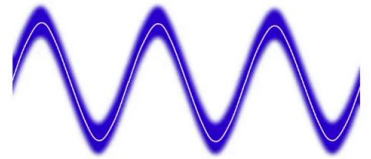


EPFL

OUTLINE

- **(Squeezed) uncertainties of a monochromatic wave**
- **Amplitude- and phase-squeezed states**
- **Heisenberg uncertainty relation**
- **Generation of squeezed light, part 1**
- **Generation of squeezed light, part 2**
- **Hamilton operators**
- **Photon number statistics of squeezed states**



With this lecture, I will give you introduction to the generation of squeezed light. I will basically consider the quantum uncertainties of a monochromatic wave. Such a wave can be in a coherent state as you can see here. Or in an amplitude or phase-squeezed state. But the main part of this lecture is about the generation of squeezed light. Finally, we will consider photon number statistics.

Notes

Summary



0m 00s

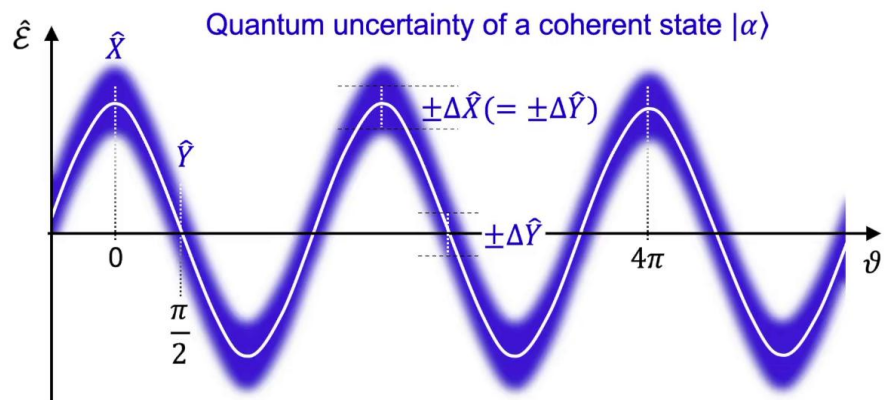
UNCERTAINTIES OF A MONOCHROMATIC WAVE

(a) Coherent state variances

$$\Delta^2 \hat{X} = \frac{1}{4}$$

$$\Delta^2 \hat{Y} = \frac{1}{4}$$

$$(\Delta^2 \hat{X}_\vartheta = \frac{1}{4})$$



$$\hat{X} \equiv \hat{X}_{0^\circ} = -\hat{X}_{180^\circ} = \hat{X}_{360^\circ} \text{ ('Amplitude quadrature')}$$

$$\hat{Y} \equiv \hat{X}_{90^\circ} = -\hat{X}_{270^\circ} \text{ ('Phase quadrature')}$$

Heisenberg uncertainty relation: $\Delta^2 \hat{X} \cdot \Delta^2 \hat{Y} \geq \frac{1}{16}$

What you see here is the electric field strength of a monochromatic wave together with its quantum uncertainty which is given in blue. The electric field strength at the extrema so here, here and here, we call 'X', the amplitude quadrature. The electric field strength in the nodes we call 'Y', the phase quadrature. And for a coherent state, the uncertainty in the electric field is independent of the phase theta. So the magnitude of the uncertainty here is identical to the one here. Quite generally in physics, the amplitudes of a wave at different phases cannot be precisely determined simultaneously. There's, in fact, an Heisenberg uncertainty relation for 'X' and 'Y' so the product of their variances, this is my symbol for the variance, is always greater or equal one over 16 where this number depends on the normalization. So for a coherent state, the variances are one-quarter which means that Heisenberg's uncertainty relation is saturated so is at its minimal, one over 16.

Notes

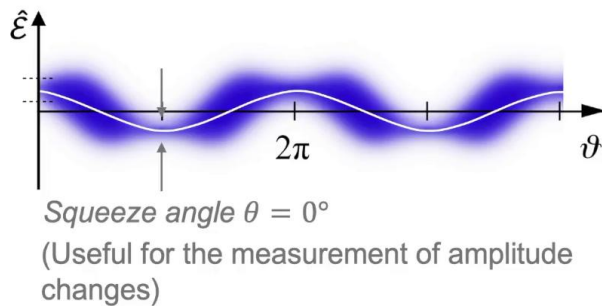
Summary



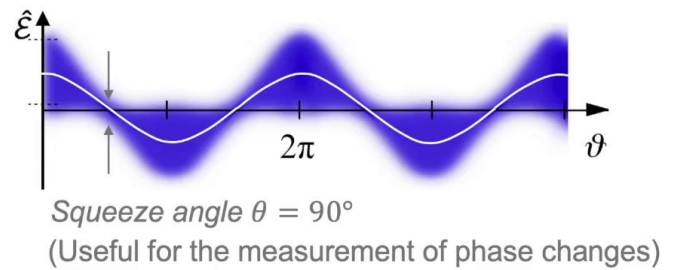
0m 34s

UNCERTAINTIES OF A MONOCHROMATIC WAVE

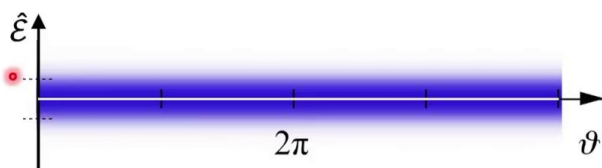
(b) Amplitude squeezed state $|\xi\rangle$, $\theta = 0^\circ$



(c) Phase squeezed state $|\xi\rangle$, $\theta = 90^\circ$



(d) Ordinary vacuum state $|0\rangle$



Let's have a look at squeezed states which are label with the Greek letter xi. If the electric field strength is squeezed in the extrema here, here and here, we call it an amplitude squeezed state. The squeeze angle is zero in this case. There is also a phase squeezed state. Here the electric field strength is squeezed around the nodes so here, here and there. In this case, the squeeze angle is 90 degrees. Now you may ask whether these states are useful in measurements. Yes, they are. So imagine you would like to measure small changes of the amplitude of the wave then it is very useful to have lowest noise in the extrema of the wave. So in this case, you would use an amplitude squeezed state. Imagine you would like to measure a distance a wave propagates. Then you would like to measure the position of the nodes and you need lowest noise in the nodes. In this case, you would use a phase squeezed state. There are more interesting states of a monochromatic wave. First of all, there is the ordinary vacuum state. It has zero photons on average. Also the expectation value of the electric field strength is zero for all phases.

Notes

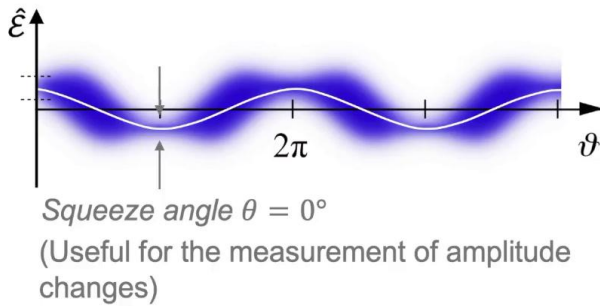
Summary



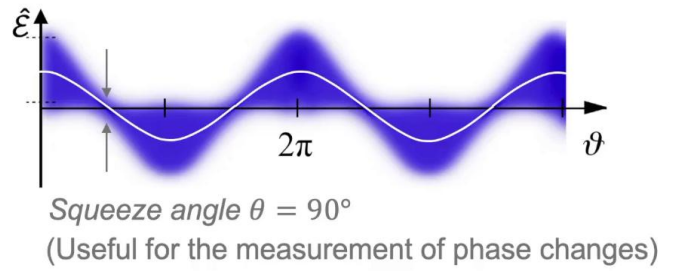
2m 04s

UNCERTAINTIES OF A MONOCHROMATIC WAVE

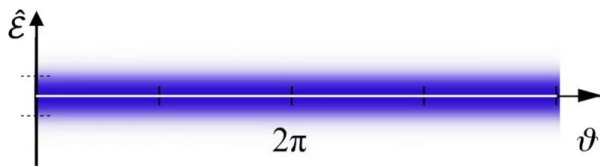
(b) Amplitude squeezed state $|\xi\rangle$, $\theta = 0^\circ$



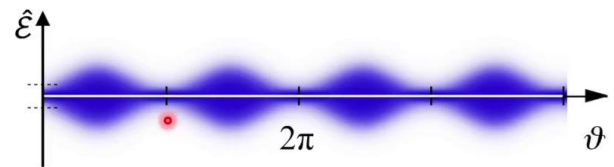
(c) Phase squeezed state $|\xi\rangle$, $\theta = 90^\circ$



(d) Ordinary vacuum state $|0\rangle$



(e) Squeezed vacuum state $|\xi\rangle$



But there is some uncertainty and this means if you take the expectation value of the square of the electric field, this is not zero. Also, the vacuum state can be squeezed then at some phases the uncertainty in the electric field strength is increased and here it is squeezed.

Notes

Summary



3m 50s

HEISENBERG UNCERTAINTY RELATION

The strength of squeezing is quantified by the squeeze factor e^{2r} , with r the squeeze parameter.

Example: From the picture, we read the scaling of the *standard deviations*. $\Delta\hat{Y}$ is about $e^r = 1.5$ times smaller than that of the coherent state.

$\Delta\hat{X}$ is larger by the *same* factor.

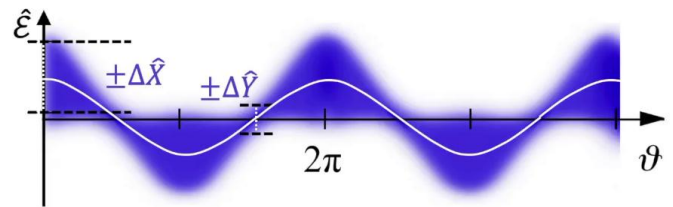
The scaling of the *variances* correspond to the squeezed factor $e^{\pm 2r}$.

→ The state is pure and saturates **Heisenberg's uncertainty relation**: $\Delta^2\hat{X} \cdot \Delta^2\hat{Y} \geq \frac{1}{16}$

Here, $\Delta^2\hat{Y}$ is $e^{2r} = 1.5^2 = 2.25$ times smaller than the variance of the coherent state.

And the squeeze factor in dB is given by: $-10 \log_{10} \left(\frac{1}{2.25} \right) \approx 3.5 \text{ dB}$

Phase squeezed state, $\theta = 90^\circ$



The strength of the squeezing is quantified by the squeeze factor 'e' to the two 'r' where 'r' is the squeeze parameter. We now want to find out how strong the squeezing is in this picture. I simply took a ruler and measured the magnitude of the uncertainty in the regions of squeezing and also in the regions of anti-squeezing. I found that this uncertainty is about 1.5 times smaller than the uncertainty of a coherent state the slides before. Here the uncertainty is about 1.5 times larger than the uncertainty of a coherent state. This factor of 1.5 correspond to the factor 'e' to the power of 'r', with 'r' the squeeze parameter. This factor describes the scaling of the standard deviations in 'Y' and in 'X'. If we square of this factor, we get the scaling of the variances and they correspond to the squeeze factor, in this case 'e' to the power of plus two 'r'. Since the factor is identical for squeezing and anti-squeezing, the state is pure so this state here is pure and it saturates Heisenberg's uncertainty relation. In our example, the square of the factor 1.5 corresponds to 2.25 which is the squeeze factor in this example and we can easily calculate the squeeze factor in dB. We take this factor while we take the inverse of this factor, take the logarithm to the bases of ten, multiply with minus ten and we get for this example 3.5 dB.

Notes

Summary



GENERATION OF SQUEEZED LIGHT (PART 1)

Simplified setup *without* resonator

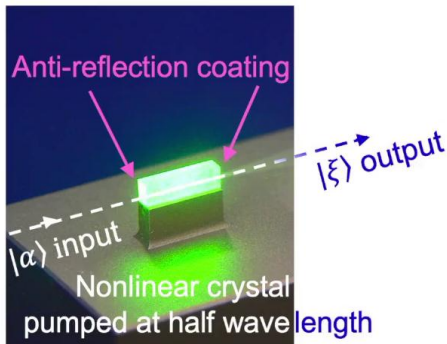
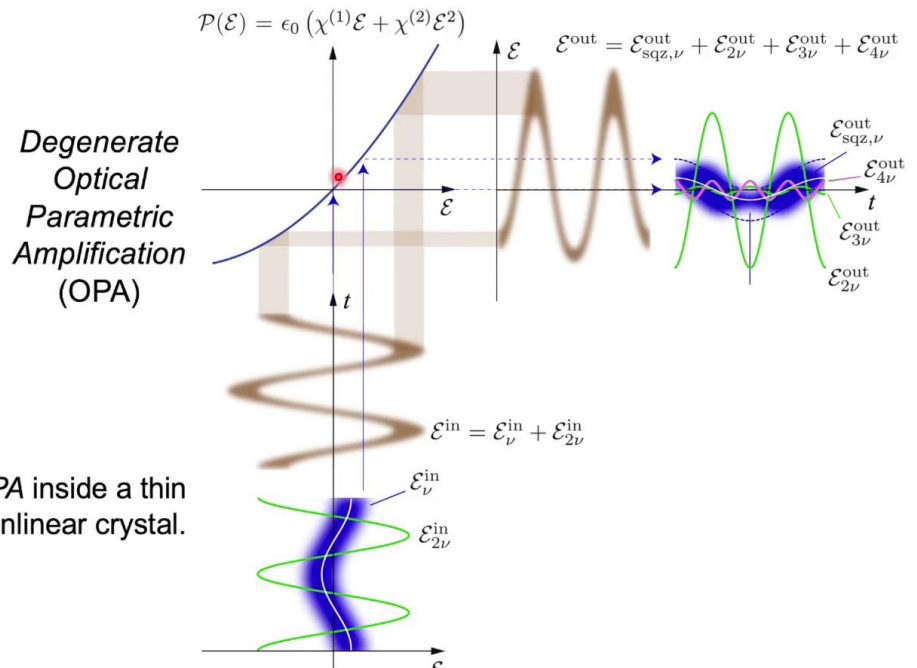


Illustration of *degenerate* OPA inside a thin layer of a 2nd-order nonlinear crystal.



We are now coming to the generation of squeezed light. First, we consider a simplified set up without any resonator. We simply have a nonlinear crystal, a coherent state input and a squeezed output. The crystal should be coated with some anti-reflection coating to avoid optical losses. What we now need to do is we need to pump the crystal with monochromatic light of half the wavelength so frequency doubled light. Then the process is called Degenerate Optical Parametric Amplification or in short, OPA. The question now is, what happens in a very thin slice of the crystal? And for this, I'm showing you a rather busy illustration which is quite useful. So 'P' is the polarization of the medium when light with the electric field strength 'E' is transmitted. There is some linear response which means that the deflection of the charges inside the medium are proportional to the electric field rings. And then there is some quadratic part. Here the deflection of the charges depends on the square of the electric field of the light. The situation is summarized in this line here. The slope of this line needs to be one at the origin of this graph, electric field strength versus polarization of the medium.

Notes

Summary



6m 24s

GENERATION OF SQUEEZED LIGHT (PART 1)

Simplified setup *without* resonator

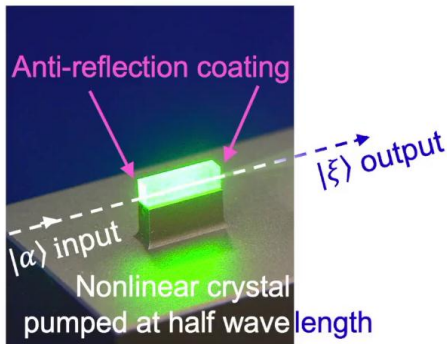
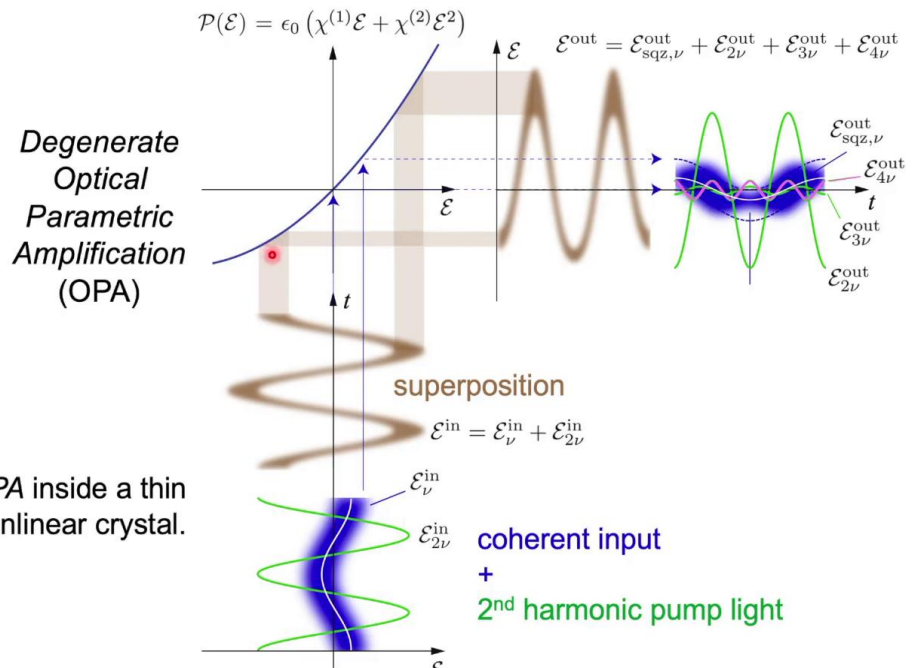


Illustration of *degenerate OPA* inside a thin layer of a 2nd-order nonlinear crystal.



And then we have the input fields. We have the very intense pump field where we not need to consider any uncertainty and there is a coherent input here with a blue uncertainty. These two inputs superimpose to this brownish wave here. And this wave hits now our polarization so hits this line. The negative extrema of the pump field bring the uncertainty of this field into the region of rather low slope. The maxima brings the uncertainty into a region of higher slope. So the charges in the material oscillate at the frequency of the input and this oscillation produces new light so the output light here. And the output light is now in this graph leaving towards the right and it is the brownish output here. This field we now need to decompose into the different frequencies. We have the green pump field at two nu frequency and we have the uncertainty at frequency nu. And now you see that there are regions where the uncertainty is squeezed and others where the uncertainty is anti-squeezed. This squeezed uncertainty comes from this situation when the pump field drives the uncertainty into the region of a below unity slope. Here you see the transition.

Notes

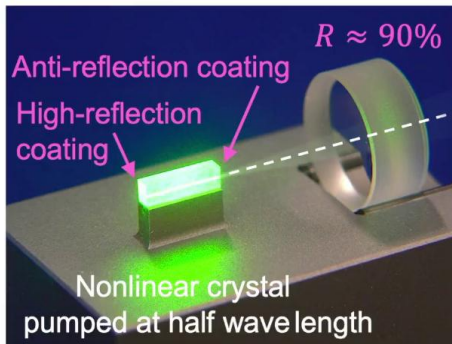
Summary



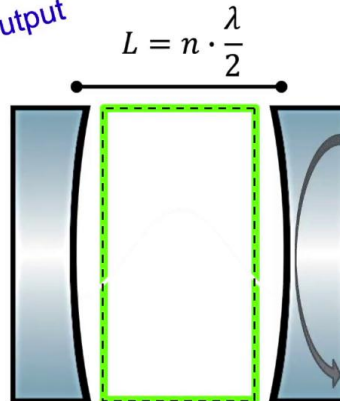
8m 18s

GENERATION OF SQUEEZED LIGHT (PART 2)

Complete setup: resonator-enhanced OPA



$|\alpha\rangle$ input
 $|\xi\rangle$ output



Purpose of the resonator in squeezed light generation

$|\alpha\rangle$ input

$|\xi\rangle$ output

And the larger uncertainty is from this region here where the pump field drives the field into the region of larger slope. Also, we have frequency doubling from two ν to four ν . In the experiment, we need to separate all this frequency to make experiments just with this squeezed uncertainty. In our case, we have an amplitude squeezed output field. So far we considered the squeezing due to a very thin slice of the crystal. In case of phase matching inside the crystal, which means that the speed of light of these two inputs are identical, the squeezing in every thin slice adds up and accumulate to a measurable squeezing in the output beam. The setup for squeezed light generation is completed by putting the crystal into an optical resonator which is here given by the back surface of the crystal and an additional coupling mirror of 90 percent reflectivity, which serves as an input and output coupler. This here is the simplified sketch of the resonator which I will now use to explain the purpose of the resonator in squeezed light generation. So the input is in a coherent state. Most of the power, in fact 90 percent, is directly reflected at the coupling mirror.

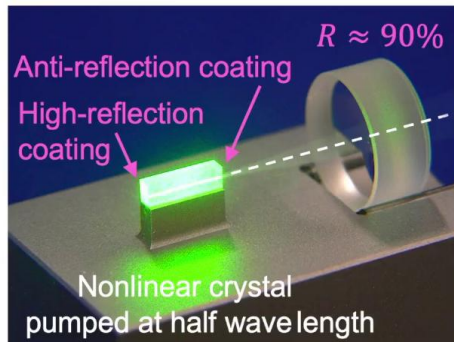
Notes

Summary

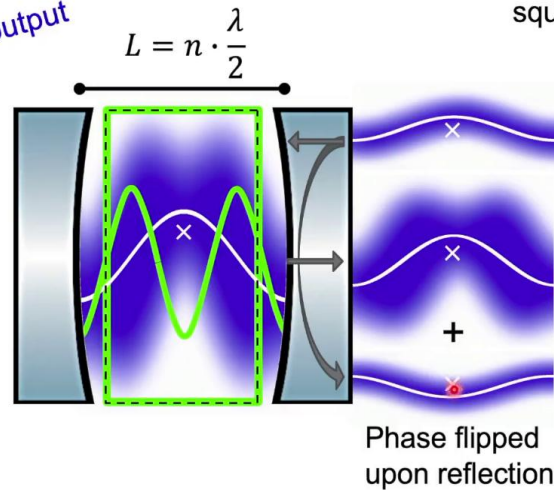


GENERATION OF SQUEEZED LIGHT (PART 2)

Complete setup: resonator-enhanced OPA



$|\alpha\rangle$ input
 $|\xi\rangle$ output



Only ten percent of the power in this case is transmitted into the optical resonator where we have the crystal which is pumped by the frequency doubled light. Due to Optical Parametric Amplification, we have a standing wave at fundamental frequency which is parametrically amplified and squeezed here where the pump field has a minimum and amplified here where the pump field has a maximum. Of course, the intracavity field is transmitted through the coupler to the outside where we now have two fields which will interfere. To understand the interference, we now label the quantum uncertainty of the input field in the following way. The crosses now mark the regions below the average field. In fact, all the quantum uncertainties here belong to the same mode. Ten percent of the power is parametrically amplified and 90 percent is reflected. So if we now label the uncertainty like this, we find the same cross here as well as here. But in the course of this reflection, we have a phase flip which is necessary to obey energy conservation at this beam splitter. So here the uncertainty is flipped and this cross now is above the average electric field.

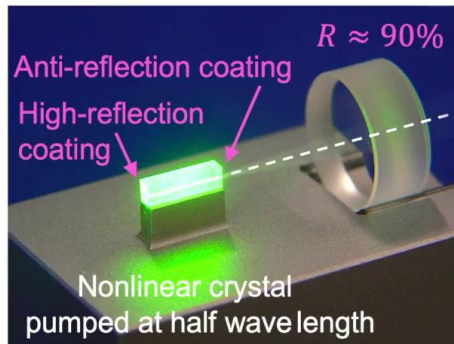
Notes

Summary



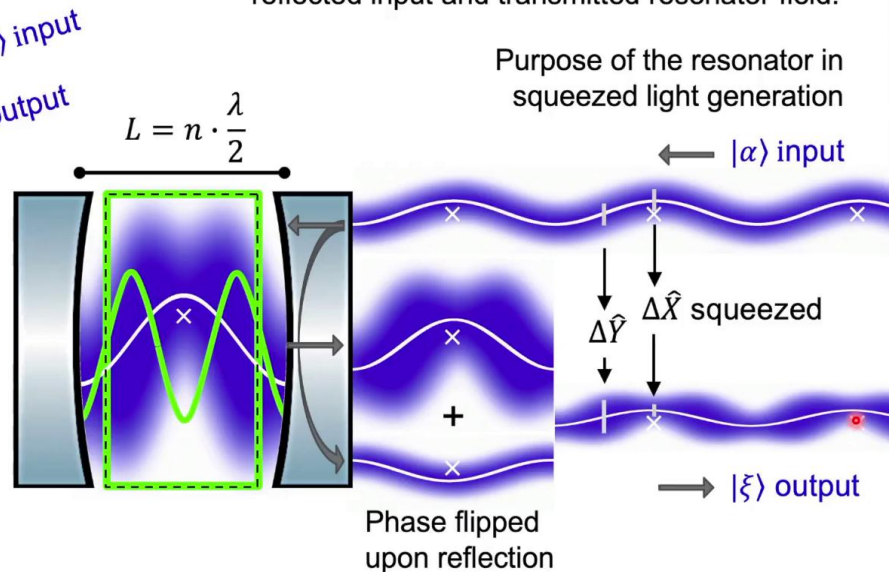
GENERATION OF SQUEEZED LIGHT (PART 2)

Complete setup: resonator-enhanced OPA



For parametric damping of the resonator field of just $G = 1/\sqrt{R}$ per round-trip, the output field would show infinitely strong squeezing.

Generally: The output field is the interference of reflected input and transmitted resonator field.



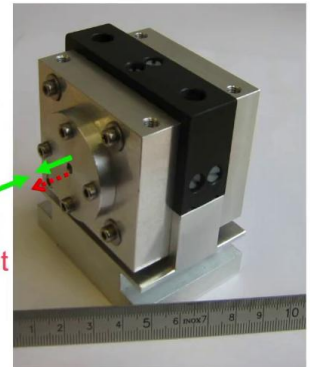
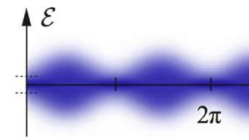
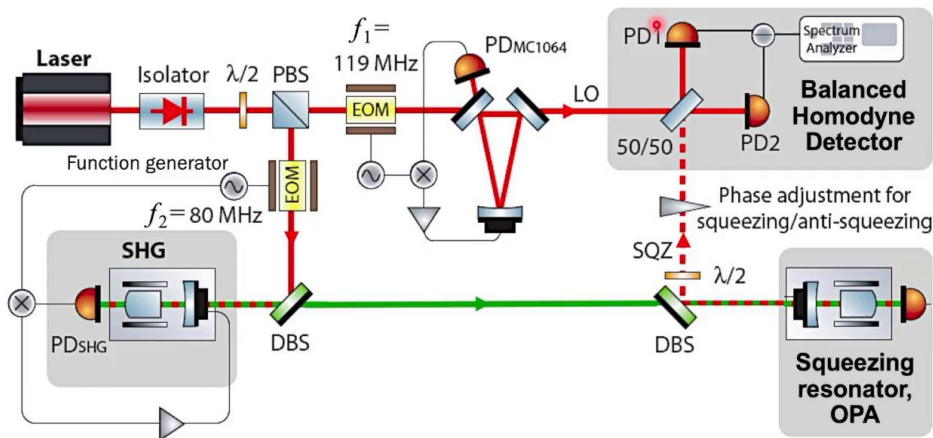
These two fields now interfere and you see that here the uncertainty is of similar magnitude with the uncertainty here and both of them are anti-correlated. So if we add up the two, we create even better squeezing at the extrema of the final output field. So we have now squeezing here or if you look at this line and this line, you see the squeezing and here if you look at the node, you see that the uncertainty is increased. Quite generally, we have interference of two fields when we work with an optical resonator and only the interference of these two fields give us the total output field. Interestingly, for parametric damping inside the optical resonator of just 'G' equal to one over the square root of 'R' where 'R' is the reflectivity and this per round-trip, we would get perfect squeezing outside the resonator. Because with this round-trip gain, this uncertainty has exactly the same uncertainty as this uncertainty and interference produces zero uncertainty at these phases.

Notes

Summary



EXPERIMENTAL SETUP



SHG: Second Harmonic Generation; PD: Photo Diode;
 EOM: Electro-Optical Modulator;
 required for Pound-Drever-Hall control loop for cavity length stabilization;
 PBS: Polarizing Beam Splitter; DBS: Dichroic Beam Splitter.

[H. Vahlbruch et al.,
 PRL 100, 033602 (2008)]

Let's have a look at an experimental setup for the generation of squeezed light. So in this set up, in fact, we produce a squeezed vacuum state. We start with a commercial laser that should be ultra-stable and continuous wave. We send the light through an isolator which protects the laser against back reflections and we split the light beam into two. Most of the power is mode matched into a second harmonic generator which is also an optical resonator. Here we produce the pump light for the squeezing resonator. So the input field of the squeezing resonator, as you can see here, is just the green pumped light in this case at 532 nanometer and a vacuum input at 1064 nanometers which is always there so we do not inject a coherent state but we take the vacuum and produce a squeezed vacuum state. The squeezed vacuum state that leave this resonator is sent to a balanced homodyne detector where we overlap the squeezed field with a local oscillator that comes from the same main laser source. We need a very good fringe visibility at this beam splitter and then we do balance detection. So we take two photodiodes, PD1 and PD2 and analyze the difference photoelectric currents.

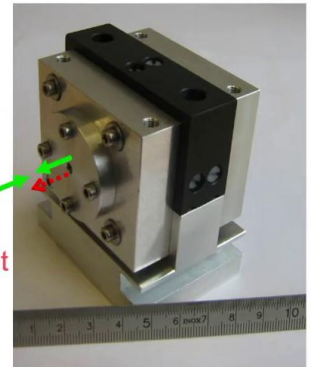
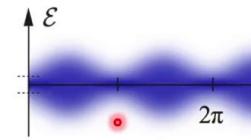
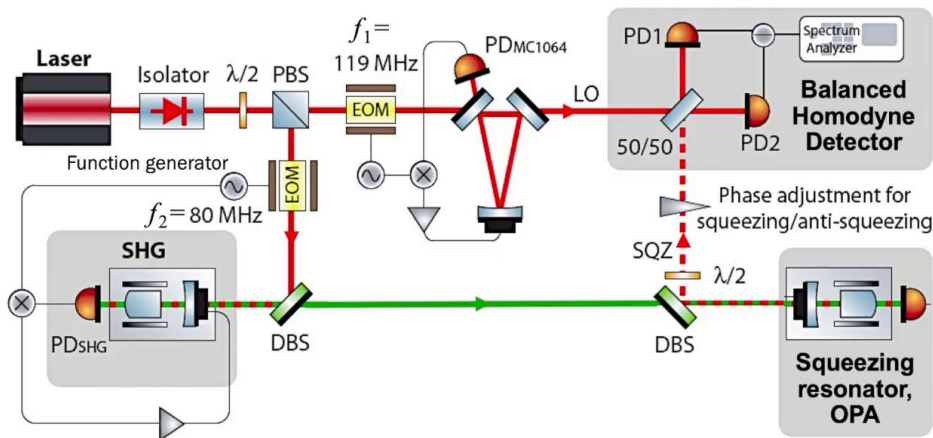
Notes

Summary

16m 15s



EXPERIMENTAL SETUP



CW pump
light input
(532nm)
Squeezed
field output
(1064nm)

SHG: Second Harmonic Generation;
EOM: Electro-Optical Modulator;
required for Pound-Drever-Hall control loop for cavity length stabilization;
PBS: Polarizing Beam Splitter;
DBS: Dichroic Beam Splitter.

[H. Vahlbruch et al.,
PRL 100, 033602 (2008)]

With such a balanced homodyne detector, we can measure the electric field strength for a certain phase. So the phase which is basically the phase difference between the two inputs needs to be set to a certain value and needs to be stabilized. This is done by an electronic control loop. So we measure the electric field strength many times for this phase. This is an ensemble measurement and afterwards we measure the electric field rings many many times for this phase. In total, we can do a full characterization of the squeezed vacuum state and we can even produce the Wigner function.

Notes

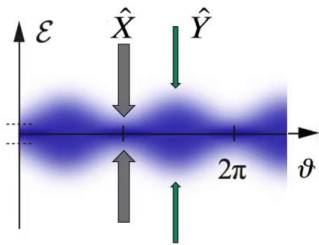
Summary



17m 58s

WIGNER FUNCTION OF SQUEEZED STATE

The Wigner function is a complete representation of a quantum state.
It is a quasi probability distribution.
It can be calculated from BHD data.

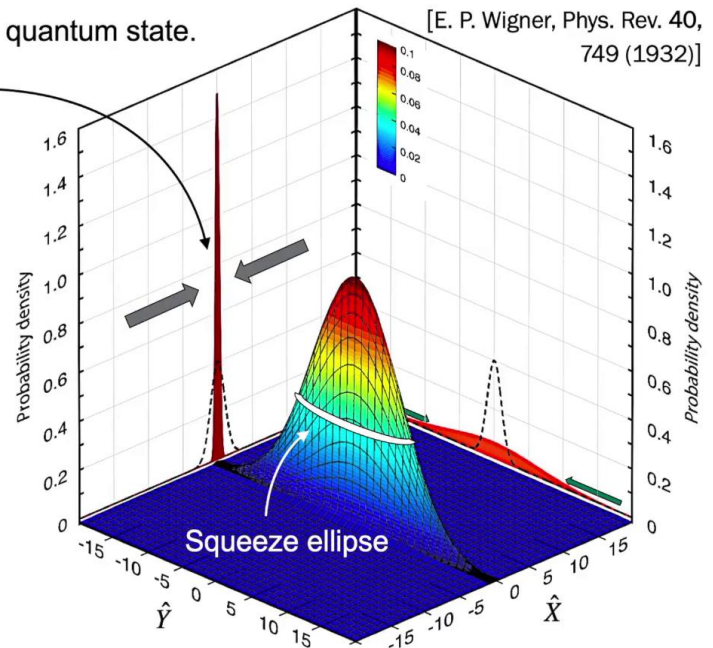


$$|\psi(\hat{X})|^2 = \int_{-\infty}^{+\infty} W(\hat{X}, \hat{Y}) dY$$

$$|\psi(\hat{Y})|^2 = \int_{-\infty}^{+\infty} W(\hat{X}, \hat{Y}) dX$$

For a squeezed state, the Wigner function reads:

$$W(\hat{X}, \hat{Y}) = \frac{1}{2\pi\sqrt{\Delta^2\hat{X}\Delta^2\hat{Y}}} e^{\left\{-\frac{\langle\hat{X}\rangle^2}{2\Delta^2\hat{X}} - \frac{\langle\hat{Y}\rangle^2}{2\Delta^2\hat{Y}}\right\}}$$



[E. P. Wigner, Phys. Rev. **40**,
749 (1932)]

The Wigner function is a complete representation of a quantum state. It is a quasi probability distribution over the phase space of 'X' and 'Y'. With a balanced homodyne detector, we can measure the histogram of all the data at this phase or we can measure the histogram of all data at this phase and this gives us these projections of the Wigner function. So in fact, the experimental data we can measure is always a projection of the Wigner function so integral over one of the phase space observables. So this projection here or this projection here. So once we have this data, so this data here, we can reproduce the Wigner function by using the inverse Radon transformation. The squeezed ellipse you find here so it is a cut through the probability distribution function of the Wigner function. For a squeezed state, the Wigner function is easy to calculate. You only need the variances and the expectation values of the two quadratures.

Notes

Summary



HAMILTON OPERATORS

Quantization of the field

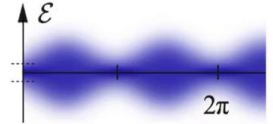
$$\hat{H} = h\nu \left(\hat{n} + \frac{1}{2} \right) = h\nu (\hat{X}_v^2 + \hat{Y}_v^2) = h\nu \left(\left(\frac{\hat{a}_v + \hat{a}_v^\dagger}{2} \right)^2 + \left(\frac{\hat{a}_v - \hat{a}_v^\dagger}{2i} \right)^2 \right)$$

\hat{a}_v : Creation operator

\hat{a}_v^\dagger : Annihilation operator

Mean Photon number of the squeezed vacuum state

$$\begin{aligned} \langle 0, \xi | \hat{n} | 0, \xi \rangle &= \langle 0, \xi | \hat{X}_v^2 + \hat{Y}_v^2 - \frac{1}{2} | 0, \xi \rangle - \overbrace{\langle 0, \xi | \hat{X}_v | 0, \xi \rangle^2}^{=0} - \overbrace{\langle 0, \xi | \hat{Y}_v | 0, \xi \rangle^2}^{=0} \\ &= \Delta_{0,\xi}^2 \hat{X}_v + \Delta_{0,\xi}^2 \hat{Y}_v - \frac{1}{2} \end{aligned}$$



Example: $\langle 0, 3\text{dB} | \hat{n} | 0, 3\text{dB} \rangle = \frac{1}{2} \frac{1}{4} + 2 \frac{1}{4} - \frac{1}{2} = \frac{1}{8}$



Let's have a look at two important Hamilton operators. So first of all, there is the Hamilton operator of the quantized harmonic oscillator. Here we have the photon number. We can rewrite everything using our electric field strength being 90 degree out of phase 'X' and 'Y' while we use their squares. And I also give you the link to the well-known creation and annihilation operators. This Hamiltonian is quite useful to make a quick calculation of the mean photon number of a squeezed vacuum state. So we take the photon number operator, we combine it with a squeezed vacuum state so zero means no displacement, and we replace 'n' by this term, minus one-half which is a zero point energy. And then we subtract twice a zero. We can do this because we already know that the expectation value of the electric field at any phase is zero. So now we find the variances. Here we have the square of 'X' expectation value minus the square of the expectation value of 'X'. This is the variance for the state for 'X'. Here you find the variance for 'Y' for the state and we have minus one-half. This equation now is quite useful and I will show you an example for a three dB squeezed vacuum state.

Notes

Summary



20m 20s

HAMILTON OPERATORS

Quantization of the field

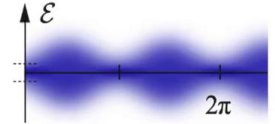
$$\hat{H} = h\nu \left(\hat{n} + \frac{1}{2} \right) = h\nu (\hat{X}_v^2 + \hat{Y}_v^2) = h\nu \left(\left(\frac{\hat{a}_v + \hat{a}_v^\dagger}{2} \right)^2 + \left(\frac{\hat{a}_v - \hat{a}_v^\dagger}{2i} \right)^2 \right)$$

\hat{a}_v : Creation operator

\hat{a}_v^\dagger : Annihilation operator

Mean Photon number of the squeezed vacuum state

$$\begin{aligned} \langle 0, \xi | \hat{n} | 0, \xi \rangle &= \langle 0, \xi | \hat{X}_v^2 + \hat{Y}_v^2 - \frac{1}{2} | 0, \xi \rangle = \underbrace{\langle 0, \xi | \hat{X}_v^2 | 0, \xi \rangle}_{=0} - \underbrace{\langle 0, \xi | \hat{Y}_v^2 | 0, \xi \rangle}_{=0} - \frac{1}{2} \\ &= \Delta_{0,\xi}^2 \hat{X}_v + \Delta_{0,\xi}^2 \hat{Y}_v - \frac{1}{2} \end{aligned}$$



Example: $\langle 0, 3\text{dB} | \hat{n} | 0, 3\text{dB} \rangle = \frac{1}{2} \frac{1}{4} + 2 \frac{1}{4} - \frac{1}{2} = \frac{1}{8}$

Degenerate OPA (and SHG)

$$\hat{H} = h\nu \left(\hat{a}_v^\dagger \hat{a}_v + \frac{1}{2} \right) + h2\nu \left(\hat{b}_{2\nu}^\dagger \hat{b}_{2\nu} + \frac{1}{2} \right) + \frac{i\hbar\chi^{(2)}}{2\pi} (\hat{a}_v^2 \hat{b}_{2\nu}^\dagger - \hat{a}_v^{\dagger 2} \hat{b}_{2\nu})$$

Degenerate OPA produces indistinguishable photon pairs at frequency ν .

The production rate depends on the crystal's 2nd order susceptibility $\chi^{(2)}$ and the pump field amplitude. •

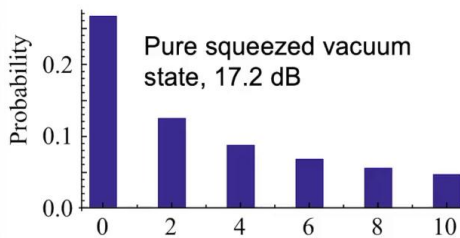
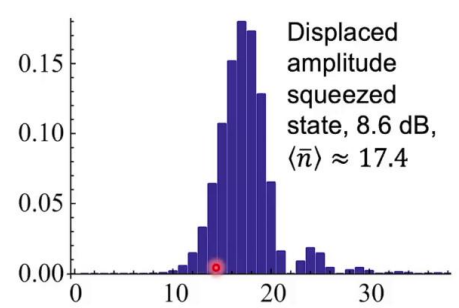
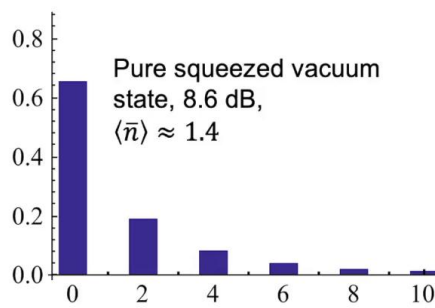
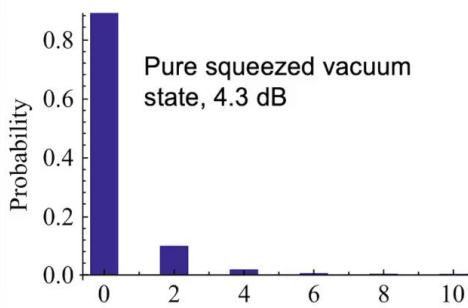
Three dB means that the variance of 'X' is halved so the variance of one-quarter is now one over eight. The variance in 'Y' is doubled and we have the zero point fluctuation. So those two cancel out and we have one over eight left. So a three dB squeezed vacuum state has on average one over eight photons. There is another Hamilton operator which is important because it describes degenerate OPA. So we have here the energy of the fundamental field. We have the energy of the intense pump field and then we have the interaction. So the interaction scales with chi two which is a non-linearity of the medium and here we see second harmonic generation. So two photons are annihilated in the fundamental wave and a second harmonic photon is created. But if there are no photons at the fundamental wavelength so when we inject a vacuum then this term dominates and we produce photon pairs from the intense pump field. So this equation tells us that degenerate OPA produces indistinguishable photon pairs at frequency nu so this is this term here. And the production rate depends on the crystal's second order susceptibility chi two and the pump field amplitude here.

Notes

Summary



PHOTON NUMBER STATISTICS



[R.S., Physics Reports 684, 1-51 (2017)]

If you look up textbooks, you will find equations how to calculate the photon number statistics of squeezed states. Here I show you the probability distribution of a pure squeezed vacuum state having 4.3 dB of squeezing. So let's assume you do measurements on ensemble of this state. Then you will find in about 90 percent of the cases zero photons. In about ten percent of the cases, you will find two photons. But you will never find one photon or three photons. If you then increase the squeeze factor, the higher order photon numbers are more pronounced. But let us go to a pure squeezed vacuum state of 8.6 dB squeezing which corresponds to a squeeze parameter 'R' equal one. I have shown you that it's easy to calculate the average photon number and for this example you would get 1.4. But in this graph you see the photon number distribution. And we now at a coherent displacement of alpha equal four. This adds 16 photons on average so we get now 17.4. We keep the squeeze factor and we assume we have a displaced amplitude squeezed state. We will find a main peak which is rather narrow and we also find some oscillations at higher photon numbers if we keep the photon number and also this squeeze factor, but now consider a phase squeezed state then the photon number distribution is rather broad.

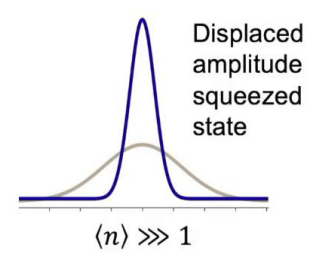
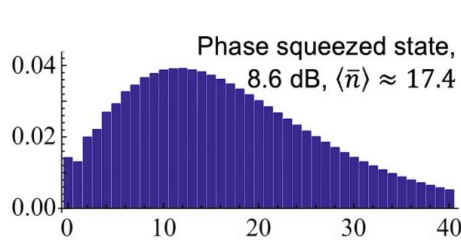
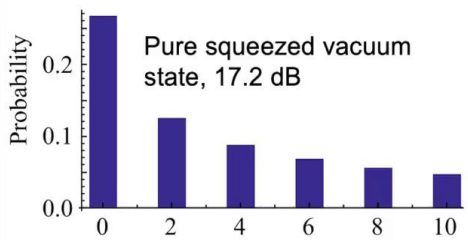
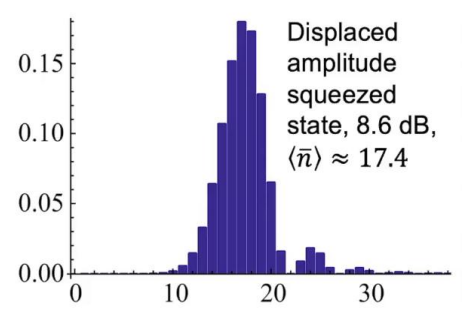
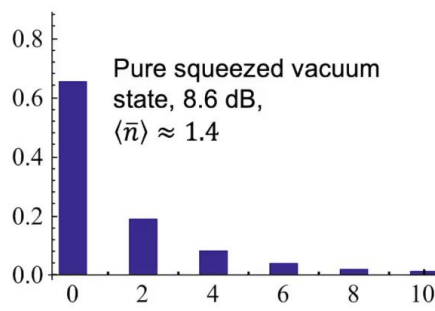
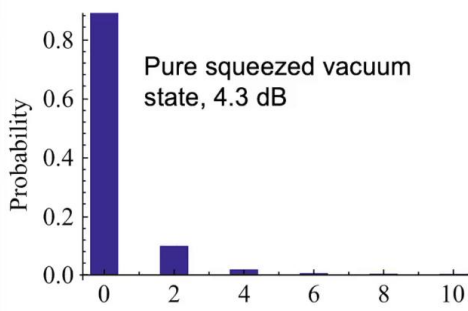
Notes

Summary



24m 19s

PHOTON NUMBER STATISTICS



[R.S., Physics Reports 684, 1-51 (2017)]

The last example here is a displaced amplitude squeezed state for very large photon numbers and then you would get a Gaussian photon number distribution with a width that is squeezed compared to coherent state having the same average photon number.

Notes

Summary



26m 22s

SUMMARY

- Squeezed states of light provide an improved signal to noise ratio of either a phase measurement or amplitude measurement.
- If the electric field at phase $\vartheta = 0^\circ$ (i.e. \hat{X}) is squeezed, the one at $\vartheta = 90^\circ$ (i.e. \hat{Y}) must be anti-squeezed and vice versa.
- Squeezed light is produced by degenerate optical parametric amplification (OPA) in a nonlinear crystal inside an optical resonator.
- Pure squeezed vacuum states contain even photon numbers only.
- Largely displaced amplitude-squeezed states have a squeezed Gaussian photon number distribution.

My summary is the following. Squeezed states of light provide an improved signal-to-noise ratio of either a phase measurement or an amplitude measurement. If the electric field at phase theta equal to zero is squeezed, the one at theta equal to 90 degrees must be anti-squeezed and vice versa. This is due to Heisenberg's uncertainty relation. Squeezed light is produced by degenerate Optical Parametric Amplification in a nonlinear crystal inside an optical resonator. And finally, I have shown you the connection to photon numbers so pure squeezed vacuum state contains only even photon numbers but if you consider a largely displaced amplitude squeezed state, you will find a Gaussian photon number distribution which is squeezed.

Notes

Summary



26m 44s

FURTHER READING

- [https://en.wikipedia.org/wiki/Squeezed_states_of_light]
- [H. Yuen, Phys. Rev. A 13, 2226 (1976)]
(First theoretical consideration of squeezed optical fields.)
- [C.C. Gerry & P.L. Knight, *Introductory Quantum Optics*, University Press, Cambridge (2005)]
(Text book about theory of squeezed states.)
- [H.-A. Bachor & T.C. Ralph, *A guide to experiments in quantum optics*, Wiley, 3rd edition (2019)]
(Text book about experiments with squeezed light.)
- [R. Schnabel, *Squeezed States of Light and their application in laser interferometers*, Physics Reports 684, 1-51 (2017), arXiv: 1611.03986]
(Review article)
- [H. Vahlbruch *et al.*, Phys. Rev. Lett. 117, 110801 (2016)]
(Observation of 15 dB squeezed light.)

And finally, some further reading for you.

Notes

Summary



27m 47s