Frequency-Dependent Squeezing for Gravitational-Wave Detectors

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Abstract

- For broadband quantum noise reduction in GW detectors, frequency-dependent squeezing with 300 m filter cavity was developed
- Frequency-dependent squeezing with rotation below 100 Hz was realized for the first time
- To improve locking accuracy of filter cavity, I suggested a new control scheme and demonstrated the improvement
- Using this technology, sensitivity of GW detectors will improve by ~50% and event rate will increase more than 3 times

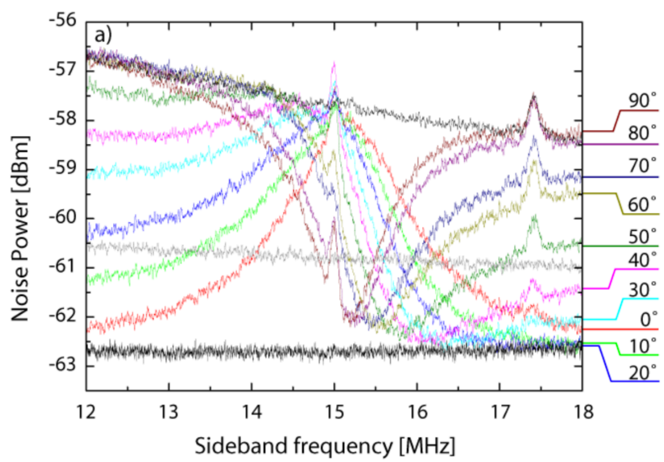
<u>This result is important for improving the sensitivity of current and future GW detectors and will push GW astronomy ahead</u>

Position of this research①

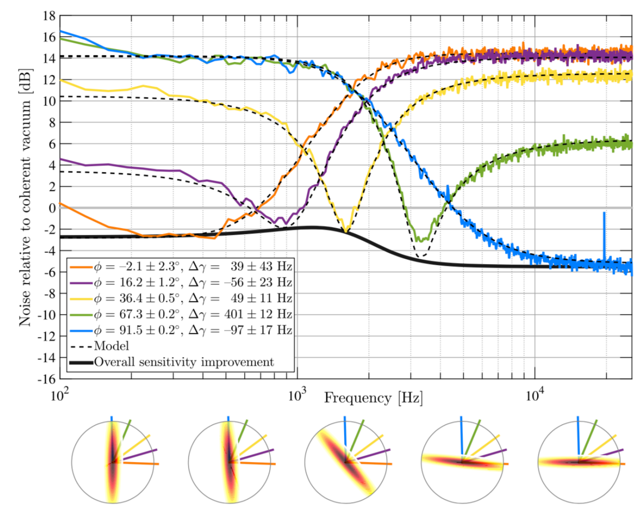
Previous research

- Frequency-dependent squeezing at MHz, kHz with 1m scale filter cavities have been demonstrated

S. Chelkowsiki et al, PRA 71, 013806 (2005)



E. Oelker et al, PRL 116, 041102 (2016)



This research

- By using 300 m filter cavity, frequency-dependent squeezing with rotation below 100Hz which is required in GW detectors has been realized

Position of this research ②

Previous research

- Filter cavity was controlled with auxiliary green field
- Controlling with auxiliary green field does not ensure the cavity length and alignment of filter cavity for squeezed field

This research

- To solve this problem, a new control scheme using coherent control field is suggested and experimentally demonstrated

- Independent of this work, control scheme using Resonant Locking Field (RLF) was developed at MIT

L. McCuller et al, PRL 124, 171102 (2020)

- Comparison of this work and RLF:

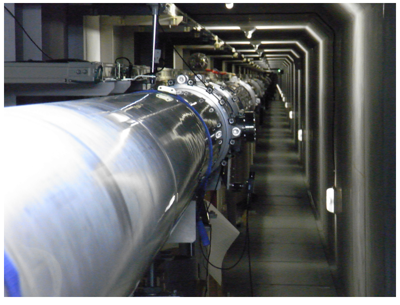
Advantage: We don't have to change setup

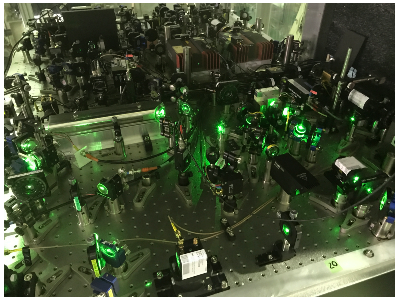
Disadvantage: shot noise is worse (, but requirement is still satisfied)

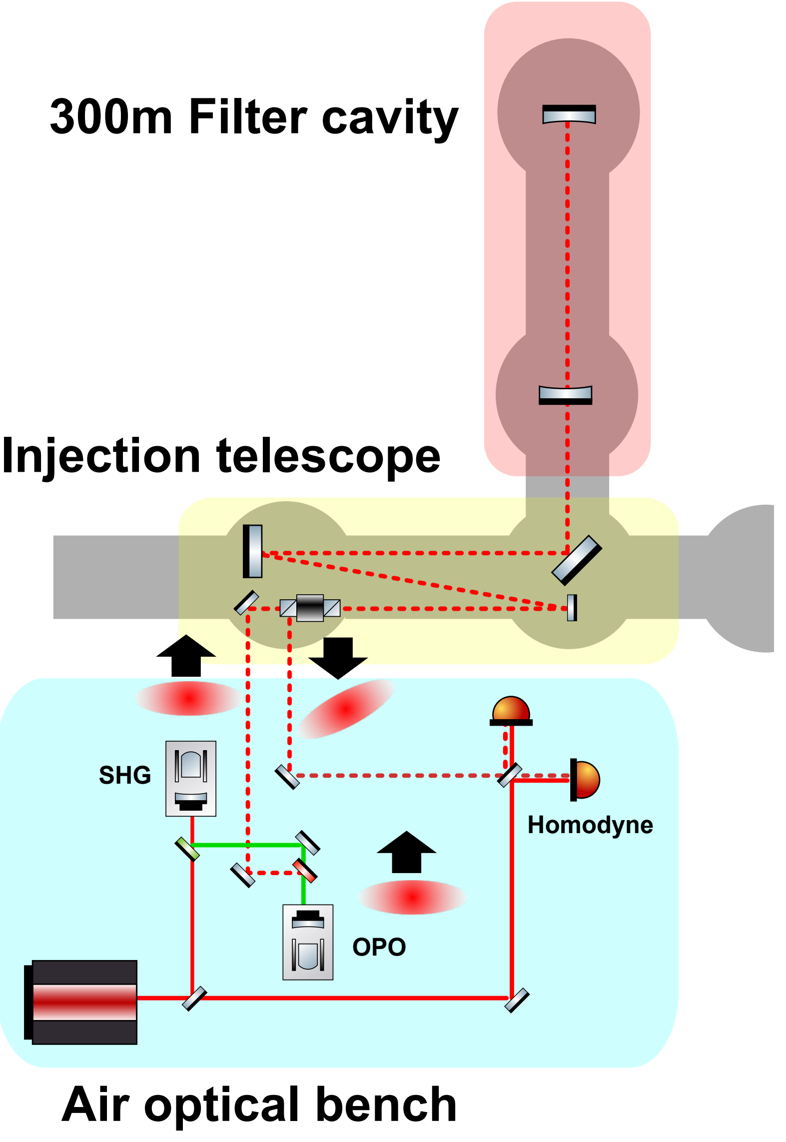
Overview of experiment

Overview of experiment:
300 m optical cavity in TAMA at NAOJ is used as a filter cavity, frequency-dependent squeezing with rotation below 100 Hz is developed

- 300 m filter cavity
  - finesse 4360 @1064nm
  - Round Trip Loss 80 ppm
- Squeezed vacuum source
  - 9dB above 10 Hz







Overview of experiment

Previous research:

- Simulation of mirror

  E. Capocasa et al, PRD 93, 082004 (2016)

- First measurement of round trip losses

  E. Capocasa et al, PRD 98, 022010 (2018)

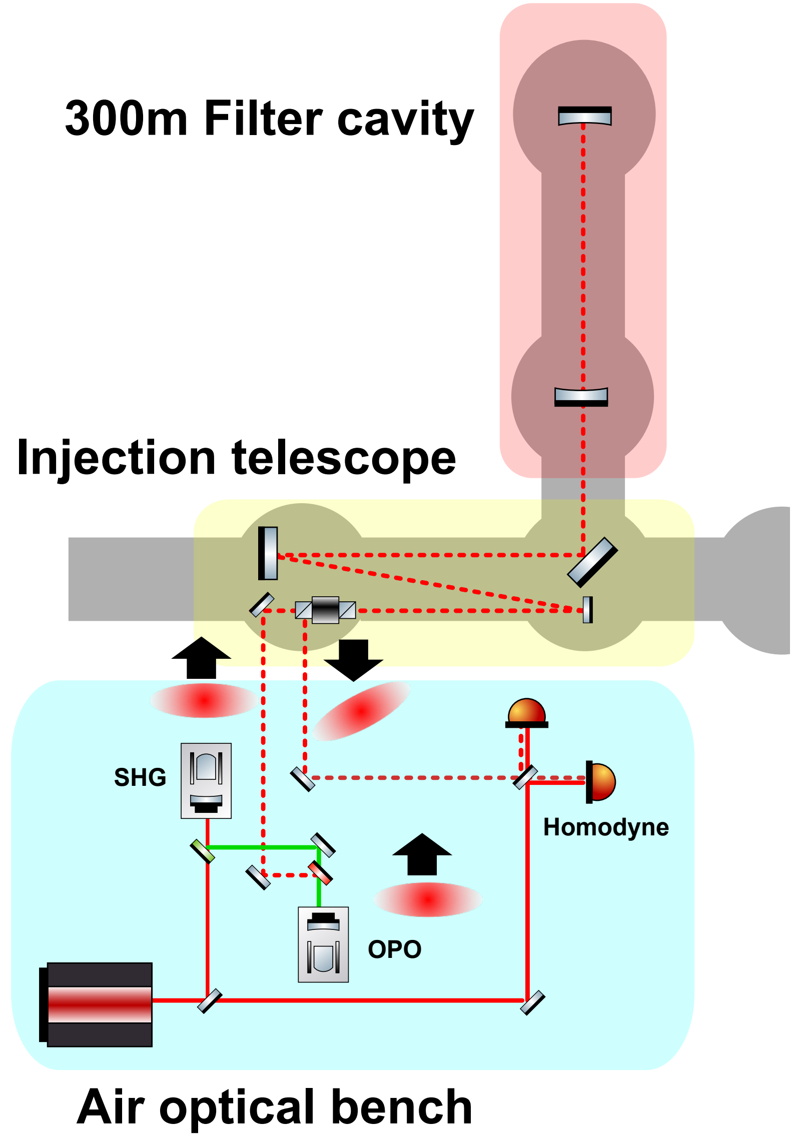
My work:

- Development of squeezing source
- Development of frequency-dependent squeezing

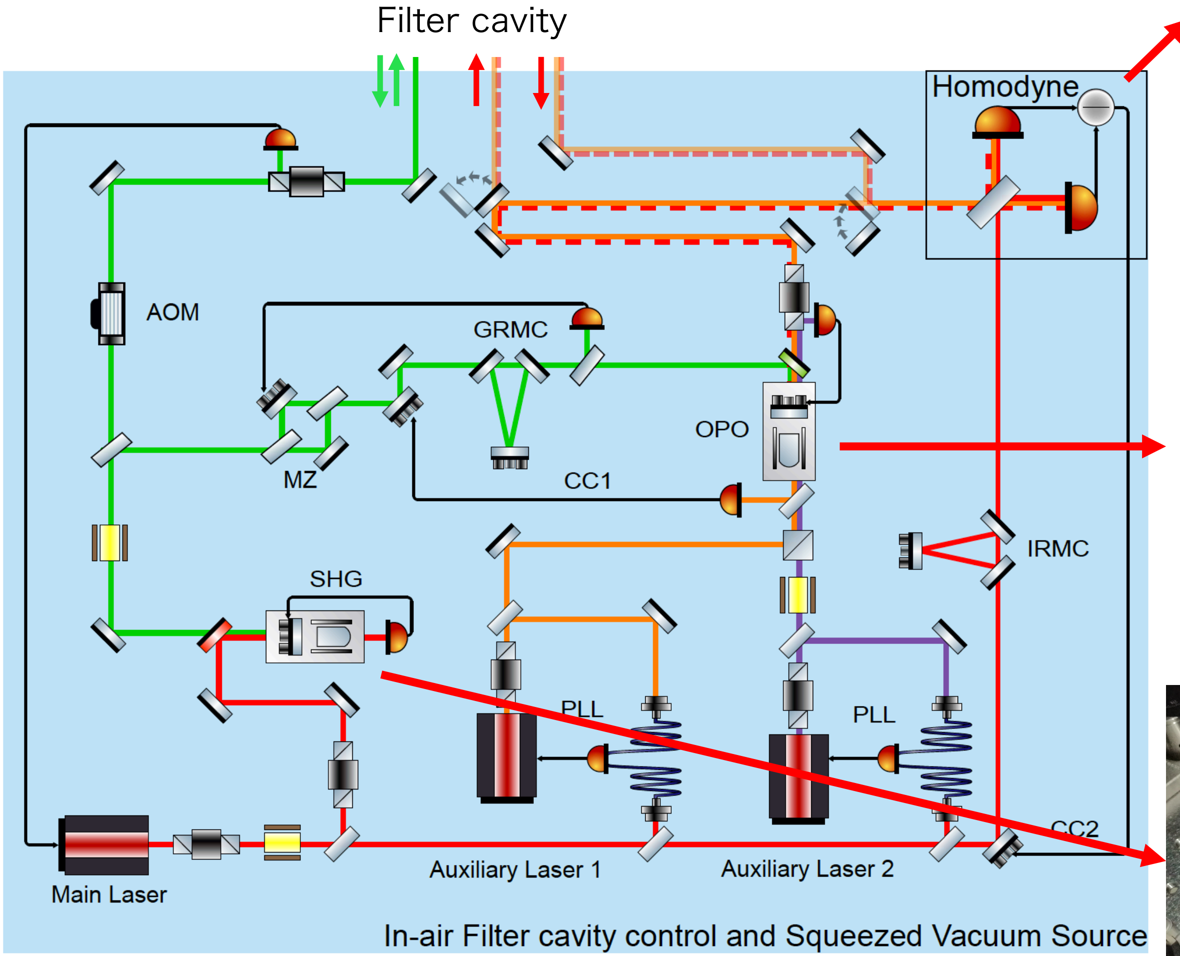
  Y. Zhao, N. Aritomi et al, PRL 124, 171101 (2020)

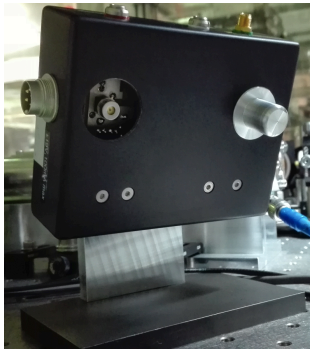
- Suggestion and demonstration of a new control scheme for filter cavity

  N. Aritomi et al, PRD 102, 042003 (2020)

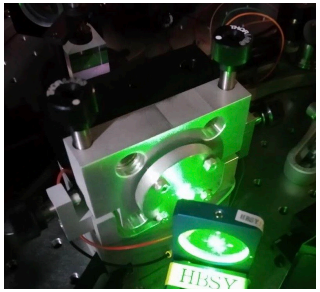


Squeezed source

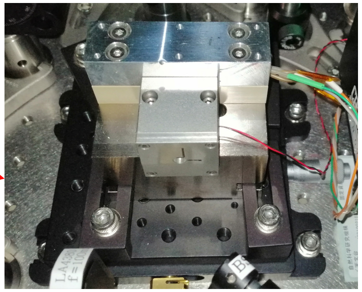




Homodyne detector



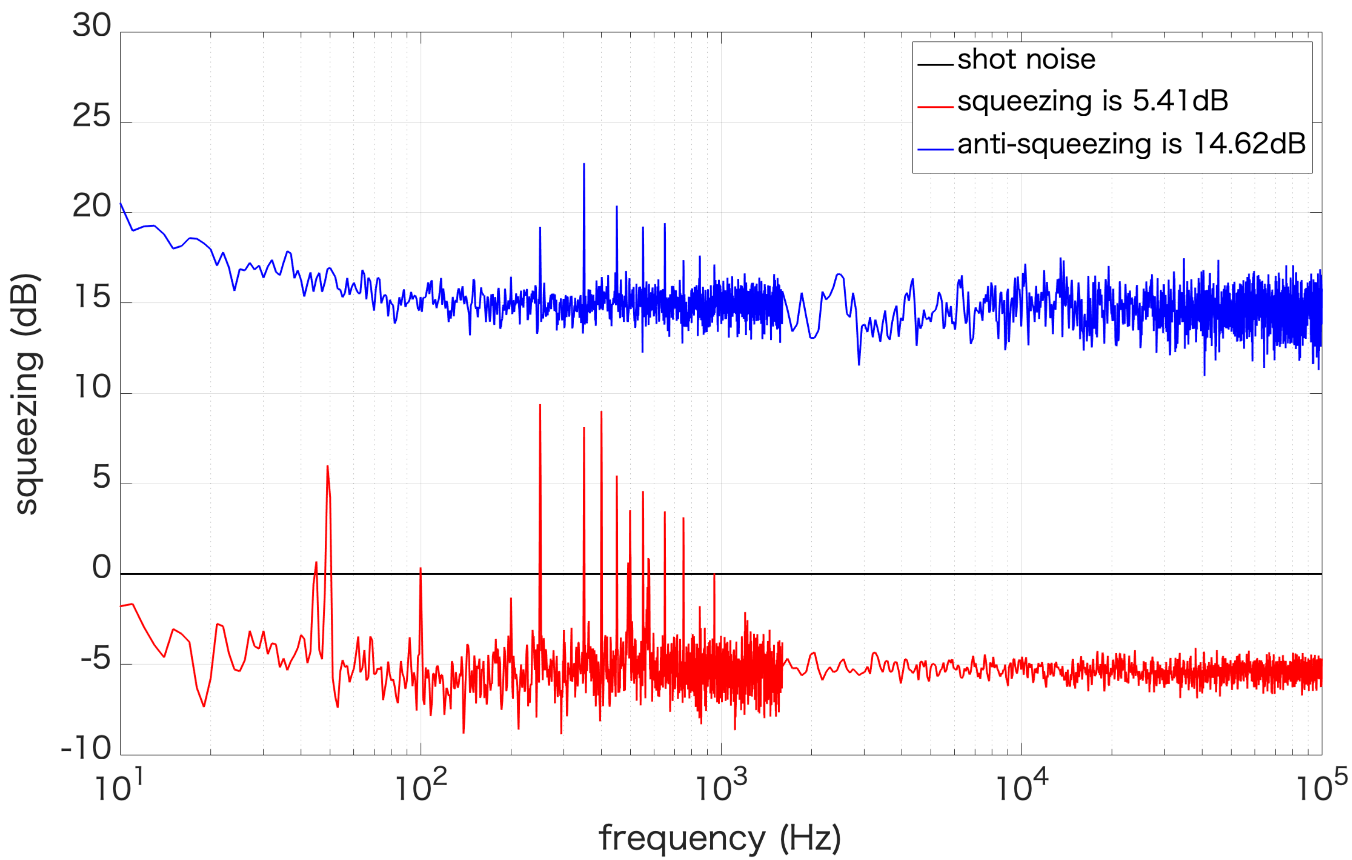
Optical parametric oscillator (OPO)



Second harmonic generator (SHG)

Frequency-independent squeezing

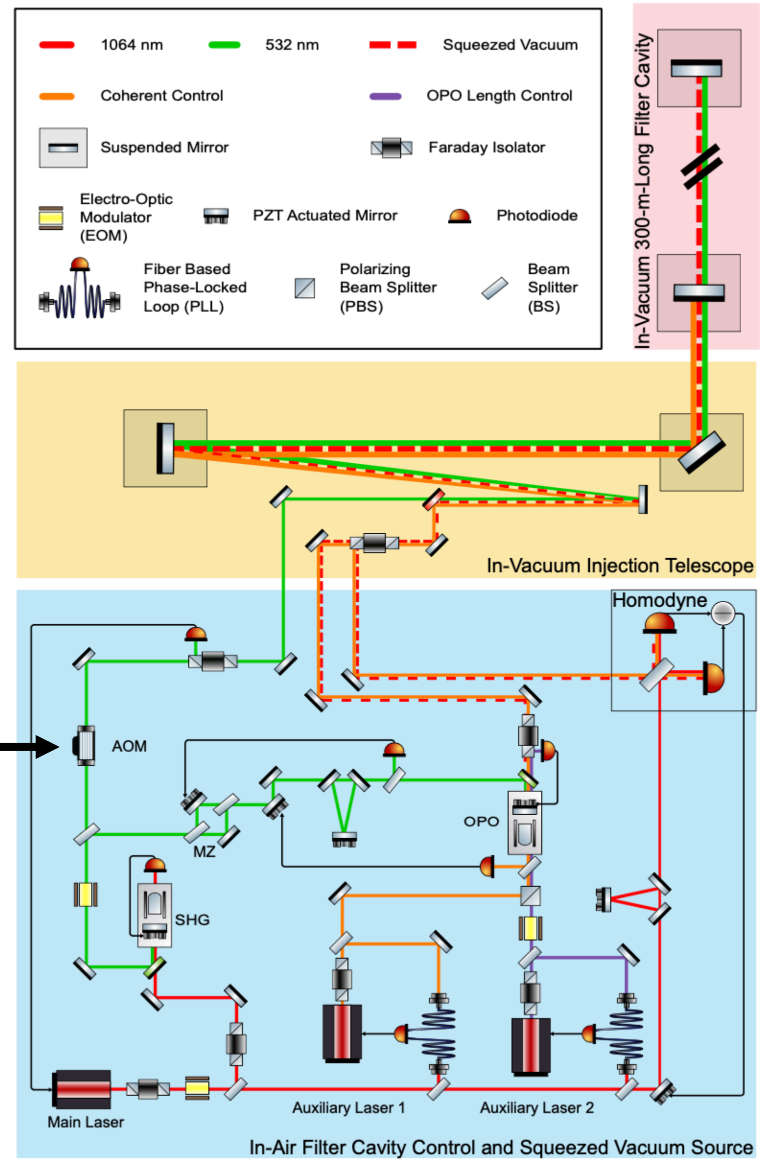
- Above 20Hz, squeezing ~ 5.4 dB, anti squeezing ~ 14.6 dB



Frequency-dependent squeezing

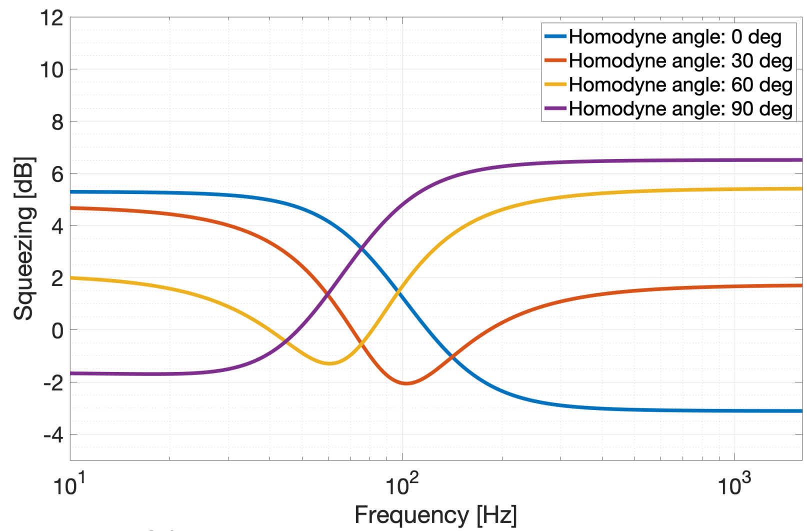
- Filter cavity is controlled with auxiliary green field
- Relative frequency of green field and squeezed field can be adjusted by acousto-optic modulator (AOM)

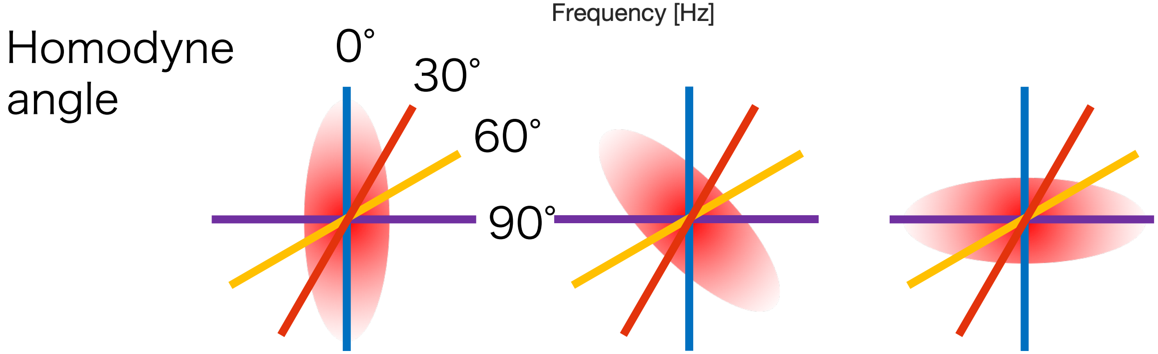
AOM



Frequency-Dependent Squeezing

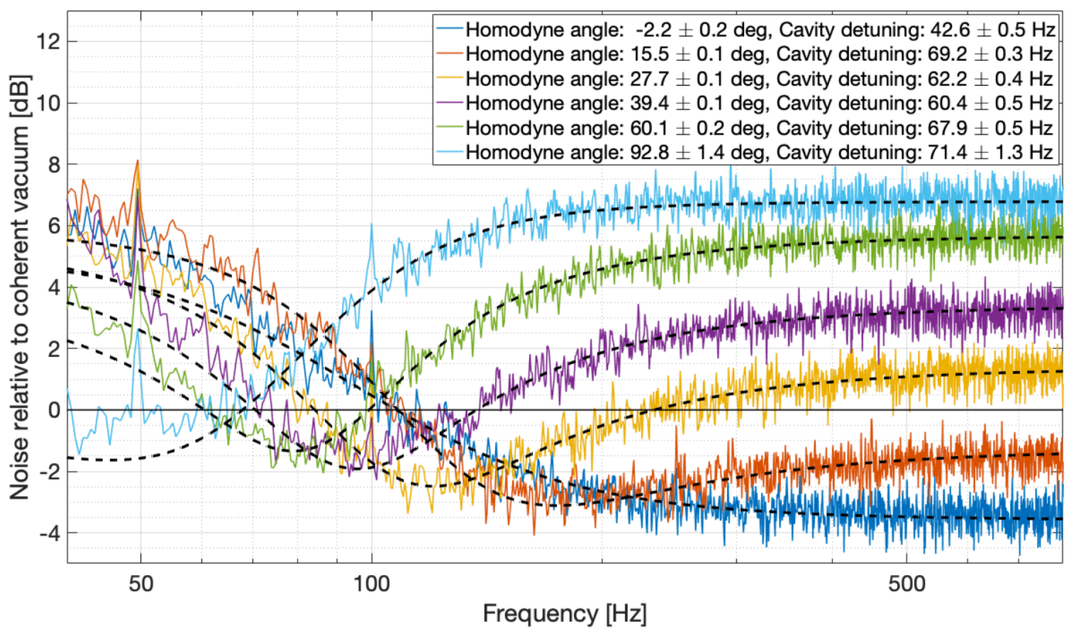
- Quantum noise of LO was measured changing LO phase (Homodyne angle)





Frequency-Dependent Squeezing

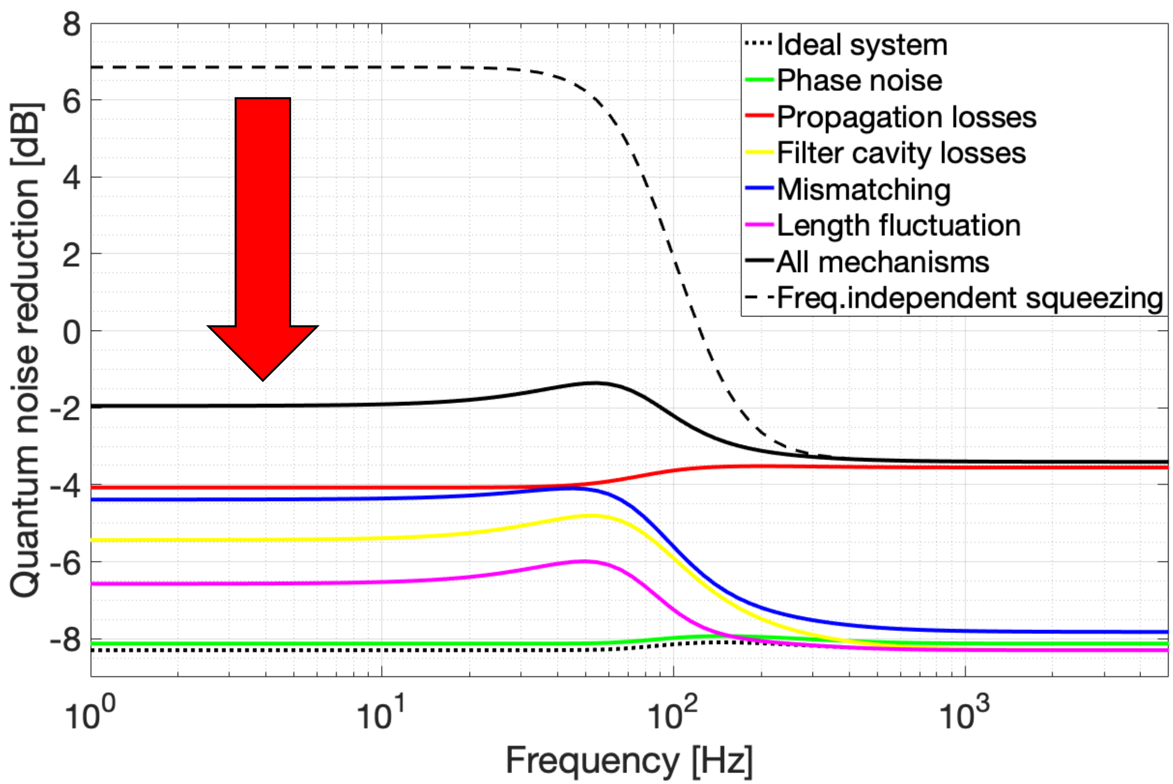
- Using 300 m filter cavity, frequency-dependent squeezing with rotation below 100 Hz was realized for the first time
- Assuming squeezing degradation sources measured independently, measurement agrees with theory



Y. Zhao, N. Aritomi et al, PRL 124, 171101 (2020)

Quantum noise reduction

- Quantum noise reduction in KAGRA with our filter cavity
- 3.4dB at high freq., 2dB at low freq.



Squeezing degradation budget

	FC loss	Loss outside FC	squeezer/FC Mode mismatch	Squeezer /LO Mode mismatch	Phase noise	FC length noise
target	80 ppm	10 %	2 %	5 %	30 mrad	1 pm
current	120(30) ppm	40(1) %	6(1) %	2(1) %	30(5) mrad	3(1) pm

Contamination of FC mirrors

In vaccum Faraday (15%)
OPO (10%)

New control scheme with coherent control field

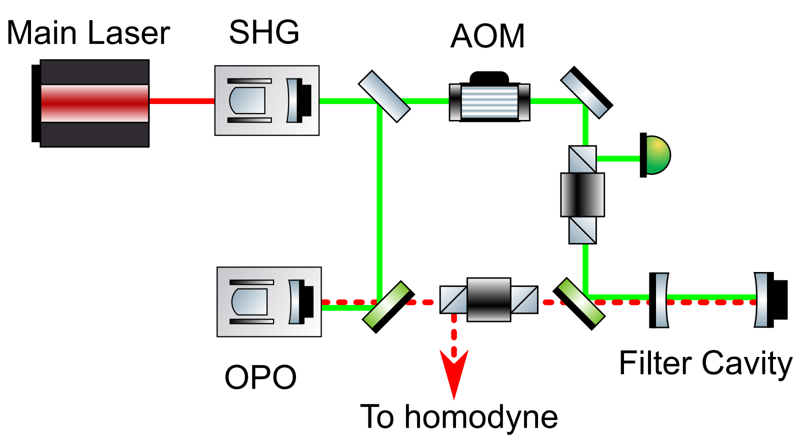
N. Aritomi et al, PRD 102, 042003 (2020)

Previous control scheme

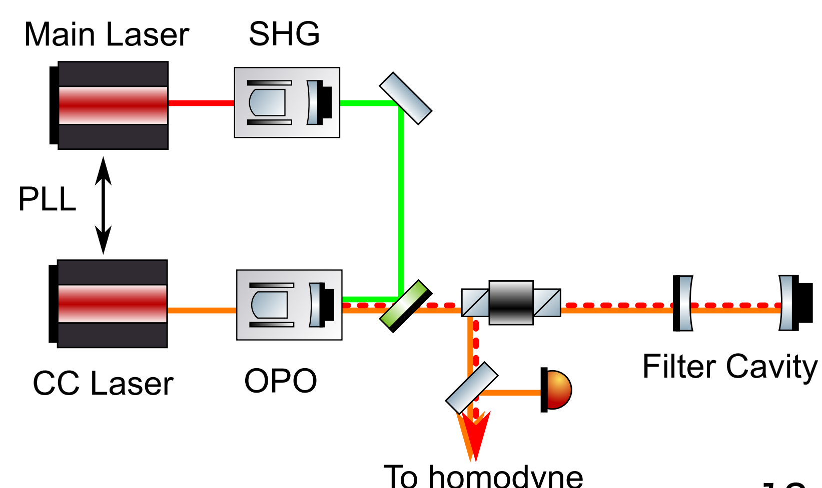
- Previously, filter cavity was controlled with green field.
  Since green field and squeezed field have different path and frequency, it does not ensure FC length and alignment for squeezed field

I suggested a new control scheme using coherent control field which has the same path and almost the same frequency as squeezed field

green lock



coherent control lock

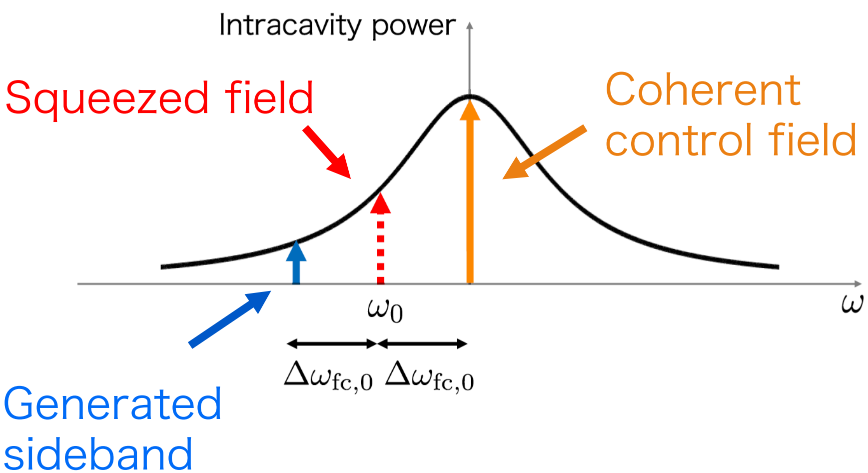


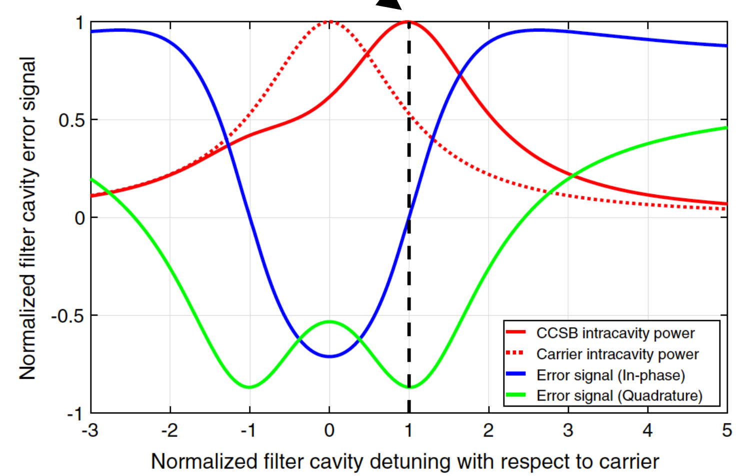
Suggestion of new control scheme

- To improve the locking accuracy of the filter cavity, I suggested a new control scheme for the filter cavity using coherent control field (CCFC)
- By choosing the frequency of CC field, one of CCSB can be resonant inside FC while squeezed field is properly detuned. FC length signal can be obtained from beat note of CCSB

$$\Omega_{\rm cc} = n \times \omega_{\rm FSR} + \Delta\omega_{\rm fc,0}$$

Optimal detuning

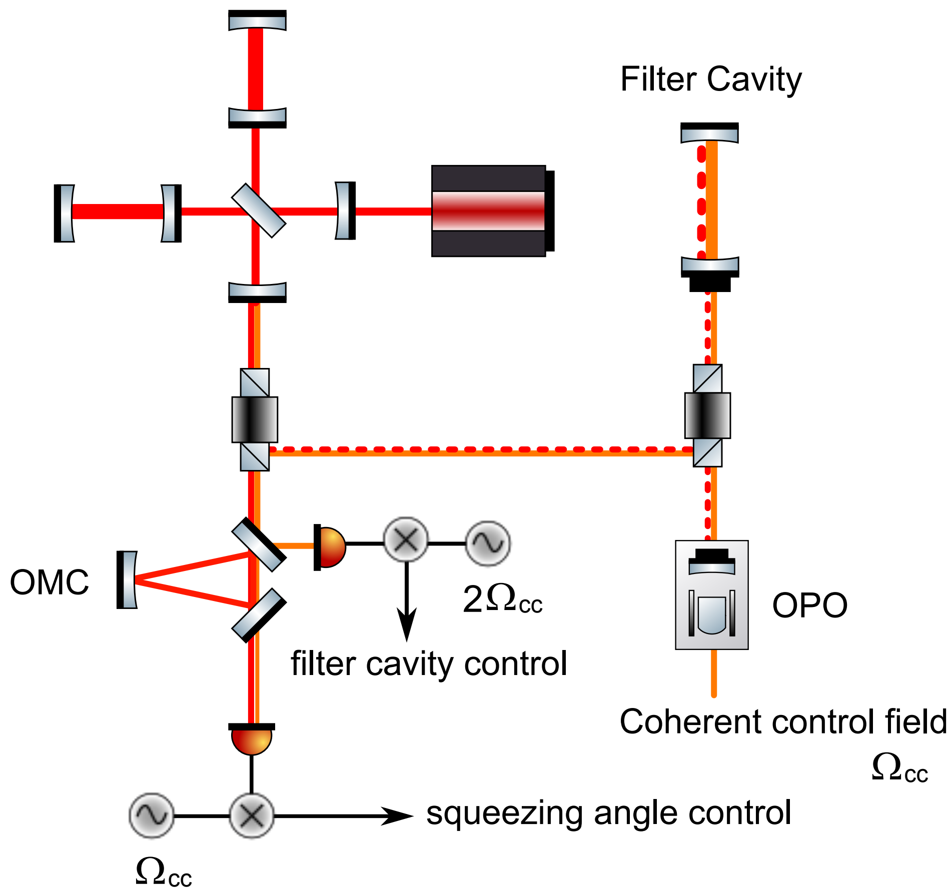




N. Aritomi et al, PRD 102, 042003 (2020)

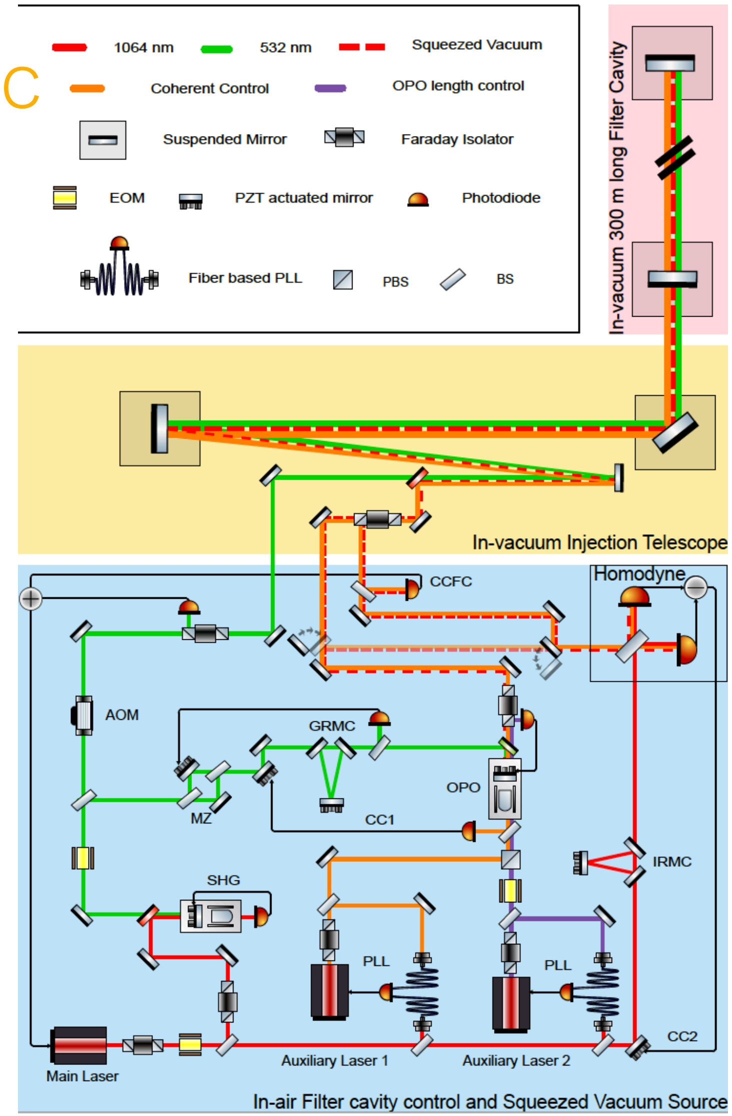
CCFC in GW detectors

- CCFC error signal can be obtained at OMC reflection in GW detectors



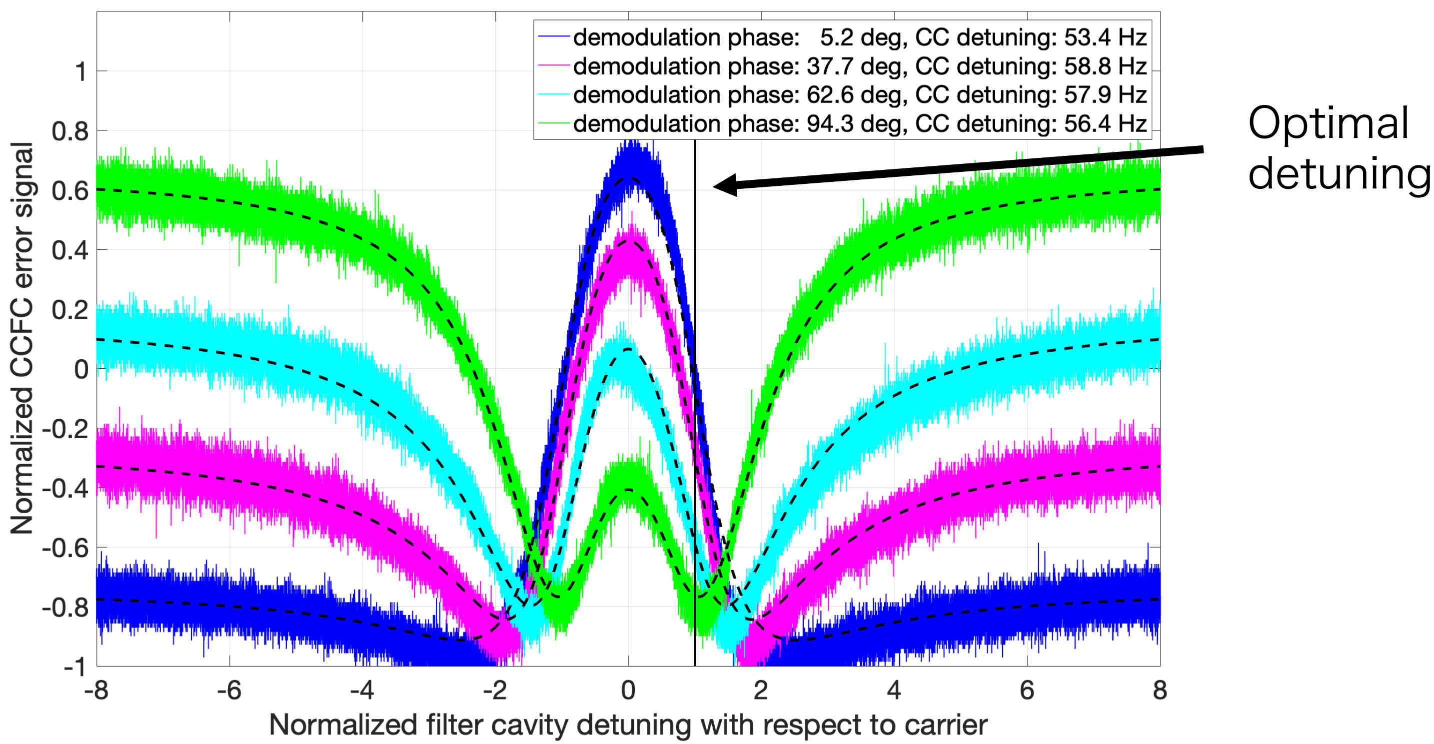
Demonstration experiment

- FC length was controlled with CCFC
- To pick off CCFC signal, BS was added in reflection path from FC
- CCFC signal is added to signal for green lock



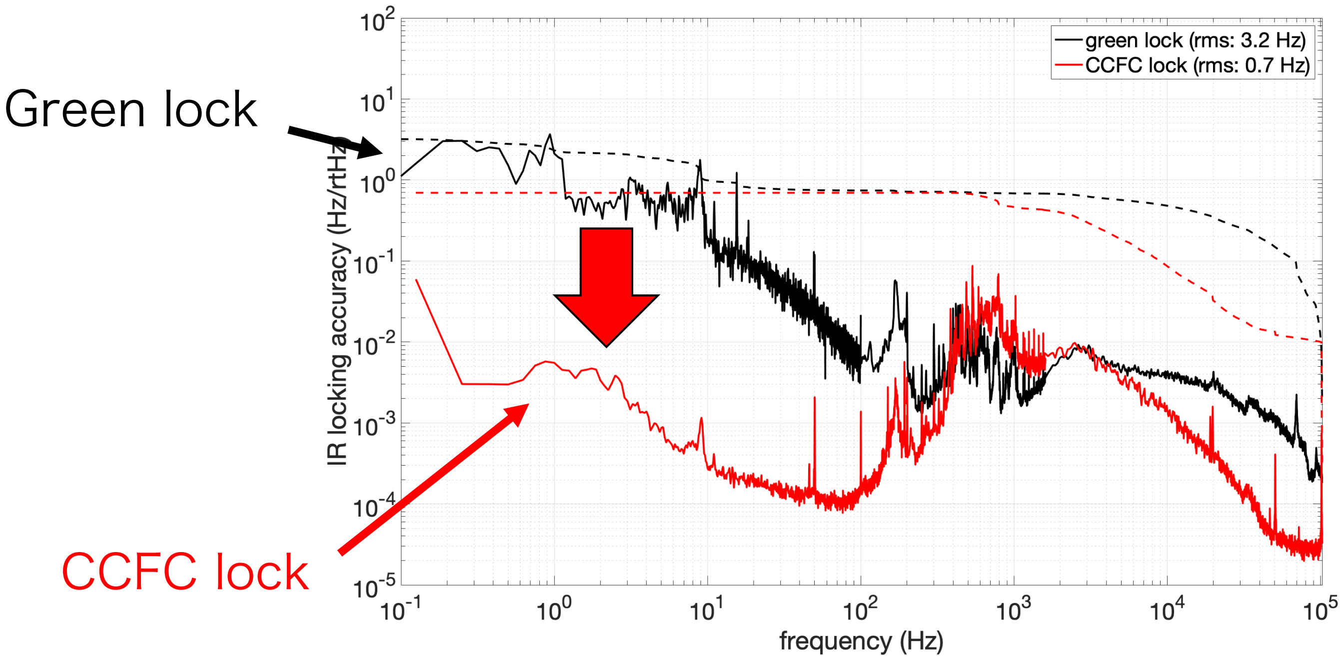
Error signal

- Behavior of theory and experiment agrees
- By choosing CC frequency, error signal crosses 0 around optimal detuning



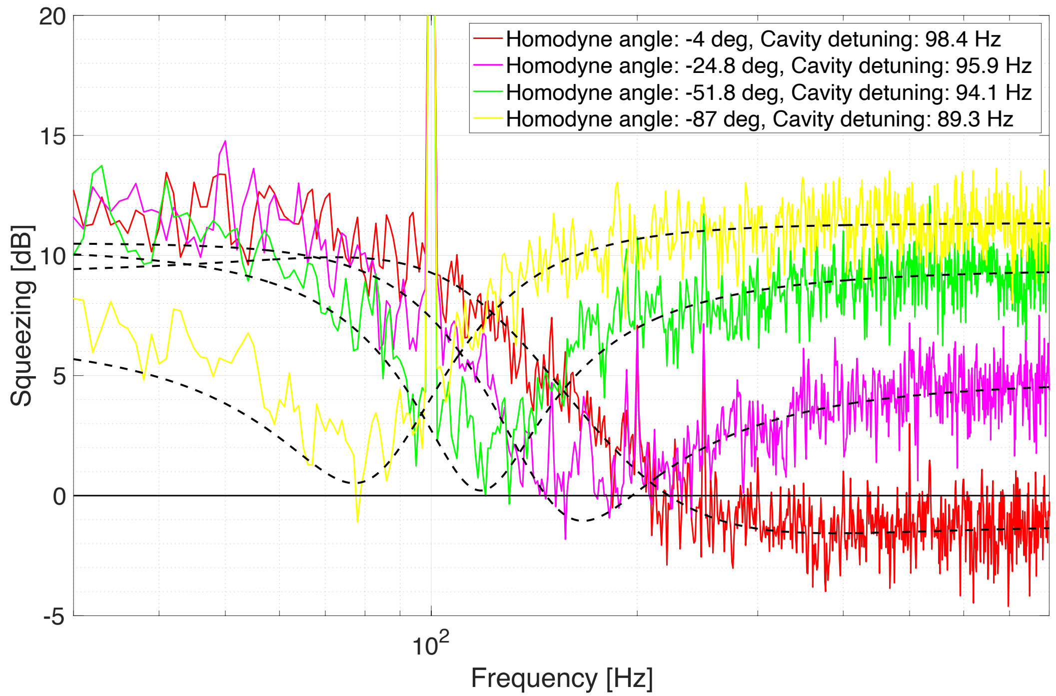
Locking accuracy with CCFC

- Locking accuracy was measured while FC was locked with CCFC
- Locking accuracy of FC was improved from 3.2 Hz to 0.7 Hz (0.75 pm) below 400 Hz. Target 1 pm was achieved.



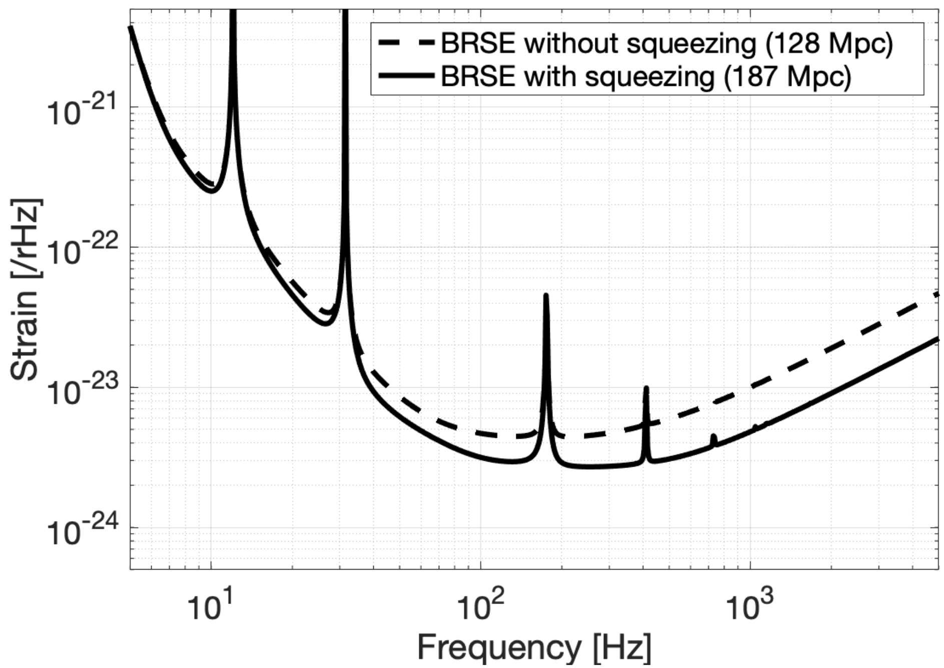
FDS with CCFC

- FDS with CCFC lock was realized
- squeeze level ~ 1.5 dB due to large loss from BS
- detuning fluctuation ~10 Hz → alignment control is necessary



Future prospect

- Further quantum noise reduction with reduction of loss, alignment control of FC.
- Installing the FC in KAGRA, sensitivity will improve from 128 Mpc to 187 Mpc, ~50%. Event rate will increase more than 3 times



Conclusion

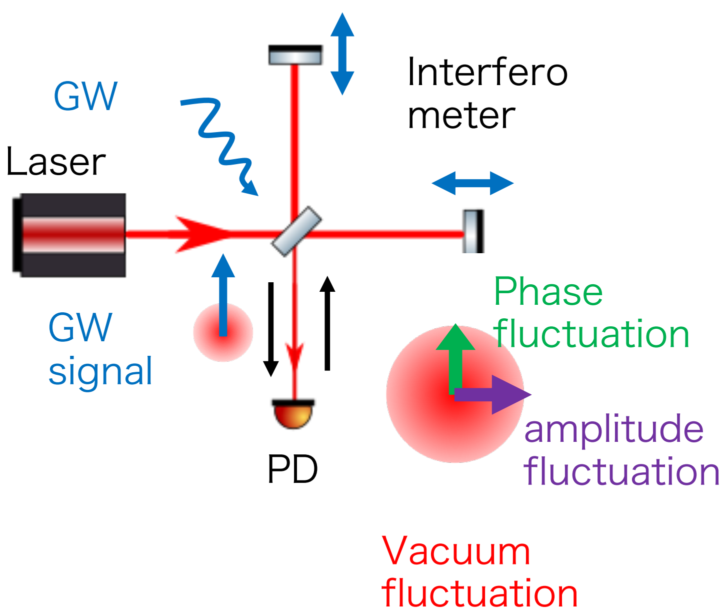
- For broadband quantum noise reduction in GW detectors, frequency-dependent squeezing with 300 m filter cavity was developed
- Frequency-dependent squeezing with rotation below 100 Hz was realized for the first time
- To improve locking accuracy of filter cavity, I suggested a new control scheme and demonstrated the improvement
- Using this technology, sensitivity of GW detectors will improve by ~50% and event rate will increase more than 3 times

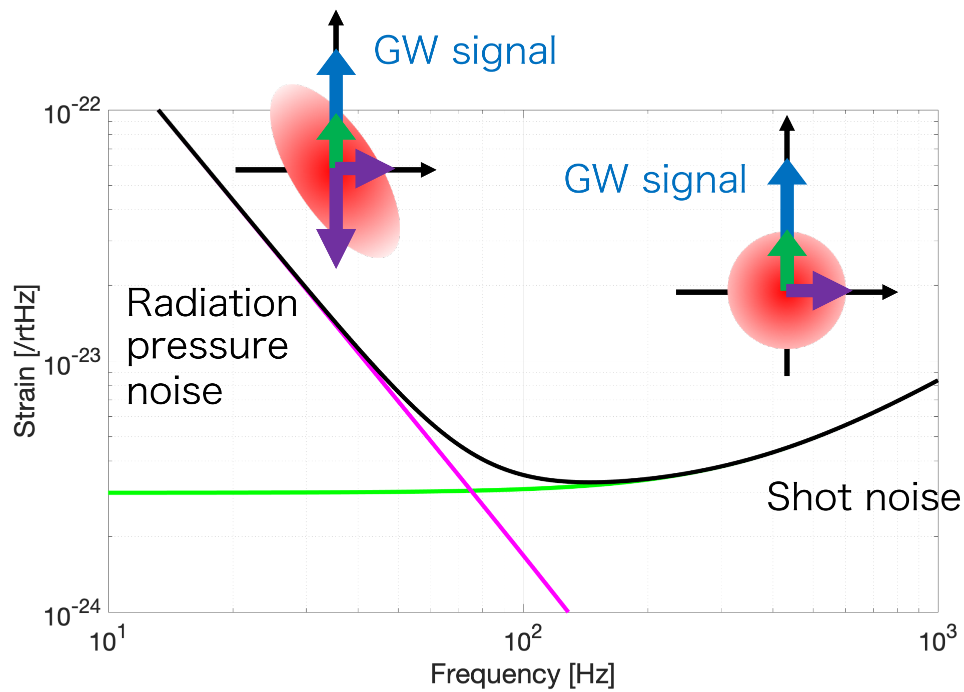
This result is important for improving the sensitivity of current and future GW detectors and will push GW astronomy ahead

Extra Slides

Quantum Noise

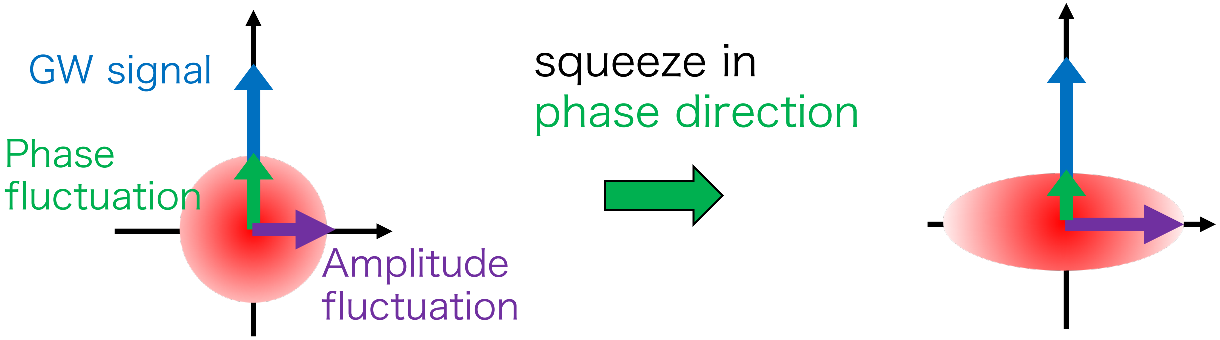
- Quantum noise originates from vacuum fluctuation entering from output port of an interferometer
- phase fluctuation of vacuum fluctuation becomes shot noise
- At low frequency (below ~70Hz), amplitude fluctuation causes mirror fluctuation and becomes radiation pressure noise



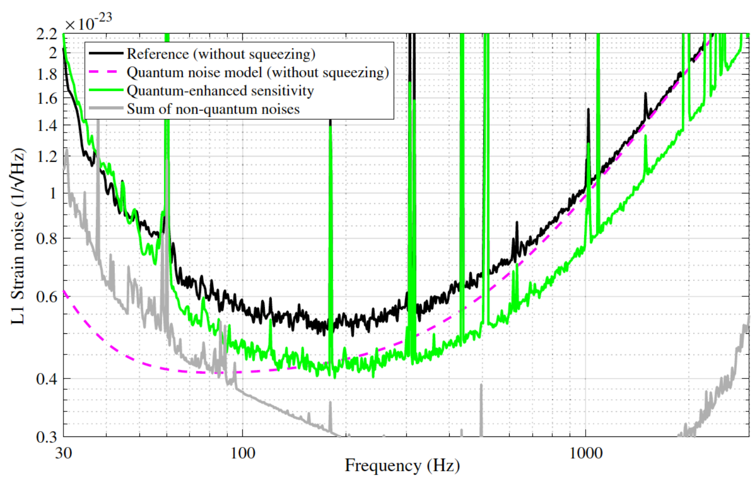


Squeezed vacuum states

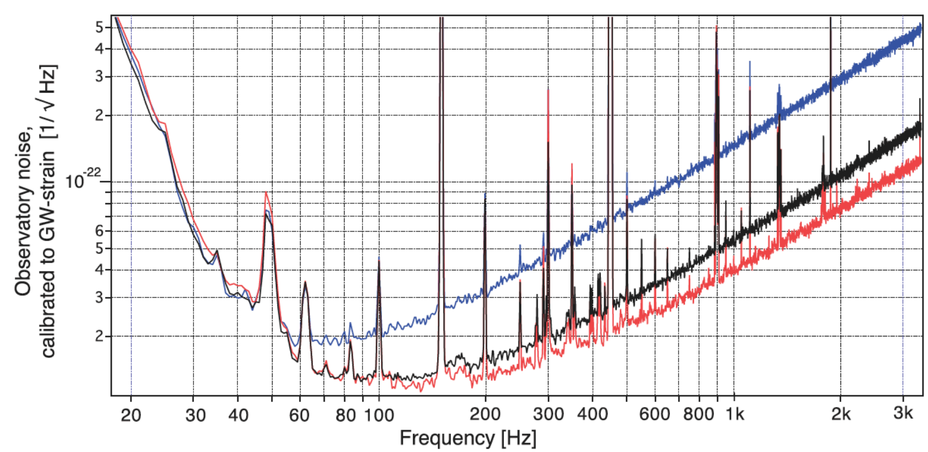
- To reduce shot noise, squeezed vacuum states are injected



- shot noise reduction by squeezing injection is realized at LIGO and Virgo. Increase of radiation pressure noise is observed



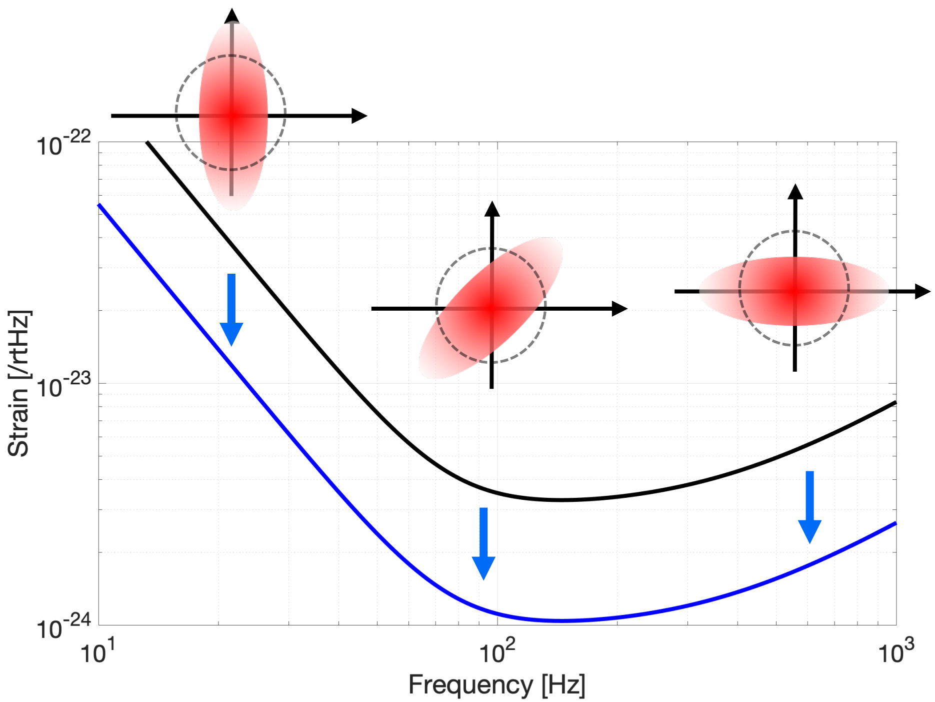
M. Tse et al, PRL 123, 231107 (2019)



F. Acernese et al, PRL 123, 231108 (2019)

Frequency-Dependent Squeezing

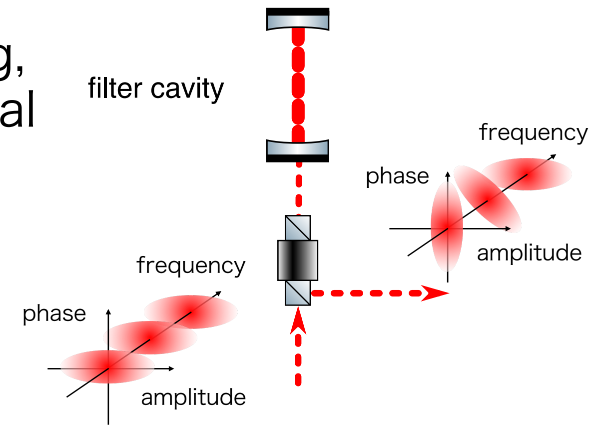
- Squeezed vacuum reduces shot noise at high frequency, but increases radiation pressure noise at low frequency
- To reduce shot noise and radiation pressure noise at the same time, frequency-dependent squeezed vacuum states are necessary. The squeezing angle rotates by 90 deg below 100 Hz



Filter Cavity

- To realize frequency-dependent squeezing, squeezed vacuum is injected into an optical cavity = Filter cavity

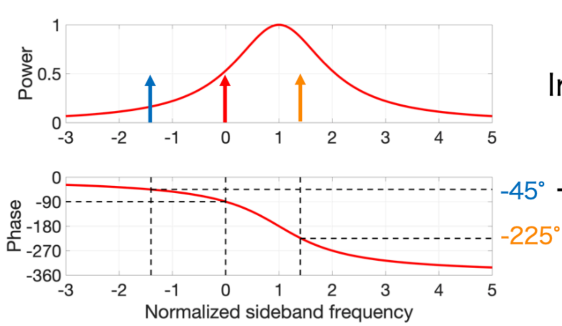
  H. J. Kimble et al, PRD 65, 022002 (2001)

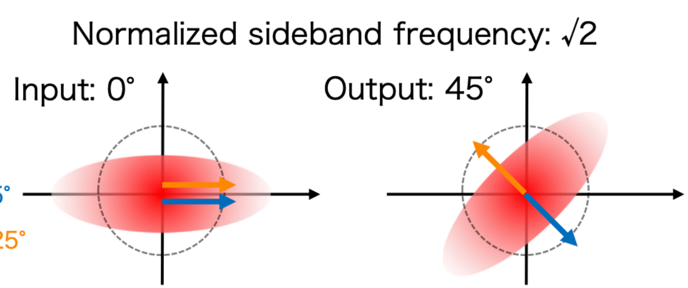


- When frequency of squeezed field is detuned with respect to resonant frequency of a filter cavity, filter cavity reflectivity has different phase for upper and lower sidebands
  → <u>squeezing angle rotates around detuning frequency</u>

FC intracavity power

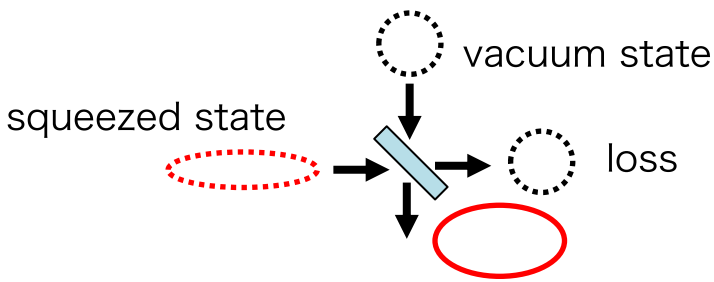
FC reflectivity phase

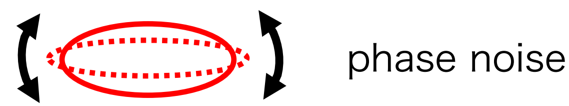




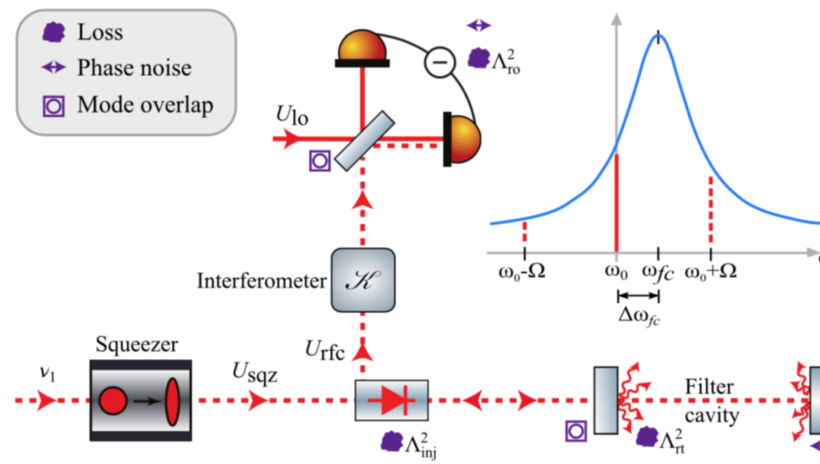
Degradation in filter cavity

- Problems to realize frequency dependent squeezing are optical loss and phase noise





- Squeezing degradation sources for a filter cavity are following
  - <u>Filter cavity loss</u>
    Loss of mirrors of a filter cavity
  - <u>Injection/Readout loss</u>
    Loss of injection/readout optics
  - <u>Mode mismatch</u>
    Mode mismatch between squeezed light and a filter cavity, squeezed light and LO
  - <u>Phase noise</u>
    Fluctuation of squeeze angle,
    Length fluctuation of a filter cavity

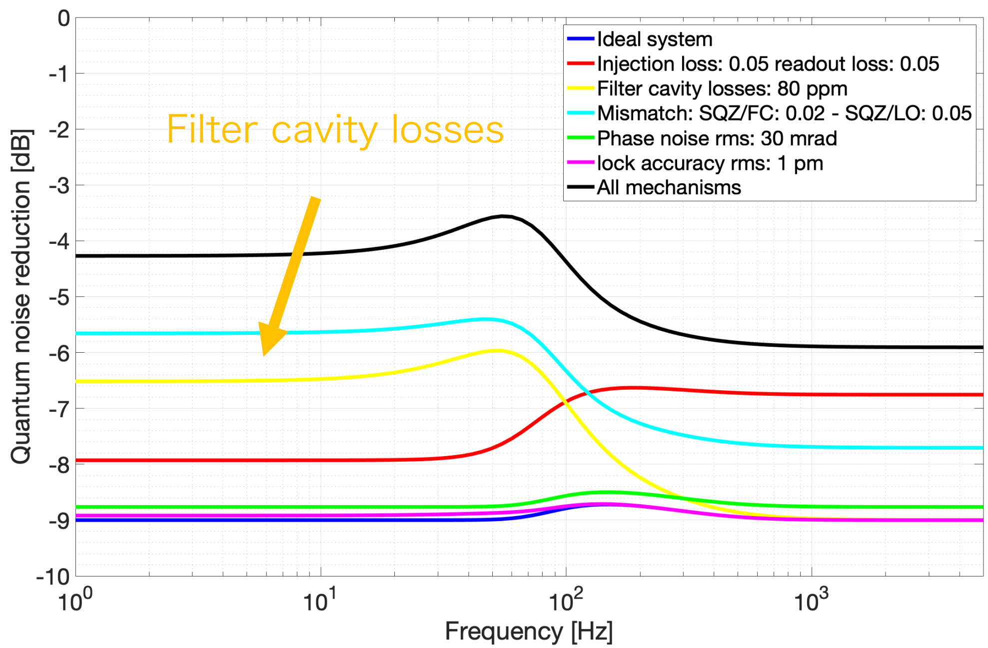


P. Kwee et al, PRD 90, 062006 (2014)

Filter cavity losses

- Effect of filter cavity losses are large at low frequency and inversely proportional to filter cavity length

When filter cavity length is 300 m, filter cavity losses are not dominant at low frequency



- LIGO, Virgo plan to use 300 m filter cavity from next observing run. Next generation GW detectors plan to use km scale filter cavities

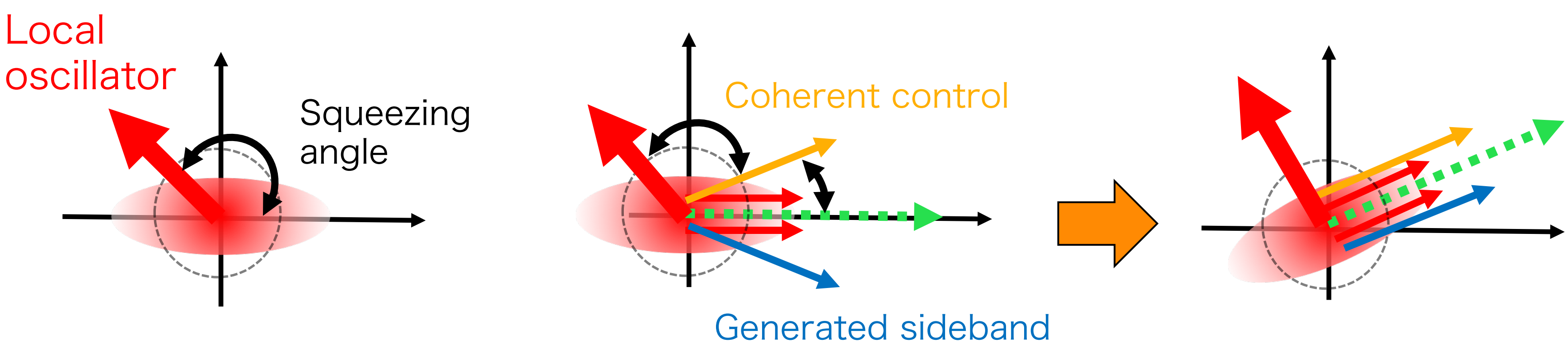
Principle of squeezing angle control

- To generate squeezing at low frequency(~10Hz), control of squeezing angle (relative phase of squeezing and LO) is necessary

  → coherent control (CC)

  S. Chelkowski et al, PRA 75, 043814 (2007)

- Relative phase of squeezing and LO can be controlled via coherent control field

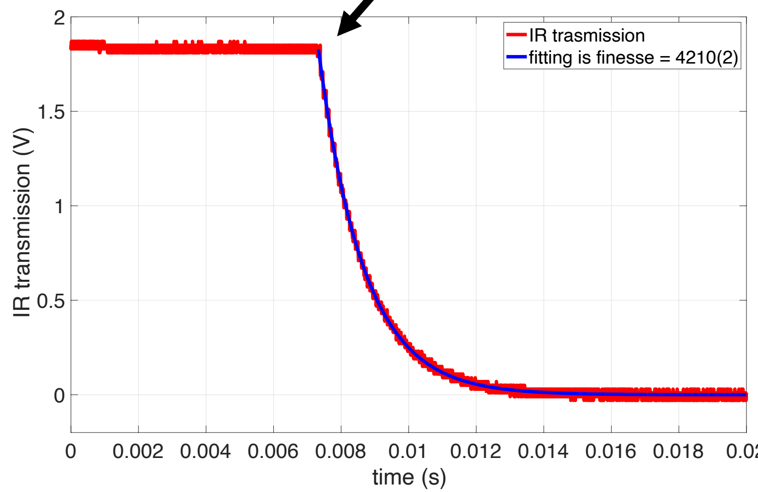


300 m Filter Cavity

Stop the injection beam

- Finesse was estimated from decay time of intracavity power
- Measured finesse: 4210

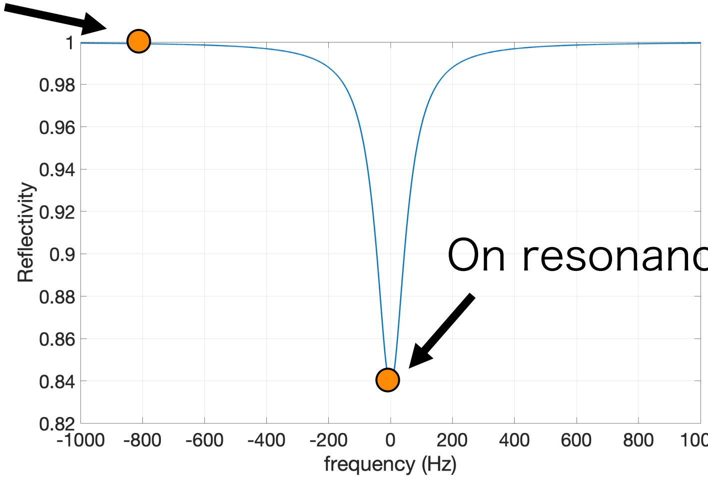
(Design finesse: 4360)



Off resonance

- Round trip loss was estimated from the ratio of reflected power on/off resonance
- Measured round trip loss: 90-150 ppm

(Design round trip loss: 80 ppm)

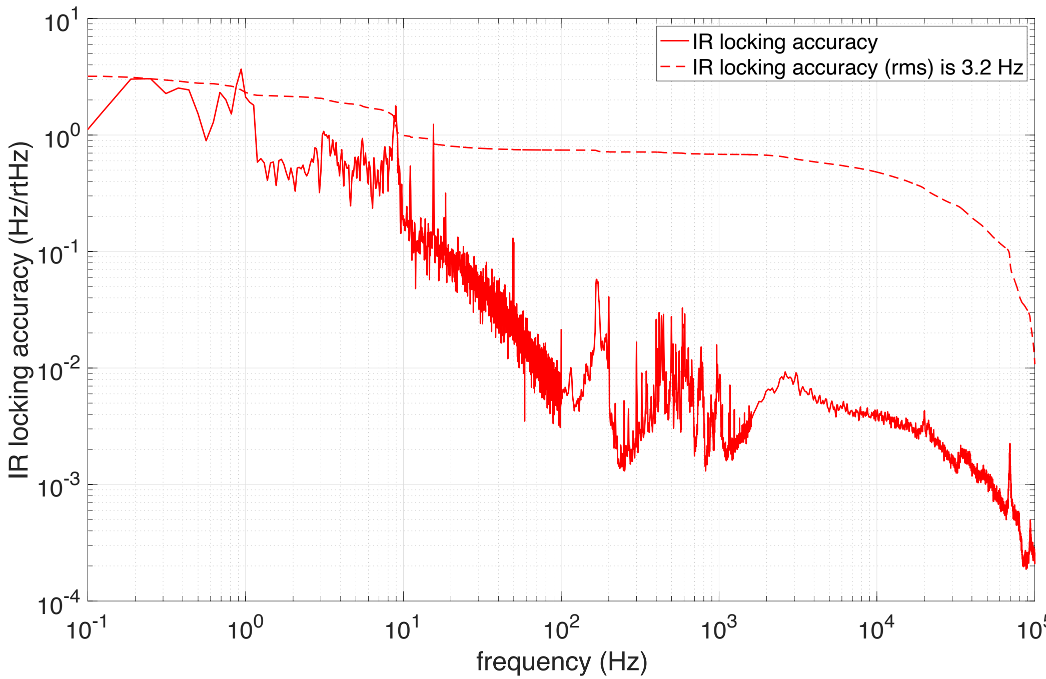


On resonance

IR locking accuracy

- To characterize FC length noise, FC locking accuracy for IR field was measured
- IR locking accuracy with green lock is 3.2 Hz (3.4 pm)   (target: 1 pm)

→ <u>Green lock is not enough to stabilize the IR locking accuracy</u>

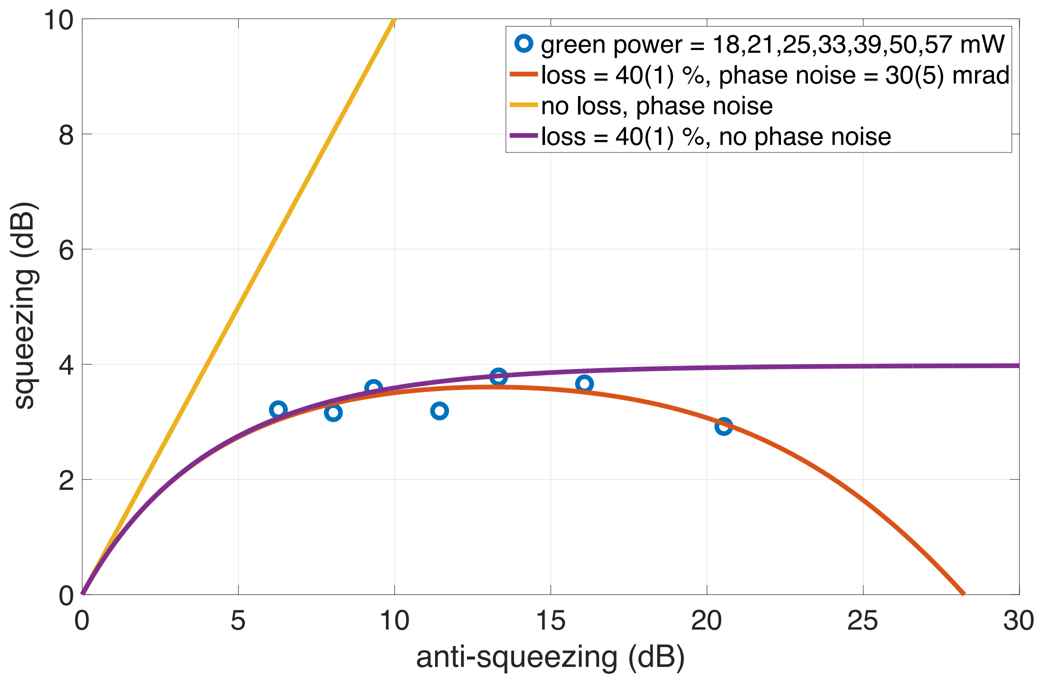


Loss and phase noise outside FC

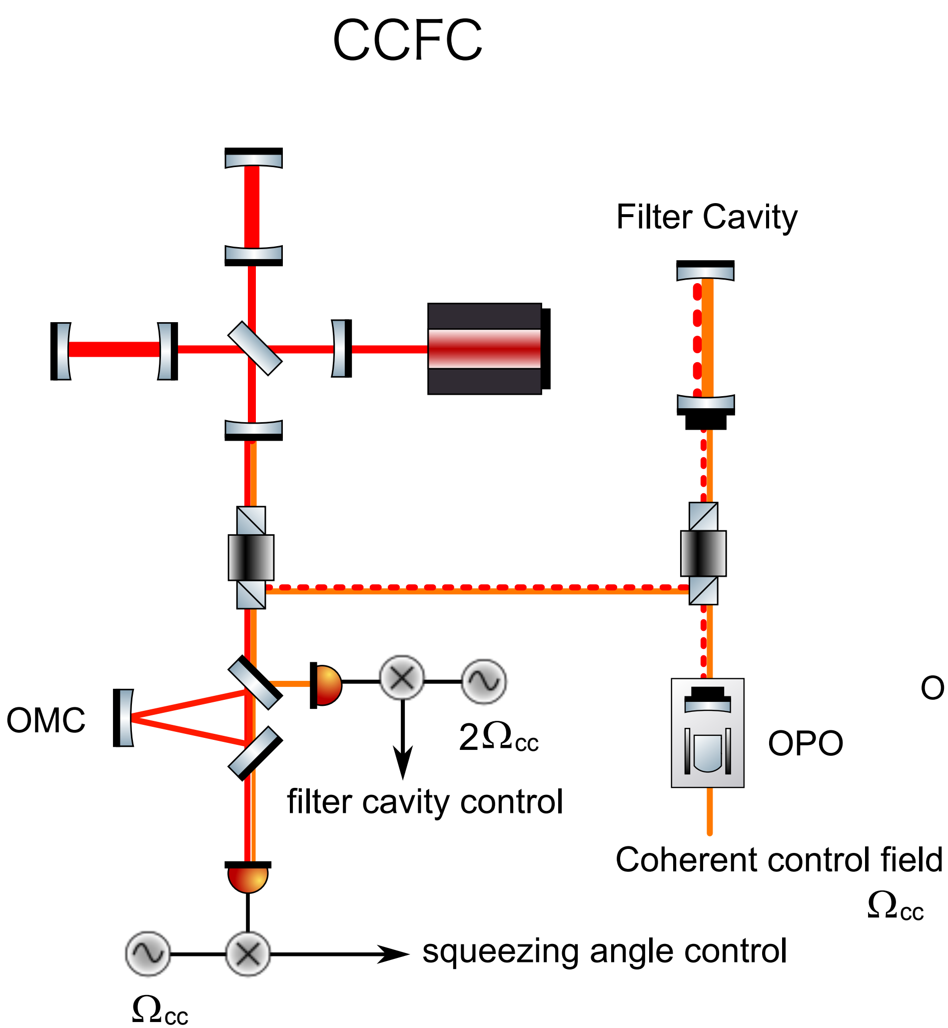
- Loss: 40 %, phase: 30 mrad

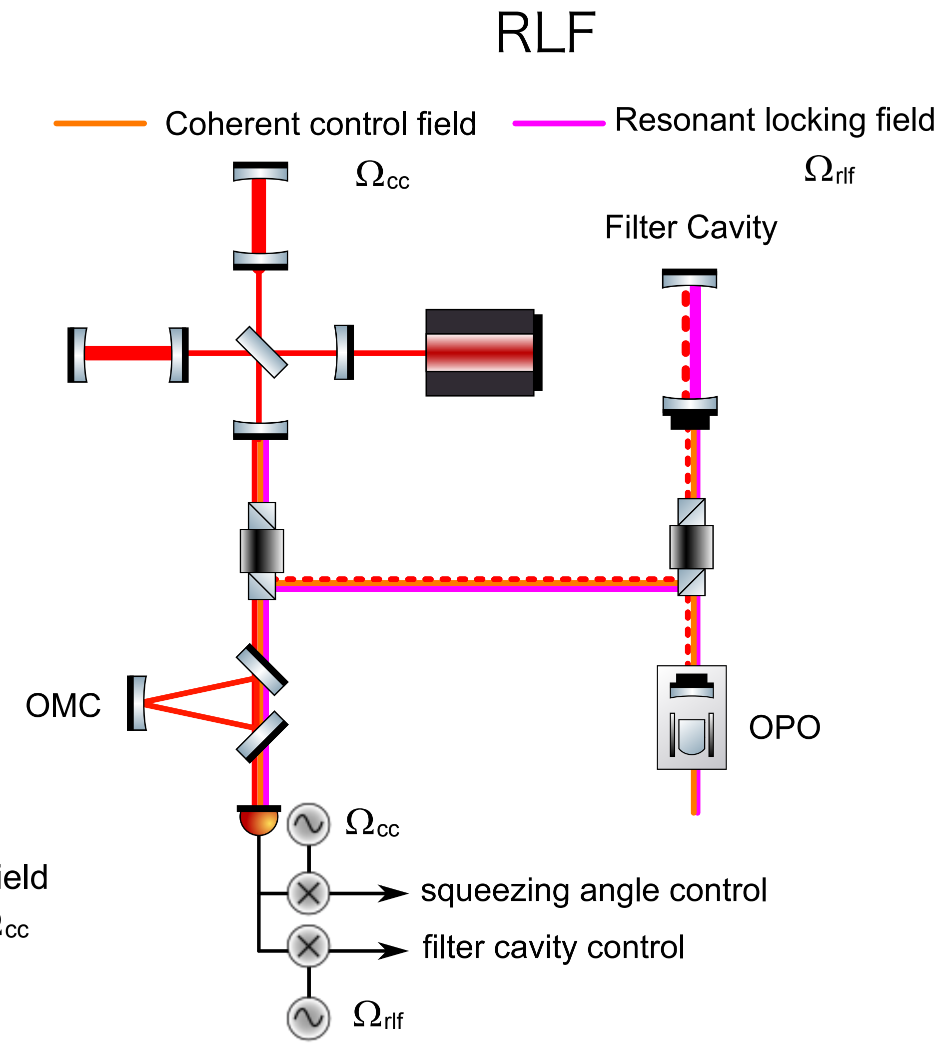
  (target loss: 10%, phase noise: 30mrad)

  - In vacuum Faraday loss: 15%



CCFC and RLF


CCFC
Filter Cavity
OMC
$2\Omega_{cc}$
filter cavity control
OPO
Coherent control field
Ω_{cc}
squeezing angle control
Ω_{cc}


RLF
Coherent control field
Ω_{cc}
Resonant locking field
Ω_{rlf}
Filter Cavity
OMC
OPO
Ω_{cc}
squeezing angle control
filter cavity control
Ω_{rlf}

Comparison of shot noise

- SNR in CCFC

$$\mathrm{SNR}_{\mathrm{CCFC}} \sim \frac{P_{\mathrm{CC}}}{\sqrt{2\hbar\omega_0 P_{\mathrm{junk}}}}\delta\alpha$$

- SNR in RLF

$$\mathrm{SNR}_{\mathrm{RLF}} \sim \frac{\sqrt{P_{\mathrm{LO}} A P_{\mathrm{RLF}}}}{\sqrt{2\hbar\omega_0 P_{\mathrm{LO}}}}\delta\alpha = \frac{\sqrt{A P_{\mathrm{RLF}}}}{\sqrt{2\hbar\omega_0}}\delta\alpha$$

- Ratio of SNR in CCFC and RLF

$$\frac{\mathrm{SNR}_{\mathrm{CCFC}}}{\mathrm{SNR}_{\mathrm{RLF}}} \sim \frac{P_{\mathrm{CC}}}{\sqrt{P_{\mathrm{junk}} A P_{\mathrm{RLF}}}} \sim \frac{1}{\sqrt{A}}\sqrt{\frac{P_{\mathrm{CC}}}{P_{\mathrm{junk}}}} \sim 0.03$$