OPTOMECHANICAL SQUEEZING

Cavity Quantum Optomechanics

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Physique quantique et applications

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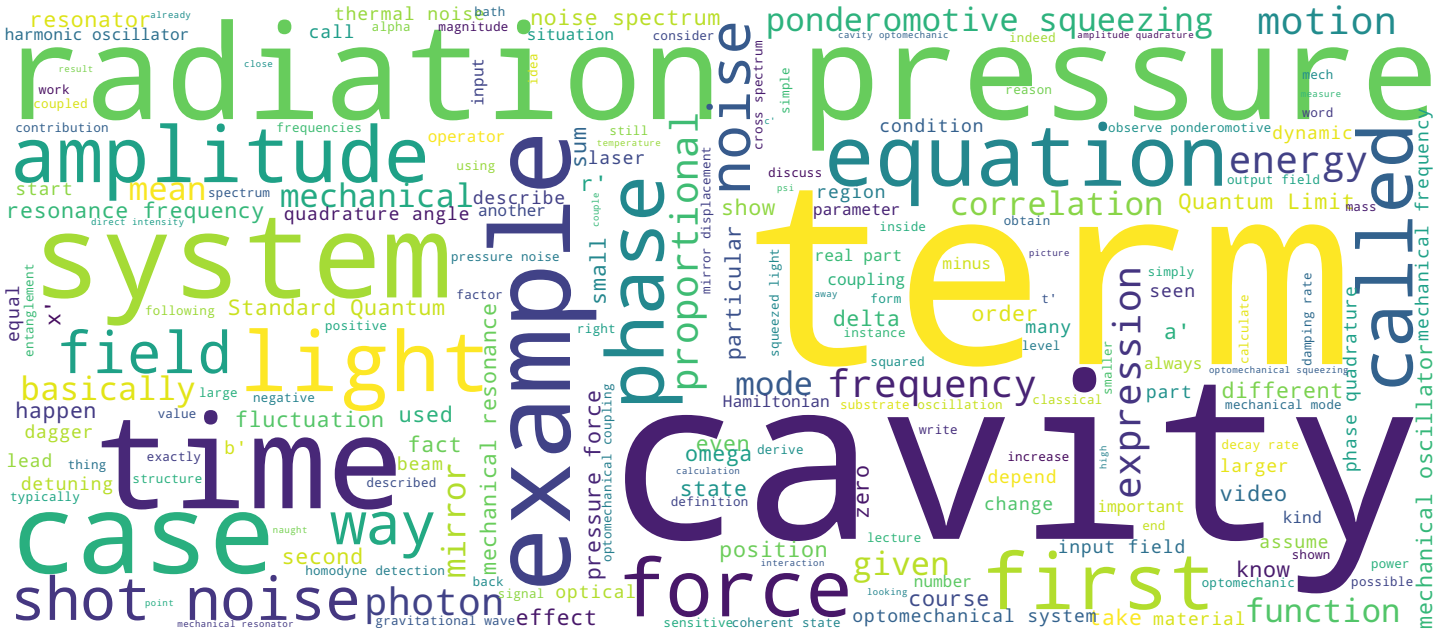

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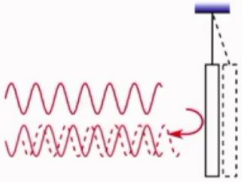
Video

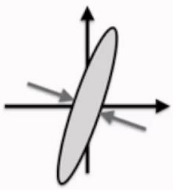
EPFL

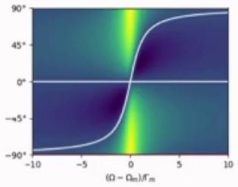
OUTLINE

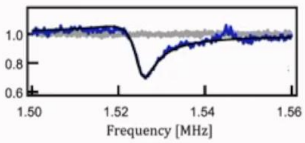
In this lesson, we will see that radiation pressure can modify the quantum properties of the light beam itself

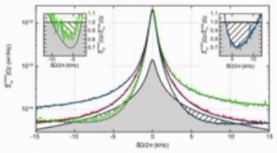
- Optomechanical correlations
- Noise spectrum of ponderomotive squeezing
- Experimental realization
- Application to sub-SQL measurements











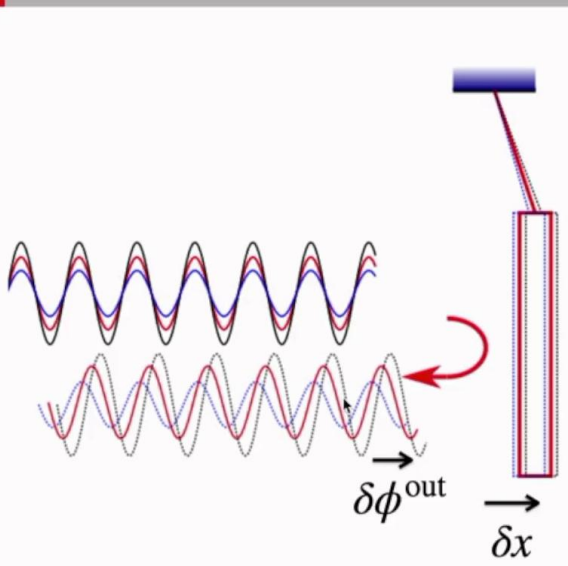
Welcome to this video on optomechanical squeezing. I'm Samuel Deléglise from Laboratoire Kastler Brossel and this video is part of the mooc cavity optomechanics of the OMT network. In many of the videos of this course, we have studied how the dynamics of the mechanical system could be modified by the optomechanical coupling. However, radiation pressure can also be utilized to strongly modify the properties of light itself. In this video, we will see that radiation pressure naturally creates correlations between the various quadratures of the light field. Under some circumstances, this correlation can give rise to a squeeze state where the noise of certain quadratures is reduced below the shot noise level. This effect is called ponderomotive squeezing. I will guide you step by step through the calculation of the noise spectrum associated to an arbitrary quadrature of the light exiting an optomechanical cavity and we will discuss the conditions that need to be fulfilled to observe ponderomotive squeezing. We will see that these conditions have been fulfilled recently in various experimental settings and such that nowadays ponderomotive squeezing is an experimental reality. Finally, we will describe the applications of ponderomotive squeezing and, in particular, the possibility to perform measurements below the Standard Quantum Limit sensitivity.

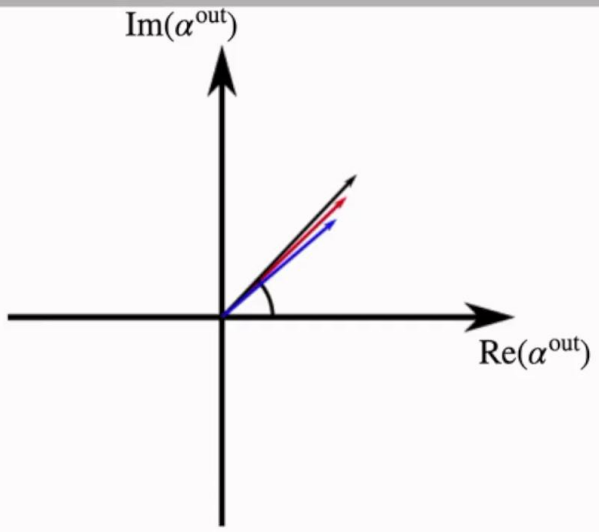
Notes

Summary

0m 00s

Optomechanical correlations





$$\delta I^{\text{out}} = \delta I^{\text{in}}$$

$$\delta\phi^{\text{out}} = \delta\phi^{\text{in}} + \frac{4\pi}{\lambda}\delta x$$

→ Radiation pressure creates intensity/phase correlations

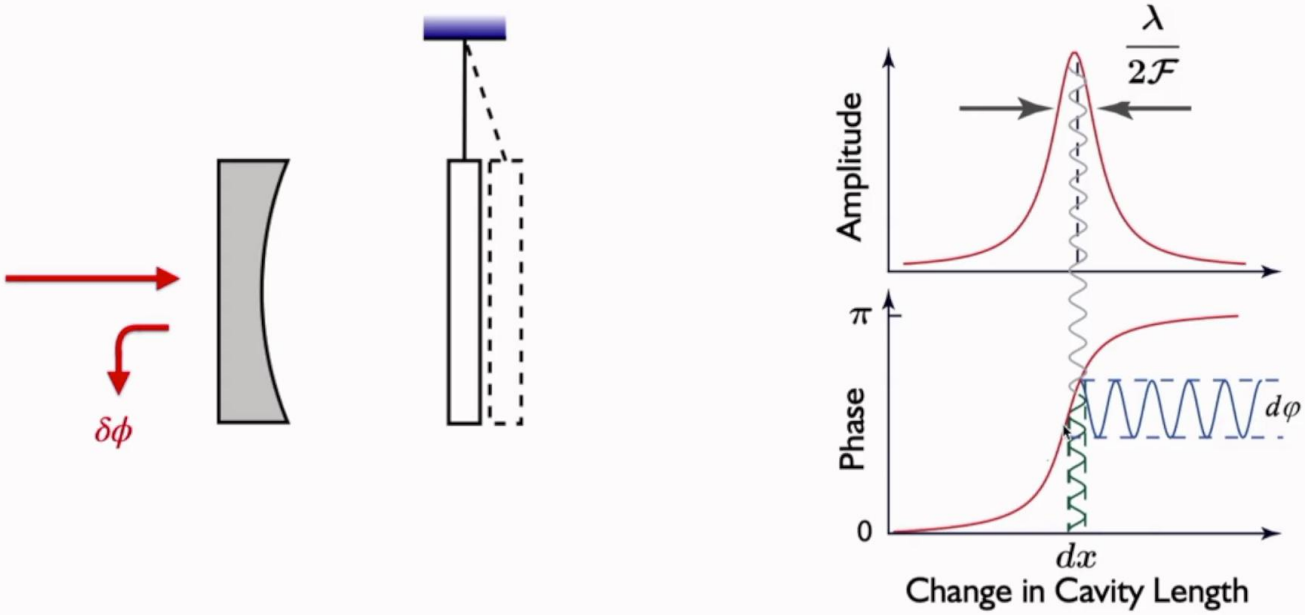
So the essence of ponderomotive squeezing can be understood with a simple interferometric measurement. So the idea is to measure the position of the mirror by looking at the phase of a beam reflected from the mirror. If the mirror is perfectly reflected, the intensity of the field is unchanged at the reflection whereas the phase acquires a term that is proportional to the mirror displacement here. If now we suppose that the mirror is light enough such that it is sensitive to radiation pressure, we immediately see that the phase of the reflected beam will depend on the intensity of the field. In this way we see that radiation pressure has created intensity phase correlations. So this effect is very similar to what happens in a Kerr nonlinear medium and it is a legitimate natural question to ask whether we can exploit this optomechanical nonlinearity to generate squeezing. And the answer is yes, provided the effect of the input quantum intensity fluctuations are strong enough to lead to a significant mirror displacement and dephasing.

Notes

Summary

1m 36s

Cavity optomechanics



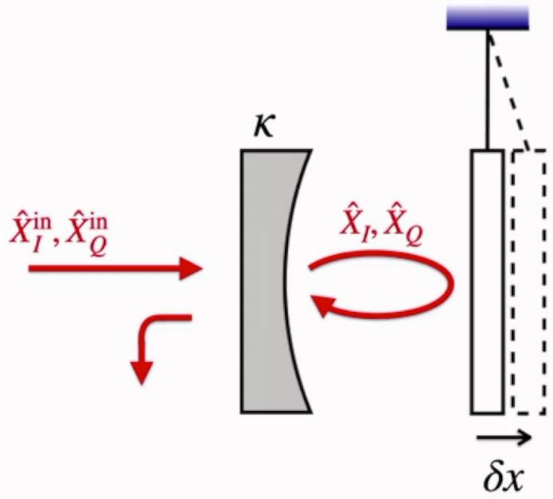
In order to achieve this, actually a very good way is to use the usual cavity optomechanical setup. So this has two advantages. Basically by going into a cavity the intracavity amplitude is amplified by the thinness of the cavity and so the fluctuations of radiation pressure are also amplified by this factor. Furthermore, the small displacements induced by quantum radiation pressure shot noise will be much more efficiently detected due to the sharp dependence of the phase as a function of mirror position within a cavity.

Notes

Summary

3m 04s

Equations of motion



Intracavity field $\hat{a} = \alpha + \delta\hat{a}$:

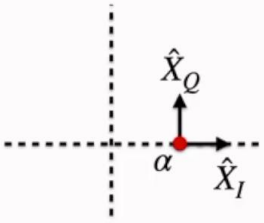
$$\delta\hat{a}[\Omega] = \chi_{\text{opt}}(\Omega)\left(iG\alpha\delta\hat{x}[\Omega] + \sqrt{\kappa}\hat{a}_{\text{in}}[\Omega]\right)$$

$$\chi_{\text{opt}}(\Omega) = \frac{1}{\kappa/2 - i(\Omega + \Delta)}$$

Field quadratures:

$$\hat{X}_I = \delta\hat{a} + \delta\hat{a}^\dagger$$

$$\hat{X}_Q = (\delta\hat{a} - \delta\hat{a}^\dagger)/i$$



Δ: Laser-cavity detuning

$G = \mathrm{d}\omega_c/\mathrm{d}x = g_0/x_{\text{zpf}}$: OM coupling

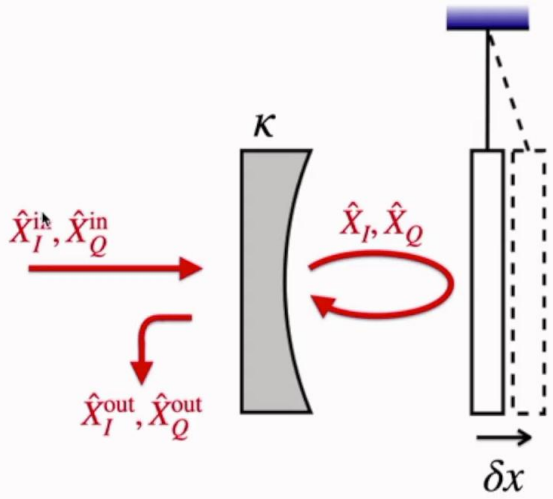
Let's now assume that the cavity is driven by a coherent state alpha-d and we are going to look for the equations of motion for the intracavity field 'a'. Actually we are going to linearize the dynamics around the steady state of the cavity alpha. And so the intracavity field is driven by two terms. First term that is the fluctuations of the input field 'a', a-in and another term that is proportional to the mirror displacement delta-x with in factor the current drive amplitude alpha and the optomechanical coupling 'G'. The enhancement factor by the finesse that we were discussing in the previous slide is actually captured by this optical susceptibility which is inversely proportional to the cavity decay rate kappa. We can assume without loss of generality that alpha is a real number because the global phase term doesn't affect the dynamics of the system. However, the field delta-a is not a Hermitian operator and it is hence, usually more convenient to work with the quadratures 'I' and 'Q' which are here described by with this convention by twice the real part of delta-a and twice the imaginary part. With alpha real, 'I' and 'Q' correspond respectively to the amplitude quadrature of the field and the phase quadrature of the field.

Notes

Summary

3m 50s

Equations of motion



Δ: Laser-cavity detuning

$G = d\omega_c/dx = g_0/x_{zpf}$: OM coupling

Intracavity field $\hat{a} = \alpha + \delta\hat{a}$:

$$\delta\hat{a}[\Omega] = \chi_{opt}(\Omega)\left(iG\alpha\delta\hat{x}[\Omega] + \sqrt{\kappa}\hat{a}_{in}[\Omega]\right)$$

$$\chi_{opt}(\Omega) = \frac{1}{\kappa/2 - i(\Omega + \Delta)}$$

Field quadratures:

$$\hat{X}_I = \delta\hat{a} + \delta\hat{a}^\dagger$$

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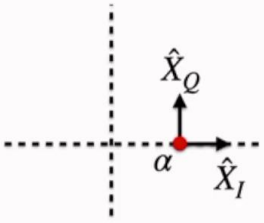


Input-output relation:

$$\hat{a}_{out} = -\hat{a}_{in} + \sqrt{\kappa}\delta\hat{a}$$

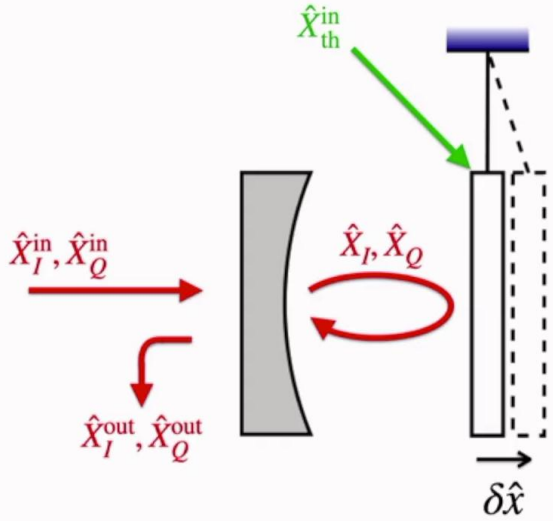
And finally, we will use the input-output relation in this cavity to derive the transfer function of the system, that is, we are looking for a relation linking the output field quadratures to the input field quadratures.

Notes

Summary

5m 29s

Optomechanical squeezing



Let's take: $\Omega \ll \kappa$ (bad cavity limit)
$\Delta = 0$ (resonant drive)

As an exercise, show that

$$\hat{X}^{\text{out}}_I[\Omega] = \hat{X}^{\text{in}}_I[\Omega]$$

$$\hat{X}^{\text{out}}_Q[\Omega] = \hat{X}^{\text{in}}_Q[\Omega] + \frac{4G\alpha}{\sqrt{\kappa}}\delta\hat{x}[\Omega]$$

Intensity dependent mirror position:

$$\delta\hat{x}[\Omega] = \chi_m[\Omega]\left(\hat{F}_{\text{rad}}[\Omega] + \hat{F}_{\text{th}}[\Omega]\right)$$

$$\chi_m[\Omega] = \frac{1}{m\left(\Omega_m^2 - \Omega^2 + i\Omega\Gamma_m\right)}$$

$$F_{\text{rad}} = \hbar G\alpha\hat{X}_I \qquad F_{\text{th}} = \sqrt{2}x_{\text{zpf}}m\Omega\sqrt{\Gamma_m}\hat{X}^{\text{in}}_{\text{th}}$$

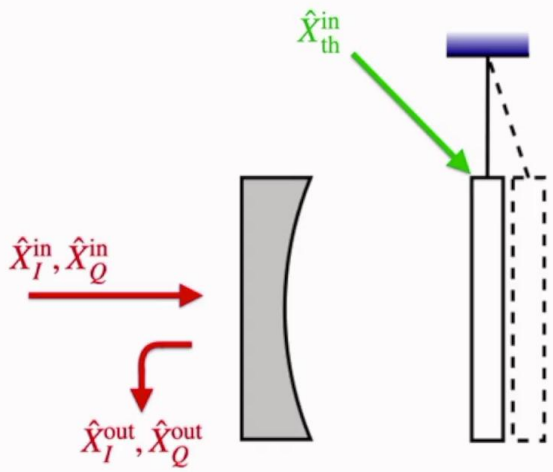
And for this we'll make a few assumption to simplify things a bit. We will assume that all the Fourier frequencies of interest are much smaller than the cavity decay rate kappa which is the bad cavity limit and we'll assume that the laser is driving the cavity on-resonance so we take a detuning delta equals zero. With this assumption we will see that the situation is actually very similar to the simple interferometer picture that I gave earlier. I leave as an exercise, for instance, to show that indeed the intensity quadrature is not modified by the system whereas the phase quadrature acquires a term that is proportional to the mirror displacement delta-x. Now if we inject the expression of delta-x as a function of the mechanical susceptibility here and the force which the mirror is subjected to namely, the radiation pressure force in red and the thermal force in green, we will start to see the correlation picture pop up in the equations. So, in particular, this radiation pressure force here is proportional to the intracavity field amplitude quadrature. On the other hand, the thermal force is proportional to the an external drive term from the mechanical bath that we call here 'X in Th'. So we see that because of this term the phase quadrature acquires a component that will be proportional to the intensity fluctuations of the drive.

Notes

Summary

5m 48s

Optomechanical squeezing



System transfer function

$$\hat{X}^{\text{out}}_I[\Omega] = \hat{X}^{\text{in}}_I[\Omega]$$

$$\hat{X}^{\text{out}}_Q[\Omega] = \underbrace{\hat{X}^{\text{in}}_Q[\Omega]}_{\text{Shot noise}} + 4(\underbrace{C\hat{X}^{\text{in}}_I[\Omega]}_{\text{Radiation pressure noise}} + \underbrace{\sqrt{C/2}\hat{X}^{\text{in}}_{\text{th}}[\Omega]}_{\text{Thermal noise}})r(\Omega)$$

Cooperativity:

$$C = \frac{4g_0^2\alpha^2}{\kappa\Gamma_m}$$

Normalized susceptibility:

$$r(\Omega) = m\Omega_m\Gamma_m\chi_m[\Omega]$$

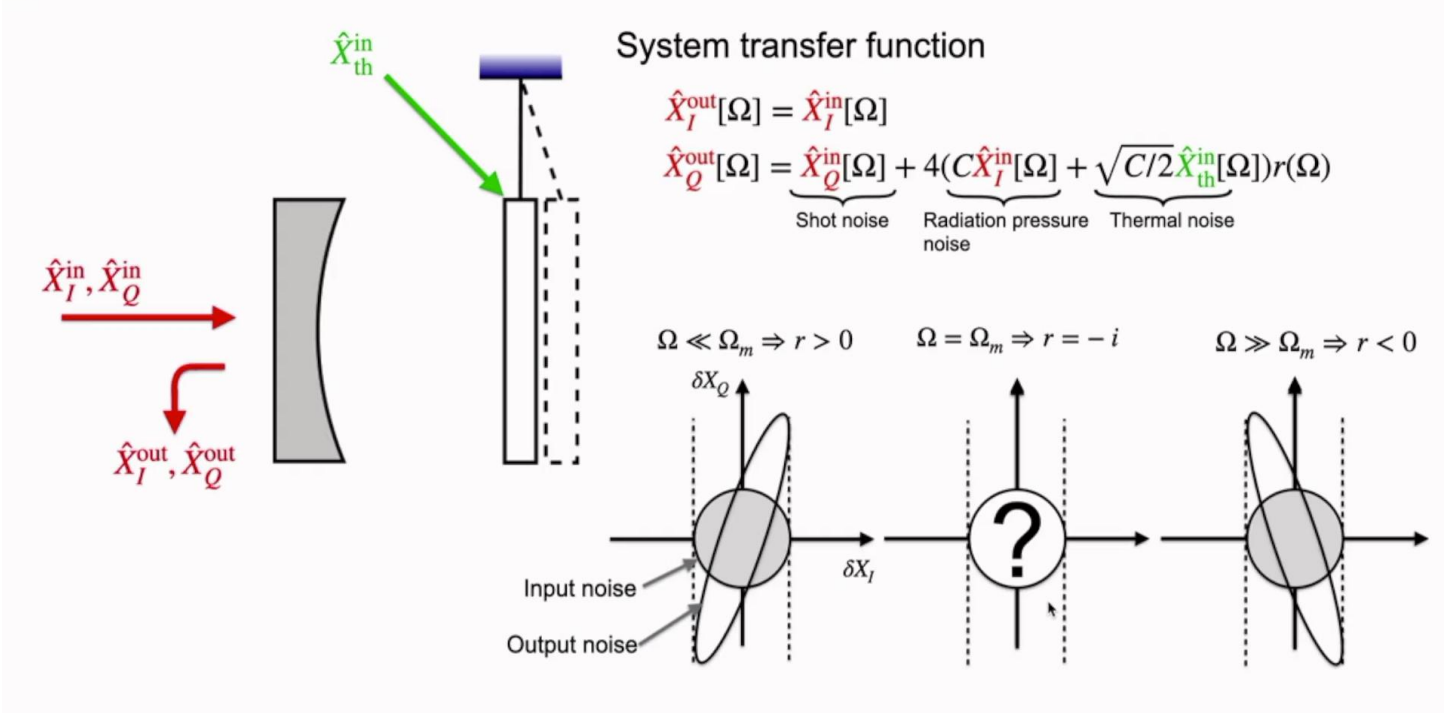
So if we collect all the terms together, we arrive at a pretty pleasant form by introducing a two dimensionless parameter, the optomechanical cooperativity 'C' and the normalized susceptibility 'r' of omega. The normalization constant here has been chosen such that the magnitude of this quantity equals to one at mechanical resonance frequency. The meaning of the various terms in this expression of the output phase is pretty transparent. The first one is the shot noise so from the input laser beam. The second one is the radiation pressure noise which is proportional to the intensity fluctuation of the field and the third one is the thermal noise, the thermomechanical noise. So we see that the relative strength between radiation pressure noise and shot noise is equal to four 'C' or in other words, at the mechanical resonance frequency, we will reach the standard quantum limit for value of 'C' of one over four. Now away from mechanical frequency, the dependence of this radiation pressure noise will be encoded by this function 'r' of omega. So, in particular, at low frequency 'r' is almost a positive real number such that the mirror response is in phase with the applied force so we'll have positive correlations between phase and intensity quadrature.

Notes

Summary

7m 43s

Optomechanical squeezing



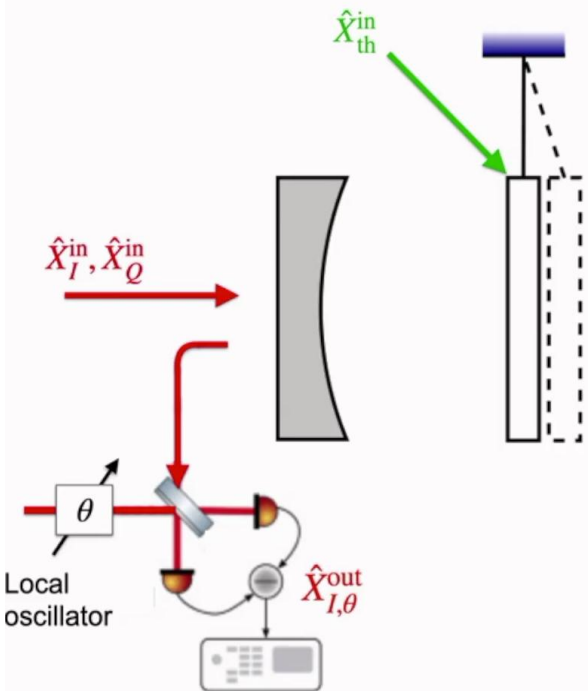
Above mechanical frequency 'r' is almost a negative number such that we have, we expect another phase in quadrature anti-correlated. And finally, at the mechanical resonance frequency where 'r' is an imaginary quantity, you might wonder how this phase space picture is going to look like. And so actually because here the resonator responds in quadrature with the radiation pressure force, we see that basically this 2D, this two-dimensional representation will fail at fully capturing the correlations, these complex correlations. However, it is still a valid question to ask whether the field is squeezed that means whether there exists a quadrature where the noise is below the shot noise level. So what we will do next is try to derive the noise spectrum for an arbitrary quadrature on the field.

Notes

Summary

9m 25s

Output spectrum



System transfer function

$$\hat{X}^{out}_{I}[\Omega] = \hat{X}^{in}_{I}[\Omega]$$

$$\hat{X}^{out}_{Q}[\Omega] = \hat{X}^{in}_{Q}[\Omega] + 4(C\hat{X}^{in}_{I}[\Omega] + \sqrt{C/2}\hat{X}^{in}_{th}[\Omega])r(\Omega)$$

Arbitrary quadrature:

$$\hat{X}^{out}_{I,\theta} = \cos(\theta)\hat{X}^{out}_{I} + \sin(\theta)\hat{X}^{out}_{Q}$$

$$= \underbrace{\cos(\theta)\hat{X}^{in}_{I} + \sin(\theta)\hat{X}^{in}_{Q}}_{\hat{X}_{Shot}} + \underbrace{4r(\Omega)\sin(\theta)\left(C\hat{X}^{in}_{I} + \sqrt{C/2}\hat{X}^{in}_{th}\right)}_{\hat{X}_{Mech}}$$

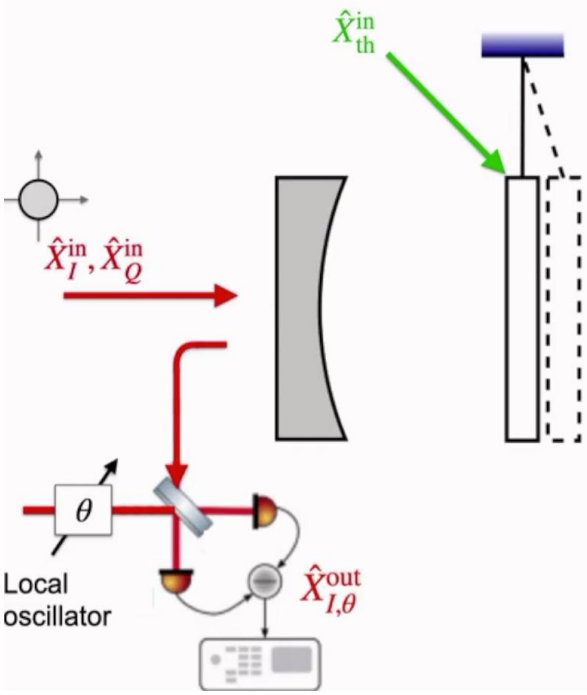
So let's imagine we are performing a homodyne detection of the output field and so the quadrature that is measured when setting the local oscillator phase to theta here is called 'X I theta out' and the associated observable is simply a rotation of the 'I' and 'Q' quadratures of the field. So since we have already calculated the system transfer function, we can inject this expression inside the expression for the output quadrature and we get the following. We have a first term that is simply the rotation of the input field quadrature. So this term we call it X-shot, it is just the shot noise of the light beam observed in the rotated quadrature. And then we have a second term that is proportional to the mirror displacement and with the sinus theta in factor. We call this X-mech. So now we can calculate the spectrum of this output quadrature by basically calculating the correlator between 'X out I theta' of omega and 'X out I theta' of minus omega and again I leave this as an exercise but bear in mind that since the input field is a coherent state, we can basically drop all the cross correlators between the various input fields.

Notes

Summary

10m 32s

Output spectrum



System transfer function

$$\hat{X}^{\text{out}}_{I}[\Omega] = \hat{X}^{\text{in}}_{I}[\Omega]$$

$$\hat{X}^{\text{out}}_{Q}[\Omega] = \hat{X}^{\text{in}}_{Q}[\Omega] + 4(C\hat{X}^{\text{in}}_{I}[\Omega] + \sqrt{C/2}\hat{X}^{\text{in}}_{\text{th}}[\Omega])r(\Omega)$$

Arbitrary quadrature:

$$\hat{X}^{\text{out}}_{I,\theta} = \cos(\theta)\hat{X}^{\text{out}}_{I} + \sin(\theta)\hat{X}^{\text{out}}_{Q}$$

$$= \underbrace{\cos(\theta)\hat{X}^{\text{in}}_{I} + \sin(\theta)\hat{X}^{\text{in}}_{Q}}_{\hat{X}_{\text{Shot}}} + \underbrace{4r(\Omega)\sin(\theta)\left(C\hat{X}^{\text{in}}_{I} + \sqrt{C/2}\hat{X}^{\text{in}}_{\text{th}}\right)}_{\hat{X}_{\text{Mech}}}$$

Noise spectral density: $S_{X^{\text{out}}_{I,\theta}X^{\text{out}}_{I,\theta}}[\Omega]2\pi\delta(\Omega+\Omega') = \langle \hat{X}^{\text{out}}_{I,\theta}[\Omega]\hat{X}^{\text{out}}_{I,\theta}[\Omega'] \rangle$

Output noise spectrum:

$$S_{X^{\text{out}}_{I,\theta},X^{\text{out}}_{I,\theta}}[\Omega] = \cos^2(\theta)S_{X^{\text{in}}_{I}X^{\text{in}}_{I}}[\Omega] + \sin^2(\theta)S_{X^{\text{in}}_{Q}X^{\text{in}}_{Q}}[\Omega] \leftarrow S_{X_{\text{Shot}}X_{\text{Shot}}}$$

$$+8C\sin^2(\theta)\left|r[\Omega]\right|^2\left(S_{X^{\text{in}}_{\text{th}}X^{\text{in}}_{\text{th}}}[\Omega] + 2CS_{X^{\text{in}}_{I}X^{\text{in}}_{I}}[\Omega]\right) \leftarrow S_{X_{\text{Mech}}X_{\text{Mech}}}$$

$$+8C\sin(\theta)\cos(\theta)\text{Re}[r(\Omega)]S_{X^{\text{in}}_{I}X^{\text{in}}_{I}}[\Omega] \leftarrow \text{Re}[S_{X_{\text{Shot}}X_{\text{Mech}}}$$

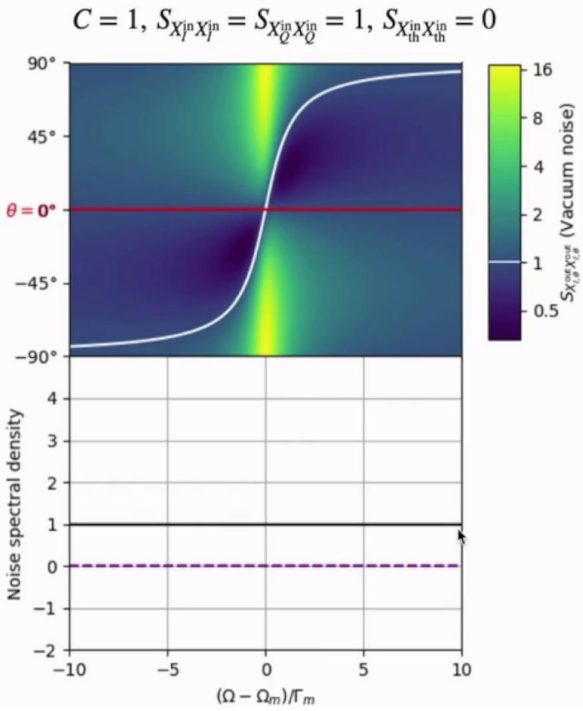
And what we get is the following expression for the output noise spectrum and it is here expressed as a function of the noise spectrum of the various input quadratures. So it is also arranged along three lines. The first one is the spectrum of this shot noise term. The second one is the spectrum of the mechanical noise and the third one is actually a term that arises because of the cross-correlator between X-mech and X-shot. So this term exists because there is this radiation pressure term which will correlate with this term in the shot noise. And this is why we have a sine theta cos theta in factor and if you do the math correctly you will also see that we have the real part of 'r' in this term. The way the homodyne detection is going to be sensitive to the correlation between X-mech and X-shot is via this cross-term which basically is the cross-spectrum, the real part of the cross-spectrum between X-shot and X-mech.

Notes

Summary

12m 03s

Output spectrum



System transfer function

$$\hat{X}_I^{out}[\Omega] = \hat{X}_I^{in}[\Omega]$$

$$\hat{X}_Q^{out}[\Omega] = \hat{X}_Q^{in}[\Omega] + 4(C\hat{X}_I^{in}[\Omega] + \sqrt{C/2}\hat{X}_{th}^{in}[\Omega])r(\Omega)$$

Arbitrary quadrature:

$$\hat{X}_{I,\theta}^{out} = \cos(\theta)\hat{X}_I^{out} + \sin(\theta)\hat{X}_Q^{out}$$

$$= \underbrace{\cos(\theta)\hat{X}_I^{in} + \sin(\theta)\hat{X}_Q^{in}}_{\hat{X}_{Shot}} + \underbrace{4r(\Omega)\sin(\theta)\left(C\hat{X}_I^{in} + \sqrt{C/2}\hat{X}_{th}^{in}\right)}_{\hat{X}_{Mech}}$$

Noise spectral density: $S_{X_{I,\theta}^{out}X_{I,\theta}^{out}}[\Omega]2\pi\delta(\Omega+\Omega') = \langle \hat{X}_{I,\theta}^{out}[\Omega]\hat{X}_{I,\theta}^{out}[\Omega'] \rangle$

Output noise spectrum:

$$S_{X_{I,\theta}^{out}X_{I,\theta}^{out}}[\Omega] = \cos^2(\theta)S_{X_I^{in}X_I^{in}}[\Omega] + \sin^2(\theta)S_{X_Q^{in}X_Q^{in}}[\Omega]$$

$$+8C\sin^2(\theta)\left|r[\Omega]\right|^2\left(S_{X_{th}^{in}X_{th}^{in}}[\Omega] + 2CS_{X_I^{in}X_I^{in}}[\Omega]\right)$$

$$+8C\sin(\theta)\cos(\theta)\mathrm{Re}[r(\Omega)]S_{X_I^{in}X_I^{in}}[\Omega]$$

← $S_{X_{Shot}X_{Shot}}$

← $S_{X_{Mech}X_{Mech}}$

← $\mathrm{Re}[S_{X_{Shot}X_{Mech}}$

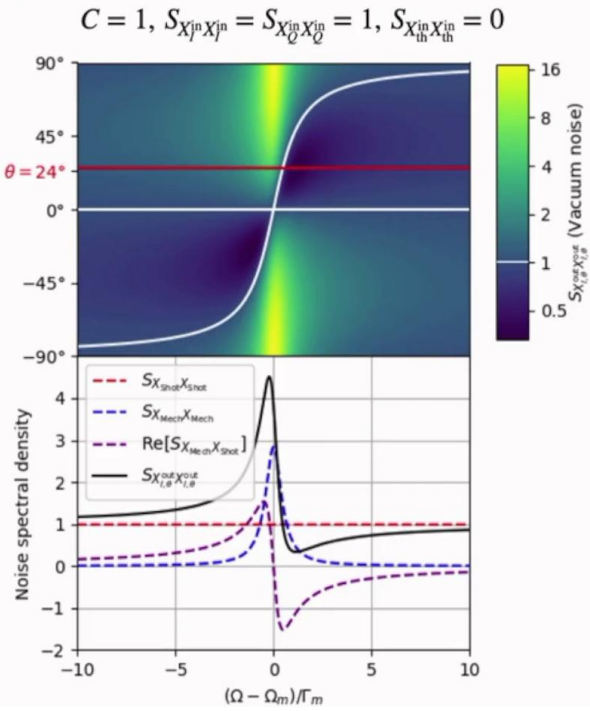
I've plotted here this expression as a function of a quadrature angle on the vertical axis theta and frequency omega on the horizontal axis and this calculation is made for the following set of parameters and you see in yellow the regions where the noise is the strongest and in blue the regions where the noise is the smallest. The regions where the noise spectrum is below one indicative of squeezings are delimited by these white lines here. So now we are going to explore this map of ponderomotive squeezing for various settings. So at first we can make a sanity check. If we choose the quadrature theta equals zero which corresponds to direct intensity detection, we see that this equation tells us that the output field is directly the input amplitude quadrature. So we expect a flat white noise with an amplitude equal to the shot noise level. And actually if we set theta equals zero in this expression, all the terms proportional to sine theta will vanish such that we are only left with the spectrum of the input intensity quadrature and so this is indeed a flat signal with an amplitude of one. So an important physical consequence of this is that there is no way, at least with our assumptions to observe ponderomotive squeezing by direct intensity detection.

Notes

Summary

13m 17s

Output spectrum



System transfer function

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$$\hat{X}_Q^{out}[\Omega] = \hat{X}_Q^{in}[\Omega] + 4(C\hat{X}_I^{in}[\Omega] + \sqrt{C/2}\hat{X}_{th}^{in}[\Omega])r(\Omega)$$

Arbitrary quadrature:

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$$= \underbrace{\cos(\theta)\hat{X}_I^{in} + \sin(\theta)\hat{X}_Q^{in}}_{\hat{X}_{Shot}} + \underbrace{4r(\Omega)\sin(\theta)\left(C\hat{X}_I^{in} + \sqrt{C/2}\hat{X}_{th}^{in}\right)}_{\hat{X}_{Mech}}$$

Noise spectral density: $S_{X_{I,\theta}^{out}X_{I,\theta}^{out}}[\Omega]2\pi\delta(\Omega + \Omega') = \langle \hat{X}_{I,\theta}^{out}[\Omega]\hat{X}_{I,\theta}^{out}[\Omega'] \rangle$

Output noise spectrum:

$$S_{X_{I,\theta}^{out}X_{I,\theta}^{out}}[\Omega] = \cos^2(\theta)S_{X_I^{in}X_I^{in}}[\Omega] + \sin^2(\theta)S_{X_Q^{in}X_Q^{in}}[\Omega] \quad \leftarrow S_{X_{Shot}X_{Shot}}$$

$$+8C\sin^2(\theta)\left|r[\Omega]\right|^2\left(S_{X_{th}^{in}X_{th}^{in}}[\Omega] + 2CS_{X_I^{in}X_I^{in}}[\Omega]\right) \quad \leftarrow S_{X_{Mech}X_{Mech}}$$

$$+8C\sin(\theta)\cos(\theta)\mathrm{Re}[r(\Omega)]S_{X_I^{in}X_I^{in}}[\Omega] \quad \leftarrow \mathrm{Re}[S_{X_{Shot}X_{Mech}}$$

So we can now look at the phase quadrature so which is the measurement setting that is traditionally employed in interferometric measurement setup so, so in this case, it's only the last term here in this expression that will vanish because of the cosine theta dependence such that the total output spectrum is just the sum of the two other terms, the shot noise which is represented here in the red and the mechanical noise that is here in blue. Because the first one is a flat spectrum of amplitude one and the second one by definition of the noise spectrum is a positive quantity, we immediately see that the total spectrum cannot take values below one. In other words, there cannot be squeezing either on the phase quadrature with these settings. So, however, for an intermediate quadrature angle, now this cross term starts to take non-zero value. It is represented here by the purple curve and the interesting thing is that contrary to the two other terms it's can take also positive values and negative values. In particular, the sign of this contribution will depend on the real part of 'r' of omega.

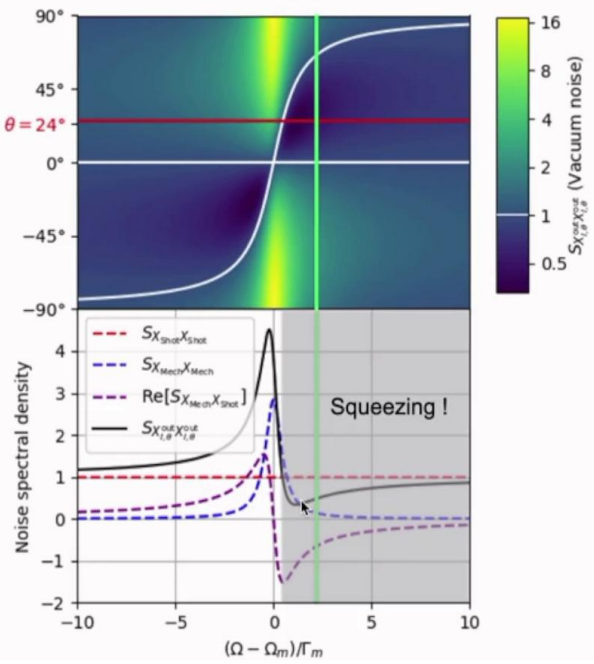
Notes

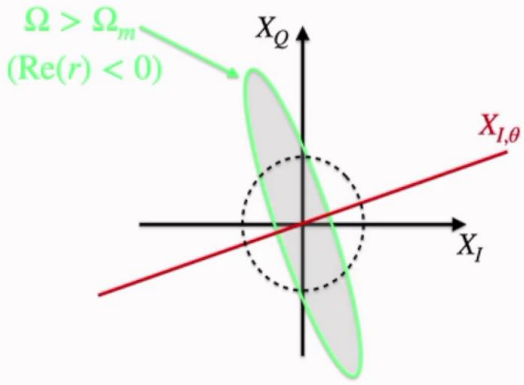
Summary

15m 03s

Output spectrum

$C = 1,\ S_{X_j^{in}X_j^{in}} = S_{X_Q^{in}X_Q^{in}} = 1,\ S_{X_{th}^{in}X_{th}^{in}} = 0$





Output noise spectrum:

$$S_{X_{I,\theta}^{out}X_{I,\theta}^{out}}[\Omega] = \cos^2(\theta)S_{X_j^{in}X_j^{in}}[\Omega] + \sin^2(\theta)S_{X_Q^{in}X_Q^{in}}[\Omega] \leftarrow S_{X_{Shot}X_{Shot}}$$

$$+8C\sin^2(\theta)\left|r[\Omega]\right|^2\left(S_{X_{th}^{in}X_{th}^{in}}[\Omega] + 2CS_{X_j^{in}X_j^{in}}[\Omega]\right) \leftarrow S_{X_{Mech}X_{Mech}}$$

$$+8C\sin(\theta)\cos(\theta)\mathrm{Re}[r(\Omega)]S_{X_j^{in}X_j^{in}}[\Omega] \leftarrow \mathrm{Re}[S_{X_{Shot}X_{Mech}}$$

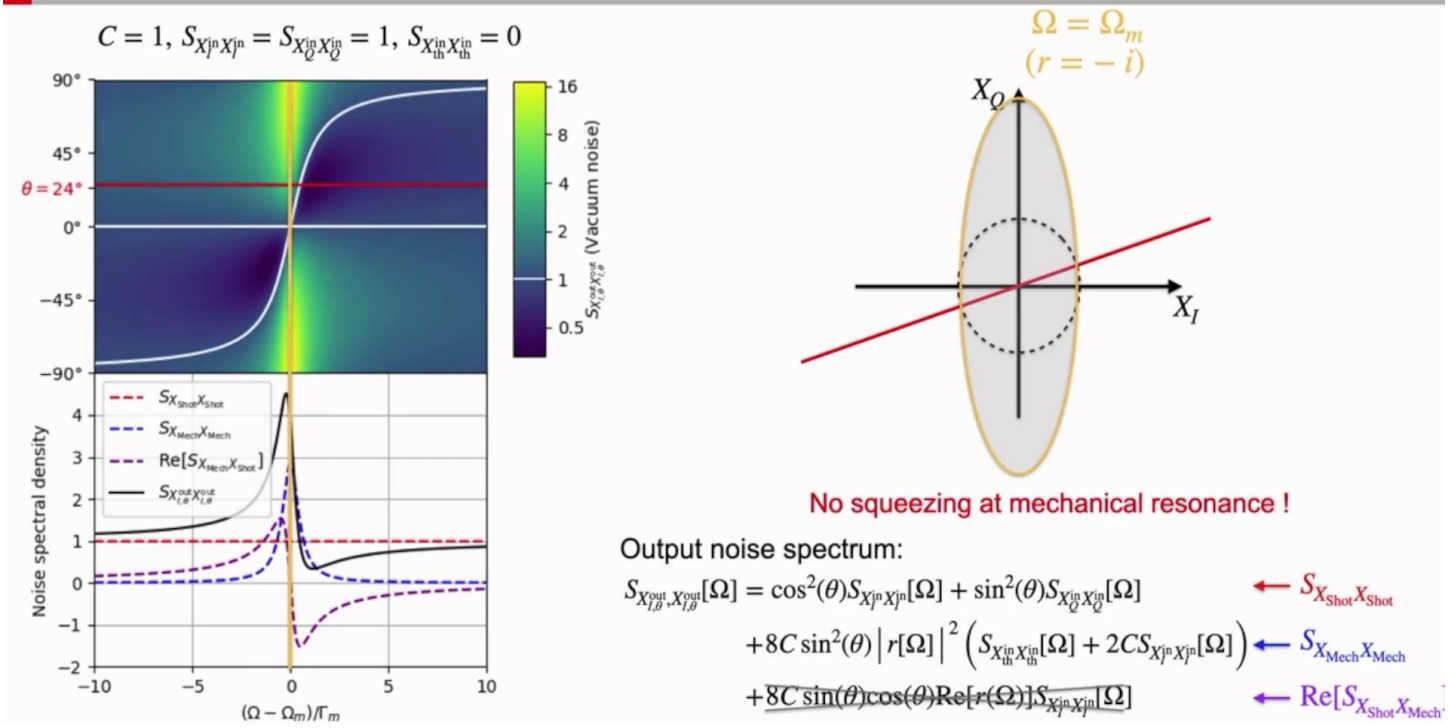
So above mechanical resonance where real of 'r' is negative will have a negative contribution of the cross-spectrum. So it is in this region that we can have a total noise below one and thus observe ponderomotive squeezing.

Notes

Summary

16m 24s

Output spectrum



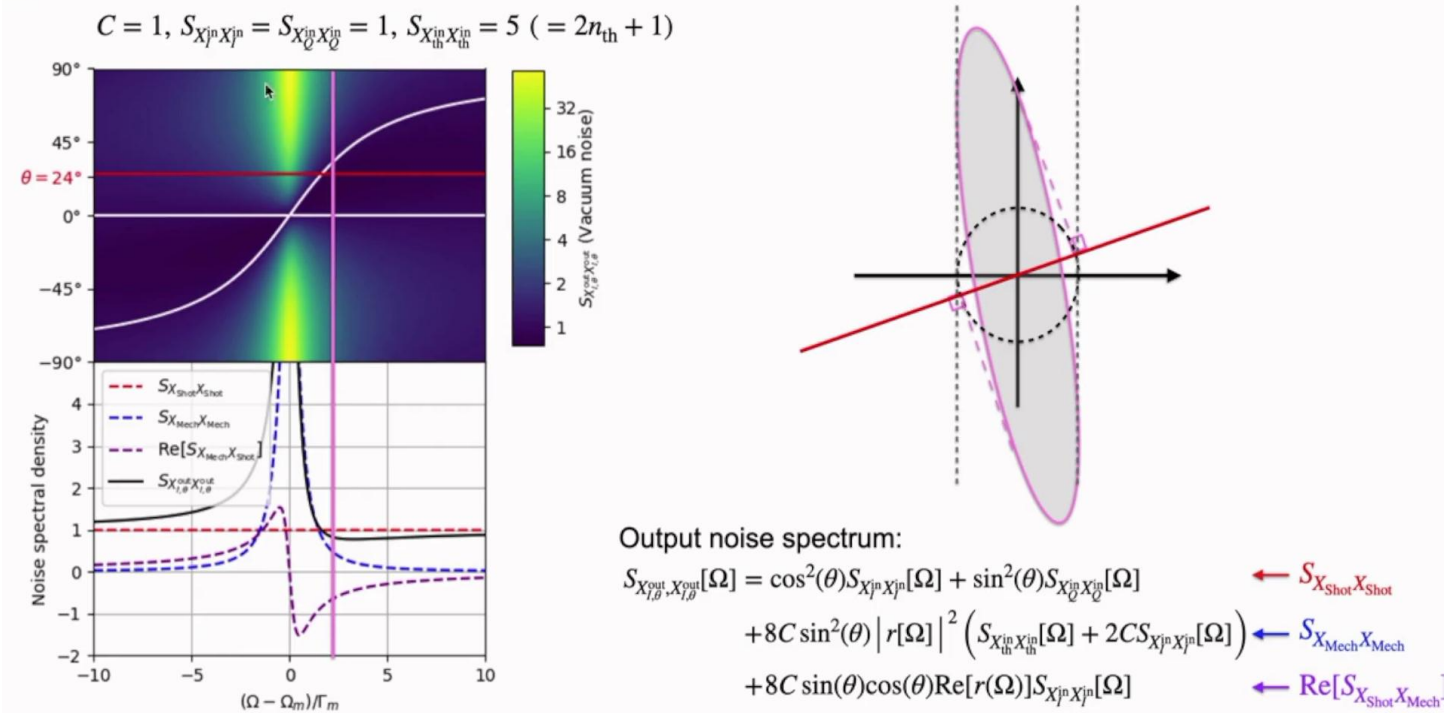
On the other hand, below mechanical resonance frequency the real of 'r' is positive such that the cross-spectrum contribution is positive and we observe an increase of noise in this region. Of course, if we had chosen a negative quadrature angle because of this sine theta here, the situation will be reversed. We would observe ponderomotive squeezing at low frequency and an increase of noise at high frequency. So now we can come back to our initial question. Can we observe ponderomotive squeezing at the mechanical resonance frequency? So this is actually a very legitimate question because it is at this frequency that the phase amplitude correlations are the strongest in magnitude. However, now that we have rigorously derived the homodyne spectrum, we can clearly see that with this kind of detection the spectrum is not sensitive to anything but the real part of the correlations. So the answer is no. There is no squeezing at the mechanical resonance frequency. So this doesn't mean that these complex correlations between amplitude and phase are impossible to detect but it's just that the homodyne detection is non-sensitive to such kind of detection of correlations.

Notes

Summary

16m 44s

Influence of thermal noise

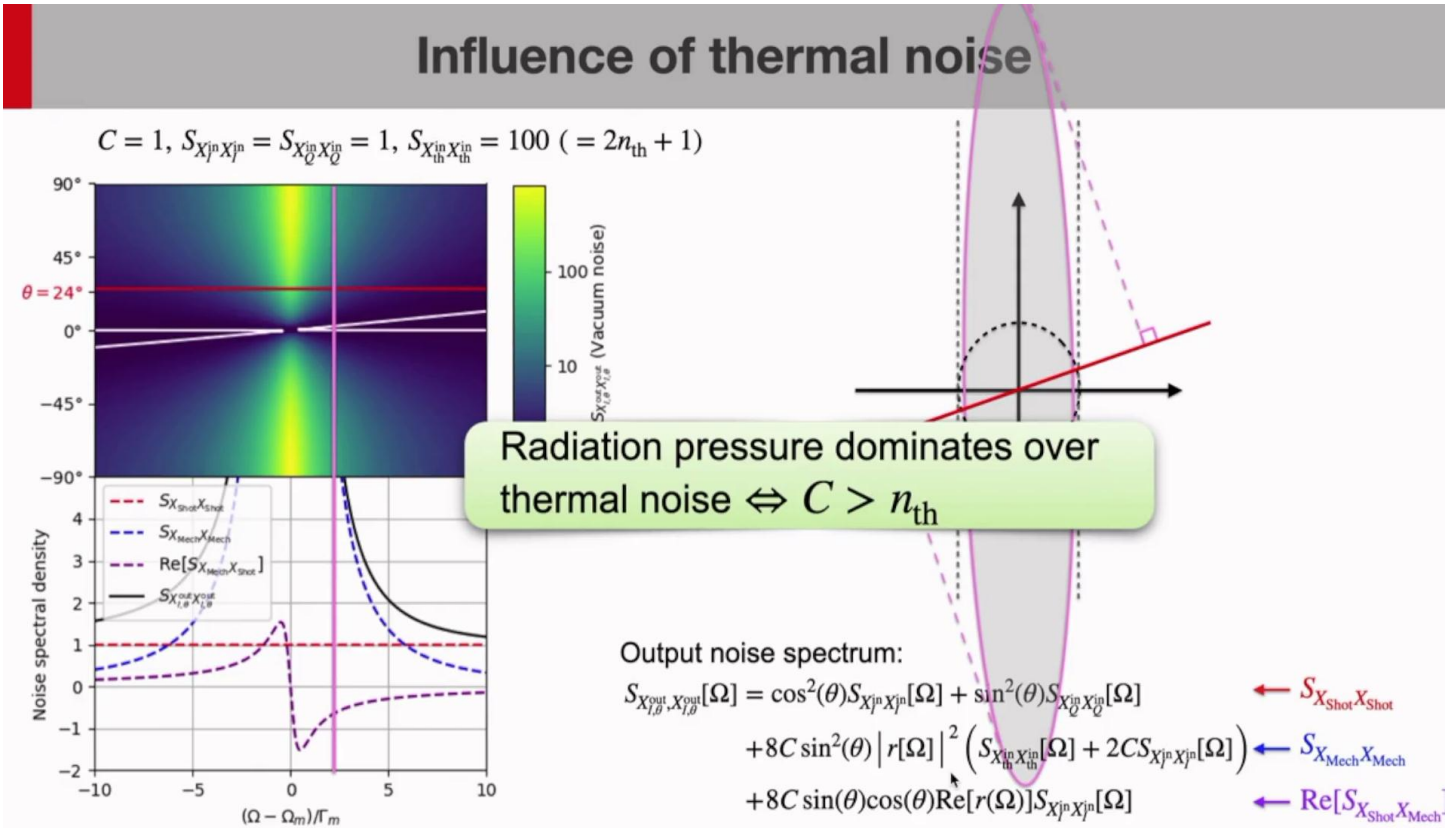


However in 2016, an alternate detection scheme was proposed that would be sensitive very sensitive to this kind of complex correlations. This goes beyond the scope of this video but I encourage you to check the reference. You might have noticed that up to this point, I never mentioned the influence of the thermal noise. Actually in these calculations, I've always taken the input thermal spectrum to be zero which, by the way, is unphysical because we know that at least quantum fluctuations need to enter through this part. So the thermal noise pop ups here in the equations. It's affecting the mechanical spectrum without affecting the shot noise or the correlation term and what I'm going to do now is that I'm going to crank up this thermal noise and we're going to look at the influence on the squeezing map here. So for relatively small noise spectrum what we see is two thing. First of all, the extent of the squeezing region decreases and second, the minimum achievable level of noise within the squeezing region goes up.

Notes

Summary

18m 12s



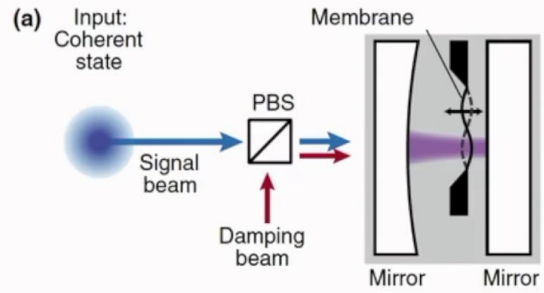
Now if we crank up the thermal noise even more, actually we see something interesting which is that away from far enough from mechanical resonance there will always be a zone where there is still some squeezing left and the reason is the following. It's that here this term which is this one, sorry, which is quadratic with respect to 'r' decreases faster with detuning than this one. So no matter what there will always be zones where there is still some squeezing left. However, in practice the level of squeezing is is so small that it will be undetectable in practice. So we arrive at basically the practical condition to observe squeezing which is that basically the thermal noise here should be smaller or comparable to the radiation pressure noise here in this term and so if we look at the condition this means that the cooperativity needs to be larger than the thermal occupation of the bath. This is this condition that has been the most challenging to fulfill in actual experiments and that's the reason why most of the demonstrations of ponderomotive squeezing to date have been performed in cryogenic environments.

Notes

Summary

19m 35s

Experimental realization



System parameters:

Mechanical parameters:
$\Omega_m/2\pi = 1.5\,\mathrm{MHz}$
$m_{\mathrm{eff}} = 7\,\mathrm{ng}$
$\Gamma_m/2\pi = 0.2\,\mathrm{Hz}$ → $\frac{\Gamma_{\mathrm{eff}}}{2\pi} = 2.5\,\mathrm{kHz}$

Optical parameters:
$\kappa/2\pi = 1.7\,\mathrm{MHz}$
$|\alpha|^2 = 10^8$

Coupling:
$g_0/2\pi = 30\,\mathrm{Hz}$

Temperature:
$T = 4\,\mathrm{K}$ → $T_{\mathrm{eff}} = 0.4\,\mathrm{mK}$

$C \sim 100$
$n_{\mathrm{th}} \sim 5$

Purdy et al., PRX **3**, 031012 (2013)

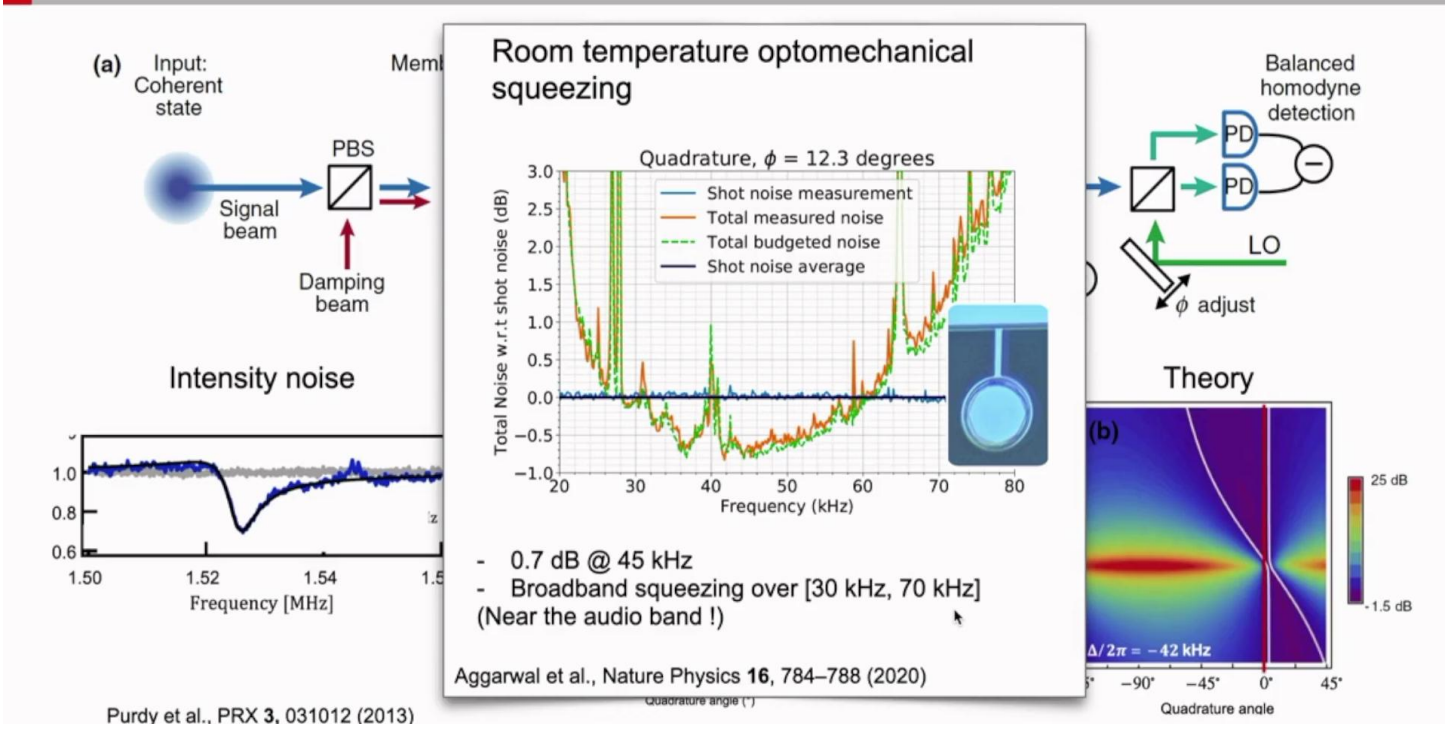
For instance, here's one of the first experimental demonstration so it employs a standard membrane in the middle setup that was cooled at the temperature of four kelvin and if you look at the system parameters and do the math, you will see that the expected ratio between radiation pressure force and thermal noise is approximately ten in this system. However, this would happen at cooperativity of more than a million and this would make the system highly unstable. That's the reason why a second damping beam was employed so this beam is performing basically laser cooling and it does two things. First of all, it provides damping, extra damping to the mechanical resonator and second, it reduces the temperature of the environment. So with this effective optomechanical system basically we see that we can get into the regime where radiation pressure shot noise dominates still by roughly a factor ten but this happens now for a cooperativity of approximately one hundred. So the detection setup was designed in such a way that one can perform either direct intensity measurement or homodyne detection with an adjustable angle.

Notes

Summary

21m 00s

Experimental realization



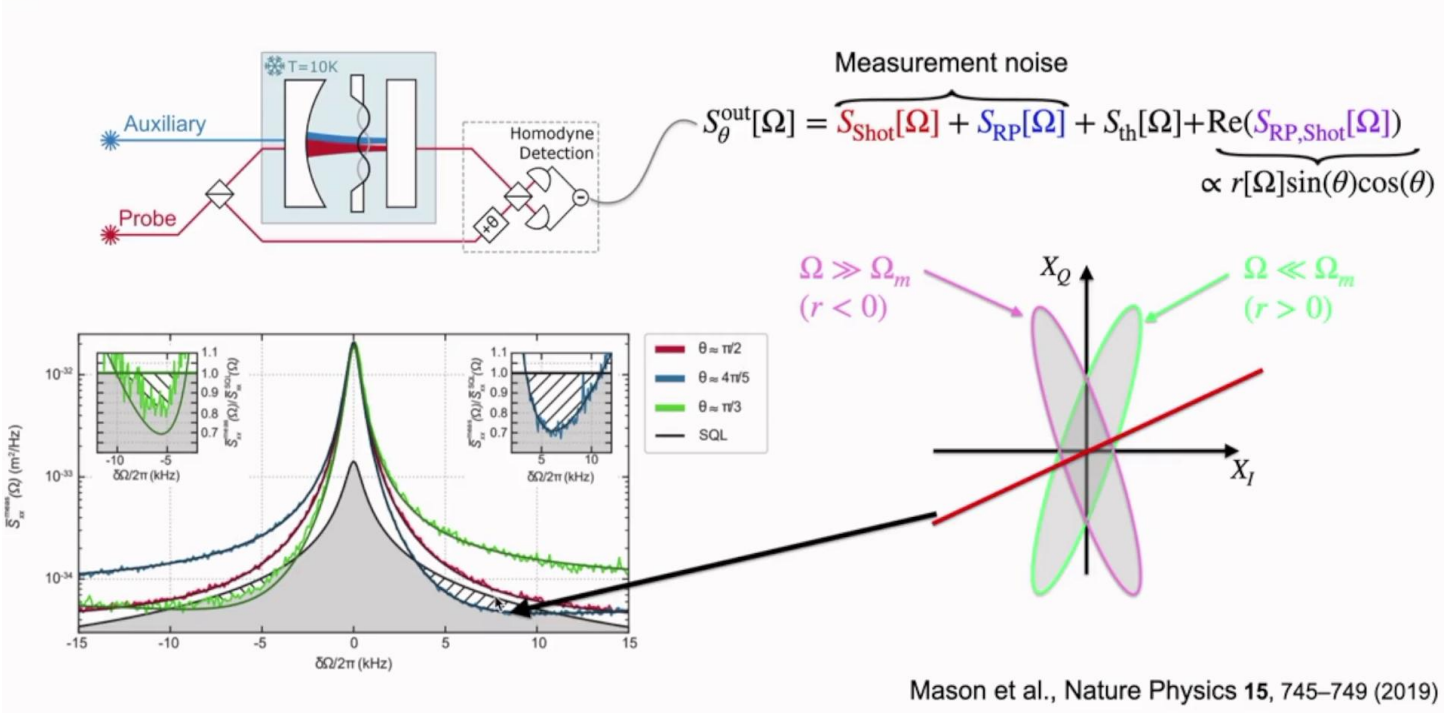
The expected spectrum resembles very much the one we have derived before except now that the vertical axis is now the frequency and the horizontal axis, the quadrature angle. The measure spectrum looks a bit more complex because of the presence of other mechanical modes here, however, close to the membrane frequency. We indeed observe ponderomotive squeezing roughly in the regions where we expect it. So furthermore, one thing that is different in this experiment compared to the model we have studied before is that there is a finite detuning between the signal beam and the cavity and in this case one can show that we indeed expect squeezing even at the zero degree quadrature angle. And so that's exactly what they observed by direct intensity detection. This is typically a 1.5 db squeezing signal. Recently, the MIT group has demonstrated a room temperature optomechanical squeezing employing ultra soft crystalline cantilever like this one. Another very exciting aspect of this work is that by operating far from mechanical frequency where the susceptibility is basically very flat, they could observe broadband squeezing and actually in a band that is very close to the audio band relevant for gravitational wave detectors. So this work shows that optomechanical squeezing might become a practical way of generating squeezed light in the future.

Notes

Summary

22m 37s

Beating the SQL with optomechanical correlations



Mason et al., Nature Physics **15**, 745–749 (2019)

As a last point, I wanted to stress that optomechanical correlations can be used to perform measurement below the Standard Quantum Limit as demonstrated recently in the Copenhagen group. So in this context, we know that the shot noise and radiation pressure noise are the two fundamental measurement noises and that they are sum if we express it in units of displacement spectrum has to be larger than the Standard Quantum Limit. However, even if we inject a coherent state inside the system, well, the optomechanical system will generate its own correlation between these two noises such that the total output spectrum can become smaller than the sum of these two noises. So actually in this graph, we see three experimental curves. The first one was acquired with a homodyne phase as pi over two and as discussed in this video, in this case the cross-spectrum term vanishes such that as expected we the total noise spectrum is always above the Standard Quantum Limit. In green a small positive quadrature angle has been chosen and indeed we observe that the noise is increased above mechanical resonance frequency and it is decreased below resonance frequency and even below the Standard Quantum Limit here in this region. For the opposite quadrature angle, we see the opposite effect.

Notes

Summary

24m 33s

CONCLUSION / SUMMARY

- The optomechanical non-linearity can be used to generate squeezed light
- Squeezing arises from the correlations induced by radiation pressure between the amplitude and phase quadratures
- Because of the mechanical susceptibility, these correlations can be complex and frequency dependent near mechanical resonance
- Room-temperature broadband optomechanical squeezing demonstrated
- Homodyne detection of the optomechanical correlations can be used to beat the SQL in interferometric position measurements

Okay, to summarize this video. We've seen that the optomechanical nonlinearity can be used to generate squeezed light. We've seen that this squeezing arises from correlation induced by radiation pressure between the amplitude and the phase quadrature of the field. And because of the mechanical susceptibility, these correlations can become complex and frequency dependent near mechanical frequency. We've seen that room-temperature broadband optomechanical squeezing has recently been demonstrated and finally, we've seen that homodyne detection of this optomechanical correlations could be used to beat the Standard Quantum Limit in interferometric position measurements.

Notes

Summary

26m 20s