Squeezed light, generation and applications.

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What is quantum optics

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, $E(t) = ae^{i(kt - \omega t)}$
- cannot explain residual measurements noise

Quantum optics

- light consists of photons: $N = a^\dagger a$
- detector measures quadratures: $X_1 = (a^\dagger + a)/2$ and $X_2 = i(a^\dagger - a)/2$
- amplitude and phase cannot be measured precisely: $\Delta X_1 \Delta X_2 \geq 1/4$
E(φ) = |a|e^{-iφ} = |a|\cos(φ) + i|a|\sin(φ) = X_1 + iX_2, \quad φ = ωt − kz

Detectors sense the real part of the field (X_1) but there is a way to see $X_2$ as well
E(φ) = |a|e^{-iφ} = |a|\cos(φ) + i|a|\sin(φ) = X_1 + iX_2, \quad φ = ωt - kz
Classical field

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Classical quadratures vs time in a rotating frame

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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 $X_2 = i(a^* - a)/2$

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

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

$$\hat{E}(\phi) \; = \; \hat{X}_1 + i\hat{X}_2$$
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

\[ \Delta X_1 \Delta X_2 \geq \frac{1}{4} \]
Heisenberg uncertainty principle and its optics equivalent

### Heisenberg uncertainty principle

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Optics equivalent strict definition

\[ \Delta X_1 \Delta X_2 \geq 1/4 \]
Light consists of photons
- \( \hat{N} = a^\dagger a \)

Commutator relationship
- \([a, a^\dagger] = 1\)
- \([X_1, X_2] = i/2\)

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

Uncertainty relationship
- \( \Delta X_1 \Delta X_2 \geq 1/4 \)
Coherent state is minimum uncertainty state

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Coherent state is minimum uncertainty state

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

![Diagram showing the relationship between X_1 and X_2 with a minimum uncertainty state.]
Coherent state is minimum uncertainty state

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

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Amplitude squeezed states

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\( X_2 \)

\( X_1 \)

\( \phi \)

Projection

0 1/2\( \pi \) \( \pi \) 3/2\( \pi \) 2\( \pi \)

\( \phi \)
Amplitude squeezed states

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Phase squeezed states

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Phase squeezed states

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\[ X_2 \]

\[ X_1 \]

\[ \phi \]

\[ \text{Projection} \]

\[ 0 \quad 1/2\pi \quad \pi \quad 3/2\pi \quad 2\pi \]

\[ \phi \]
Phase squeezed states

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Diagram showing the relationship between phase squeezed states and projection on the phase space.
Phase squeezed states

$$\Delta X_1 \Delta X_2 = \frac{1}{4}$$
Phase squeezed states

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Squeezed quantum states zoo

Unsqueezed coherent

Amplitude squeezed

Phase squeezed

Vacuum squeezed
Squeezed quantum states zoo

Unsqueezed coherent

Amplitude squeezed

Vacuum squeezed

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Squeezed quantum states zoo

Unsqueezed coherent

Amplitude squeezed

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Phase squeezed

Vacuum squeezed
Squeezed field generation recipe

Take a vacuum state $|0>$

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

Take a vacuum state $|0\rangle$

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

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

\[ H = \frac{1}{2} \]

Notice $\Delta X_1 \Delta X_2 = \frac{1}{4}$
Squeezed field generation recipe

Take a vacuum state $|0\rangle$

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

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

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

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

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

$$\langle \alpha, \xi | X_2 | \alpha, \xi \rangle = Im(\alpha)$$
Squeezed field generation recipe

Take a vacuum state $|0\rangle$

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

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

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

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

Notice $\Delta X_1 \Delta X_2 = \frac{1}{4}$
Squeezed state $|\xi\rangle = \hat{S}(\xi)|0\rangle >$ properties

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

If $\theta = 0$

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

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

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

$$< \xi| (\Delta X_2)^2 |\xi> = \frac{1}{4} (\cosh^2 r + \sinh^2 r + 2 \sinh r \cosh r \cos \theta)$$
Photon number of squeezed state $|\xi>$

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
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

[Image of a squeezer device]
Squeezer appearance
Crystal squeezing setup scheme

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Squeezed light  
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improvements any shot noise limited optical sensors
noiseless signal amplification
secure communications (you would notice eavesdropper)
photon pair generation, entanglement, true single photon sources
quantum memory probe and information carrier
interferometers sensitivity boost (for example gravitational wave antennas)
light free measurements
Vacuum input
Squeezing and interferometer

Vacuum input

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

(i) Pre-Stabilized Laser
- PD3
- Reference Cavity
- PBS PD2
- λ/4
- PD1
- Pre-Mode Cleaner
- PO PO

(ii) Mode Cleaner
- (a) Interferometer
- ETMY
- ETMX
- PD4
- PO
- BS
- PO
- PD5
- SRM

(iii) Interferometer
- Gravity Wave

(iv) Squeezer
- SHG
- OPO
- Flipper Mirror
- Homodyne Detector

(v) Length Sensing Detector
- Circulator
GW 40m detector with 4dB of squeezed vacuum

Signal to noise improvement by factor of 1.43
Cavity parameters with squeezing

![Diagram of cavity parameters with squeezing](image)


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Cavity parameters with squeezing


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Cavity parameters with squeezing

Cavity parameters with squeezing

Low frequency squeezing with light free noise lock

Noise vs frequency (cavity locked by 10kHz modulation)

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 a single photon in a squeezed state (Furusawa and Lvovsky PRL 2008).

Squeezed state requirements for a quantum memory probe:
- Squeezing carrier at atomic wavelengths (780nm, 795nm)
- Squeezing within narrow resonance windows at frequencies (< 100kHz)

Traditional nonlinear crystal based squeezers are capable of it, but they are extremely technically challenging especially at short wavelengths.
Quantum memory with atomic ensembles

Storage and retrieval of single photon squeezed state (Furusawa and Lvovsky PRL 100 2008)

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Quantum memory with atomic ensembles

Probe transparency dependence on its detuning.

Storage and retrieval

$
\begin{aligned}
|a\rangle &\rightarrow \omega_d |c\rangle \\
|b\rangle &\rightarrow \omega_{bc} |a\rangle \\
|c\rangle &\rightarrow \omega_p |b\rangle
\end{aligned}
$
Quantum memory with atomic ensembles

Storage and retrieval

- single photon
Quantum memory with atomic ensembles

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

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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

\[ a_{out} = a_{in} + \frac{igL}{2}(a_{in}^\dagger - a_{in}) \]
Will something so simple work?


Observed 0.85dB of squeezing at bandwidth 5-10MHz

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- **Definitely** Philippe Grangier et al. Optics Express, 18, Issue 5, pp. 4198-4205 (2010)
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Setup

PBS

RB

LO

V.Sq
Noise contrast vs detuning in hot $^{87}$Rb vacuum cell

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

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

Eugeniy E. Mikhailov (W&M)
Low frequency squeezing vs power in $^{87}\text{Rb}$ at 795 nm

$^{87}\text{Rb}$ 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.
MOT squeezer

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 NSF
Squeezing is exiting
many applications benefit from squeezing
there is still a lot of interesting physics to do