gain	r>1  Anti-lossy mirror	r<1  Lossy mirror
phase	ϕ>0  Travelling with time	ϕ<0  Travelling against time

Unstable optomechanical filter for bandwidth enhancement

Current status of unstable filters

Original design (Reflection-readout)



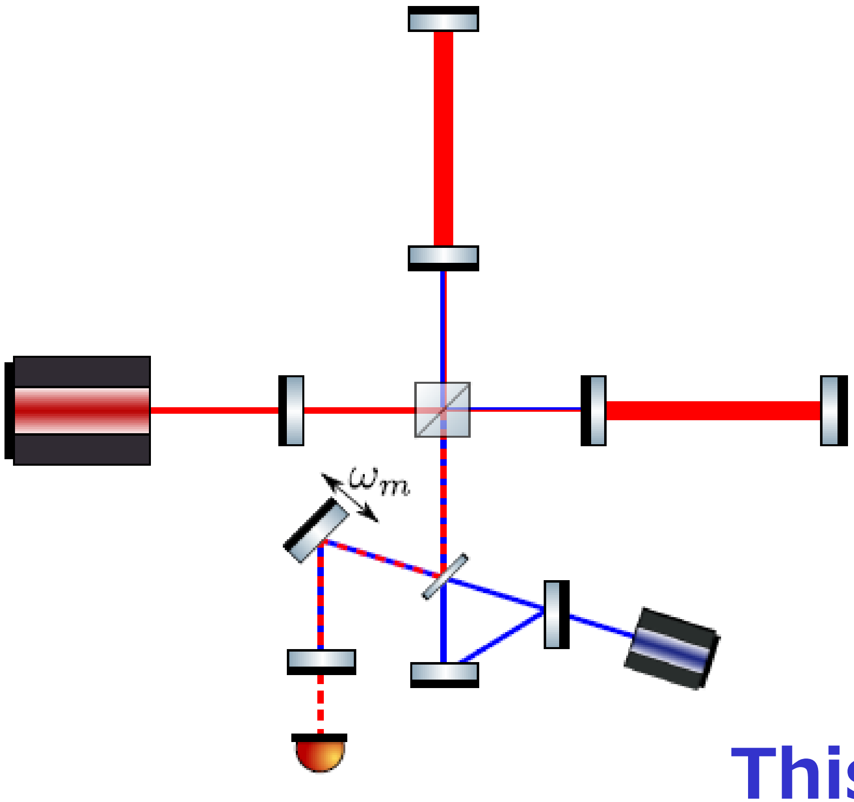


The design is suitable for high frequency measurements.

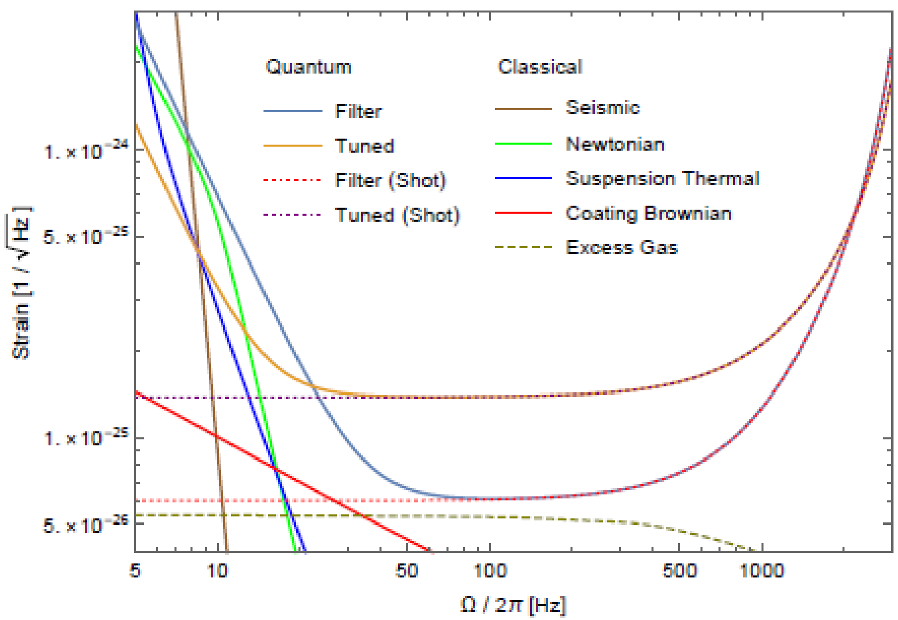
[LIGO-G1800440-v7]

Current status of unstable filters

New design (Transmission-readout)



Best-case improvement



CE params
10 dB squeezing
$L_{\text{arm}} = 40\,\text{km}$
$L_{\text{SRC}} = 20\,\text{m}$
$T_{\text{ITM}} = 0.045$
$T_{\text{SRM}} = 0.00035$
$m_{\text{oscill.}} = 10\,\text{mg}$
$\omega_m = 2\pi \times 1\,\text{kHz}$
$P_{\text{SRC}} = 237.9\,\text{W}$

With these parameters we get $\sim 7\,\text{dB}$ improvement from 50 to 500 Hz

Effective BW $\sim \frac{c}{2\sqrt{2}}\left(\frac{T_{\text{ITM}}T_{\text{SRM}}^2}{L_{\text{arm}}L_{\text{SRC}}^3}\right)^{\frac{1}{4}}$

This design provides better sensitivity at low frequencies as well and can be better for long baseline detectors.

[LIGO-G1800440-v7]

Current status of unstable filters

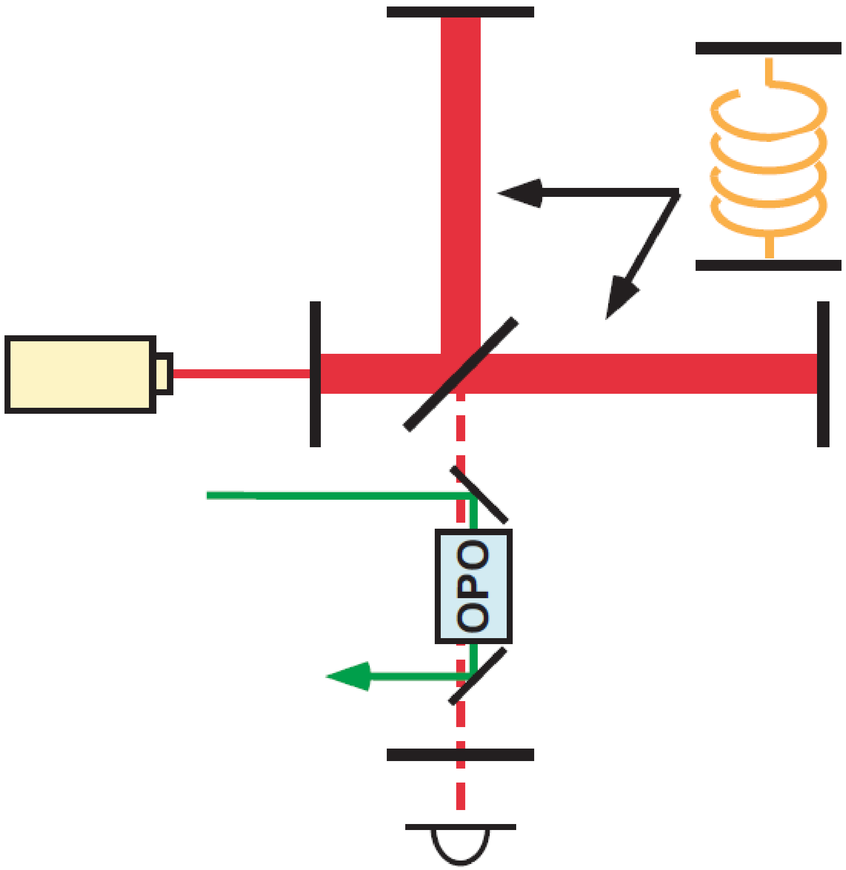
- **Further to increase the BW will decrease the peak sensitivity; it can mitigate with the refl-readout**
- **Control of the system is an issue**
- **Denis Martynov is trying to realize it experimentally**

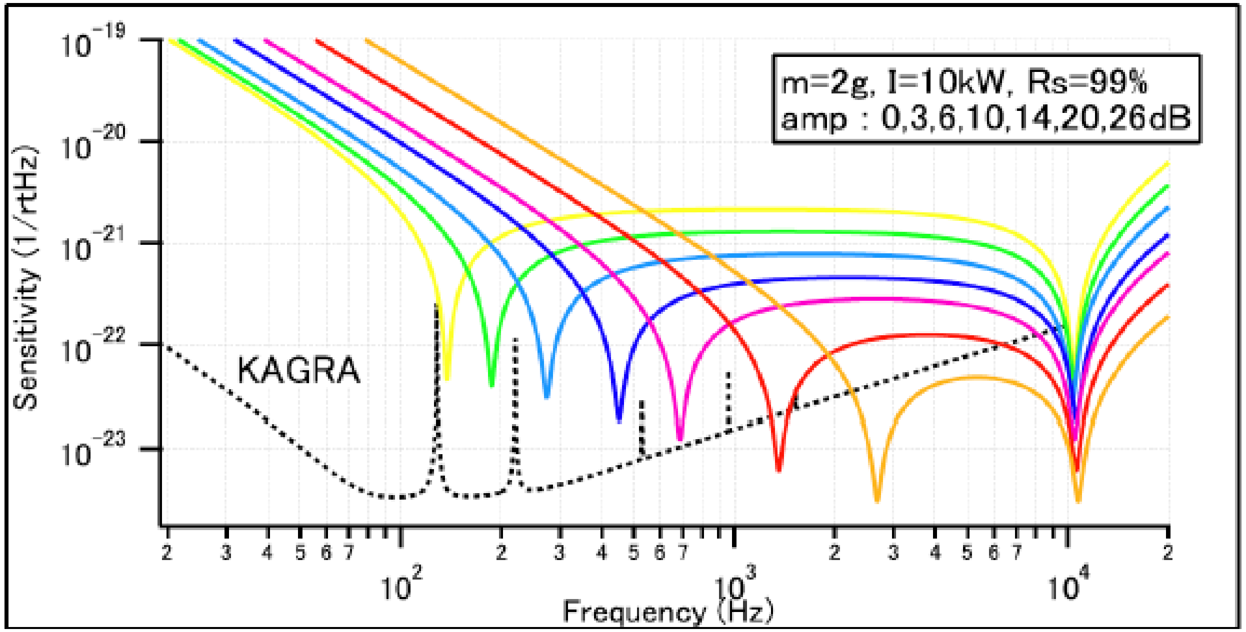
Reference

- H.Miao et al., PRL 115, 211104 (2015)
- H.Miao et al., arXiv:1712.07345 (2017)

Intracavity OPO for signal amplification

Intracavity OPO

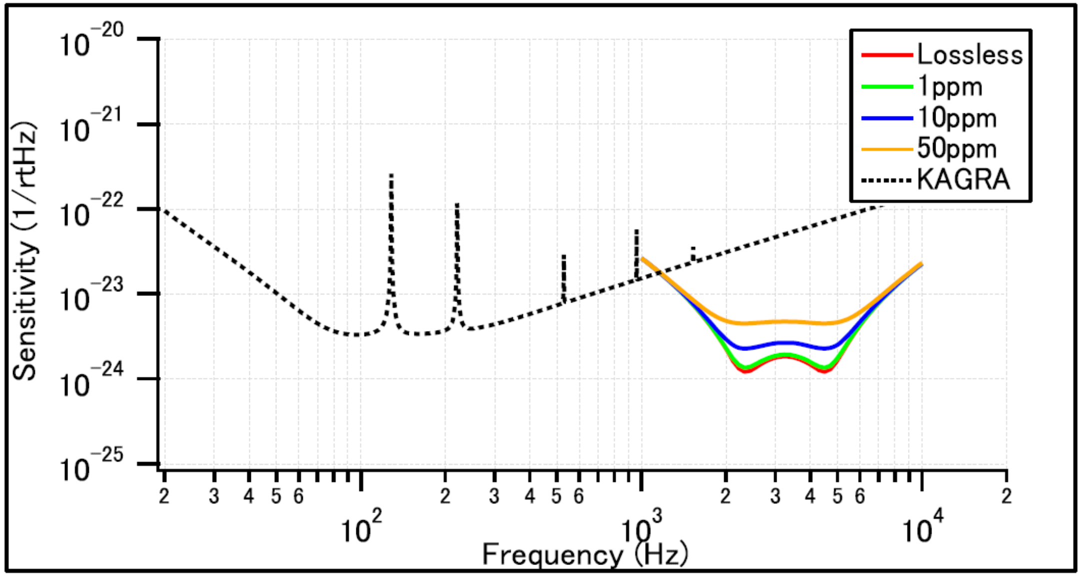




$$\Omega \cong \sqrt{\frac{8\omega_0 I_0}{mL^2\gamma^2}} \frac{\sin 2\phi}{\left(r+\frac{1}{r}\right)-\left(s+\frac{1}{s}\right)\cos 2\phi}$$

The optical spring frequency increases by tuning the OPO gain to make the denominator close to zero.

Mysteries in the current setup



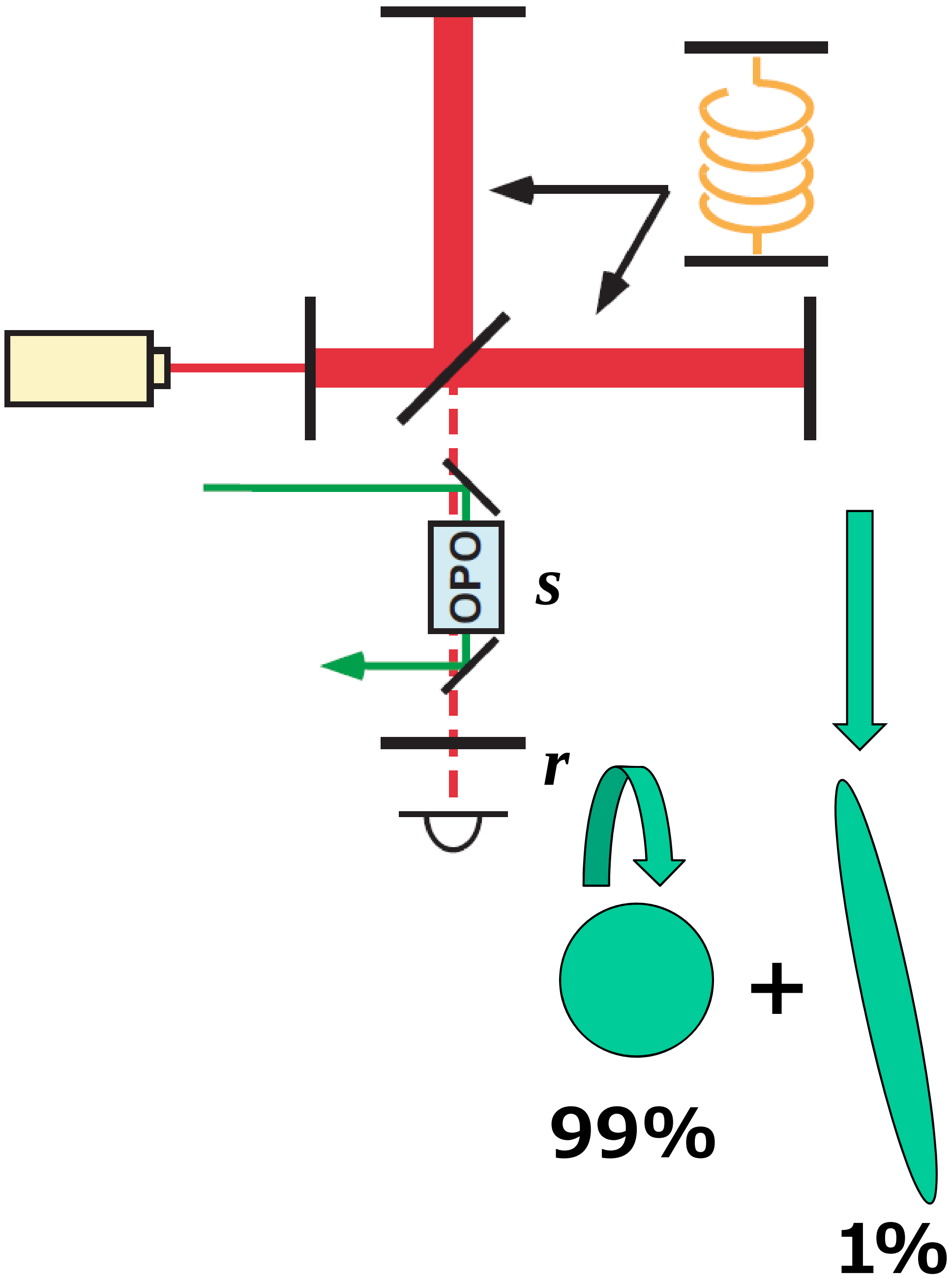
This sensitivity is obtained with

- 34dB anti-squeezing
- nearly 45 deg detuning
- no BS loss included

I expected much smaller anti-squeezing factor and almost no contribution of the optical losses.

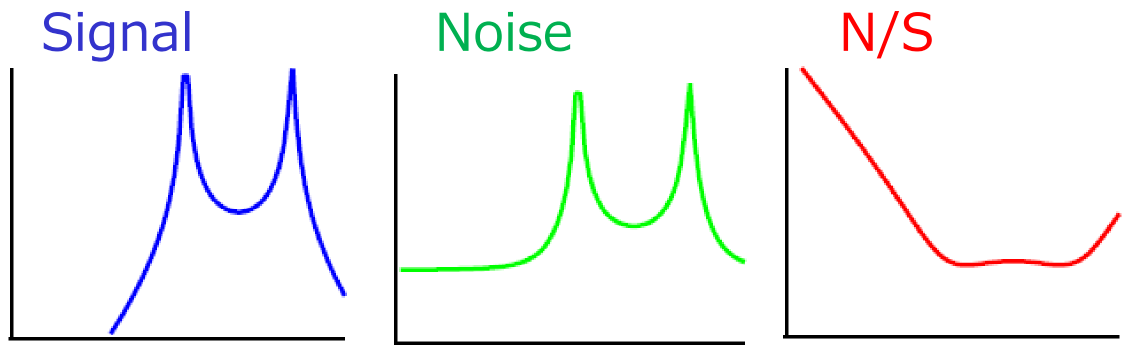
Why is the life not too easy for me?

Why 45 deg?

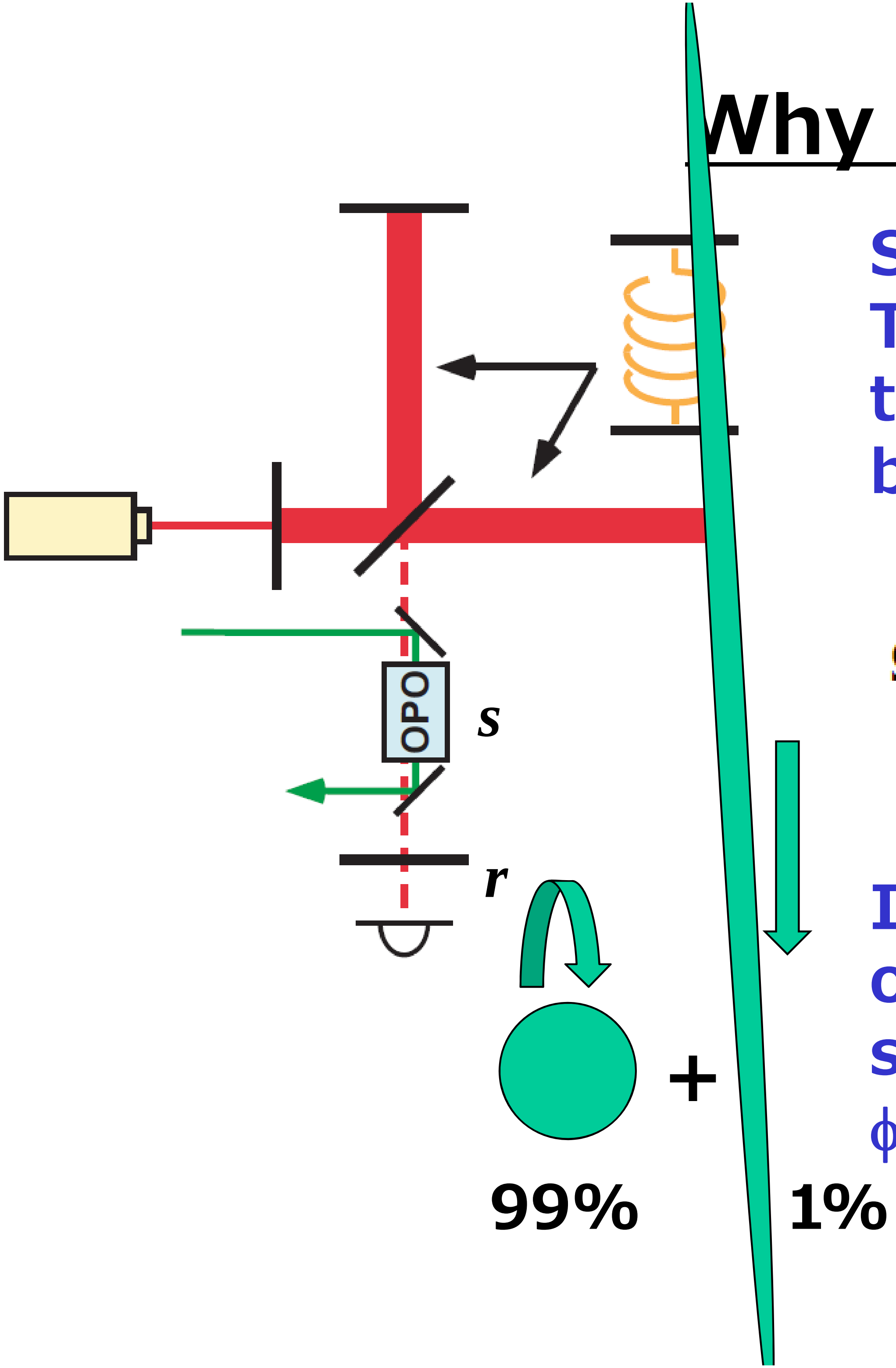


Both signal and noise increase in the interferometer.

However, as most of the noise field is directly reflected by SRM, the SNR can be improved by the optical spring at its resonance.



Why 45 deg?

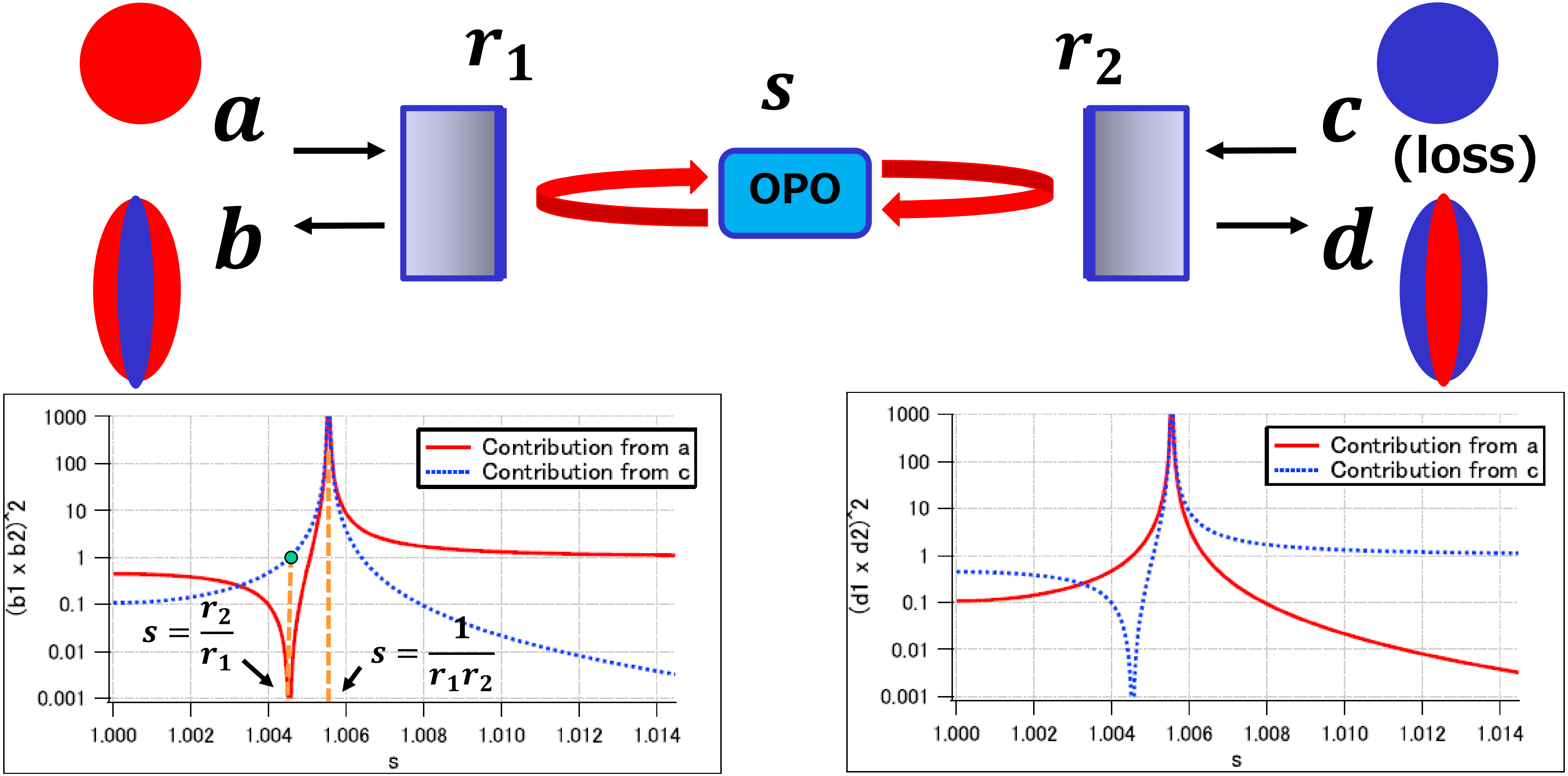


Situation changes with an OPO. The intracavity gain is so high that the directly reflected field becomes negligible.

$$\Omega \cong \sqrt{\frac{8\omega_0 I_0}{mL^2\gamma^2}\frac{\sin 2\phi}{\left(r+\frac{1}{r}\right)-\left(s+\frac{1}{s}\right)\cos 2\phi}}$$

It means we do not see the optical spring peak in the sensitivity spectrum, unless ϕ is set to be 45 deg ($\cos 2\phi \sim 0$).

How come the loss matters so much?

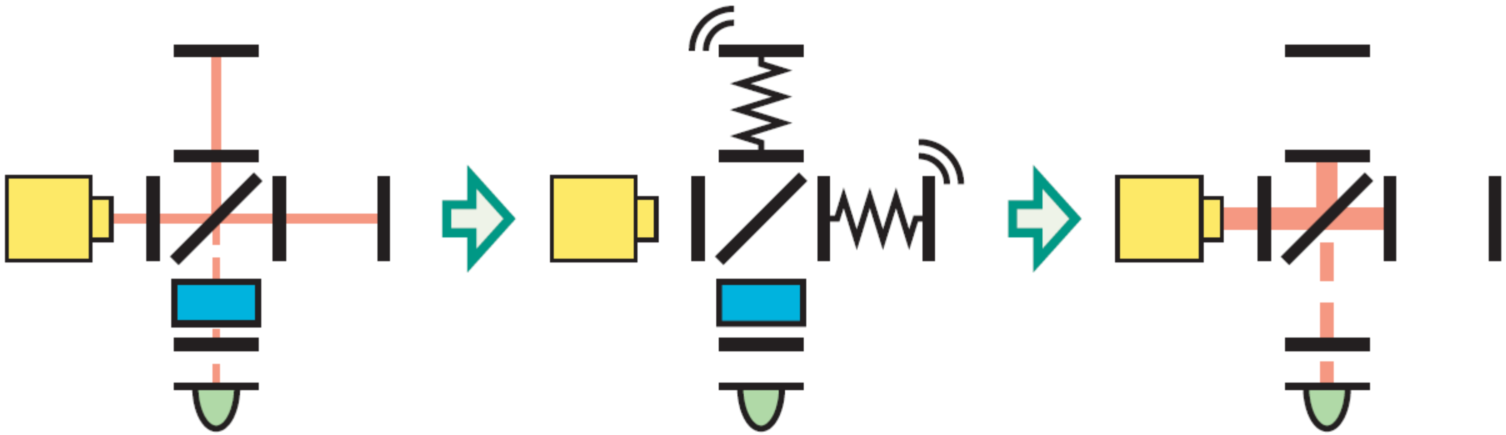


After $s>r_2/r_1$, the size of a in b becomes larger than unity while a coherent sum of a in b and d is still unity.

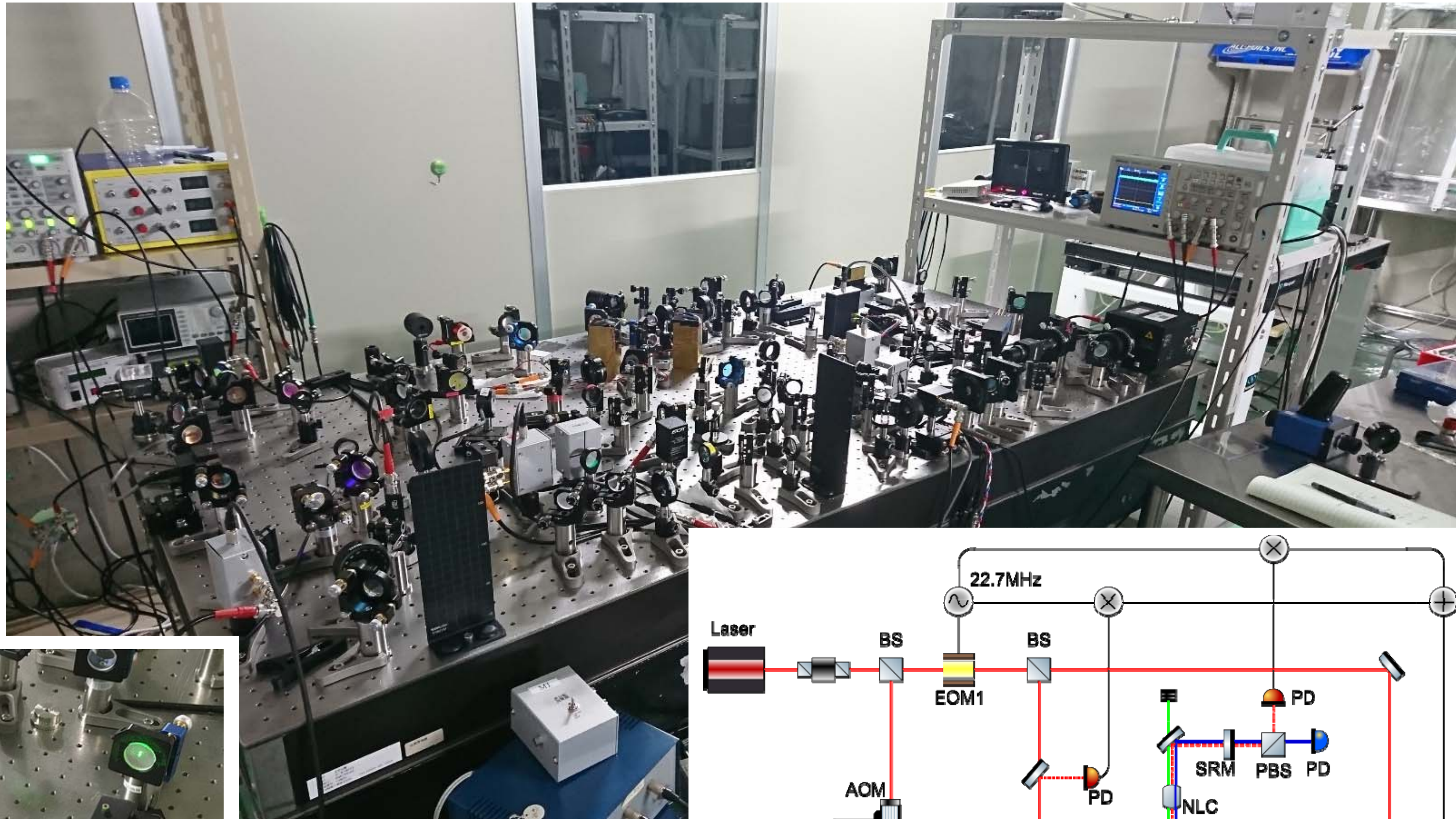
What should we do now?

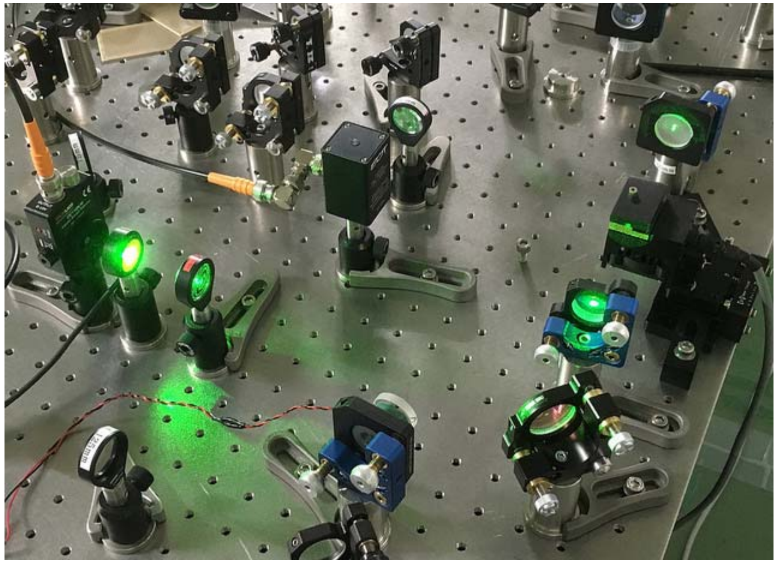
(1) Go straigh to work as planned.
Find a low loss BS and make a high gain OPO
to realize the current configuration.

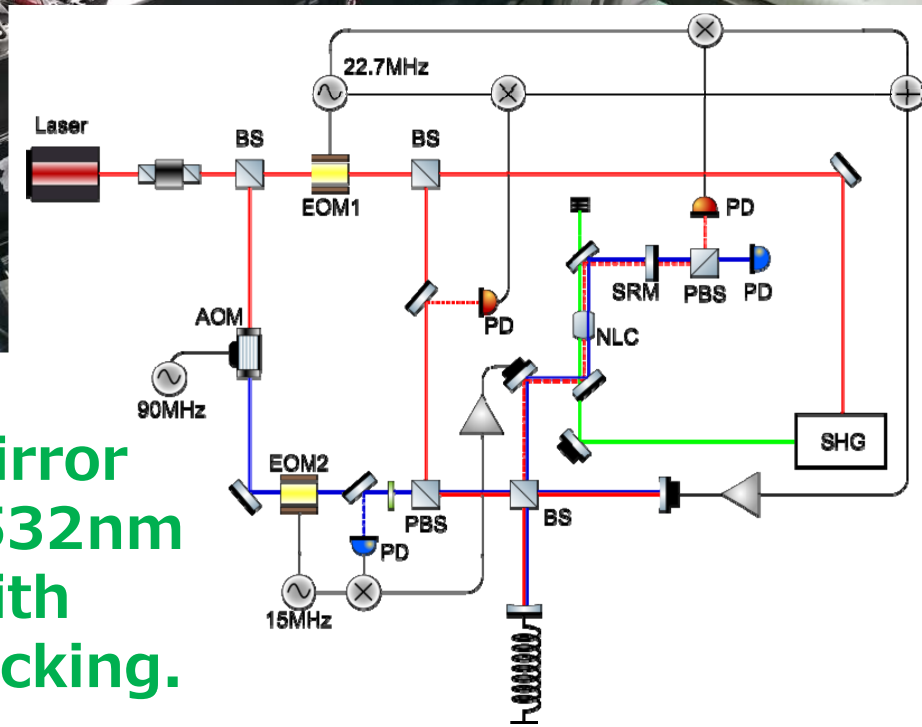
(2) Maybe we can try an *optical bar* regime.



Current status of a prototype experiment

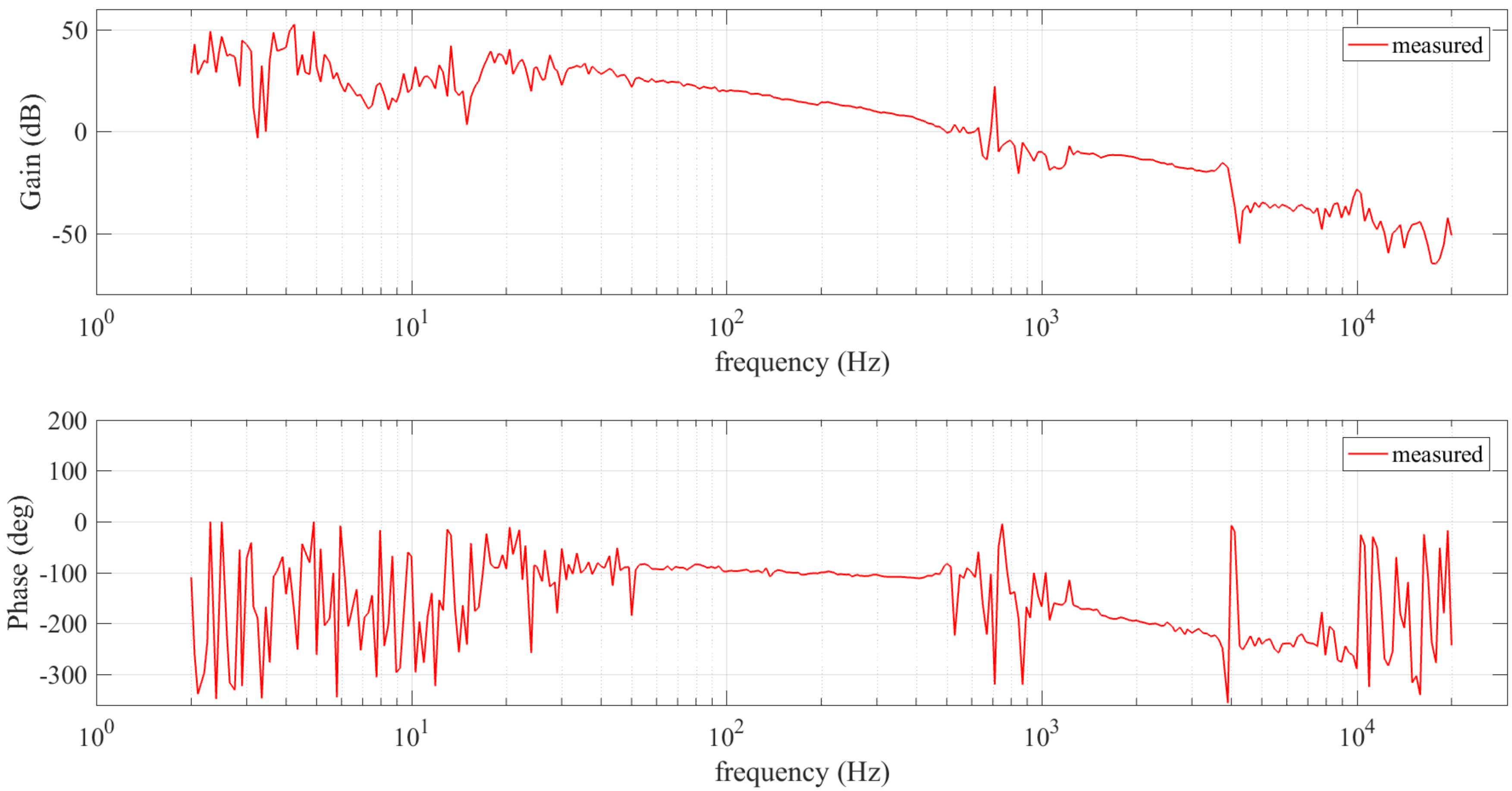






- 200mg susp mirror
- SHG: 200mW 532nm
- Tunable SRC with a sub-carrier locking.

Current status of a prototype experiment



- Stable operation of detuned SRMI with an intracavity OPO
- No observation of optical spring yet

Summary

- Intracavity schemes are under development
- Control is an issue for unstable filter
- Intracavity loss mechanism has been explained
- Experimental demos are on-going/planned

Supplementary

Comparison

	Kentaro	Haixing
Title	Signal amplification	Negative dispersion
Goal	Optical spring at 5kHz	Bandwidth of 5kHz
Target detector	GEO-HF	aLIGO/CE
Nonlinear device	OPO	Optical spring
Challenge	Intracavity loss	Thermal noise
Stability	Marginally stable	To be controlled
Prototype	On-going	Planned