Quantum enhanced measurements

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From ray optics to semiclassical 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, $E(t) = ae^{i(kz-\omega t)}$
- cannot explain residual measurements noise
Classical field

\[ E(\phi) = |a| e^{-i\phi} = |a| \cos(\phi) + i |a| \sin(\phi) = X_1 + i X_2, \quad \phi = \omega t - kz \]

Detectors sense the real part of the field \((X_1)\) but there is a way to see \(X_2\) as well.
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\[ \phi \quad X_1 \quad X_2 \]

Projection

\[ \phi \quad 0 \quad 1/2\pi \quad \pi \quad 3/2\pi \quad 2\pi \]
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Classical quadratures vs time in a rotating frame

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

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

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Heisenberg uncertainty principle and its optics equivalent

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Optics equivalent strict definition
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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 \( \hat{N} \)
- 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

$$\Delta X_1 \Delta X_2 = 1/4$$
Coherent state is minimum uncertainty state

$\Delta X_1 \Delta X_2 = \frac{1}{4}$
Coherent state is minimum uncertainty state

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\begin{align*}
\text{Projection} & \\
X_2 & \\
X_1 & \\
\phi & \\
0 & \frac{1}{2}\pi & \pi & \frac{3}{2}\pi & 2\pi
\end{align*}
Coherent state is minimum uncertainty state

\[ \Delta X_1 \Delta X_2 = 1/4 \]
Coherent state is minimum uncertainty state

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

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

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Projection

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Amplitude squeezed states

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Phase squeezed states

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Phase squeezed states

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

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![Diagram showing phase squeezing states with projections and graphs illustrating the phase space evolution.](image)
Phase squeezed states

\[ \Delta X_1 \Delta X_2 = \frac{1}{4} \]
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Squeezed quantum states zoo

Unsqueezed coherent

Amplitude squeezed

Phase squeezed

Vacuum squeezed

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Squeezed quantum states zoo

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

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

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

Take a vacuum state $|0 \rangle$

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

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

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

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

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

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

$<\alpha, \xi | X_2 | \alpha, \xi> = Im(\alpha)$
Take a vacuum state $|0\rangle$

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

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

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

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

$$<\alpha, \xi|X_2|\alpha, \xi> = Im(\alpha)$$
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 $\theta = 0$

$$\langle \xi | (\Delta X_1)^2 | \xi \rangle = \frac{1}{4} e^{-2r}$$
$$\langle \xi | (\Delta X_2)^2 | \xi \rangle = \frac{1}{4} e^{2r}$$

$$\langle \xi | (\Delta X_1)^2 | \xi \rangle = \frac{1}{4} (\cosh^2 r + \sinh^2 r - 2 \sinh r \cosh r \cos \theta)$$
$$\langle \xi | (\Delta X_2)^2 | \xi \rangle = \frac{1}{4} (\cosh^2 r + \sinh^2 r + 2 \sinh r \cosh r \cos \theta)$$
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

\[
\langle \alpha, \xi | a\dagger a | \alpha, \xi \rangle = \alpha + \sinh^2 r
\]
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
Squeezer appearance
Squeezer appearance
Crystal squeezing setup scheme

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Possible squeezing applications

- Improvements for any shot noise limited optical sensors
- Noiseless signal amplification
- Secure communications (you would notice an 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
Vacuum input

laser

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

(i) Pre-Stabilized Laser

LASER

PD3
Reference Cavity

Pre-Mode Cleaner

PO

PO

λ/4

PD1

(ii) Mode Cleaner

(iii) Interferometer

Gravity Wave

Vacuum

PD4

ETMY

ETMX

PO

BS

PO

PD5

SRM

Circulator

Flipper Mirror

Homodyne Detector

(V) Length Sensing Detector

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GW 40m detector with 4dB of squeezed vacuum

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

\[ \text{Cavity parameters with squeezing} \]

\[ \text{Nd:YAG LASER SQZ NL Servo PDH Servo SA FI BS S PZT2 PZT1 HD1 HD2 PD OC2 EOM AOM OC1 TEST CAVITY} \]

\[ \text{Frequency (MHz)} \]

\[ \text{Quadrature Variance w.r.t. Shot Noise (dB)} \]

This figure illustrates the concept of cavity parameters with squeezing. It shows the interactions between various components such as Nd:YAG laser, squeezing, and different servo systems like NL, PDH, and PD. The diagram indicates the flow of light and parameters like frequency, variance, and shot noise. The reference 'Noninvasive measurements of cavity parameters by use of squeezed vacuum' is cited from Physical Review A, 74, 033817, (2006).
Cavity parameters with squeezing


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Cavity parameters with squeezing

Nd:YAG LASER

NL Servo

PDH Servo

SA

FI

BS

S

PZT2

PZT1

HD1

HD2 PD

OC2

EOM

AOM

OC1

TEST CAVITY

PZT2

Frequency (MHz)

Quadrature Variance w.r.t. Shot Noise (dB)


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Squeezed light
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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

![Graph of probe transparency dependence on its detuning.]

Probe transparency dependence on its detuning.

\[ |a\rangle \]

\[ |b\rangle \]

\[ |c\rangle \]

\[ \omega_p \]

\[ \omega_{bc} \]

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.
Quantum memory with atomic ensembles

Probe transparency dependence on its detuning.

\(|a\rangle\) \quad \omega_p

\(|b\rangle\) \quad \omega_{bc}

\(|c\rangle\) \quad \omega_d

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

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Storage and retrieval
Quantum memory with atomic ensembles

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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?

Yes! J. Ries, B. Brezger, and A. I. Lvovsky, Experimental vacuum squeezing in rubidium vapor via self-rotation, PRA 68, 025801 (2003). 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.

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

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

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

Noise vs detuning

Noise vs quadrature angle

Transmission  PSR noise
Magnetometer with squeezing enhancement

![Diagram of a magnetometer with squeezing enhancement](image)

**Figure (a)** Coherent probe vs. squeezed probe sensitivity at different atomic densities (atoms/cm$^3$).

**Figure (b)** Sensitivity vs. atomic density for coherent and squeezed probes.

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Squeezed light
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Support from

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Summary

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