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Interpretation of sideband asymmetry in optomechanics

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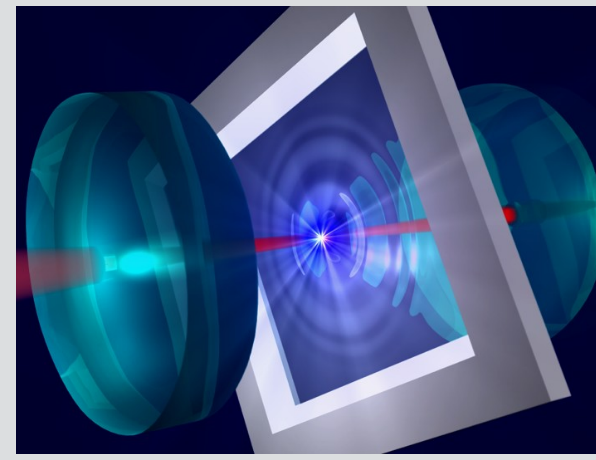
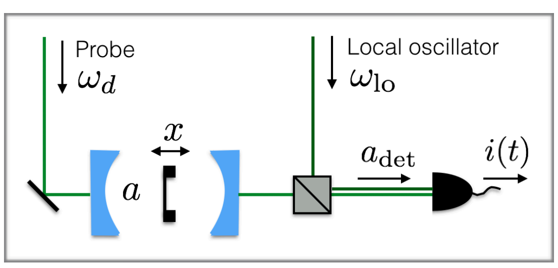


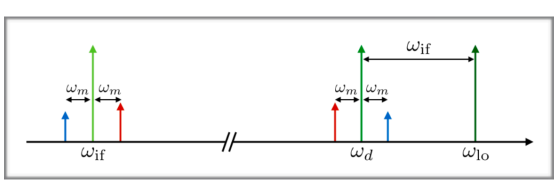
Introduction

- Light scattered from a quantum mechanical oscillator exhibits sideband asymmetry
- It has been claimed that with heterodyne photodetection, this asymmetry results from correlations between optical quantum vacuum noise and the oscillator's position. [1,2] Conversely, with direct photodetection of the sidebands, the asymmetry results from the oscillator's intrinsic quantum noise. [2]
- We reexamine heterodyne detection in more detail and show that the interpretation depends on the detector model [3]
- Relates to older issue of the origin of photocurrent shot noise - quantum field noise or the photodetection process itself? [4]
- We also examine if a classical interpretation always exists [3]

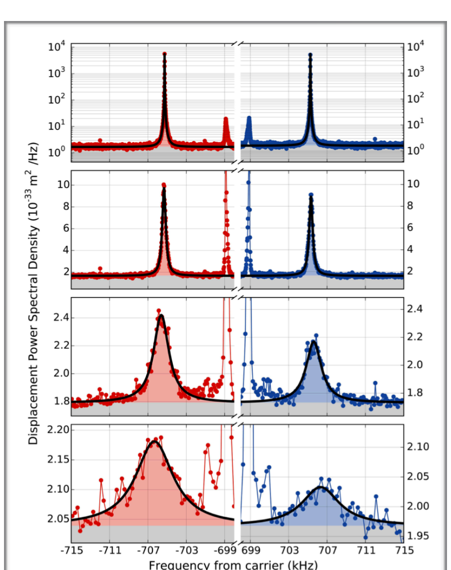
The measurement



- Send in probe light at cavity resonance frequency, i.e. $\omega_d = \omega_c$
- Mix output with local oscillator detuned by intermediate frequency ω_{if}
- Measure photocurrent $i(t)$ and compute its spectrum $S[\omega]$



- The mechanical oscillator gives sidebands at $\omega_d \pm \omega_m$
- The sidebands are mixed down to $\omega_{\mathrm{if}} \pm \omega_m$



- At high temperatures $T \gg \hbar\omega_m/k_B$ the red- and blue-shifted sidebands are of equal magnitude
- At low temperatures, the ratio of blue and red sideband powers is $n_{\mathrm{th}}/(n_{\mathrm{th}}+1)$ where n_{th} is the average phonon occupation number
- The results above are from Ref. [5]. Sidebands are shown for different powers of additional cooling laser

Model

- System Hamiltonian:

$$H_{\mathrm{sys}} = \hbar\left(\omega_c + g_0 x\right) a^\dagger a + H_{\mathrm{mech}}$$

No assumptions on commutation relations for x and p

- What is measured? The photocurrent spectrum:

$$S[\omega] = \int_{-\infty}^{\infty} d\tau\, e^{i\omega\tau}\, \overline{i(t+\tau)i(t)}$$

The bar indicates ensemble average

Interpretation

- **(Semi)classical detector [1,2]:**

$$\overline{i(t+\tau)i(t)} = \langle I(t+\tau)I(t)\rangle$$

$\langle\cdots\rangle$ indicates average over noise in optical and mechanical degrees of freedom

Classical field: $I = \frac{c}{2}\{a_{\mathrm{det}}, a^\dagger_{\mathrm{det}}\}$ $\quad (c \text{ constant})$

Sideband asymmetry originates from classical opto-mechanical correlations:

$$\langle\Gamma(t+\tau)x(t)\rangle \neq 0$$

Γ is classical background noise of the e.m. field or classical laser noise

Quantum field: $I = c\, a^\dagger_{\mathrm{det}} a_{\mathrm{det}}$

Sideband asymmetry originates from quantum or classical optomechanical correlations

Γ is quantum vacuum noise of the e.m. field or classical laser noise

- **Quantum detector [4,6]:**

$$\overline{i(t+\tau)i(t)} = \langle : I(t+\tau)I(t) : \rangle + c\,\delta(\tau)\langle I(t)\rangle$$

Sideband asymmetry from quantum asymmetry in position spectrum $S_{xx}[\omega]$ or from classical optomechanical correlations

$$S_{xx}[\omega] = \int_{-\infty}^{\infty} d\tau\, e^{i\omega\tau}\langle x(t+\tau)x(t)\rangle$$

$S_{xx}[\omega] \neq S_{xx}[-\omega]$ impossible for a classical oscillator

Same interpretation for classical and quantum field

Quantum vacuum noise of e.m. field does not affect interpretation, since the detector does not «see» vacuum noise

- **Equivalence**

We can show that the two detector models are equivalent by using standard quantum commutation relations, i.e., if we assume *a priori* that standard quantum theory is correct.

Always a classical interpretation?

- In some cases, classical background noise of the e.m. field can be ruled out by a proper characterization of the detector. In addition, laser noise can be filtered away
- In other cases, f.ex. for systems in the microwave regime, one might have to entertain the possibility of classical noise
- Is it then always possible to explain sideband asymmetry using a classical model?

- A theory with only quantum noise in the e.m. field gives the red and blue sidebands

$$S_{rr}[\omega] = 1 + (\tilde{n}_{\mathrm{th}} + 1)L[\omega]$$

$$S_{bb}[\omega] = 1 + \tilde{n}_{\mathrm{th}}L[\omega]$$

when expressed in units of the noise floor, the function $L[\omega]$ is proportional to a Lorentzian with width equal to the mechanical linewidth, and

$$\tilde{n}_{\mathrm{th}} = n_{\mathrm{th}} + p$$

where p results from heating of the oscillator from the probe itself.

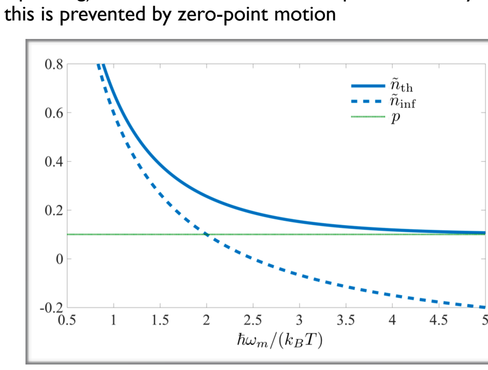
- In a fully classical theory with noise at the same level as in the quantum theory, we get the same sidebands, but with $\tilde{n}_{\mathrm{th}}$ replaced by

$$\tilde{n}_{\mathrm{inf}} = \frac{k_B T}{\hbar\omega_m} + p - \frac{1}{2}$$

- This means that at temperatures

$$T < \frac{\hbar\omega_m}{k_B}\left(\frac{1}{2} - p\right)$$

classical and quantum theories are distinguishable, since a classical theory then gives a negative sideband (noise squashing) at the blue sideband. In the quantum theory, this is prevented by zero-point motion



- The downside is that this difference is completely masked if the oscillator is laser cooled using another cavity mode subject to the same classical background noise
- However, other cooling methods, e.g., direct cryogenic cooling, would not have this problem

Conclusion

- The interpretation of sideband asymmetry depends on detector model. Standard photodetection theory shows that sideband asymmetry directly reflects quantum asymmetry of the oscillator's position spectrum
- Classical and quantum theories are distinguishable at sufficiently low temperatures

References

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Figure in upper right corner by courtesy of Jack Sankey