Development of Frequency Dependent Squeezing for Gravitational Wave Detectors

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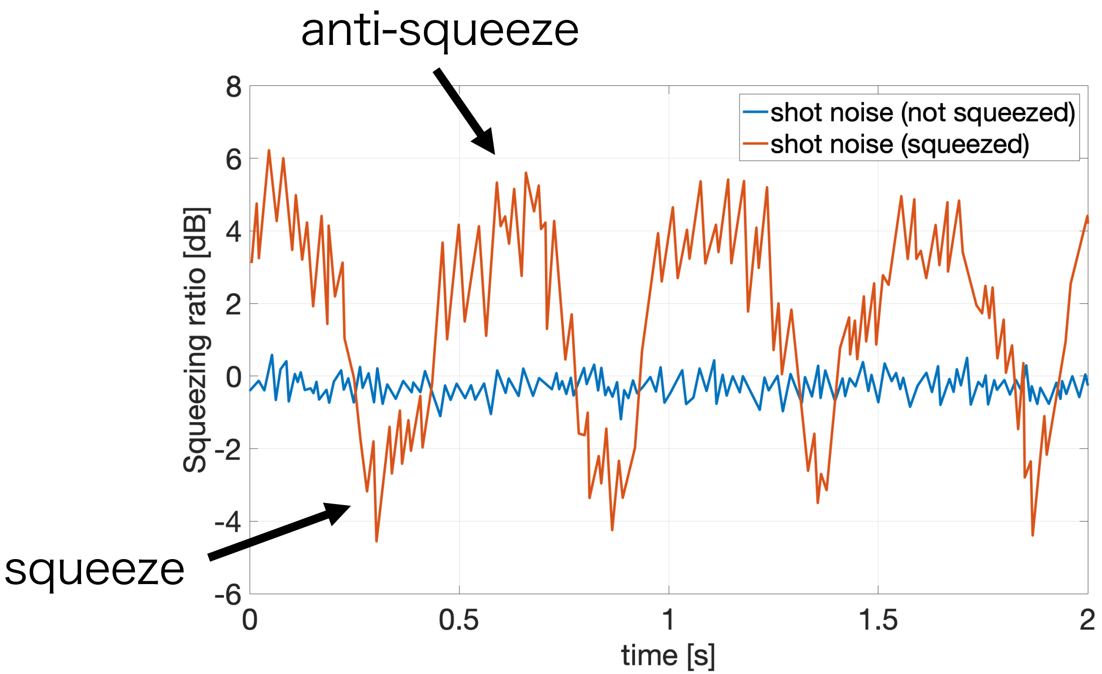
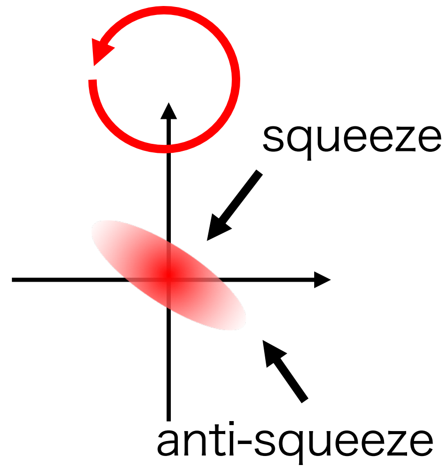
Abstract

- To reduce quantum noise which limits sensitivity of gravitational wave detectors, we are developing frequency dependent squeezing with a 300m long cavity which is one of TAMA's arms
- We succeeded in measuring squeezing for the first time at TAMA
- measured squeezing is squeeze: 3dB, anti-squeeze: 5dB @200kHz

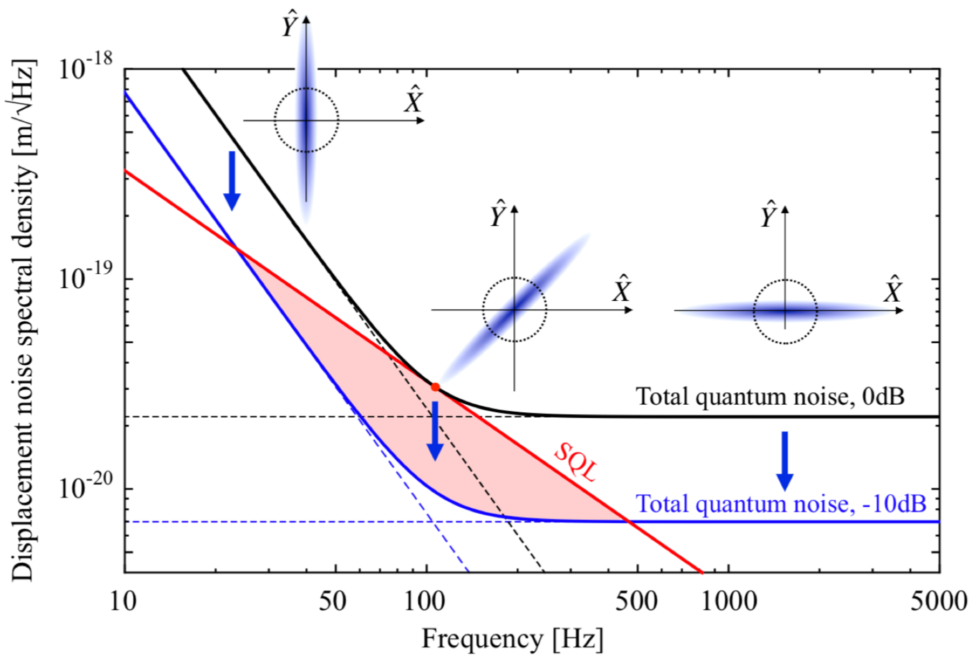




Contents

Quantum noise

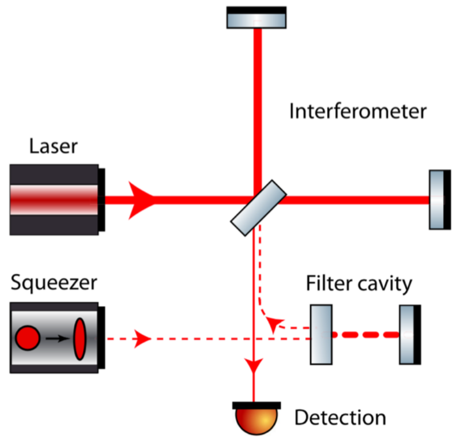
- sensitivity of gravitational wave detectors is limited by quantum noise in the future



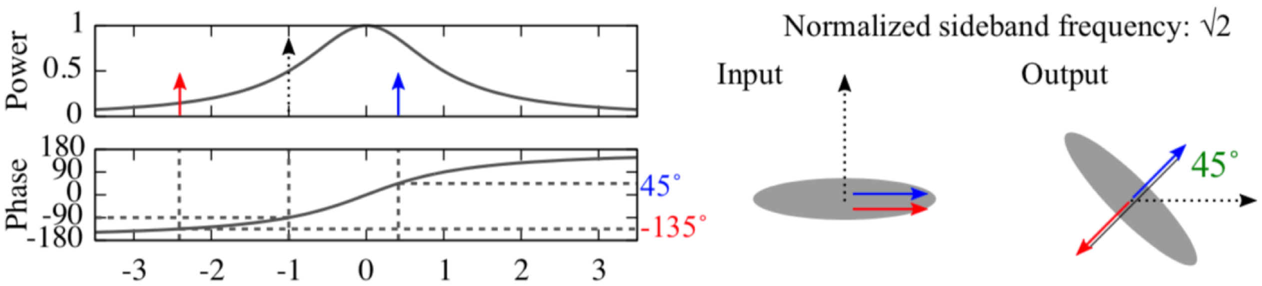
- To achieve broadband quantum noise reduction, squeezed vacuum which is phase squeezed at high frequency and amplitude squeezed at low frequency is required

Filter Cavity

- To realize frequency dependent squeezing, squeezed light is injected to a detuned cavity = Filter Cavity
  (H. J. Kimble et al, PRD 65, 022002 (2001))

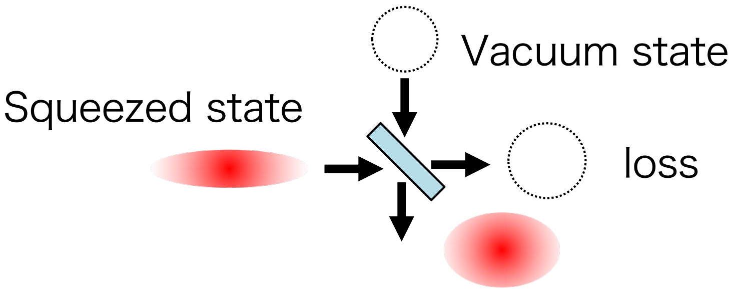


- upper sideband and lower sideband have different phase rotation→squeezing angle rotates around detuning frequency



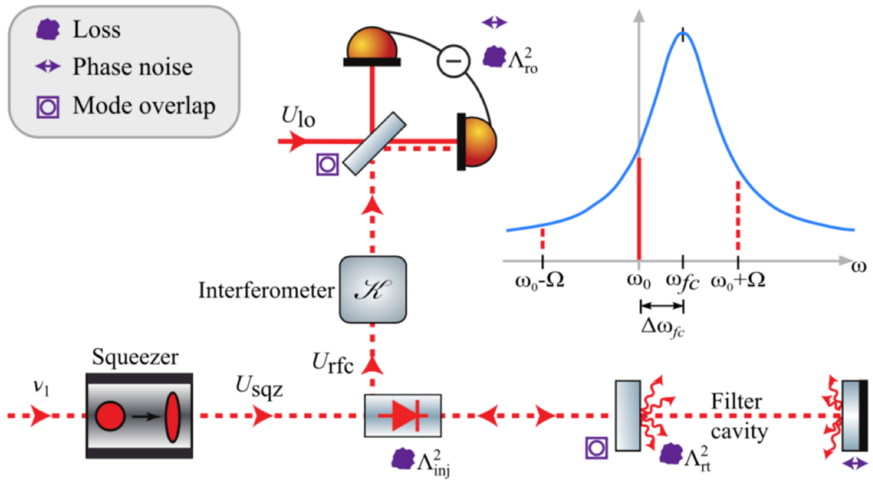
Loss in filter cavity

- Problems to realize a filer cavity are optical losses. Vacuum state is mixed by optical losses and squeeze level degrades



- In a filter cavity, squeeze degradation sources are following

  - Filter cavity loss
    Loss of mirrors of a filter cavity
  - Injection/Readout loss
    Loss of injection/readout optics
  - Mode mismatch
    Mode mismatch between squeezed light and a filter cavity, squeezed light and LO
  - Phase noise
    Fluctuation of squeeze angle, length fluctuation of a filter cavity



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

Filter cavity loss

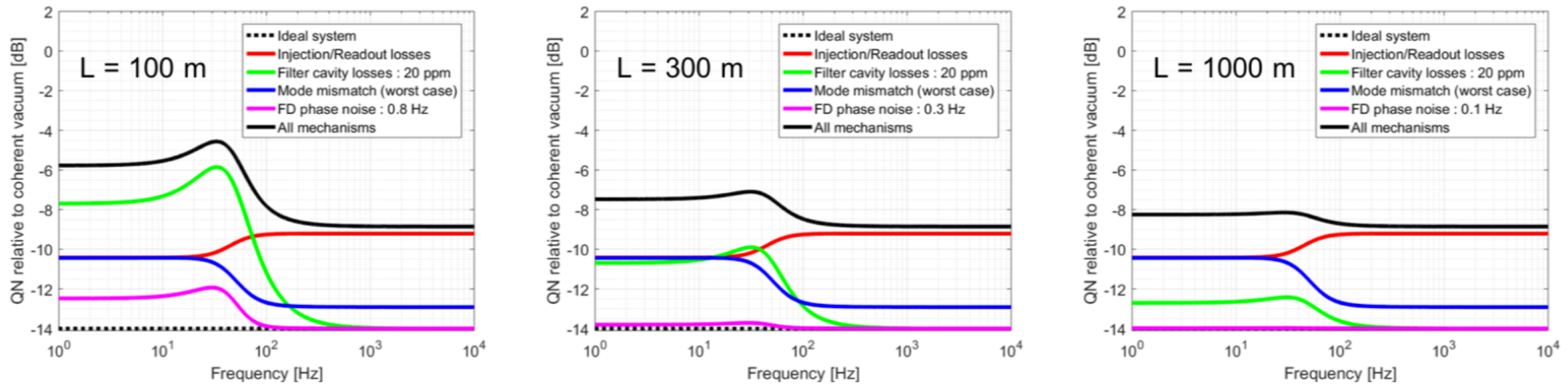
- Filter cavity loss is dominant at low frequency and proportional to filter cavity length

$$\text{Filter cavity loss} \propto \Lambda_{\mathrm{rt}}^2/\mathrm{L}$$

Λ_{rt}^2: round trip loss
L: filter cavity length

Squeezing degradation budget for AdV+

VIR-0660A-18 (2018)

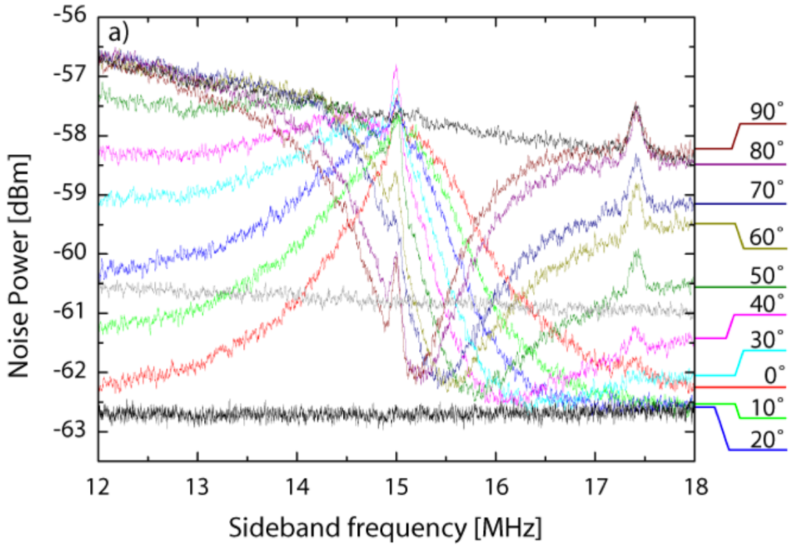


- A+, AdV+ plan to use 300m Filter cavity in O4(2023-)

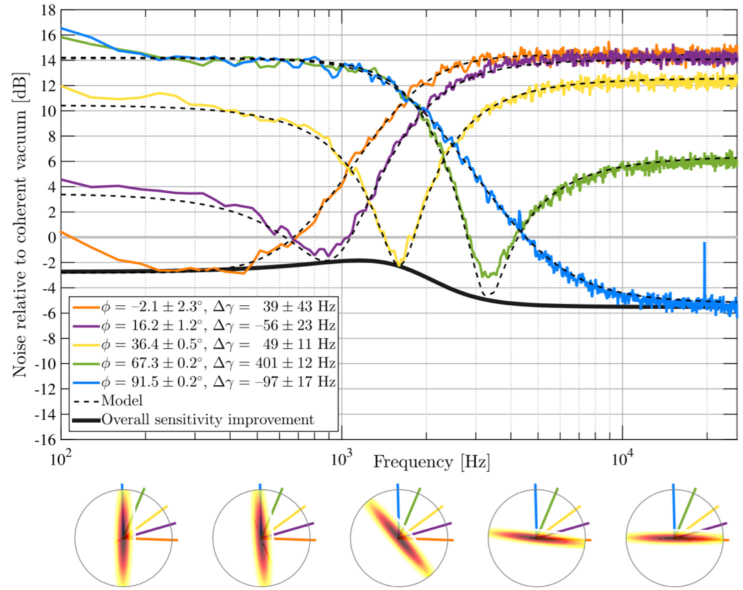
Previous Research

- frequency dependent squeezing is demonstrated at MHz and kHz

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



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



- However, frequency dependent squeezing around 70 Hz which is bandwidth of gravitational wave detectors is not achieved yet

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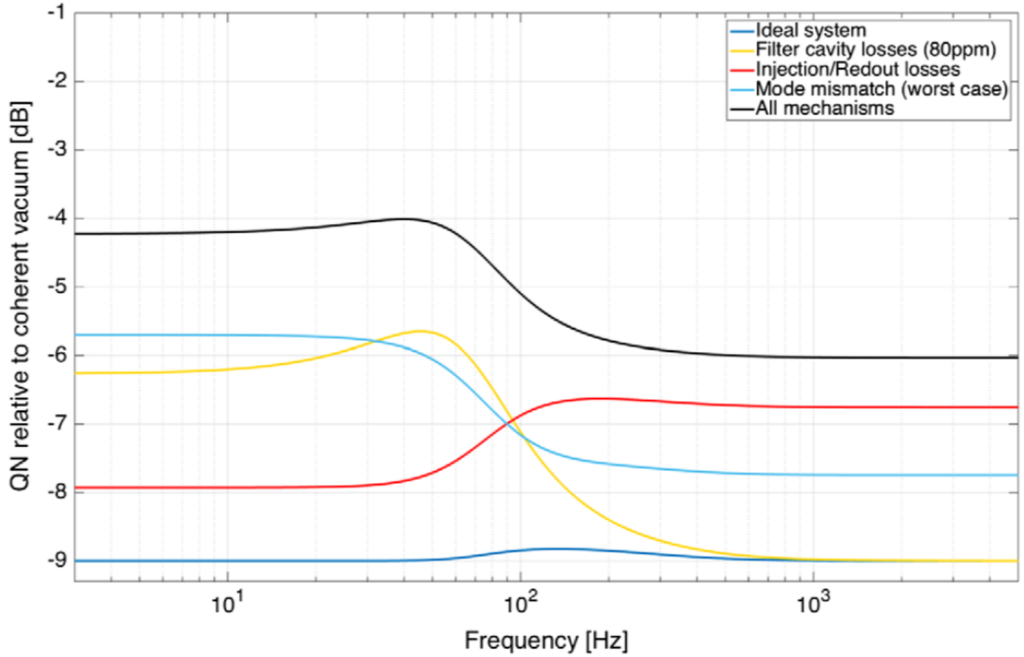
Goal

Goal: achieve frequency dependent squeezing around 70 Hz with a 300 m long filter cavity with suspended mirrors

Squeezing degradation budget

- Filter cavity loss is not dominant at all frequency with 80ppm round trip loss
- Injected squeeze level is 9dB and achievable squeeze level is 4dB at low frequency, 6dB at high frequency

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



Loss budget

Parameter	Symbol	Value
Filter cavity losses	Λ^2_{rt}	80 ppm
Injection losses	Λ^2_{inj}	5 %
Readout losses	Λ^2_{ro}	5 %
Mode-mismatch squeezer-filter cavity	$\Lambda^2_{\mathrm{mmFC}}$	2 %
Mode-mismatch squeezer-local oscillator	$\Lambda^2_{\mathrm{mmLO}}$	5 %
Frequency independent phase noise (RMS)	$\delta\zeta$	30 mrad
Filter cavity length noise (RMS)	δL_{fc}	0.3 pm
Injected squeezing	σ_{dB}	9 dB

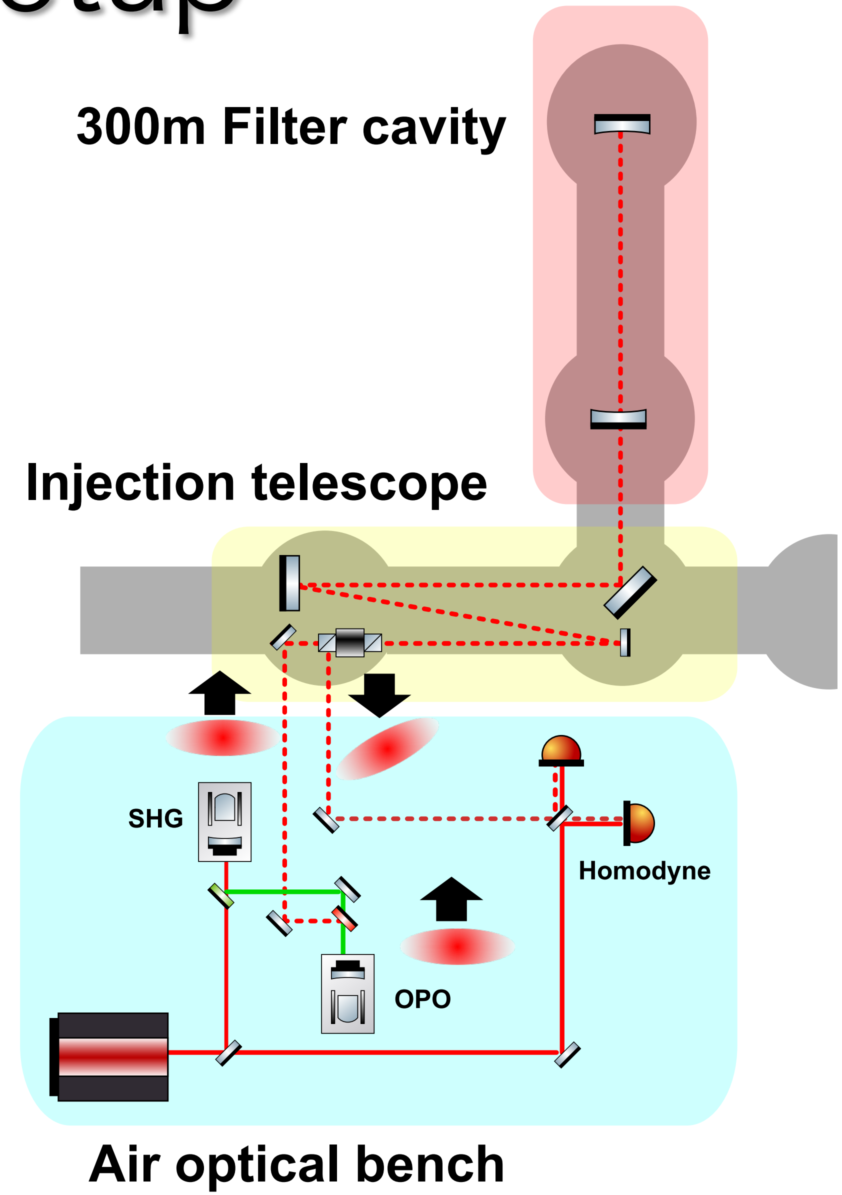
Overall setup

- 300m long cavity
  - Finesse 4400 @1064nm
  - Round Trip Loss 80 ppm

    initial Virgo class mirror
    Double pendulum suspension (type C)

- squeezed source
  - 9dB above 10Hz
  - Based on AEI/Virgo squeezer

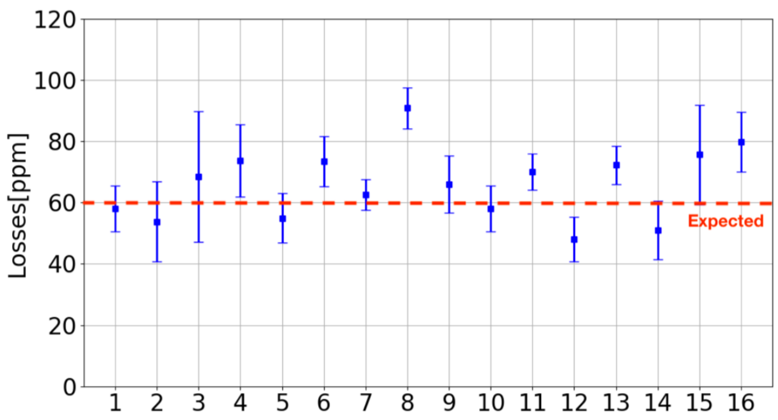
Parameter	Symbol	Value
Filter cavity losses	$\Lambda^2_{\rm rt}$	80 ppm
Injection losses	$\Lambda^2_{\rm inj}$	5%
Readout losses	$\Lambda^2_{\rm ro}$	5%
Mode-mismatch squeezer-filter cavity	$\Lambda^2_{\rm mmFC}$	2%
Mode-mismatch squeezer-local oscillator	$\Lambda^2_{\rm mmLO}$	5%
Filter cavity length noise (RMS)	$\delta L_{\rm fc}$	0.3 pm
Injected squeezing	$\sigma^2_{\rm dB}$	9 dB

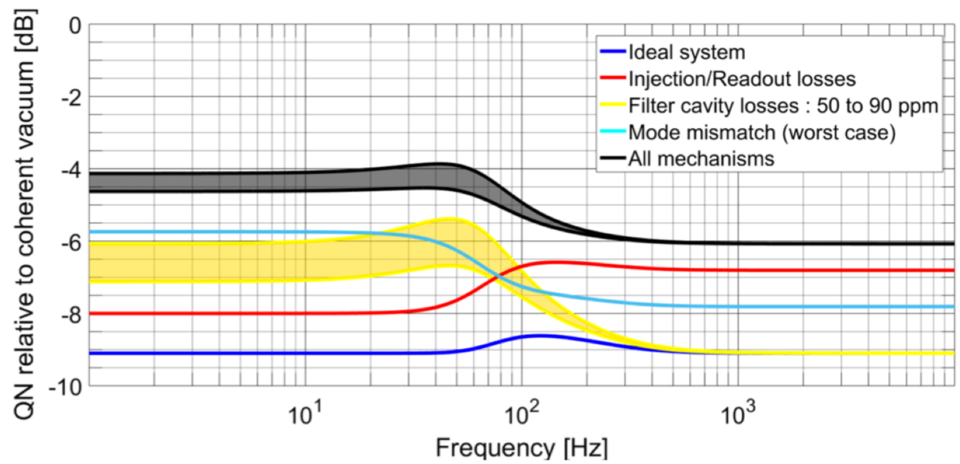


Current status

- successfully locked. Measured finesse is 4425 and measured round trip loss is 50-90 ppm, which is consistent with expected value

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





- installation of digital system and auto alignment is ongoing

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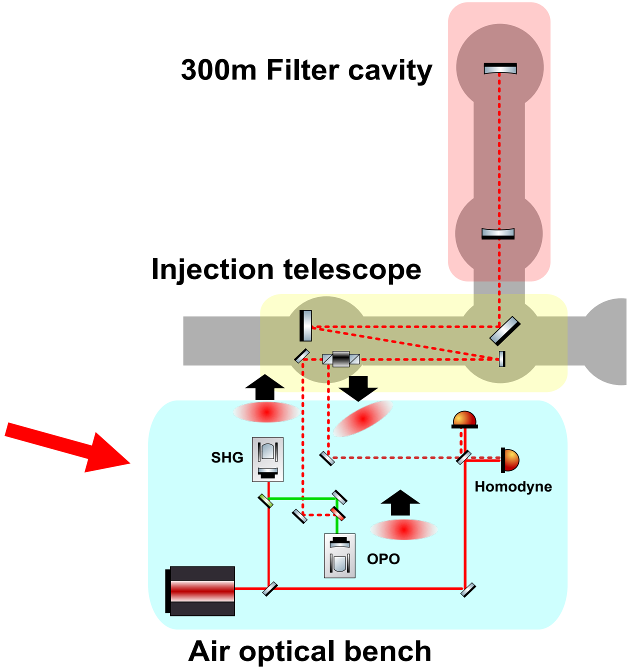
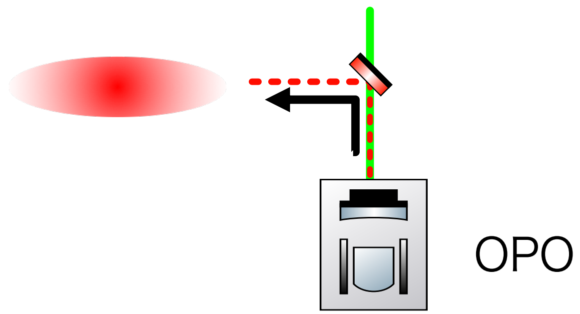
Development of squeezed light

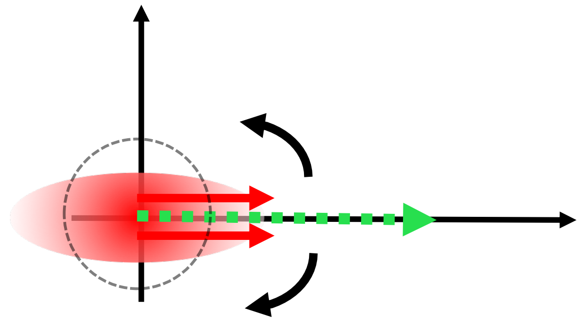
- Theory
- Experimental setup
- Results
  - Characterization of OPO (parametric amplification)
  - Characterization of homodyne detector (alignment, noise)
  - Measurement of squeezed light



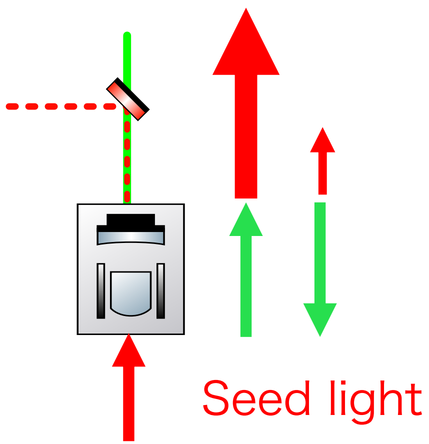
Theory

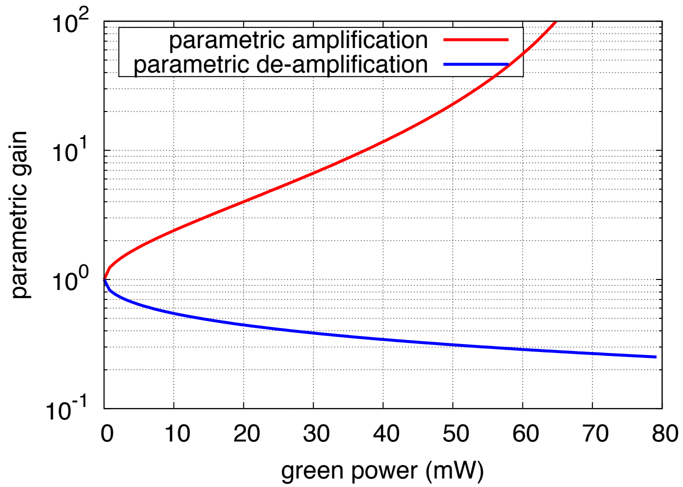
- When green pump light is injected to OPO, two correlated sidebands($\omega+\Omega$, $\omega-\Omega$) are created from green (2ω) due to nonlinear effect→squeezed light





- OPO nonlinear effect can be measured by injecting pump and seed light to OPO and measuring amplification of seed light (parametric amplification) and de-amplification of seed light (parametric de-amplification)



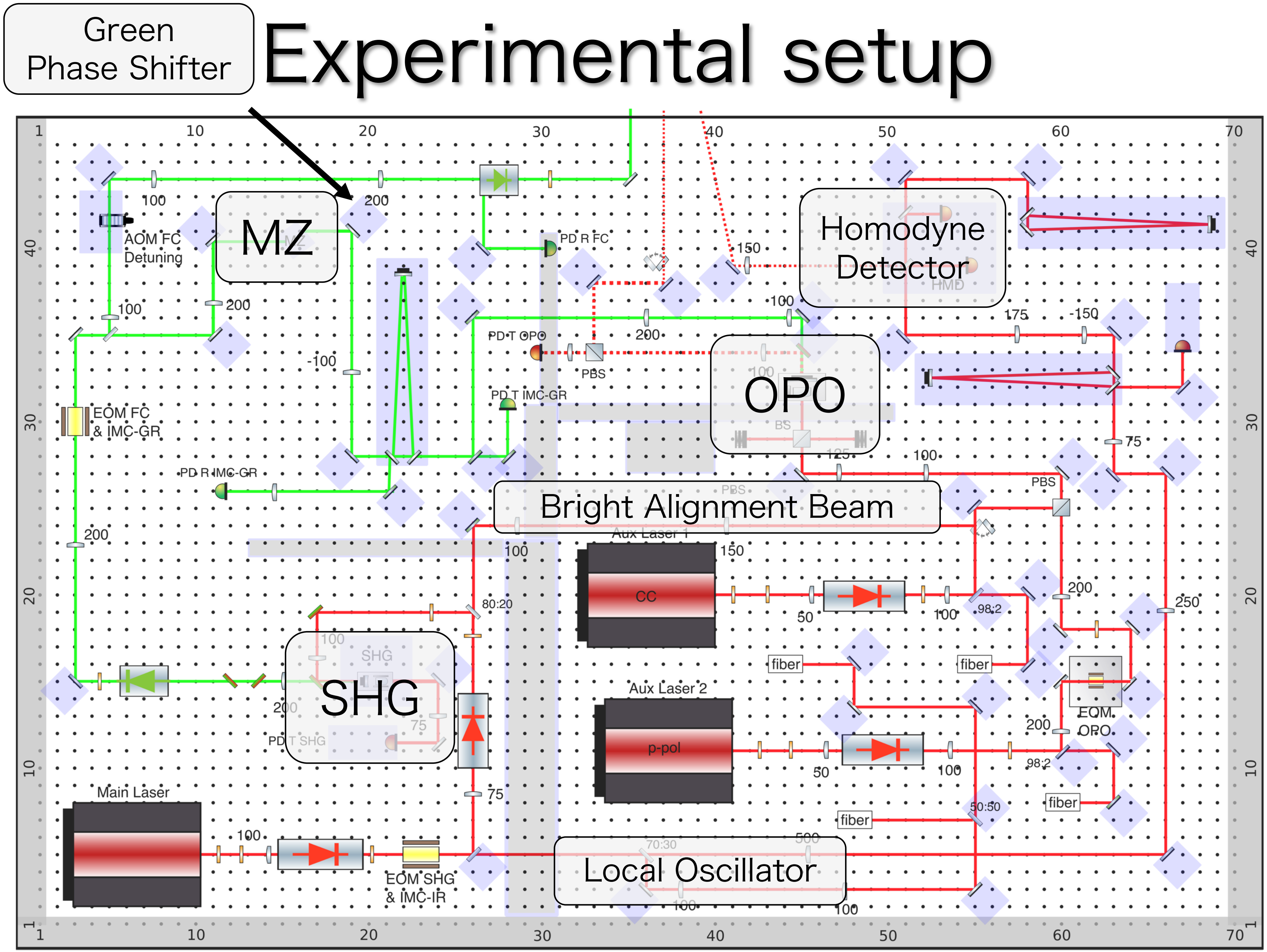


$$G = \frac{1}{\left(1 \mp \sqrt{P/P_{th}}\right)^2}$$

$$P_{th} \propto 1/\varepsilon^2$$

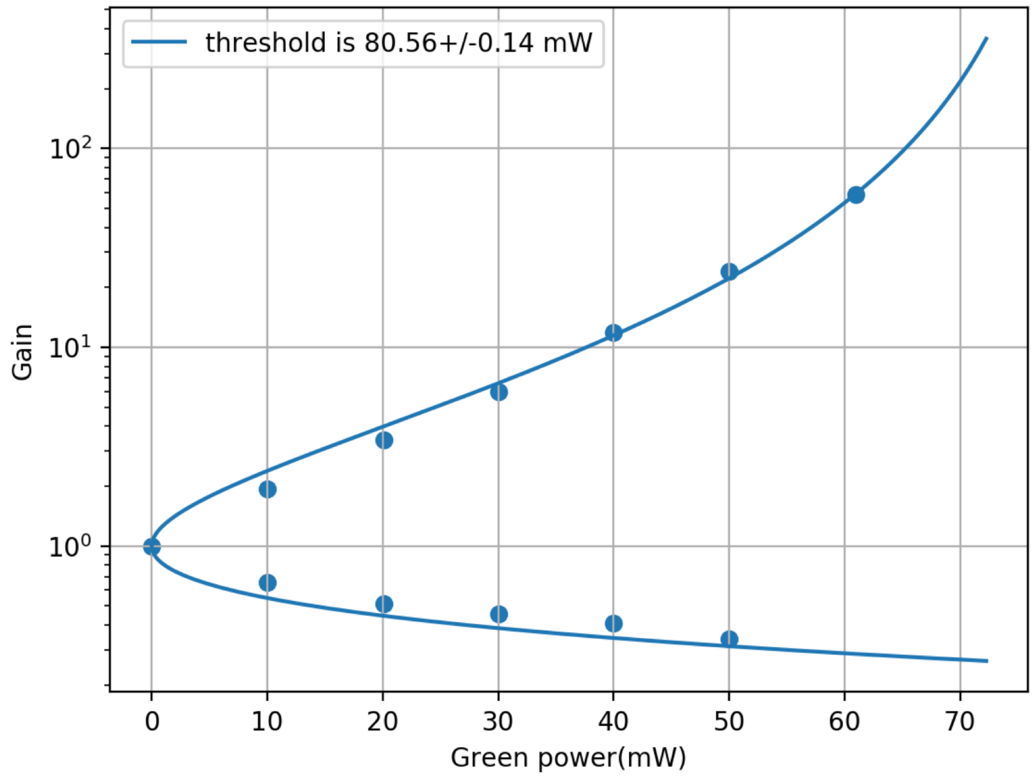
P_{th}: threshold power
ε : nonlinear coupling

Experimental setup



Parametric amplification

- By scanning green phase, parametric amplification and de-amplification are measured
- Measured threshold power is 80.6 mW, which is consistent with simulation



$$G = \frac{1}{\left(1 \mp \sqrt{P/P_{th}}\right)^2}$$

$$P_{th} \propto 1/\varepsilon^2$$

P_{th}: threshold power
ε : nonlinear coupling

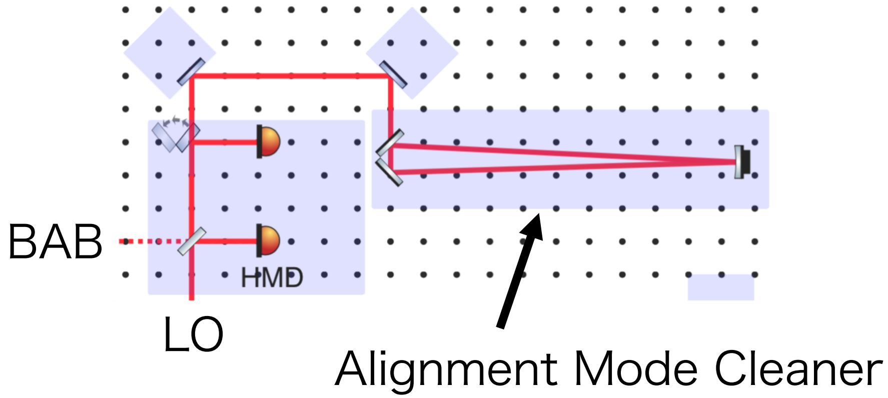
Alignment of Homodyne Detector

- Requirement for visibility of LO and squeezed light: 99%
- To match the alignment of LO and squeezed light, we aligned LO and BAB to Alignment Mode Cleaner (AMC)

  - Mode matching

    LO and AMC: 99.9%

    BAB and AMC: 94.1%



- visibility of LO and BAB
  - Measured visibility: 0.364
  - Calculated visibility from LO and BAB power: 0.384

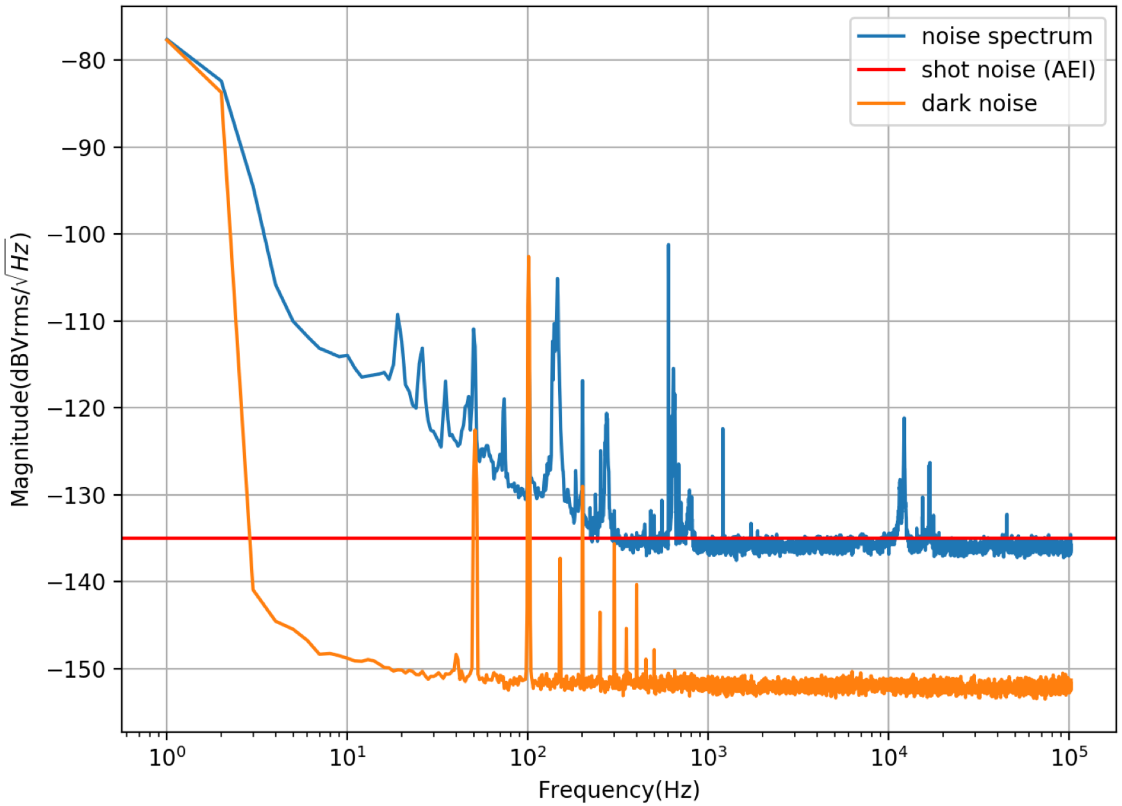
$$V = \frac{2\sqrt{P_1 P_2}}{P_1 + P_2}$$

  - Mode matching of LO and BAB estimated from visibility: 0.364/0.384 = 94.8%

- Although the visibility should be improved, alignment with AMC is good

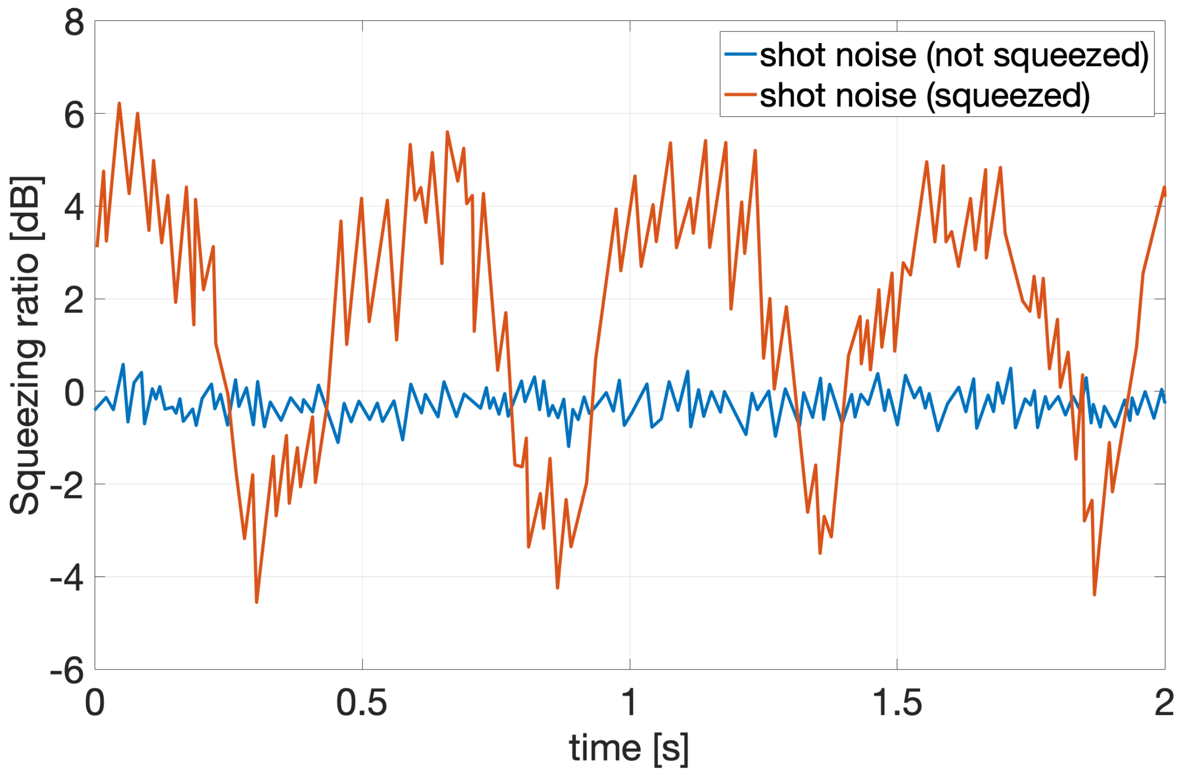
Noise of Homodyne Detector

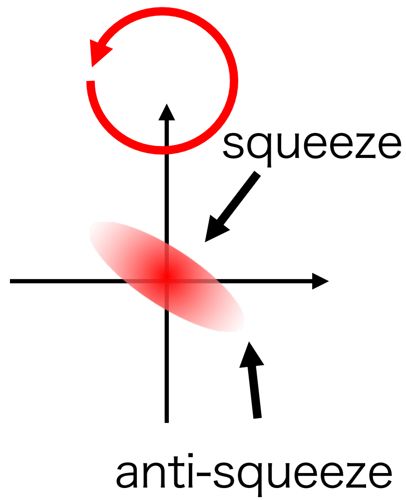
- clearance: ~20dB
- shot noise limited above 1kHz
- noise source at low frequency is under investigation (intensity noise, jitter, scattering, vibration)



First squeezing measurement

- green phase is modulated and shot noise of LO at 200kHz is measured (zero span measurement)
- squeeze ~ 3dB, anti-squeeze: ~ 5dB
- Estimated squeezer loss is around 30%. It will be reduced below 10% with squeezed angle stabilization and improvement of visibility etc.





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Summary & Future

Summary

- OPO and Homodyne Detector have been characterized
- Squeezed light was successfully measured for the first time at TAMA
- measured squeezing: 3dB, anti-squeezing: 5dB @200kHz

Future plan

2019

- Squeezed angle stabilization (<30mrad), reduction of loss (<10%)
- Noise hunting of homodyne detector, shot noise limited above 10Hz
- Installation of digital system and auto alignment

2020

- achieve frequency dependent squeezing

Extra Slides