Squeezed light, generation and applications.

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Classical/Geometrical optics
- light is a ray
- which propagates straight
- cannot explain diffraction and interference

Semiclassical optics
- light is a wave
- color (wavelength/frequency) is important
- amplitude \(a\) and phase are important, \(E(t) = ae^{i(kz - \omega t)}\)
- cannot explain residual measurements noise
Classical field

\[ E(\phi) = |a|e^{-i\phi} = |a|\cos(\phi) + i|a|\sin(\phi) = X_1 + iX_2, \quad \phi = \omega t - kz \]

Detectors sense the real part of the field \((X_1)\) but there is a way to see \(X_2\) as well.
\[ E(\phi) = |a| e^{-i\phi} = |a| \cos(\phi) + i|a| \sin(\phi) = X_1 + iX_2, \quad \phi = \omega t - kz \]

![Graph showing classical field with coordinates and wave functions](image)
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Detector quantum noise

Simple photodetector

\[ V \sim N \]

\[ \Delta V \sim \sqrt{N} \]
Detector quantum noise

Simple photodetector

\[ V \sim N \]

\[ \Delta V \sim \sqrt{N} \]

Balanced photodetector

\[ V = 0 \]

\[ \Delta V \sim \sqrt{N} \]
Transition from classical to quantum field

**Classical analog**
- Field amplitude $a$
- Field real part
  $$X_1 = (a^* + a)/2$$
- Field imaginary part
  $$X_2 = i(a^* - a)/2$$

$$E(\phi) = |a|e^{-i\phi} = X_1 + iX_2$$

**Quantum approach**
- Field operator $\hat{a}$
- Amplitude quadrature
  $$\hat{X}_1 = (\hat{a}^\dagger + \hat{a})/2$$
- Phase quadrature
  $$\hat{X}_2 = i(\hat{a}^\dagger - \hat{a})/2$$

$$\hat{E}(\phi) = \hat{X}_1 + i\hat{X}_2$$
Heisenberg uncertainty principle and its optics equivalent

Heisenberg uncertainty principle

\[ \Delta p \Delta x \geq \frac{\hbar}{2} \]

The more precisely the POSITION is determined, the less precisely the MOMENTUM is known, and vice versa

Optics equivalent

\[ \Delta \phi \Delta N \geq 1 \]

The more precisely the PHASE is determined, the less precisely the AMPLITUDE is known, and vice versa

Optics equivalent strict definition

\[ \Delta X_1 \Delta X_2 \geq \frac{1}{4} \]

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Heisenberg uncertainty principle

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**Optics equivalent**

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**Optics equivalent strict definition**

\[ \Delta X_1 \Delta X_2 \geq 1/4 \]
Light consist of photons
\[ \hat{N} = a \dagger a \]

Commutator relationship
\[ [a, a \dagger] = 1 \]
\[ [X_1, X_2] = i/2 \]

Detectors measure
- number of photons \( N \)
- Quadratures \( \hat{X}_1 \) and \( \hat{X}_2 \)

Uncertainty relationship
\[ \Delta X_1 \Delta X_2 \geq 1/4 \]
Coherent state is minimum uncertainty state

$$\Delta X_1 \Delta X_2 = 1/4$$
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Amplitude squeezed states

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Projection
Amplitude squeezed states

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\[ \phi \]

Projection

\[ X_1 \]

\[ X_2 \]
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\[ \begin{align*}
X_2 \\
X_1
\end{align*} \]

Projection

\[ \phi \]

\[ \begin{align*}
0 & \quad 1/2\pi & \quad \pi & \quad 3/2\pi & \quad 2\pi
\end{align*} \]
Amplitude squeezed states

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Diagram showing the phase squeezing states with projections for different values of \( \phi \).
Phase squeezed states

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Diagram showing the phase squeezing with axes $$X_1$$ and $$X_2$$, and a projection plot with $$\phi$$ as the parameter.
Phase squeezed states

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Squeezed quantum states zoo

Unsqueezed coherent

Vacuum squeezed

Amplitude squeezed

Phase squeezed

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Squeezed quantum states zoo

Unsqueezed coherent

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Squeezed quantum states zoo

 Unsqueezed coherent

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 Phase squeezed

 Vacuum squeezed
Squeezed field generation recipe

Take a vacuum state $|0\rangle$

$$H = \frac{1}{2}$$
Squeezed field generation recipe

Take a vacuum state $|0\rangle$

Apply squeezing operator $|\xi\rangle = \hat{S}(\xi)|0\rangle$

\[
\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2} \xi a^\dagger^2}
\]

$H = \frac{1}{2}$
Squeezed field generation recipe

Take a vacuum state \( |0> \)

Apply squeezing operator \( |\xi> = \hat{S}(\xi)|0> \)

Apply displacement operator \( |\alpha, \xi> = \hat{D}(\alpha)|s> \)

\[
\hat{S}(\xi) = e^{\frac{1}{2}\xi^*a^2 - \frac{1}{2}\xi a^\dagger 2}
\]

\[
\hat{D}(\alpha) = e^{\alpha a^\dagger - \alpha^* a}
\]

\[
<\alpha, \xi | X_1 | \alpha, \xi > = \Re(\alpha),
\]

\[
<\alpha, \xi | X_2 | \alpha, \xi > = \Im(\alpha)
\]
Squeezed field generation recipe

Take a vacuum state $|0\rangle$

Apply squeezing operator $|\xi\rangle = \hat{S}(\xi)|0\rangle$

Apply displacement operator $|\alpha, \xi\rangle = \hat{D}(\alpha)|s\rangle$

$H = \frac{1}{2}$

Notice $\Delta X_1 \Delta X_2 = \frac{1}{4}$

$\hat{S}(\xi) = e^{\frac{1}{2}\xi^* a^2 - \frac{1}{2}\xi a^\dagger^2}$

$\hat{D}(\alpha) = e^{\alpha a^\dagger - \alpha^* a}$

$\langle \alpha, \xi | X_1 | \alpha, \xi \rangle = Re(\alpha)$

$\langle \alpha, \xi | X_2 | \alpha, \xi \rangle = Im(\alpha)$
\[ \hat{S}(\xi) = e^{\frac{1}{2} \xi^* a^2 - \frac{1}{2} \xi a^\dagger}, \quad \xi = re^{i\theta} \]

If \( \theta = 0 \)

\[ <\xi| (\Delta X_1)^2 |\xi> = \frac{1}{4} e^{-2r} \]

\[ <\xi| (\Delta X_2)^2 |\xi> = \frac{1}{4} e^{2r} \]

\[ <\xi| (\Delta X_1)^2 |\xi> = \frac{1}{4} (\cosh^2 r + \sinh^2 r - 2 \sinh r \cosh r \cos \theta) \]

\[ <\xi| (\Delta X_2)^2 |\xi> = \frac{1}{4} (\cosh^2 r + \sinh^2 r + 2 \sinh r \cosh r \cos \theta) \]
Probability to detect given number of photons $C = \langle n | \xi >$ for squeezed vacuum

- even

$$C_{2m} = (-1)^m \frac{\sqrt{(2m)!}}{2^m m!} \frac{(e^{i\theta} \tanh r)^m}{\sqrt{\cosh r}}$$

- odd

$$C_{2m+1} = 0$$

Average number of photons in general squeezed state

$$\langle \alpha, \xi | a^\dagger a | \alpha, \xi > = \alpha + \sinh^2 r$$
Tools for squeezing

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Tools for squeezing
Tools for squeezing

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Squeezed light

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Two photon squeezing picture

Squeezing operator

$$\hat{S}(\xi) = e^{\frac{1}{2} \xi^* a^2 - \frac{1}{2} \xi a^\dagger 2}$$

Parametric down-conversion in crystal

$$\hat{H} = i\hbar \chi^{(2)}(a^2 b^\dagger - a^\dagger 2 b)$$

Squeezing

result of correlation of upper and lower sidebands
Squeezer appearance
Squeezer appearance
Crystal squeezing setup scheme

[Diagram of a crystal squeezing setup scheme with various components such as PZT, PM, AOM, Oscilloscope, Spectrum Analyzer, Laser, SHG, OPA, and other optical elements.]
improvements any shot noise limited optical sensors
noiseless signal amplification
secure communications (you would notice eavesdropper)
photon pair generation, entanglement, true single photon sources
interferometers sensitivity boost (for example gravitational wave antennas)
light free measurements
quantum memory probe and information carrier
Squeezing and interferometer
Squeezing and interferometer

Vacuum input
Squeezing and interferometer

Vacuum input

Squeezed input

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- $L = 4 \text{ km}$
- $h \sim 10^{-21}$
- $\Delta L \sim 10^{-18} \text{ m}$
- $\Delta \phi \sim 10^{-10} \text{ rad}$
GW 40m detector and squeezer

(i) Pre-Stabilized Laser

(ii) Mode Cleaner

(iii) Interferometer

Gravity Wave

LASER

PO

(Pre-Mode Cleaner)

λ/4

PD1

PBS PD2

PD3

Reference Cavity

Circulator

Flipper Mirror

Homodyne Detector

(V) Length Sensing Detector
GW 40m detector with 4dB of squeezed vacuum

Signal to noise improvement by factor of 1.43

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Cavity parameters with squeezing


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Cavity parameters with squeezing


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Squeezed light

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Low frequency squeezing with light free noise lock

Noise vs frequency (cavity locked by 10kHz modulation)

shot noise
squeezing

“Quantum noise locking”,
Squeezing level vs time (homodyne angle lock is on)

OPO cavity lock is on

OPO cavity lock is off

linear trend
initial squeezing level
SQL

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Summary for crystal squeezing

Pros

- mainstream: many different nonlinear crystals available
- so far the best squeezers
  - maximum squeezing value detected 11.5 dB at 1064 nm
- well understood

Cons

- crystals have limited transparency window
- thus squeezing is hard to generate at visible wavelength
  - at 795 nm only 4-6 dB squeezing is reported
- this limits applications of such squeezers for spectroscopy
Quantum memory with atomic ensembles

Probe transparency dependence on its detuning.

Storage and retrieval of single photon squeezed state (Furusawa and Lvovsky PRL 2008)

Squeezed state requirements for a quantum memory probe

Squeezing carrier at atomic wavelength (780nm, 795nm)

Squeezing within narrow resonance window at frequencies (< 100kHz)

Traditional nonlinear crystal based squeezers are capable of it, but they are extremely technically challenging especially at short wavelength.
Probe transparency dependence on its detuning.

**Graph 1:**
- X-axis: Probe detuning [Arb. Unit]
- Y-axis: Transparency [Arb. Unit]

**Graph 2:**
- X-axis: Probe detuning [Arb. Unit]
- Y-axis: Transparency [Arb. Unit]

**Diagram:**
- States: \(|a\rangle, |b\rangle, |c\rangle\)
- Frequencies: \(\omega_p, \omega_d, \omega_{bc}\)

**Text:**
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- Traditional nonlinear crystal based squeezers are capable of it, but they are technically challenging especially at short wavelength.
Quantum memory with atomic ensembles

Storage and retrieval
Storage and retrieval

- single photon
Quantum memory with atomic ensembles

Storage and retrieval

- single photon
- squeezed state (Furusawa and Lvovsky PRL 100 2008)
Quantum memory with atomic ensembles

Storage and retrieval
- single photon
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Squeezed state requirements for a quantum memory probe
Quantum memory with atomic ensembles

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Squeezed state requirements for a quantum memory probe
- squeezing carrier at atomic wavelength (780nm, 795nm)
- squeezing within narrow resonance window at frequencies(<100kHz)
Quantum memory with atomic ensembles

Storage and retrieval

- single photon
- squeezed state (Furusawa and Lvovsky PRL 100 2008)

Squeezed state requirements for a quantum memory probe

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Traditional nonlinear crystal based squeezers are capable of it, but they are extremely technically challenging especially at short wave length.
Self-rotation of elliptical polarization in atomic medium

A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

\[ a_{out} = a_{in} + \frac{igL}{2}(a_{in}^\dagger - a_{in}) \]  

(2)
Will something so simple work?


Observed 0.85dB of squeezing at bandwidth 5-10MHz.

No! M. T. L. Hsu et al., Effect of atomic noise on optical squeezing via polarization self-rotation in a thermal vapor cell, PRA 73, 023806 (2006).

Observed 6dB of excess noise after the cell.

Possible. A. Lezama et al., PRA 77, 013806 (2008).


1.4 dB of squeezing.
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- **Definitely** Philippe Grangier et al. Optics Express, 18, Issue 5, pp. 4198-4205 (2010)
  
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Noise contrast vs detuning in hot $^{87}$Rb vacuum cell

$F_g = 2 \rightarrow F_e = 1, 2$

Noise vs detuning

$F_g = 1 \rightarrow F_e = 1, 2$

Noise vs detuning

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Squeezed light
March 22, 2011
Low frequency squeezing vs power in $^{87}$Rb at 795 nm

$^{87}$Rb cell + 2.5Torr Ne, T=63.3°C P=1.5 mW

Low frequency squeezing vs detuning in $^{87}$Rb at 795 nm

$^{87}$Rb cell + 2.5Torr Ne, $T=63.3^\circ$C
(a) $P=1.0$ mW, (b) $P=1.5$ mW, (c) $P=4.2$ mW, (d) $P=6.6$ mW
Squeezing theory and experiment

- $^{87}$Rb cell
- no buffer gas
- density $2 \cdot 10^{11}$ cm$^{-3}$
- laser power 6 mW
- beam size 0.2 mm

E.E. Mikhailov, A. Lezama, T. Noel and I. Novikova,
Theoretical prediction for MOT squeezing with $^{87}\text{Rb}$

$F_g = 2 \rightarrow F_e = 1, 2$ high optical density is very important

![Graphs showing normalized noise power vs. laser detuning with different optical density and coupling strengths.](image-url)
Cloud size = 1 mm, $T = 200 \, \mu K$, $N = 7 \times 10^9 \, 1/cm^3$, 
OD = 2, beam size = 0.1 mm, $10^5$ interacting atoms
Noise contrast in MOT with $^{87}\text{Rb}$ $F_g = 2 \rightarrow F_e = 1$
Squeezing in MOT with $^{87}\text{Rb}$ $F_g = 2 \rightarrow F_e = 1$
Support from
Squeezing is exiting
many applications benefit from squeezing
there is still a lot of interesting physics to do