Quantum Squeezing Scheme for Heterodyne Readout

Paper review

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Review paper

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Quantum Squeezing Schemes for Heterodyne Readout

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Advanced gravitational-wave detectors are limited by quantum noise in their most sensitive frequency band. Quantum noise suppression techniques, such as the application of the quantum squeezed state of light, have been actively studied in the context of homodyne readouts. In this paper, we consider quantum squeezing schemes for the heterodyne readouts. This is motivated by a successful suppression of the higher-order-mode content by stable recycling cavities in advanced detectors. The heterodyne readout scheme requires precise tuning of the interferometer parameters and a broadband squeezing source, but is conceptually simple and elegant. We further show that it is compatible with the frequency-dependent squeezing, which reduces both the shot noise and the radiation-pressure noise. We propose a test of the heterodyne readout with squeezing in Advanced LIGO. This can serve as a pathfinder not only for the implementation in future detectors, such as Einstein Telescope and Cosmic Explorer, but also for general high-precision optical measurements.

I. INTRODUCTION

The Pound-Drever-Hall heterodyne technique [1–9] is a powerful tool for stabilisation of optical cavities in modern precision instruments, such as frequency references for optical atomic clocks, passive laser gyroscopes, and gravitational-wave detectors. In the heterodyne readout, phase modulated light probes the motion of the optical

quantum radiation-pressure noise. As discussed in Sec II and III, we find that quantum squeezing works for the heterodyne readout if (i) the source of squeezed states of light has a bandwidth at least twice the RF modulation frequency (ω_m), (ii) the filter cavity for the frequency-dependent squeezing is tuned the same as in the current homodyne readout scheme, and (iii) the power imbalance of the upper and lower RF sidebands which are on

About the paper

- This paper discusses the possibility to use heterodyne readout from the view point of squeezing.
- Note that homodyne readout + squeezing is successfully used for the current gravitational detectors.

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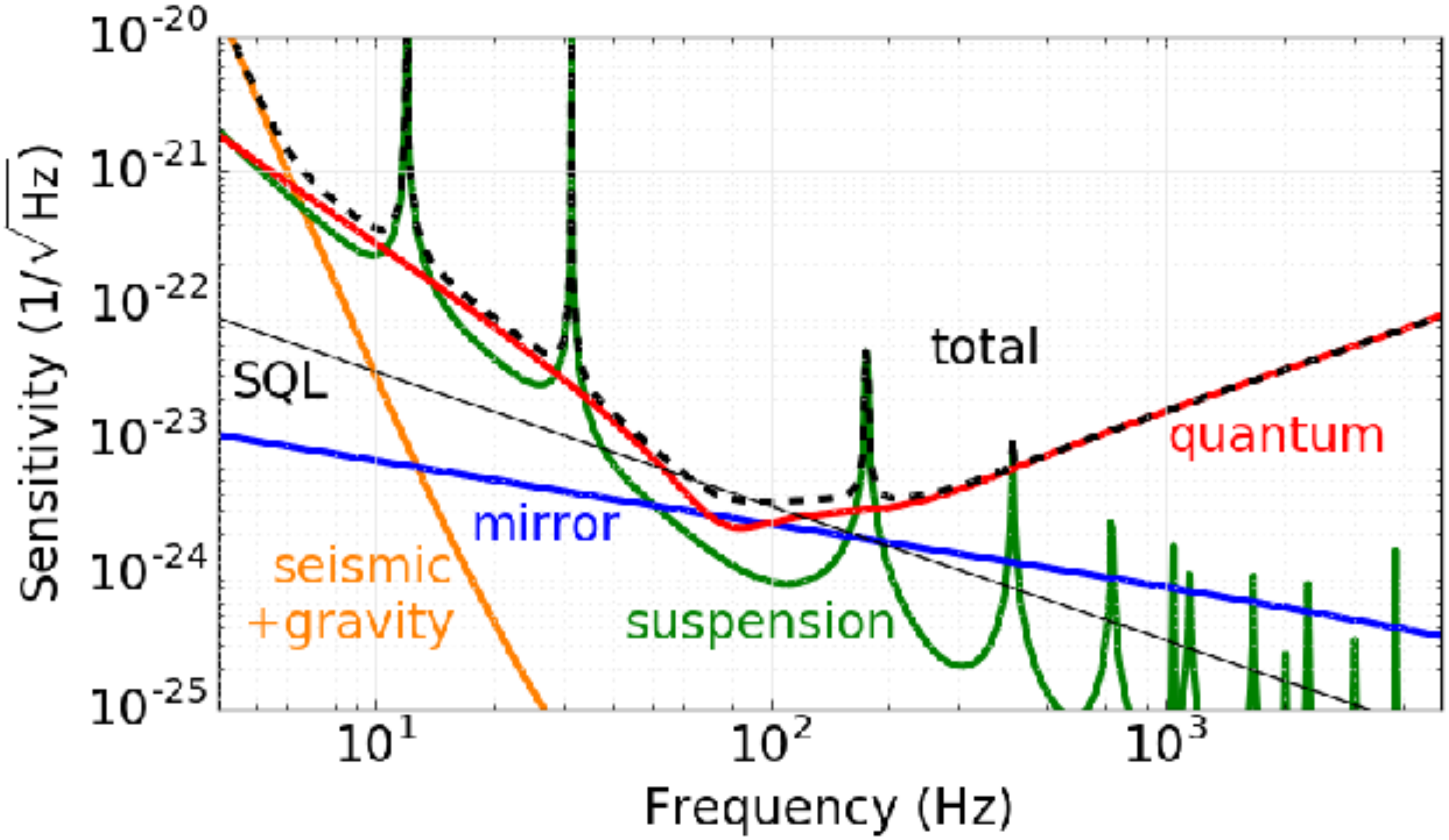
- Introduction
- Squeezing for heterodyne readout
- Higher-order-modes and schnupp asymmetry
- Heterodyne in Advanced LIGO
- Conclusion

Contents

Introduction

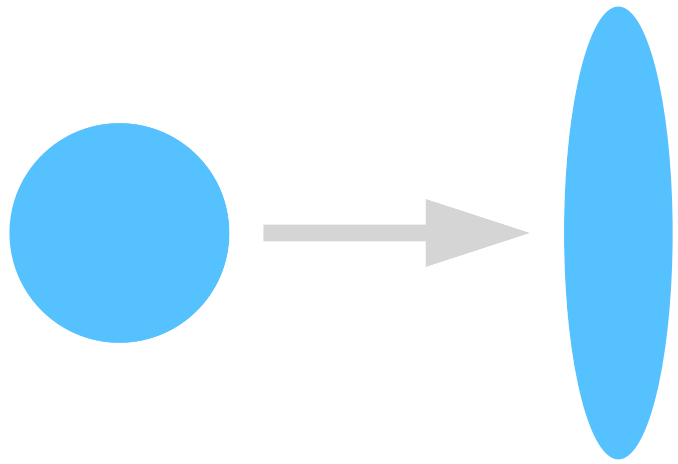
Quantum noise in gravitational wave detectors

- Advanced gravitational wave detectors are limited by quantum noise in their most sensitivity frequency band.

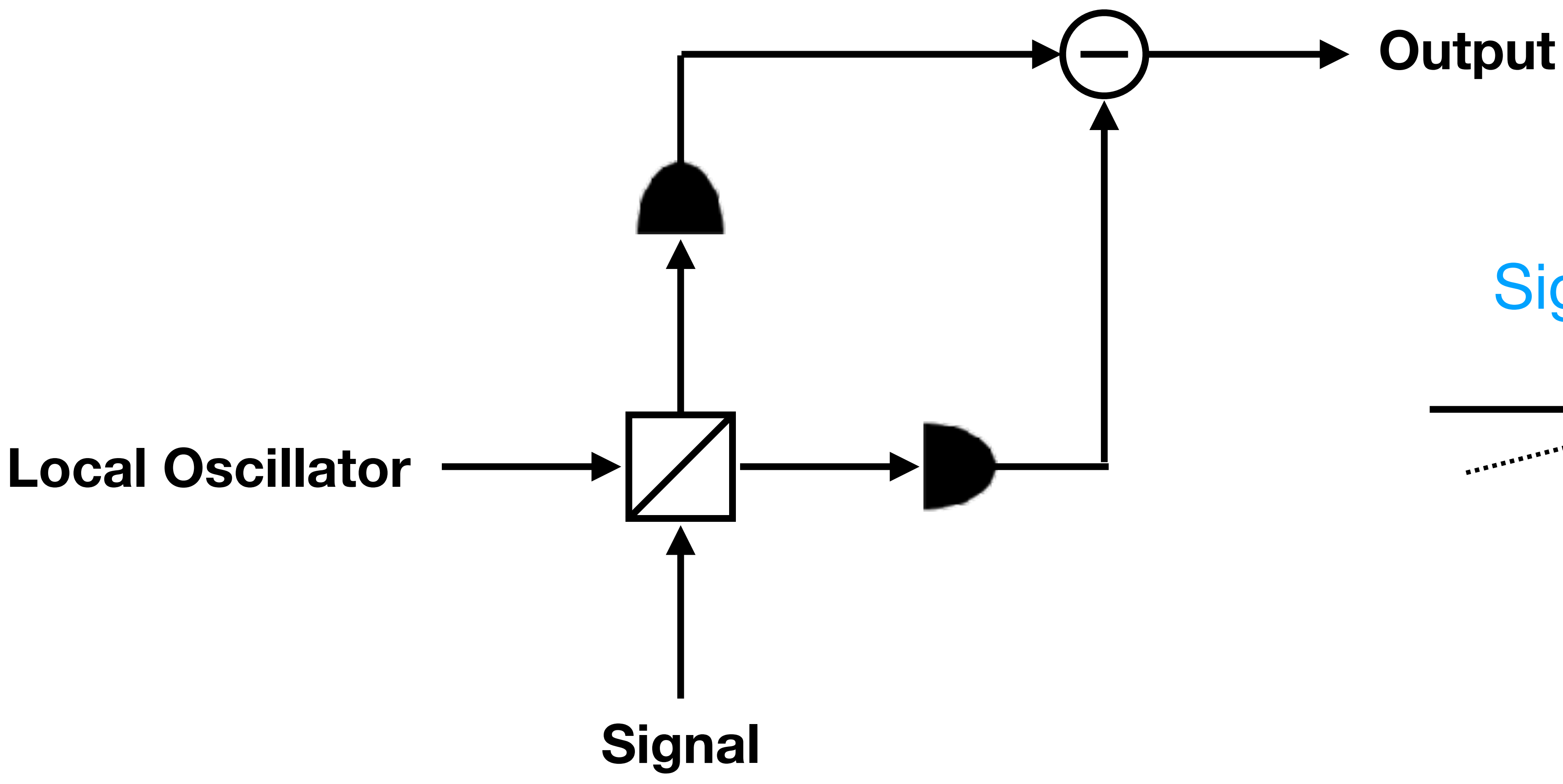


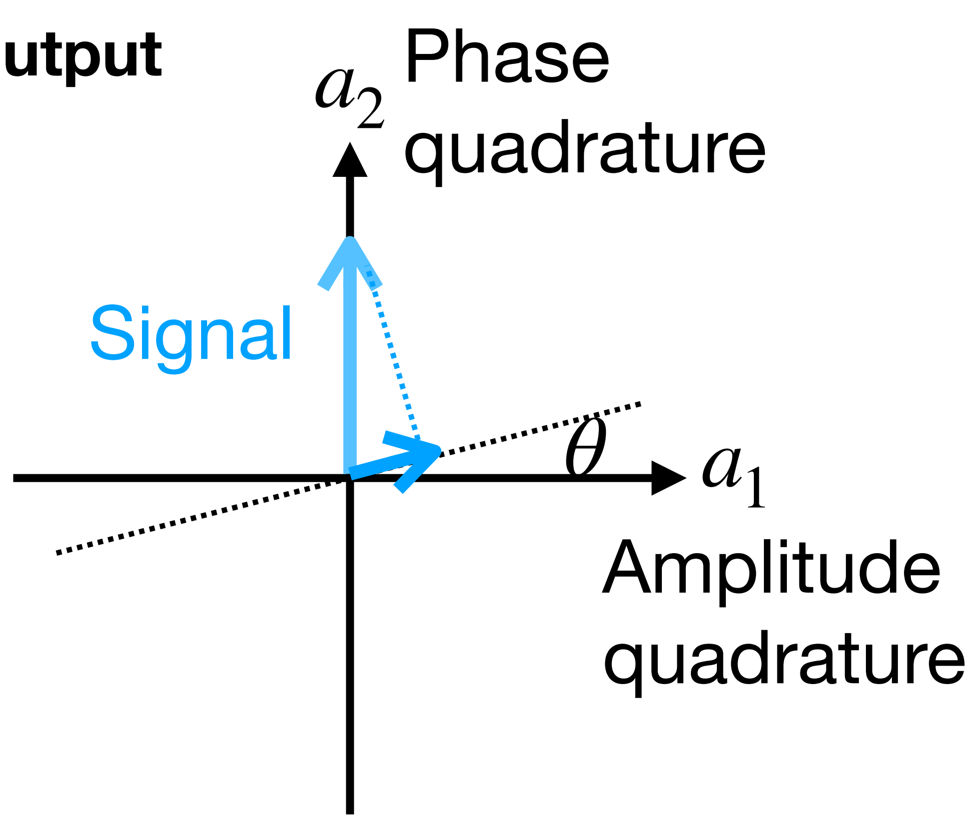
Introduction

Suppressing quantum noise



- Squeezing and homodyne detection (currently used)

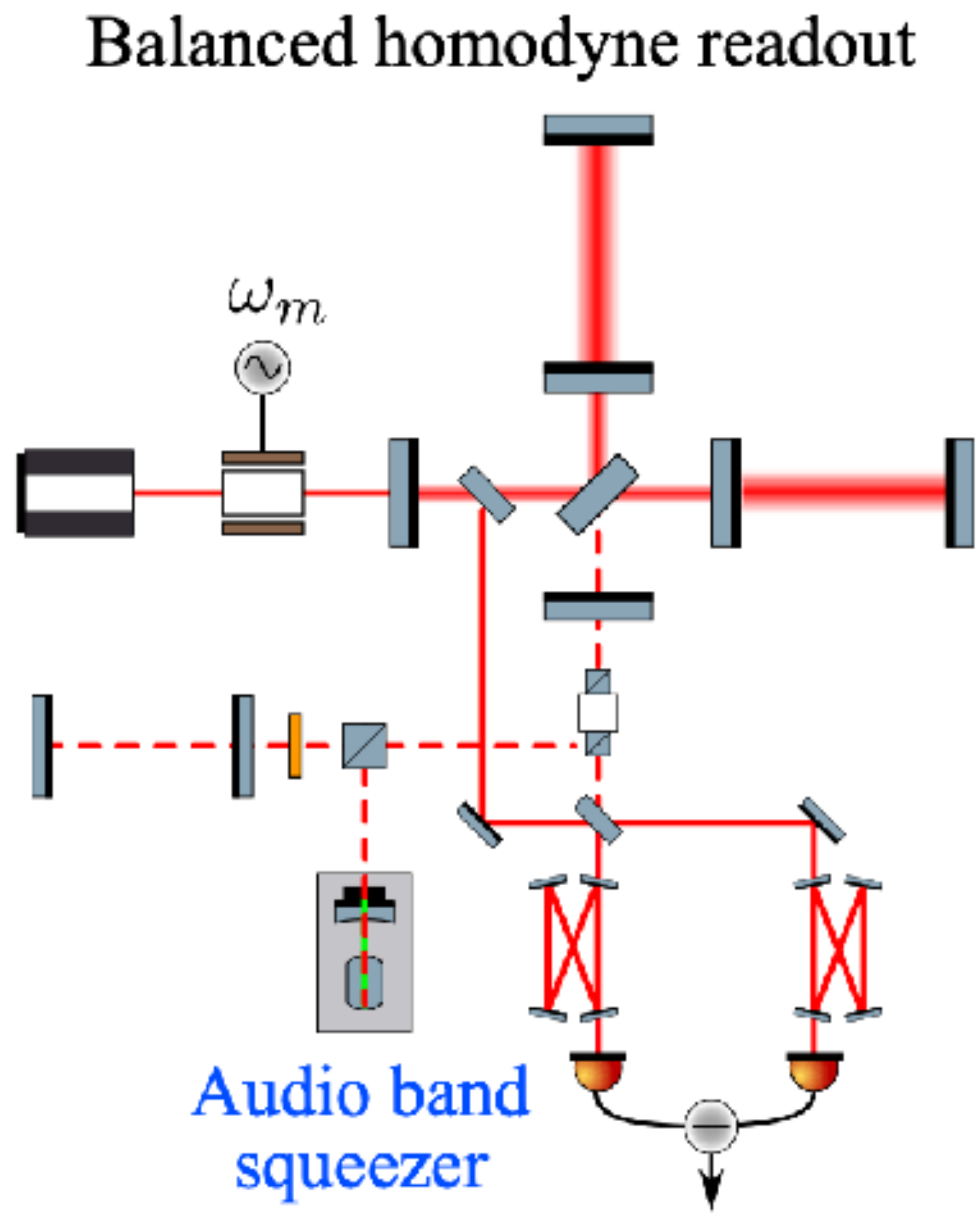




Introduction

Problem in the homodyne readout

- Complex configuration
  - Additional local oscillator field
  - Additional optical cavities to filter the carrier field from the RF side bands (OMC)

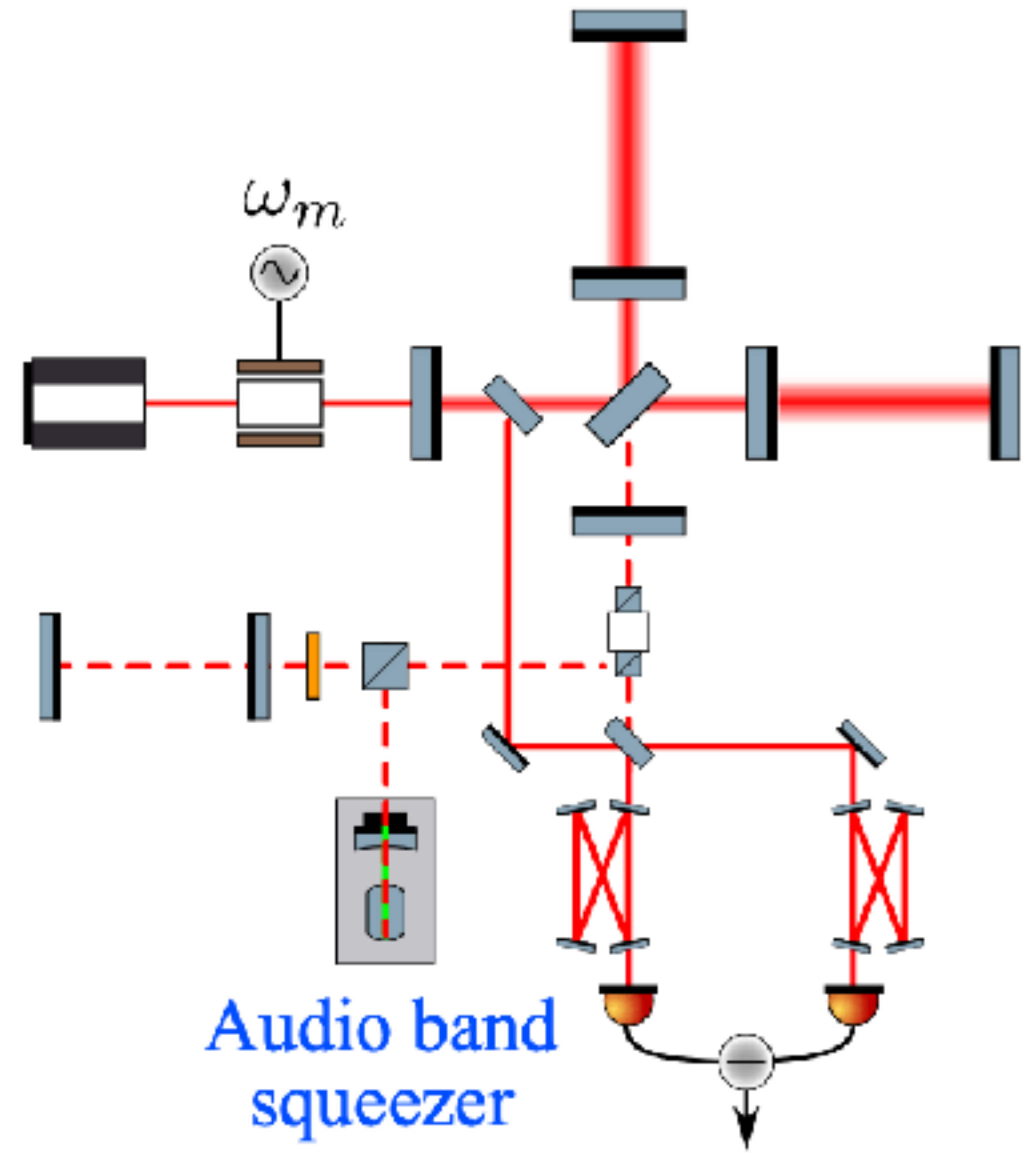


Introduction

Problem in the homodyne readout

- Currently, additional local oscillator field is derived by offsetting the interferometer from its operating point. (DC readout)
  - The offset couples technical noises sources
  - will not allow future gravitational wave detectors to reach their design sensitivity at low frequency

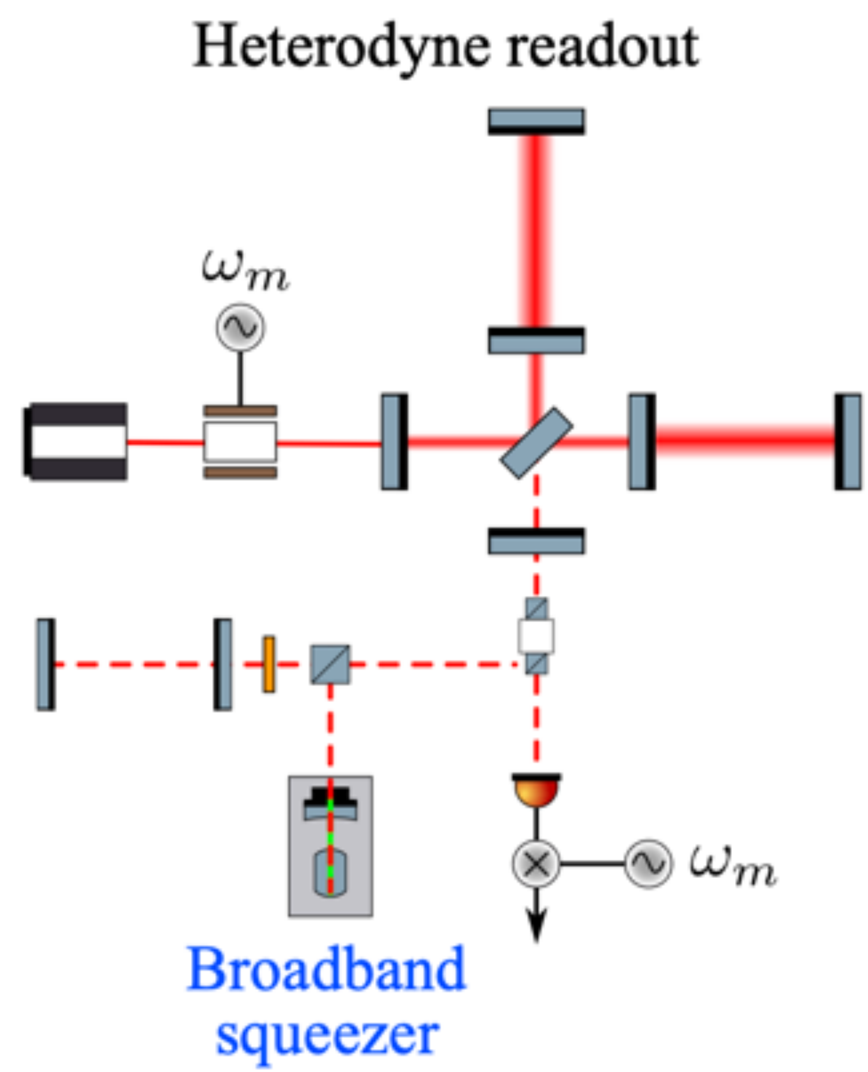
Balanced homodyne readout



Introduction

Advantage in heterodyne readout

- Simple configuration
  - RF phase modulated light -> photo detector -> demodulation



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- Introduction
- Squeezing for heterodyne readout
- Higher-order-modes and schnupp asymmetry
- Heterodyne in Advanced LIGO
- Conclusion

Squeezing for heterodyne readout
phase quadrature and the spectrum

- Output phase quadrature of the heterodyne readout
  - $$\hat{Y}(\Omega) = \underbrace{\hat{Y}_0(\Omega)}_{\text{for } \omega_0} + \frac{\hat{Y}_{+2}(\Omega) + \xi \hat{Y}_{-2}(\Omega)}{1+\xi}$$

    for $\omega_0 - 2\omega_m$
- memo
  - ξ: amplitude ratio of two RF sidebands
  - Ω: audio band (detection band)
  - ω_0: carrier frequency
  - ω_m: RF (moduration frequency)

Squeezing for heterodyne readout

phase quadrature and the spectrum

- Output phase quadrature of the heterodyne readout
  - $$\hat{Y}(\Omega) = \underbrace{\hat{Y}_0(\Omega)}_{\text{for } \omega_0} + \boxed{\frac{\hat{Y}_{+2}(\Omega) + \xi \hat{Y}_{-2}(\Omega)}{1+\xi}}$$

    for $\omega_0 - 2\omega_m$

    Additional terms
- ex.) Vacuum state
  - $$S_{YY} = 1 + \boxed{\frac{1+\xi^2}{(1+\xi)^2}}$$
  - $$S_{YY}\Big|_{\text{balanced}} = \frac{3}{2} > 1$$

Squeezing for heterodyne readout

Broad band squeezing versus broadband squeezing

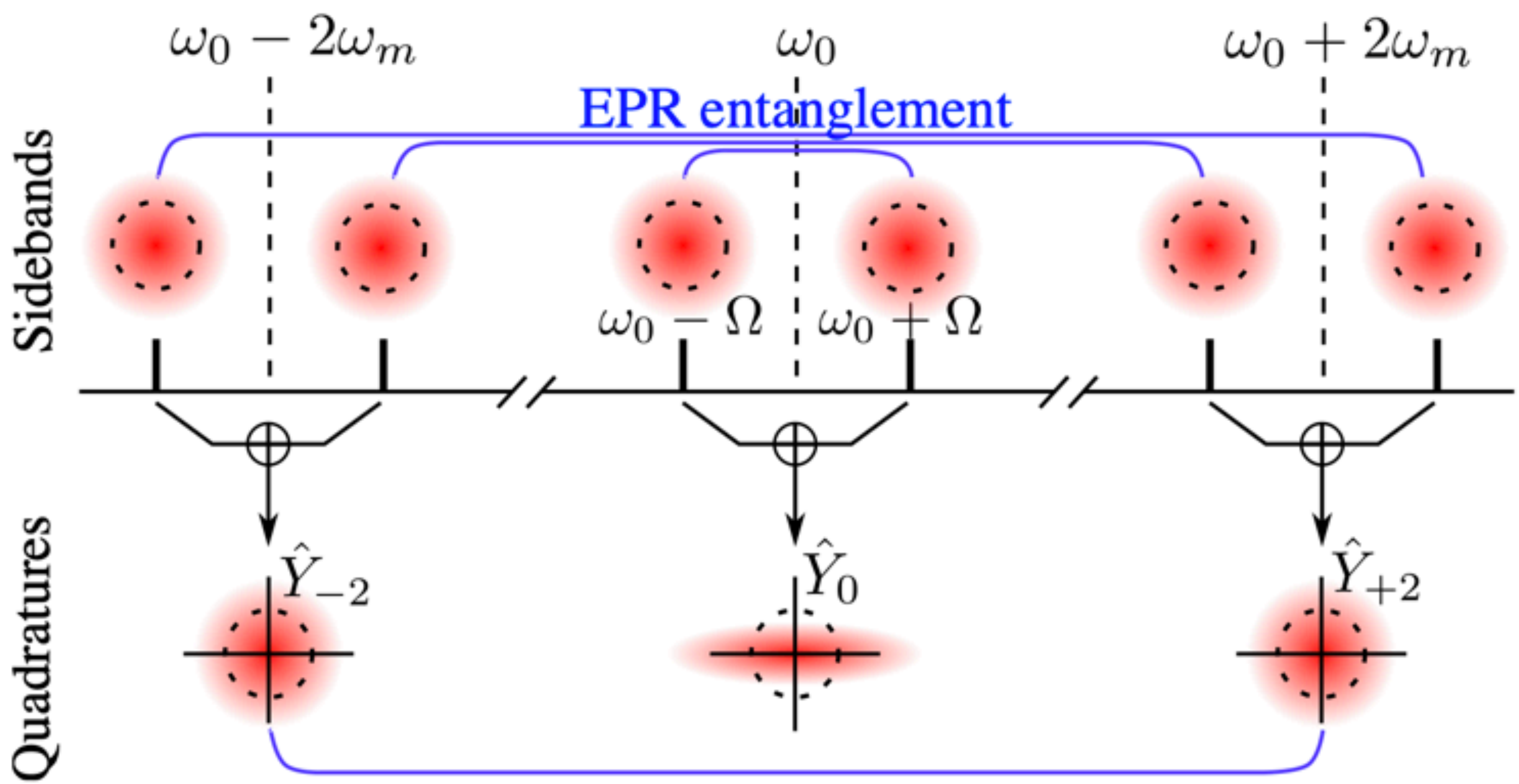
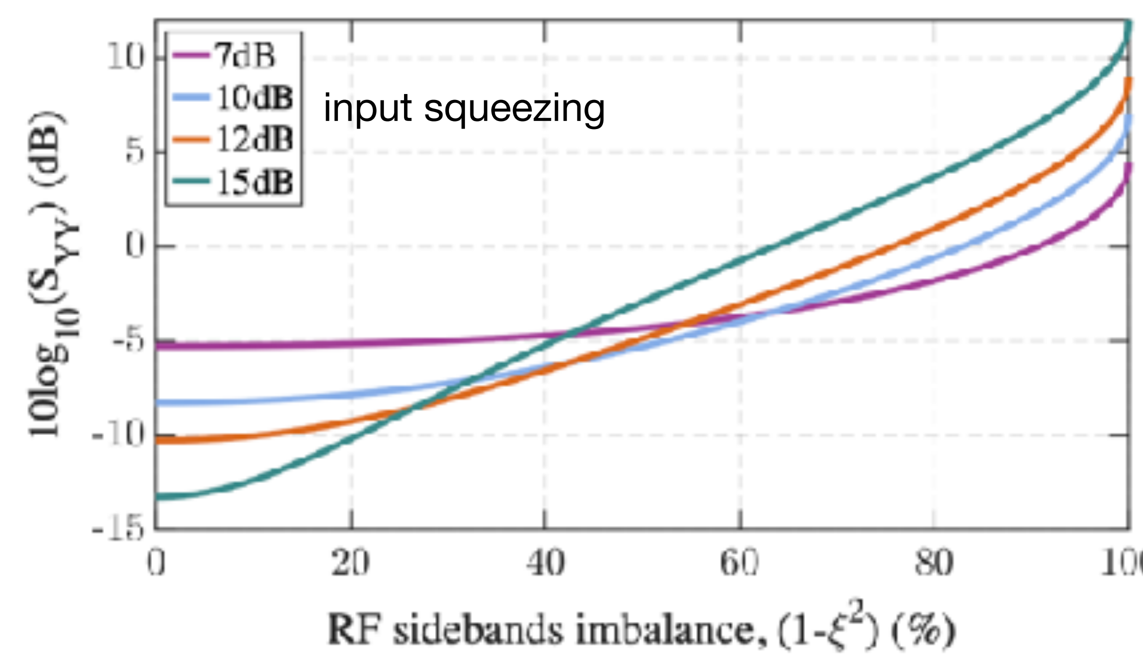


FIG. 2. Schematics of a broadband squeezer in the sideband and the quadrature picture. In contrast for an audio band squeezer, the sidebands are entangled only for Ω up to kHz.

Squeezing for heterodyne readout

Broad band squeezing versus broadband squeezing

- Audio band squeezing
  - $$S_{YY} = e^{-2r} + \frac{1+\xi^2}{(1+\xi)^2}, \quad r: \text{squeezing factor}$$
- Broadband
  - $$S_{YY} = \frac{3}{2}e^{-2r} + \left(\frac{1-\xi}{1+\xi}\right)^2 \frac{e^{2r}}{2}$$
  - smaller imbalance is important



Squeezing for heterodyne readout

Frequency-dependent squeezing

- Frequency-dependent squeezing is important to simultaneously suppress the shot noise and the quantum radiation pressure noise.
  - Use the filter cavity
- However, the filter cavity could add fluctuation around $\omega_0 \pm 2\omega_m$.
  - Can be a problem in heterodyne detection?

Squeezing for heterodyne readout

Frequency-dependent squeezing

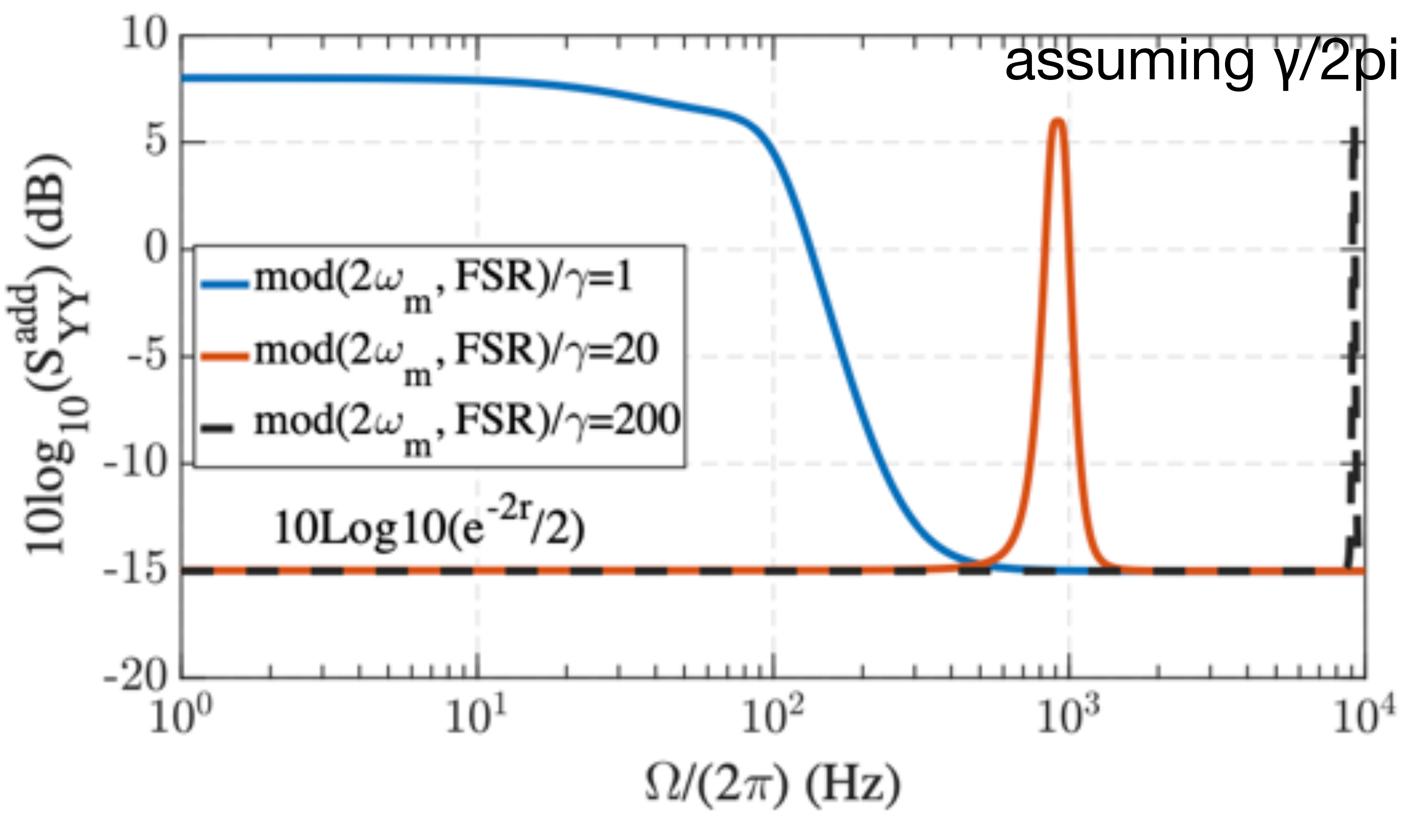
- $S_{YY}^{\text{add}} = \dfrac{1}{2}\left[\cosh 2r - \sinh 2r \cos\left(\Phi_{+2} - \Phi_{-2}\right)\cos\left(\theta_{+2} + \theta_{-2}\right)\right]$
  - minimum: = $e^{-2r}/2$ when $\Phi_{\pm 2} = \theta_{\pm 2} = 0.$
  - $\Phi_{\pm 2}$: phase angle for quadratures of $\omega_0 \pm 2\omega_m$
  - $\theta_{\pm 2}$: rotational angle for quadratures of $\omega_0 \pm 2\omega_m$
- Condition for the minimum noise
  - $2\omega_m$ away from any FSR of the filter cavity

Squeezing for heterodyne readout

Frequency-dependent squeezing

- Condition for the minimum noise
  - $2\omega_m$ away from any FSR of the filter cavity

assuming γ/2pi = 45.8 Hz (A+ design)



- Filter cavity noise for heterodyne readout can be avoided with proper parameter selection

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Higher-order-mode and schnupp asymmetry

Higher-order mode versus OMC loss

- In this heterodyne readout, no OMC
  - higher-order-mode at the carrier frequency and in the RF sidebands will both introduce additional quantum noise at $\omega_0 \pm \omega_m$, which are in the vacuum state.
  - $S_{YY}^{\text{Heterodyne}} = \frac{3}{2}e^{-2r} + \zeta_{\text{HOM}}$
- cf.)
  - $S_{YY}^{\text{Homodyne}} = \left(1 - \zeta_{\text{OMC}}\right) e^{-2r} + \zeta_{\text{OMC}}$
  - Loss acts the contamination of the vacuum state and degradation the squeezing.

Higher-order-mode and schnupp asymmetry

Higher-order mode versus OMC loss

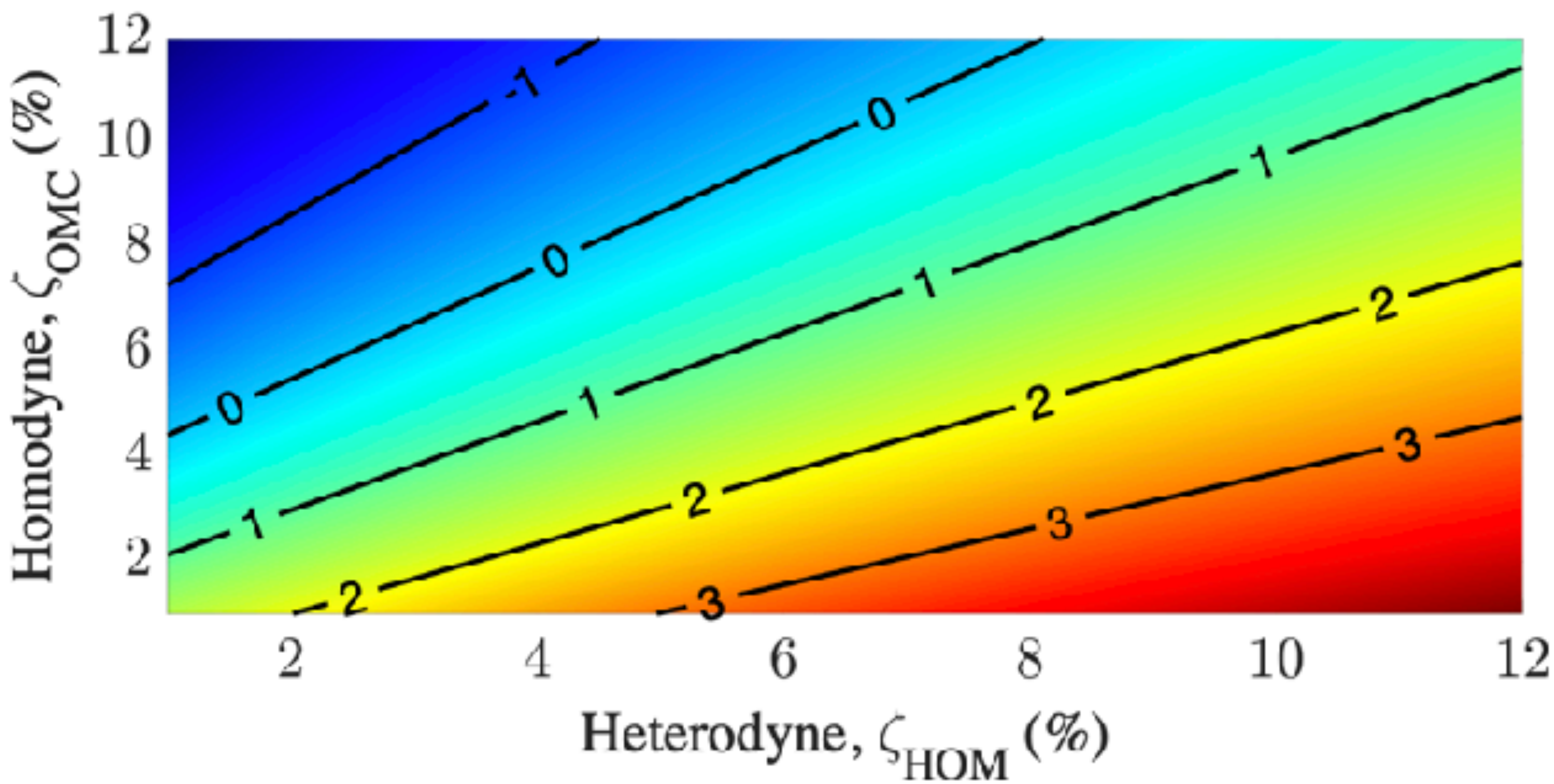


FIG. 5. Figure shows the ratio of the quantum noise spectral density of the heterodyne readout over the that of homodyne readout as a function of the OMC loss (ζ_{OMC}) in homodyne readout and HOM content (ζ_{HOM}) in heterodyne readout in the unit of dB. The contour line of 0 dB denotes the cases when the two noise levels are equal. 12 dB input squeezing is assumed.

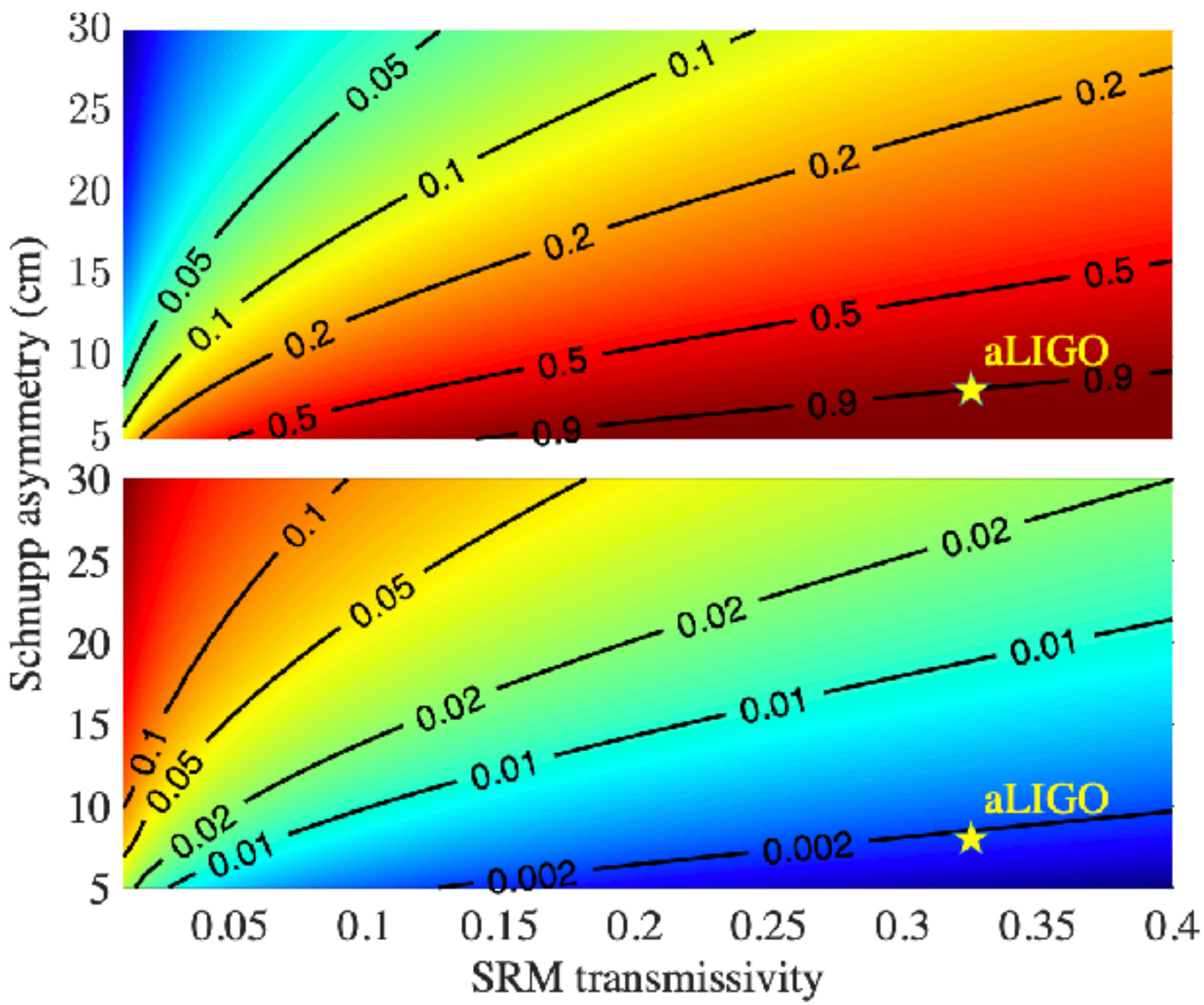
Higher-order-mode and schnupp asymmetry

Schnupp asymmetry noise

- Schnupp asymmetry allows the RF sidebands from the bright port to transmit to the readout port (dark port).
- However, it also couples the vacuum noise from the bright port to the dark port.
- Problem?
  - Solution: Transmit ω_m sidebands. Block $2\omega_m$ sidebands.
    - Parameters of Schnupp asymmetry and SRM transmissivity are important

Higher-order-mode and schnupp asymmetry

Transmissivity of the sidebands



45 MHz

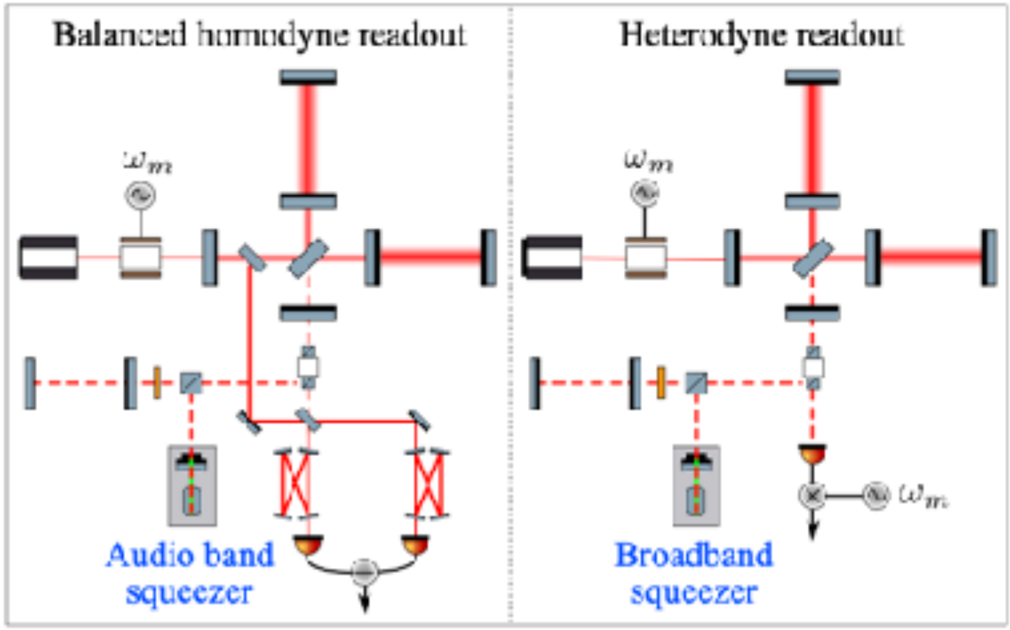
90 MHz

Contents

Heterodyne in Advanced LIGO

as an example

- Current Advanced LIGO with squeezing and homodyne readout
  - 7.2 ± 0.3 dB source injection squeezing
  - 3.2 ± 0.1 dB observed (maximum)
  - The degradation is due to the optical loss in the interferometer.
- How about changing homodyne to heterodyne?



Heterodyne in Advanced LIGO

as an example

- Parameters
  - ξ_{HOM} = 0.12 (The higher-order-mode content is dominated by the 02 mode of the RF sideband)
  - $2\omega_m$ = 90 MHz
  - Bandwidth of the LIGO squeezing ~ 10 MHz (much smaller than 90 MHz)
  - 5-15% loss from OMC is neglected because we omit OMC in heterodyne readout.
- Estimated squeezing level with heterodyne readout
  - 1.7 ± 0.2 dB with current parameters of Advanced LIGO
  - (cf. 3.2 ± 0.1 dB homodyne)

Heterodyne in Advanced LIGO

as an example

- How to optimize parameters
  - increase the bandwidth of the squeezing source ~100 MHz (<- 10 MHz)
    - 3.9 ± 0.2 dB
    - (cf. 3.2 ± 0.1 dB homodyne, 1.7 ± 0.2 dB heterodyne)
  - Reduce 02 mode: ξ_{HOM} = 0.02 (<- 0.12)
    - 4.7 ± 0.3 dB

Contents

Conclusion

- Squeezing for the heterodyne readout in advanced gravitational wave detectors is calculated and discussed.
  - Heterodyne readout is compatible with frequency-dependent squeezing.
  - Higher-order-mode and Schnupp asymmetry problems turned out to be negligible.
- Heterodyne readout scheme has advantage in less auxiliary optics and the sensitivity compatible to that of homodyne readout.