SQUEEZED LIGHT FOR GRAVITATIONAL WAVE DETECTORS

Cavity Quantum Optomechanics

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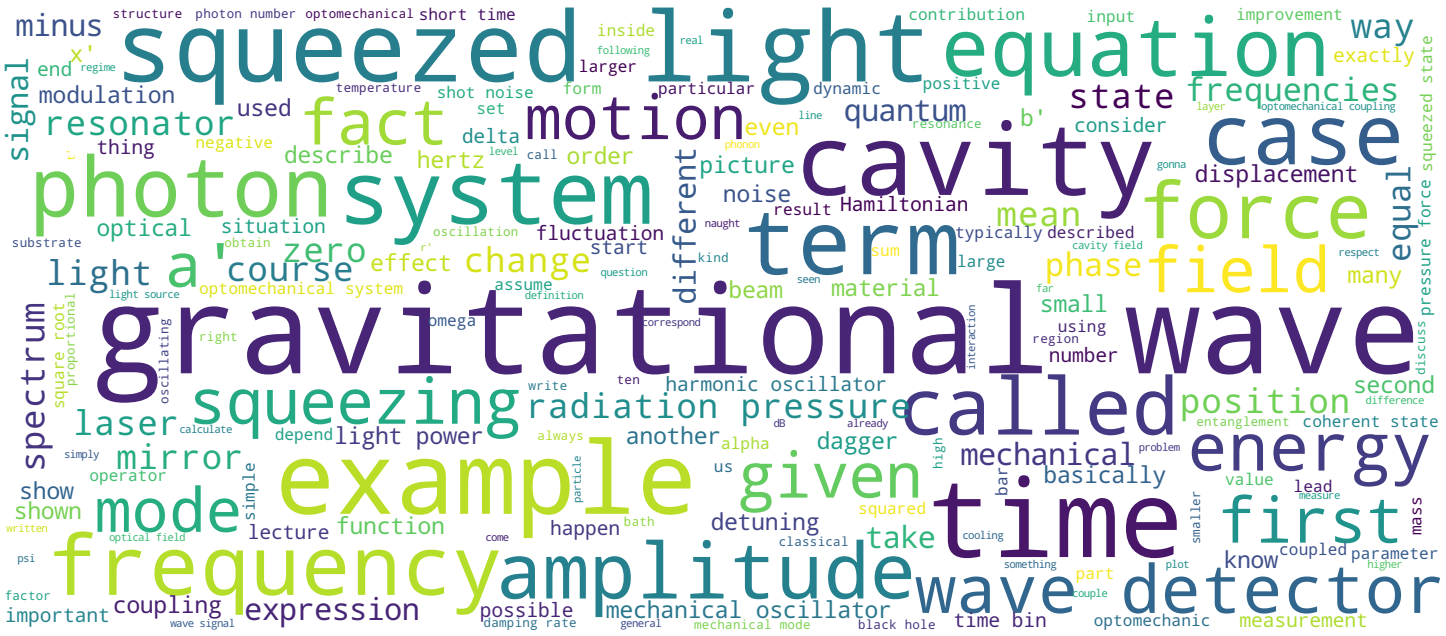

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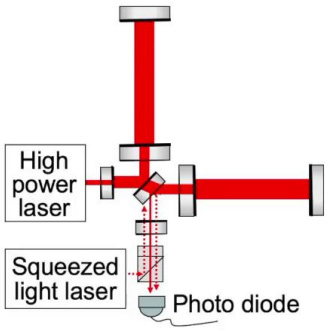
OUTLINE

- **Gravitational-wave (GW) detection**
- **GW signal: modulated continuous-wave light**
- **Spectrum of modes in squeezed states**
- **Squeezed light at GW signal frequencies**
- **The first squeezed-light source for a GW detector**
- **Higher sensitivities of GW observatories with squeezed light**
- **The 'quantum weirdness' of squeezed light**



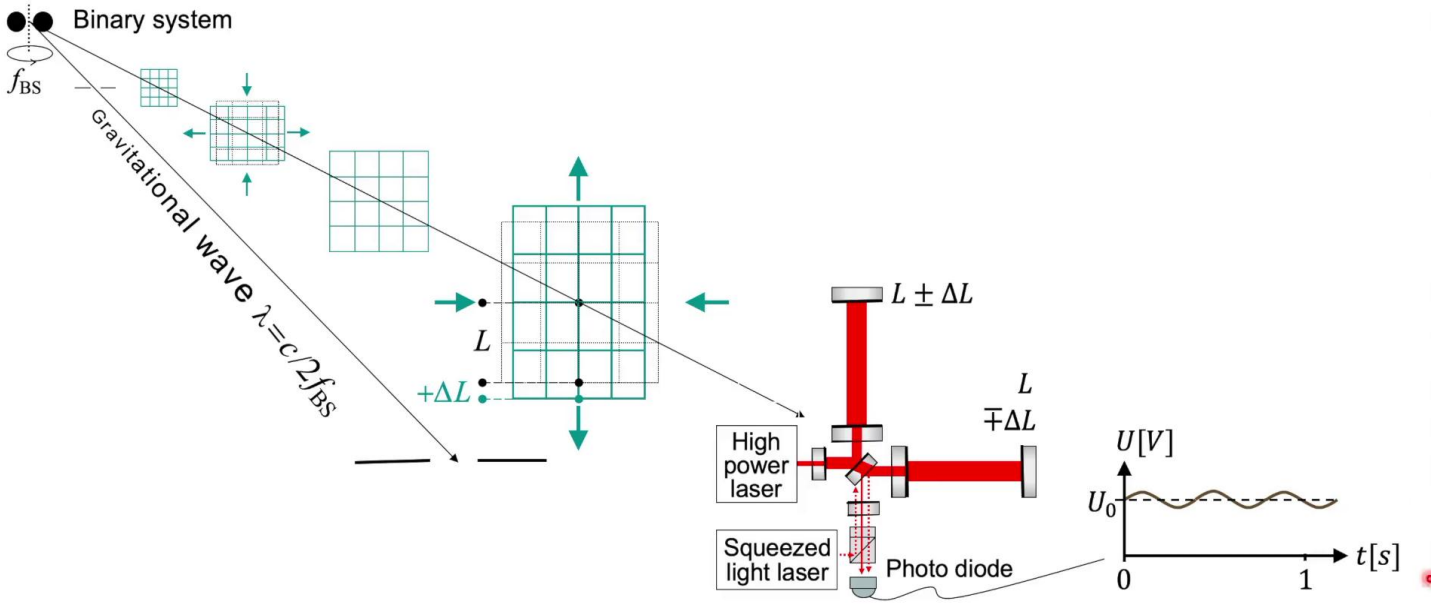
This lecture is about a highly topical subject because research and development of squeezed light for gravitational wave detectors have been paying extremely well since April 2019. What you see here is the laser interferometer for the detection of gravitational waves. Laser light in the arms measures the distance between mirrors. What is brand new in such gravitational wave detectors are the squeezed light lasers. They improve the signal-to-noise ratio in the observation of gravitational waves. First, I will give you a short introduction to gravitational wave detection and then we consider the kind of signal that is recorded by such a gravitational wave detector and the spectrum of squeezed states which are required for the improvement. I will also talk about the first squeezed light source for gravitational wave detector that was realized in 2010.

Notes

Summary

0m 00s

GRAVITATIONAL-WAVE DETECTION



Gravitational waves are, for instance, produced by massive stars orbiting around each other. For example, two black holes. A gravitational wave has a speed of light and resides in expanding and as well as shrinking space-time. For typical gravitational waves, the effect on Earth is tiny but still measurable with a laser interferometer. A photodiode in the output port measures a constant light power level if there is no gravitational wave. So here given as a photoelectric voltage but when the space-time is oscillating due to the gravitational wave also the light power level is oscillating at the same frequency.

Notes

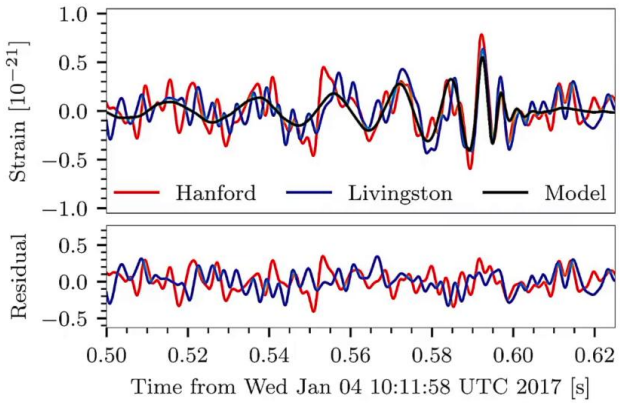
Summary

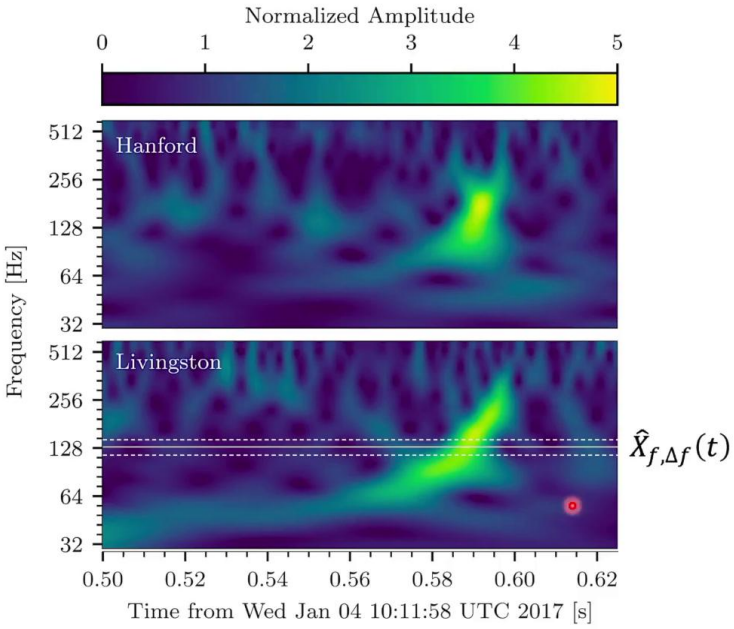
1m 11s

GRAVITATIONAL-WAVE SIGNAL

GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence by LIGO.

[Abbott *et al.*, Phys. Rev. Lett. **118**, 221101 (2017)]
[https://www.ligo.caltech.edu/images]





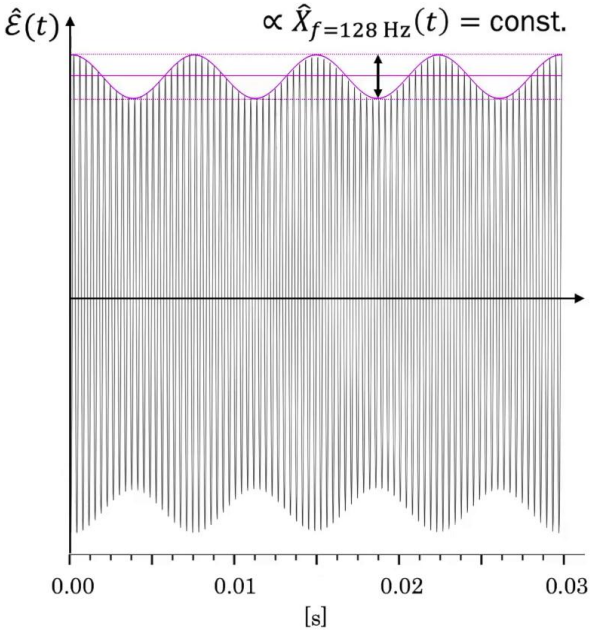
On this slide, you see the gravitational wave signal from two merging black holes as recorded by the two LIGO observatories in Hanford and Livingston. So within just about a hundred milliseconds, the two black holes came closer here and finally merged to a single black hole. So what you see here is the modulation of the light power level as shown on the previous slide, the two recorded signals and also a model. The recorded signal can also be nicely displayed not just over time but also over frequencies. And now we can see the time dependence of every modulation frequency. For example, we can see the amplitude of the modulation at 128 hertz which was almost zero in this region then this modulation gave the strong contribution here to this modulation and finally, the frequencies were even higher.

Notes

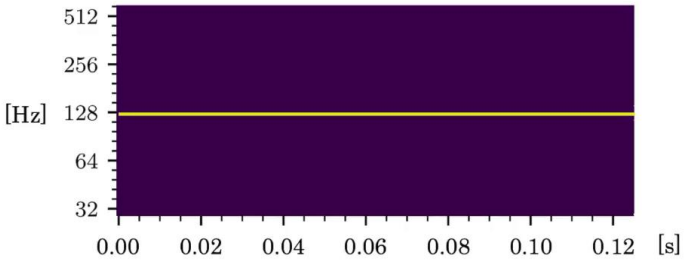
Summary

2m 10s

MODULATED LIGHT



Signal produced by a monochromatic GW at f=128 Hz.



The modulation at f may change. To make these changes observable we need a (small) bandwidth Δf around f.
A GW signal is thus described by a spectrum of $\hat{X}_{f,\Delta f}(t)$.

$\hat{X}_{f,\Delta f}(t)$ are called *amplitude quadrature amplitudes*.

To improve the S/N we need to squeeze the quantum noise of these observables.

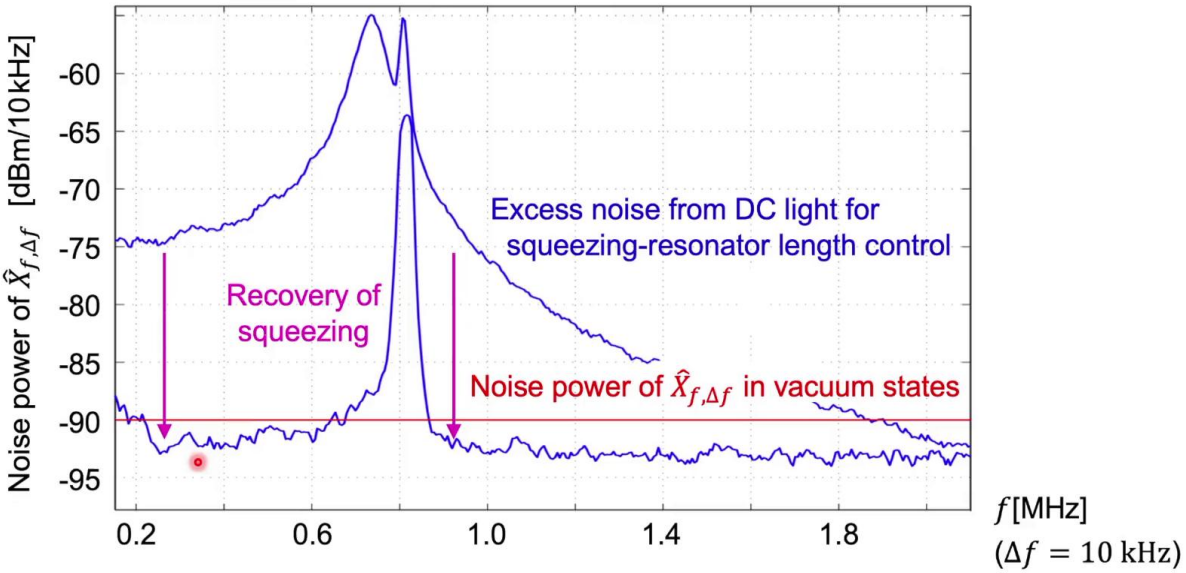
Here I explain in more detail the meaning of the observable 'Xf'. So if we had a monochromatic gravitational wave at frequency 128 hertz, you would see in the output port of a gravitational wave detector and optical field that is modulated at exactly this frequency. Since the signal is monochromatic, this modulation will not change in time. So our time frequency analysis would simply show a single thin line at 128 hertz. Of course, the modulation will change in frequency with time and to make these changes observable, we need a small bandwidth delta-f around 'f'. So the operator 'Xf' needs to be written as 'Xf' plus minus delta-f. For example, 128 hertz plus minus one hertz. And the full gravitational wave signal is then described by a spectrum of these observables. They, in fact, are called the amplitude quadrature amplitudes. To improve now the signal-to-noise ratio, we squeeze light. We need a full spectrum of squeezing for all frequencies where we expect a gravitational wave signal.

Notes

Summary

3m 28s

SPECTRUM OF MODES IN SQUEEZED STATES



[W.P. Bowen, R. Schnabel, N. Treps, H.-A. Bachor, P.K. Lam, J. Opt. B 4, 421 (2002)]

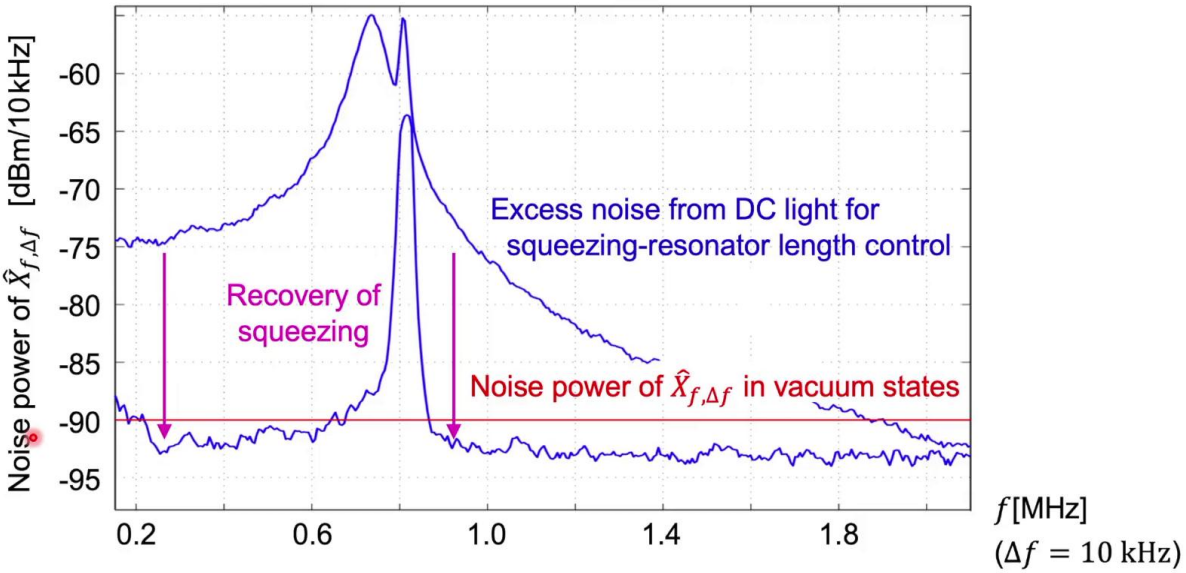
If you simply plug the cable from a photoelectric detector to a spectrum analyzer, you will see the contributions to the overall noise from the different modulation or also called sideband frequencies. So here plotted from 200 kilohertz to about two megahertz. So here we now have a spectrum of many operators 'X' at frequency 'f' with some bandwidth delta-f which is the resolution bandwidth you can set at the spectrum analyzer. This data we took in 2001 at the Australian National University and we expected to see some squeezing. Some squeezing with respect to this line here this we calibrated and this line represented the vacuum noise of our modulations. We saw some small value of squeezing here and some more squeezing at higher frequencies, but here now, I'm focusing on the low frequencies, where, in fact, we observed huge excess noise which was far above the shot noise reference. Later we found out that this noise came from excess noise from the DC light which we used for controlling the length of our squeezing resonator and we were able to reduce this noise. So this measurement now shows to the improvement. We were, in fact, able to recover the squeezing at frequencies at modulation frequencies down to about 250 kilohertz.

Notes

Summary

5m 04s

SPECTRUM OF MODES IN SQUEEZED STATES



[W.P. Bowen, R. Schnabel, N. Treps, H.-A. Bachor, P.K. Lam, J. Opt. B 4, 421 (2002)]

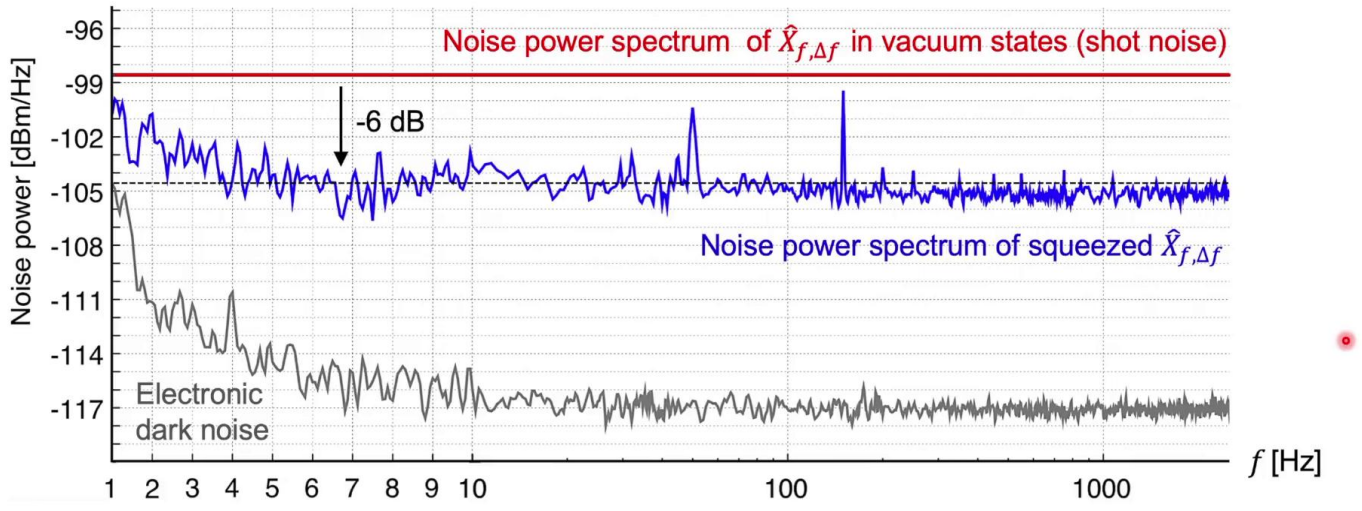
At that time, this was rather surprising for us and we were highly motivated to try to bring down the squeezing spectrum to frequencies in the audio band of gravitational wave detectors so at frequencies where we expected gravitational waves between ten hertz and ten kilohertz.

Notes

Summary

7m 07s

SQUEEZED LIGHT AT GW SIGNAL FREQUENCIES



[H. Vahlbruch, S. Chelkowski, K. Danzmann, R.S., New J. Phys. 9, 371 (2007)] (new control scheme and back-scatter reduction)
First audio-band squeezing: [McKenzie *et al.*, PRL **93**, 161105 (2004)]

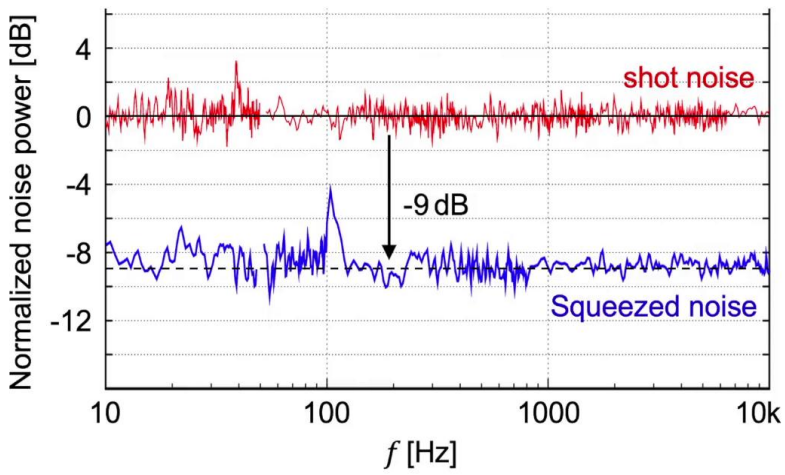
It took several years to expand the squeezing spectrum down to frequencies required for gravitational wave detectors. So this result was published in 2007 and you see about six dB of squeezing from a few hertz over kilohertz up to about 30 megahertz. So this was almost possible by inventing a completely new control scheme to stabilize the length of the squeezing resonator and also to stabilize the squeeze angle in respect of the balanced homodyne detector. Also, we invented techniques to reduce the disturbances from back scattered light which was previously dominating the regime below 100 hertz. So this spectrum is already suitable to improve the gravitational wave detector at frequencies expected for gravitational waves.

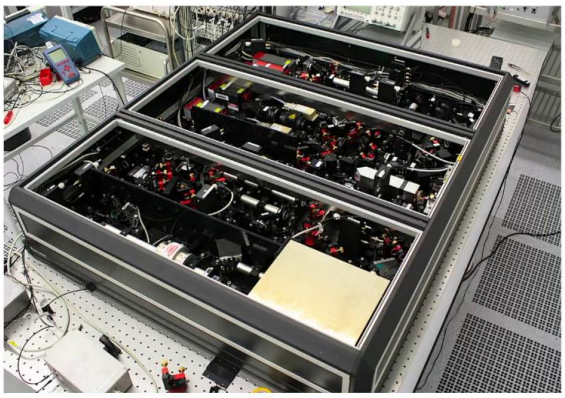
Notes

Summary

7m 29s

SQUEEZED-LIGHT SOURCE FOR A GW DETECTOR





Squeezed light source for GEO600, built by H. Vahlbruch and A. Khalaidovski in 2009/2010. Real-time control system by Nico Lastzka and Christian Gräf.

[H. Vahlbruch, A. Khalaidovski, N. Lastzka, C. Gräf, K. Danzmann, R. Schnabel, Class. Quantum Grav. 27, 084027 (2010)]

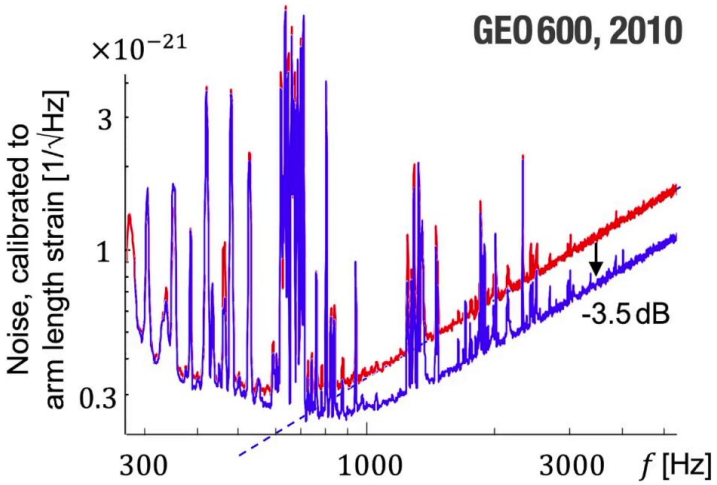
In 2009 and 2010, my group at that time in Hanover built the first squeezed light source with the purpose to be implemented in a gravitational wave detector. Here you see a photograph of the laser which has a footprint of about 1.5 square meters and had a mass of about 130 kilograms. It was built by Henning Vahlbruch and Alexander Khalaidovski and the real-time control system was built by Nico Lastzka and Christian Graf. Here you see the performance of the squeezed light source shown from ten hertz to ten kilohertz which is exactly the signal spectrum for ground-based gravitational wave detectors. And you see that about 9 dB of squeezing was achieved over the spectrum. The laser was set up on the breadboard and was transportable and in 2010, it was implemented in the British German gravitational wave detector GEO 600.

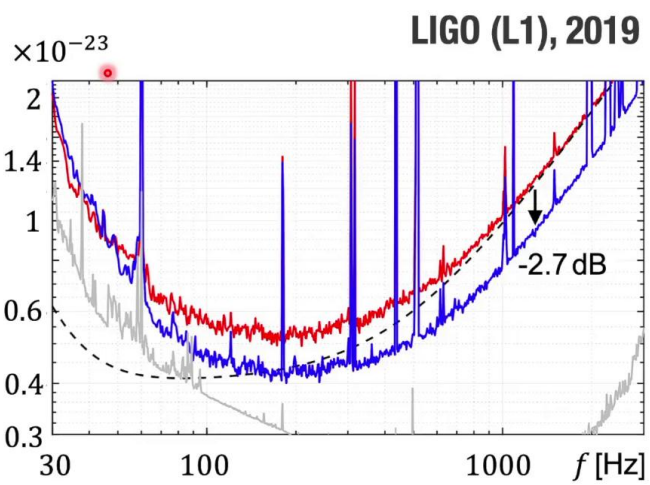
Notes

Summary

8m 39s

HIGHER SENSITIVITIES WITH SQUEEZED LIGHT





[LIGO Scientific Collaboration, Nature Physics **7**, 962 (2011)]

[M. Tse *et al.*, Phys. Rev. Lett. **123**, 231107 (2019)]

Squeezed light in Virgo: [F. Acernese *et al.*, Phys. Rev. Lett. **123**, 231108 (2019)]

What you see here is the performance of this squeezed light source in GEO 600 achieved in 2010. You see that the noise of the observatory was reduced by up to 3.5 dB from 800 hertz to several kilohertz. So this value was limited by optical loss that's the squeezed light experience when propagating along the 600 meter long arms and the transmission through all the optics. At lower frequencies so in this region here, an improvement with squeezed light was not possible because GEO 600 was not shot noise limited here. This graph is slightly different from the previous ones because here not the noise power is shown but the square root of the noise power and this one calibrated to the arm length strain so to the strain of space-time. And you see that GEO 600 was able to measure gravitational waves with the strength of ten to the minus 21. Very recently then also the noise of LIGO and also Virgo has been reduced by squeezed light. In LIGO Livingston, the improvement is about 2.7 dB and here it covers the complete spectrum down to about 50 hertz. The overall sensitivity of LIGO is much higher here gravitational waves with straight amplitudes of ten to the minus 23 can be measured. And this low noise or this high sensitivity is sufficient for the LIGO observatories and also Virgo to measure gravitational waves on a weekly basis.

Notes

Summary

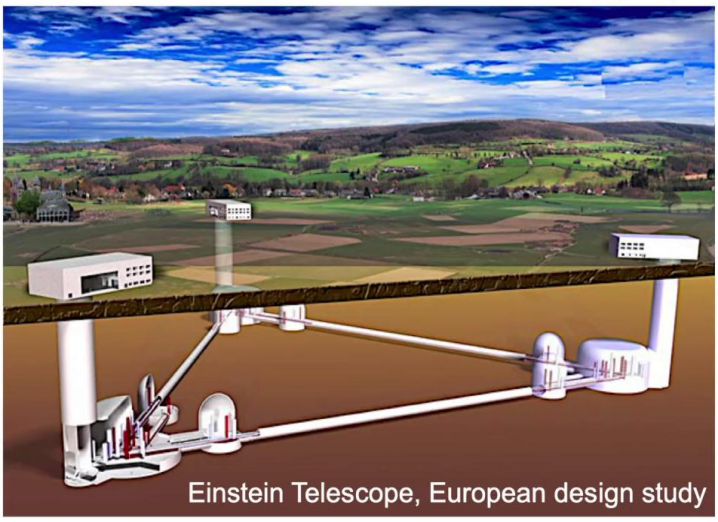
10m 08s

THE NEXT GENERATION: THE EINSTEIN TELESCOPE

LIGO and VIRGO observe GW signals on a weekly basis.

But to resolve the merger ring downs and possibly the GW back ground from the Big Bang requires a sensitivity increase of about a factor of ten.

The Einstein Telescope will reach this goal by going under ground (~100 m), by increasing the arms lengths to 10 km, and many more improvements. Squeezed light will be one of the key technologies.



http://www.et-gw.eu/

[M. Punturo *et al.*, Class. Quantum Grav. 084007 (2010)]

But to resolve the merger ring downs and possibly the gravitational wave background from the Big Bang, much higher sensitivities are required. What you see here is a picture you can find on this website. It shows the vision of the European Einstein telescope, which is a underground telescope with arm length of about ten kilometer and which has many more improvements and squeezed light will be one of the key technologies.

Notes

Summary

12m 20s

IN APPLICATION – BUT 'WEIRD'

(Potential) applications of squeezed light

- Reduction of shot noise in optical measurements, e.g. gravitational-wave detection
- Quantum teleportation for quantum memories
  [Furusawa *et al.*, Science **282**, 706 (1998); Bowen *et al.,* Phys. Rev. A **67**, 032302 (2003)]
- Calibration of photo detectors without lamp with calibrated radiance
  [Vahlbruch *et al.*, Phys. Rev. Lett. **117**, 110801 (2016)]
- Quantum key distribution with one-sided device independent security
  [Gehring *et al.*, Nat. Comm. **6**, 8795 (2015)]

"*Squeezed light is well-described by quantum theory, however, constitutes an example of 'quantum weirdness'. The latter term has been used to describe a list of experiments, including gedanken experiments, that all lack a comprehensive physical understanding that a clear majority of physicists agrees on*."

[R. Schnabel, arXiv:1909.13723, Annalen der Physik, accepted]

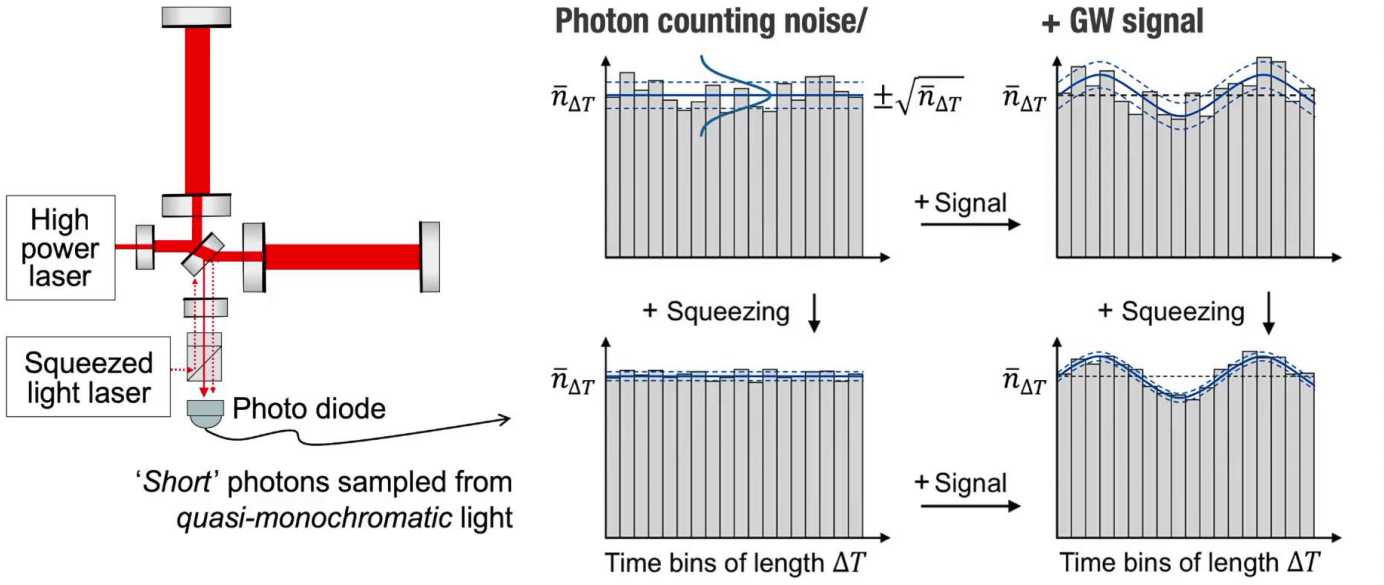
So squeezed light is successfully used in gravitational wave detectors and there are more potential applications. For example, squeezed light can be used to do quantum teleportation which is required in quantum memories. You can use squeezed light to calibrate photodetectors without having a lamp of calibrated radiance and you can do quantum key distribution with one-sided device independence. However, I would like to make the following statement. Squeezed light is well-described by quantum theory, you know, but it constitutes an example of quantum weirdness. The latter term has been used to describe a list of experiments including gedanken experiments involving entanglement which all lack a comprehensive physical understanding that the clear majority of physicists agrees on. From the following slides I would like to explain you what is a bit about squeezed light.

Notes

Summary

12m 55s

PHOTON COUNTING NOISE IN GW DETECTORS



[R. Schnabel, arXiv:1909.13723, Annalen der Physik, accepted]

When the light field in the gravitational wave detector output port is detected by the photodiode then this energy transfer is quantized. So we will see photon counting noise which is just another word for shot noise. So we collect the energy of the photons in rather short time bins delta-t and we will get different photon numbers. For a coherent state, in fact, we have a standard deviation of square root of 'n' where 'n' is the expectation value for the photon number for a time bin of length delta-t. And if you do a lot of measurements, you'll be here and get a Gaussian distribution with this standard deviation. The problem, of course, is that if you want to measure a faint modulation. In this picture as it is shown here this modulation corresponding to gravitational wave is hardly visible. With squeezed light, the situation is improved because the photon counting noise is squeezed and you can see a gravitational wave signal much more clearly. There is one thing that does not change when you go from a coherent state to a squeeze state and that is this light here is very monochromatic and you do sampling of photons in very short time bins.

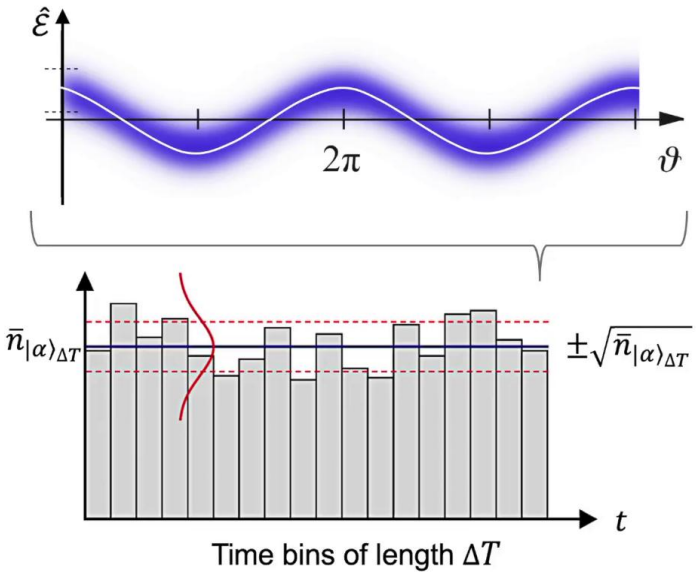
Notes

Summary

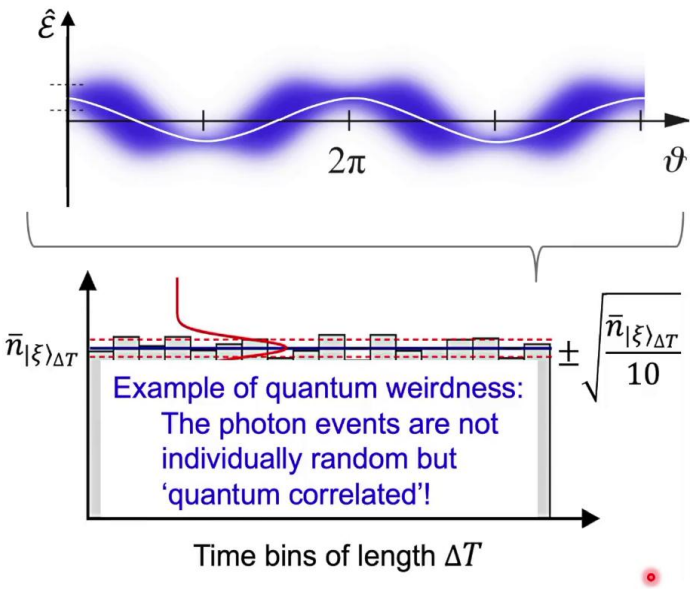
14m 00s

SHORT MEASUREMENTS ON MONOCHROMATIC LIGHT

Coherent state $|\alpha\rangle_{\Delta t}$



Amplitude squeezed state $|\xi\rangle_{\Delta t}$



On this slide, I'm comparing again the coherent state with the amplitude squeezed state. Both are states of rather monochromatic light. So the coherence length delta-t here is very long, maybe one second. And we sample now photons in very short time bins delta capital 'T' which is much shorter than delta-t. Here the energy distribution is undetermined over the coherence length. So there are no photons that are determined on such a short time scale. Nevertheless, when we sample the photons then have to appear truly randomly in every time bin and this randomness gives rise to our Poissonian distribution. The situation here is exactly the same. We have a huge uncertainty of the localization of photons over a second but we sample photons into short time bins so again, every photon is previously not determined. So again, they have to appear in a random way. But then how is it possible that the Poisson distribution is squeezed here by a factor of square root ten. Shouldn't the statistics be again the statistics of individually random photon events? This is the quantum weirdness. And this is why squeezed light is an example of quantum weirdness. The photon events are not individually random but this is what we say, they are quantum correlated.

Notes

Summary

15m 46s

SUMMARY

- **Squeezed light allows for the sensitivity improvement of laser interferometers without increasing the light power. 3 dB corresponds to doubling the light power, 10 dB to a tenfold light power in the interferometer arms.**
- **Dedicated experimental research and development of squeezed light for gravitational-wave observatories started in 2002.**
  The goal was to realize a 'turn-key' source for a spectrum of squeezed states from.
  10 Hz to 10 kHz, with significant squeeze factors. This was achieved in 2010.
- **Its routine application in GW observatories proves that squeezed light becomes cost effective once too high light powers produce problems such as thermal lensing in optics, back-scatter disturbances and parametric optomechanical instabilities.**
- **Nevertheless, a comprehensive physical understanding of squeezed light is still lacking.**

And this is my summary. Squeezed light allows for the sensitivity improvement of laser interferometers without increasing the light power. Three dB, for example, corresponds to doubling the light power and ten dB to a tenfold light power in the interferometer arms. Dedicated experimental research and development of squeezed light for gravitational wave observatories started in 2002 and the goal was to realize a turn-key source for a spectrum of squeezed states from ten hertz to ten kilohertz with significant squeeze factors and that was achieved in 2010. It's routine application in gravitational wave observatories proves that squeezed light becomes cost-effective once too high light powers produce problems such as thermal lensing in optics, back-scatter disturbances and parametric optomechanical instabilities. Nevertheless, a comprehensive physical understanding of squeezed light is still lacking.

Notes

Summary

18m 00s

FURTHER READING

- [C. Caves, Phys. Rev. D 23, 1693 (1981)]
- [R. Schnabel, N. Mavalvala, D. E. McClelland, P. K. Lam, Nature Communications 1, 121 (2010)]
- [R. Schnabel, *Squeezed States of Light and their application in laser interferometers,* Physics Reports 684, 1-51 (2017)]
- https://www.ligo.caltech.edu/news/ligo20191211b
- https://www.aei.mpg.de/2435237/squeezed-light-success-at-virgo
- https://physicsworld.com/a/quantum-squeezing-boosts-performance-of-ligo-and-virgo-gravitational-wave-detectors/

And finally, some further reading.

Notes

Summary

19m 07s