Squeezed states of light with hot atoms

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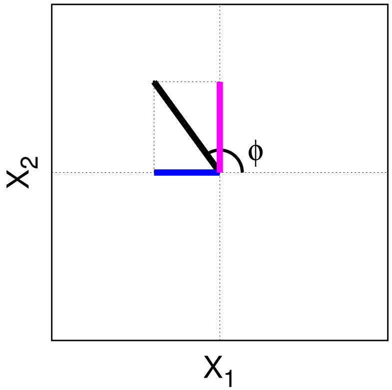
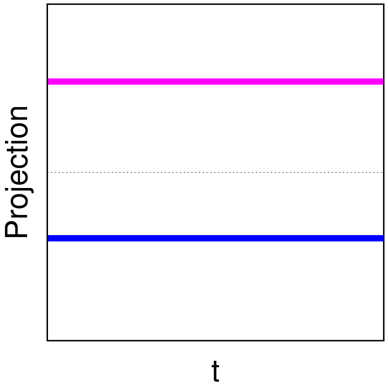
Classical field quadratures vs time

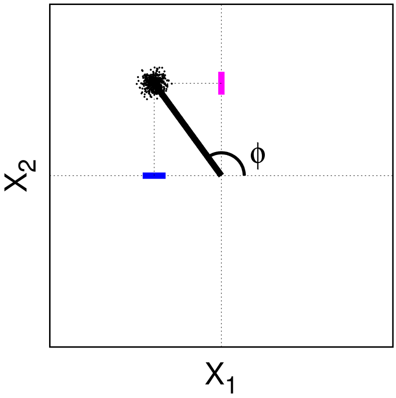
$$E(\phi) \;=\; |a|e^{-i\phi} = |a|\cos(\phi) + i|a|\sin(\phi) = X_1 + iX_2, \quad \phi = \omega t - kz$$

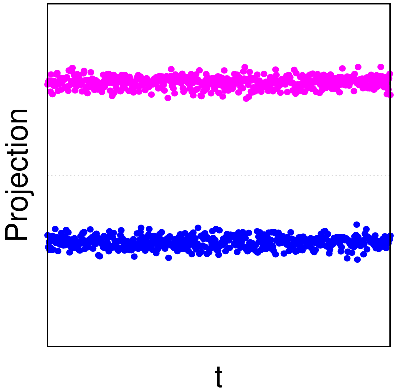




Reality check quadratures vs time

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



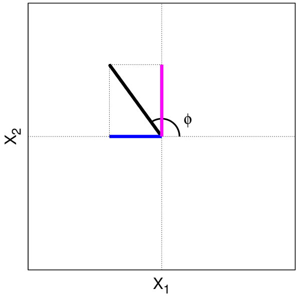


Transition from classical to quantum field

Classical analog

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

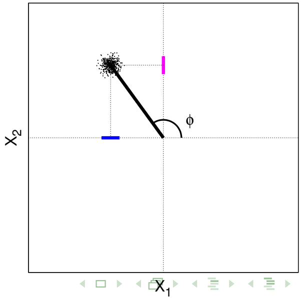
$$E(\phi) \quad = \quad |a|e^{-i\phi} = X_1 + iX_2$$

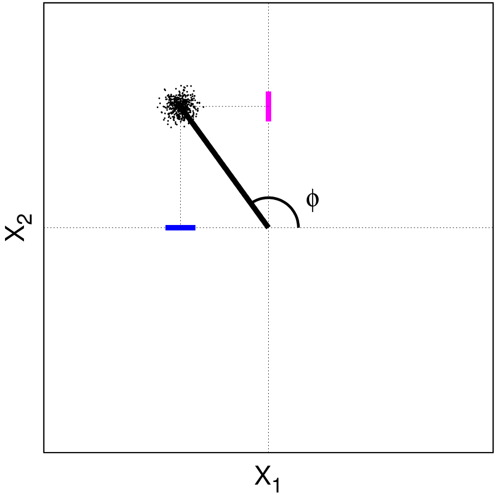


Quantum approach

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

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





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

- $\Delta X_1 \Delta X_2 \geq 1/4$

Heisenberg uncertainty principle and its optics equivalent

Heisenberg uncertainty principle

$\Delta p \Delta x \geq \hbar/2$

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

Heisenberg uncertainty principle and its optics equivalent

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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

Heisenberg uncertainty principle and its optics equivalent

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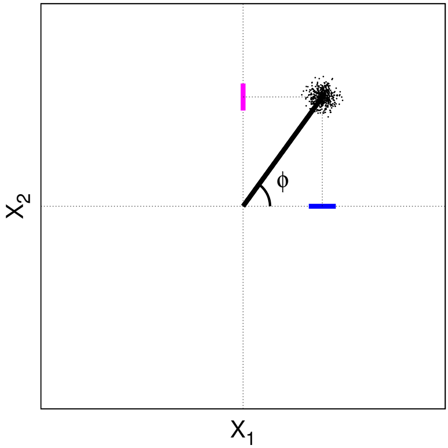
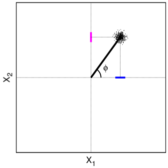
Optics equivalent strict definition

$\Delta X_1 \Delta X_2 \geq 1/4$

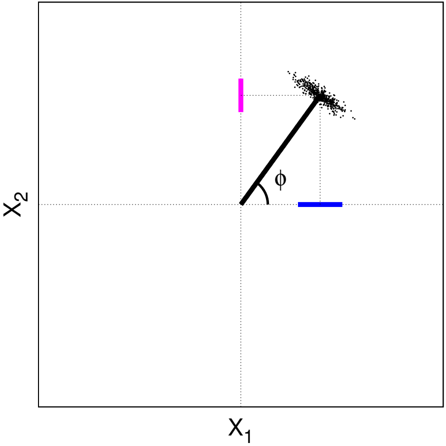
Squeezed quantum states zoo



Unsqueezed coherent



Squeezed quantum states zoo



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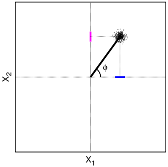
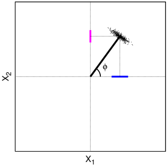
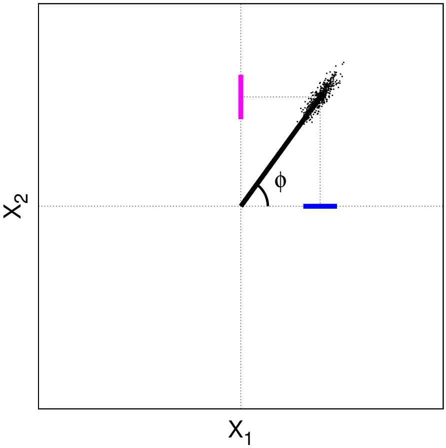


Amplitude squeezed



Squeezed quantum states zoo



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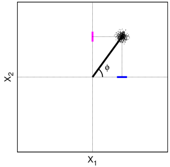
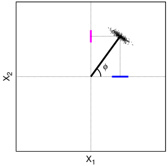
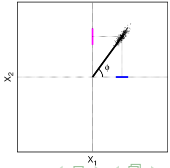


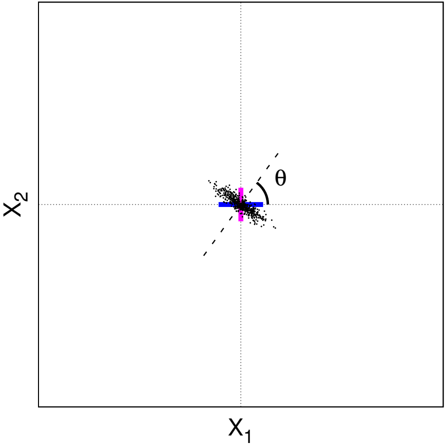
Amplitude squeezed



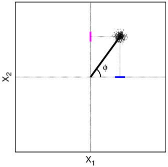
Phase squeezed



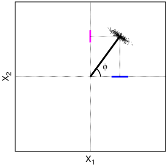
Squeezed quantum states zoo



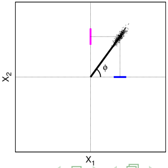
Unsqueezed coherent



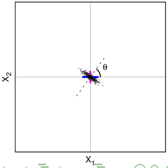
Amplitude squeezed



Phase squeezed

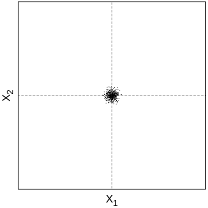


Vacuum squeezed



Squeezed field generation recipe

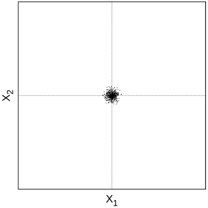
Take a vacuum state $|0>$



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

Squeezed field generation recipe

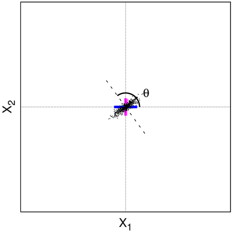
Take a vacuum state $|0>$



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

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

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



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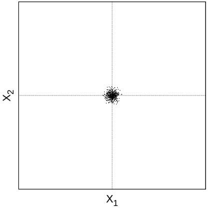

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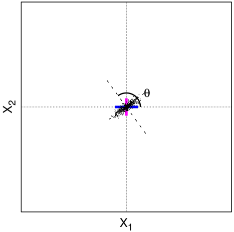
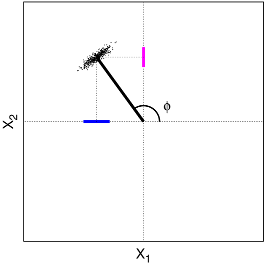


Apply displacement operator $|\alpha, \xi >= \hat{D}(\alpha)|s>$

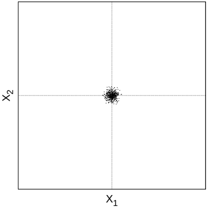
$$\hat{D}(\alpha) = e^{\alpha a^\dagger - \alpha^* a}$$



$$< \alpha, \xi | X_1 | \alpha, \xi > \quad = \quad Re(\alpha),$$
$$< \alpha, \xi | X_2 | \alpha, \xi > \quad = \quad Im(\alpha)$$

Squeezed field generation recipe

Take a vacuum state $|0>$

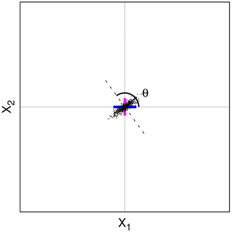


$$H = \frac{1}{2}$$

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

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

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



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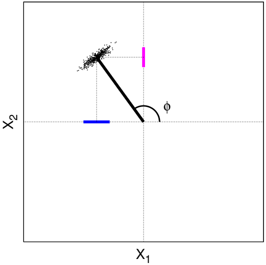

$$< \alpha, \xi | X_1 | \alpha, \xi > = Re(\alpha),$$
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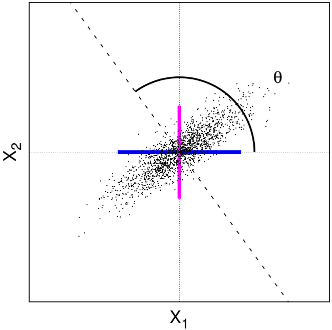
Photon number of squeezed state $|\xi>$



Probability to detect given number of photons $C =< n|\xi >$ for squeezed vacuum

- even

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

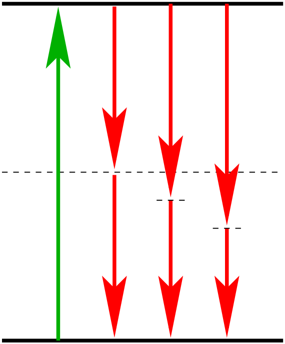
- odd

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

Average number of photons in general squeezed state

$$< \alpha, \xi|a^\dagger a|\alpha, \xi >= \alpha + \sinh^2 r$$

Two photon squeezing picture

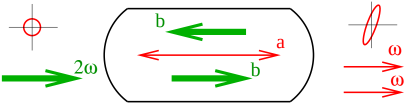


Squeezing operator

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

Parametric down-conversion in crystal

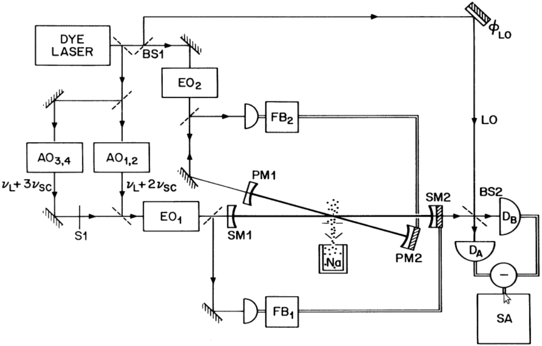
$$\hat{H} = i\hbar\chi^{(2)}(a^2 b^\dagger - a^{\dagger 2} b)$$

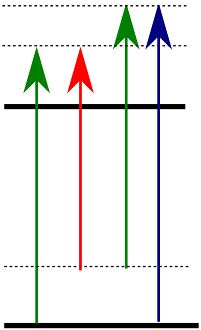


Squeezing

maximum squeezing value detected 11.5 dB at 1064 nm
Moritz Mehmet, Henning Vahlbruch, Nico Lastzka, Karsten Danzmann, and Roman Schnabel, Phys. Rev. A **81**, 013814 (2010)

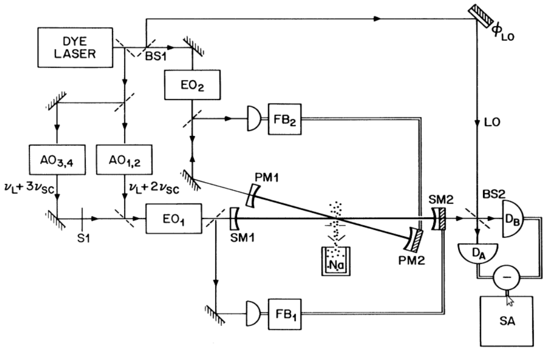
R. E. Slusher, L. W. Hollberg, B. Yurke, J. C. Mertz, and J. F. Valley.
Phys. Rev. Lett. 55, 2409-2412 (1985)



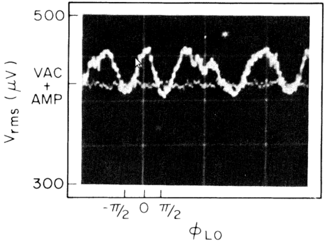


Squeezed States Generated by Four-Wave Mixing

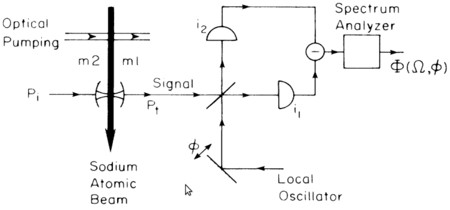
R. E. Slusher, L. W. Hollberg, B. Yurke, J. C. Mertz, and J. F. Valley. Phys. Rev. Lett. 55, 2409-2412 (1985)

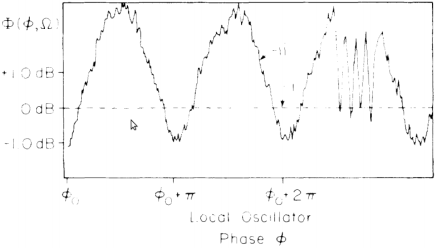


Analysis frequency = 422 MHz



M. G. Raizen, L. A. Orozco, Min Xiao, T. L. Boyd, and H. J. Kimble
Phys. Rev. Lett. 59, 198-201 (1987)



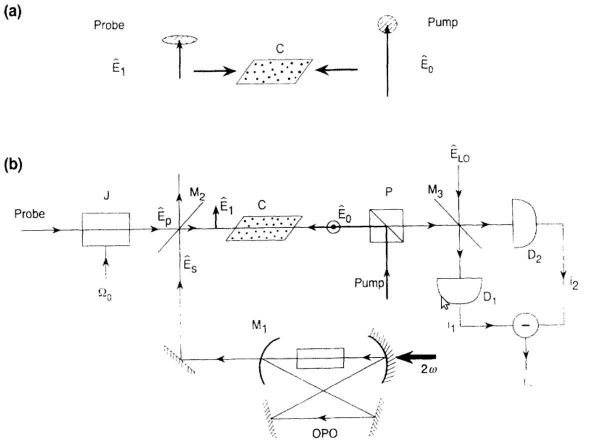


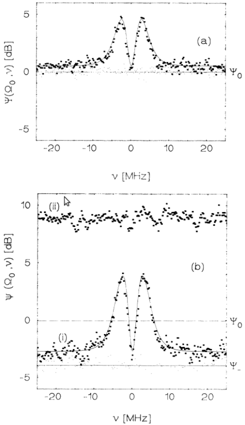
Analysis frequency = 270 MHz

Doppler-free spectroscopy of Cs with squeezing

E. S. Polzik, J. Carri, and H. J. Kimble Phys. Rev. Lett. 68, 3020-3023 (1992)

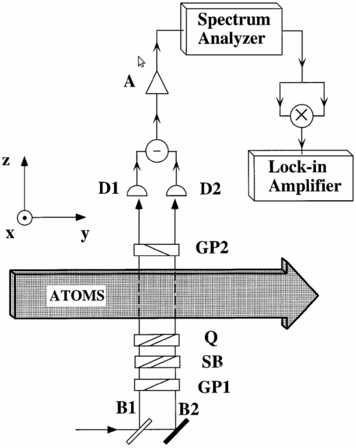
Analysis frequency = 2.7 MHz

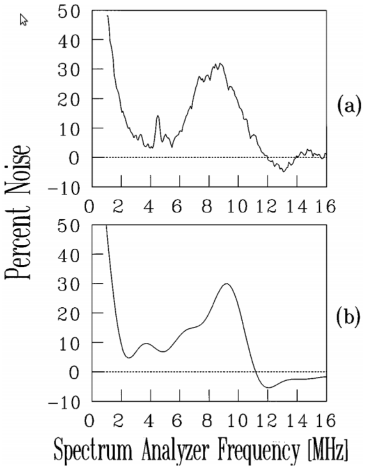




Squeezing in Fluorescence of Two-Level Atoms ^{174}Yb

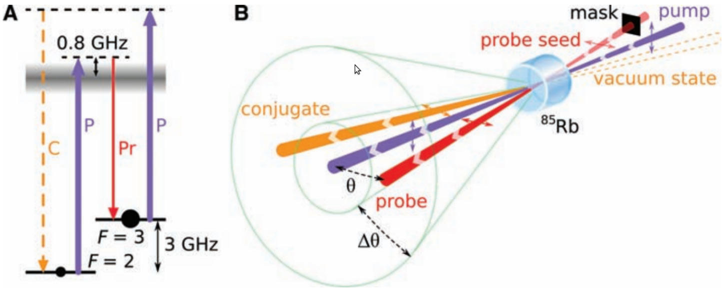
Z. H. Lu, S. Bali, and J. E. Thomas. Phys. Rev. Lett. 81, 3635-3638 (1998)





Four-wave-mixing induced squeezing

Vincent Boyer, Alberto M. Marino, Raphael C. Pooser and Paul D. Lett
Science, Vol. 321 no. 5888 pp. 544-547 (2008)



Four-wave-mixing induced squeezing

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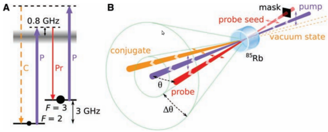
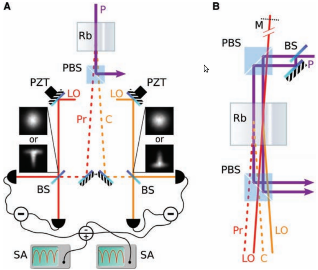
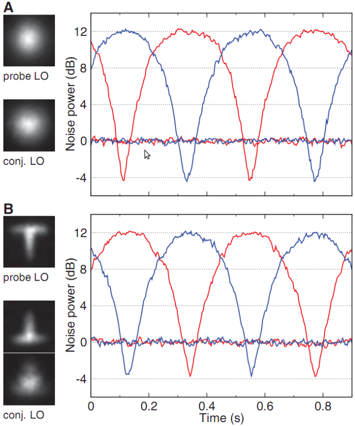
Science, Vol. 321 no. 5888 pp. 544-547 (2008)

Analysis frequency = 3.5 MHz

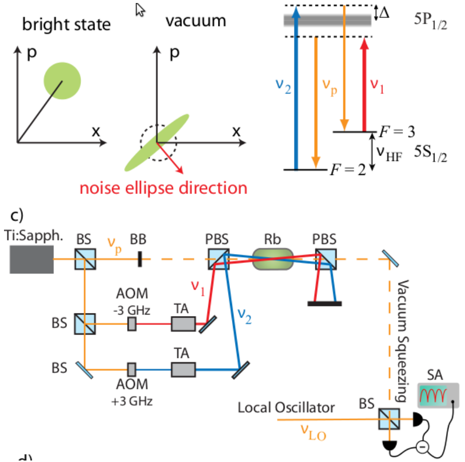


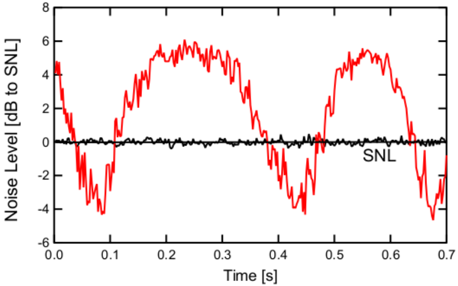




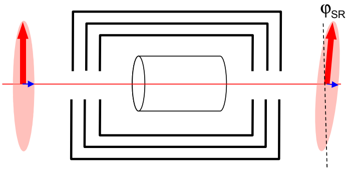
Degenerate vacuum squeezing via four-wave-mixing

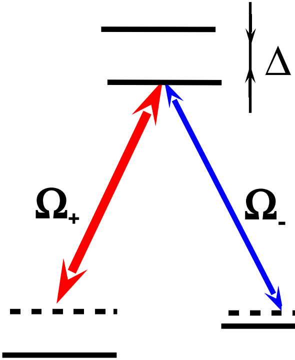
Neil V. Corzo, Quentin Glorieux, Alberto M. Marino, Jeremy B. Clark, Ryan T. Glasser, and Paul D. Lett Phys. Rev. A 88, 043836 (2013)





Self-rotation of elliptical polarization in atomic medium

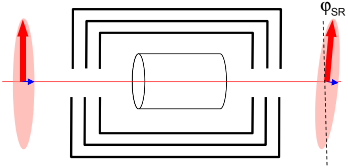


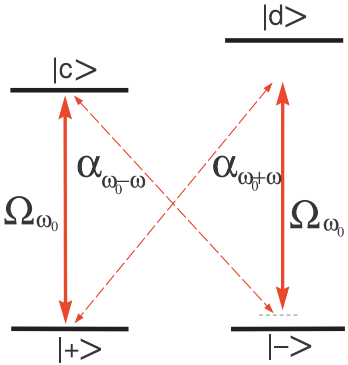


A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

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

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

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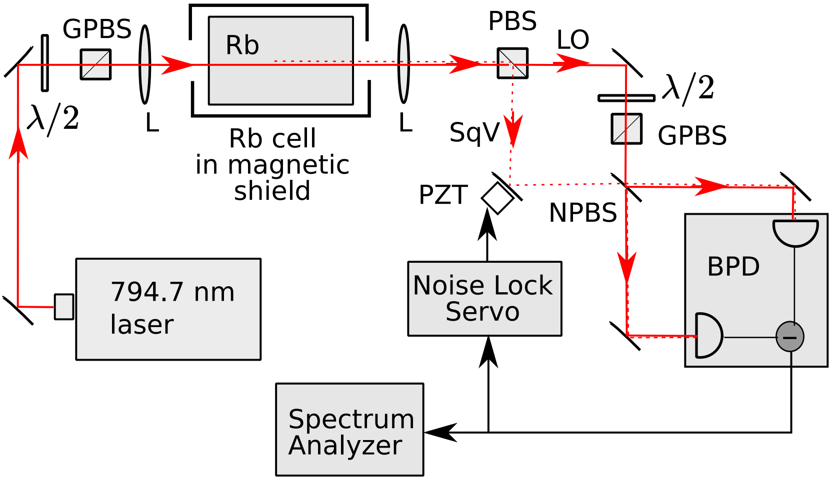
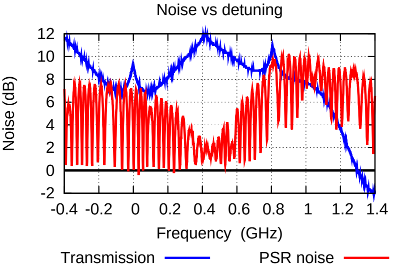
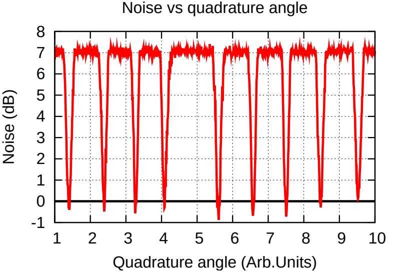
Setup


GPBS
Rb
PBS
LO
$\lambda/2$
L
Rb cell
in magnetic
shield
L
SqV
$\lambda/2$
GPBS
PZT
NPBS
BPD
794.7 nm
laser
Noise Lock
Servo
Spectrum
Analyzer

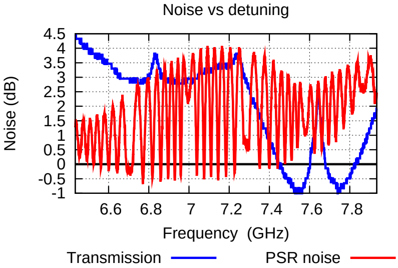
Noise contrast vs detuning in hot ^{87}Rb vacuum cell

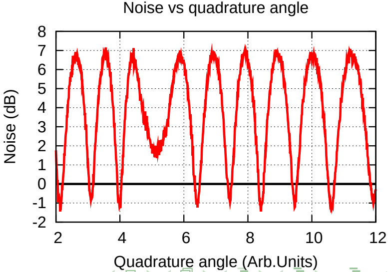
$F_g = 2 \rightarrow F_e = 1, 2$



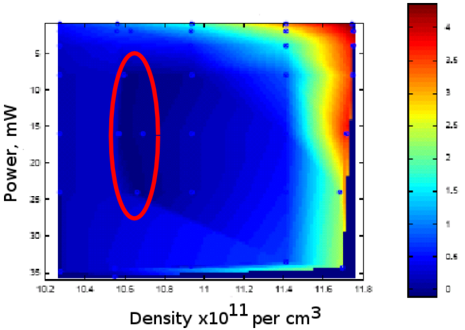


$F_g = 1 \rightarrow F_e = 1, 2$

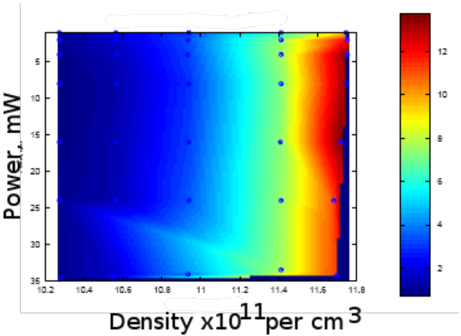




Squeezing



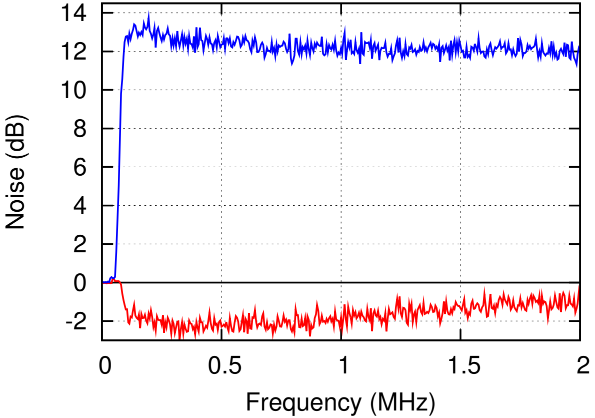
Anti-squeezing



Observation of reduction of quantum noise below the shot noise limit is corrupted by the excess noise due to atomic interaction with atoms.

Maximally squeezed spectrum with ^{87}Rb

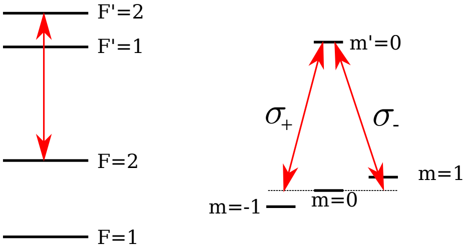
W&M team. ^{87}Rb $F_g = 2 \to F_e = 2$, laser power 7 mW, T=65° C



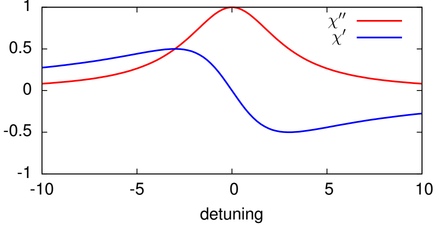
Lezama et.al report 3 dB squeezing in similar setup
Phys. Rev. A 84, 033851 (2011)

Optical magnetometer based on Faraday effect

^{87}Rb D_1 line

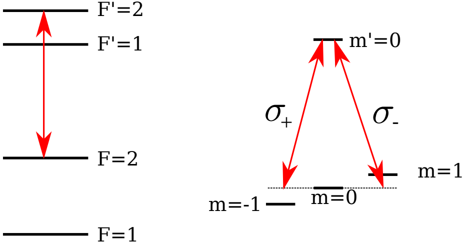


Susceptibility vs B

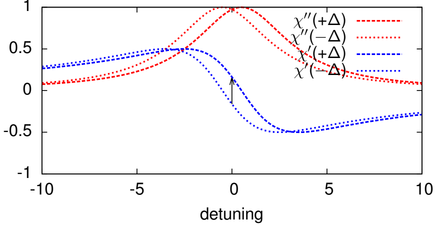


Optical magnetometer based on Faraday effect

^{87}Rb D_1 line

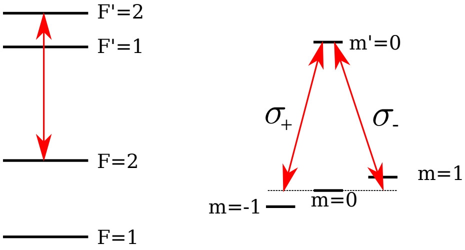


Susceptibility vs B

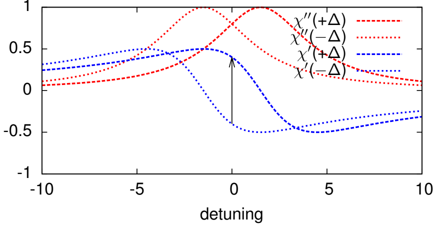


Optical magnetometer based on Faraday effect

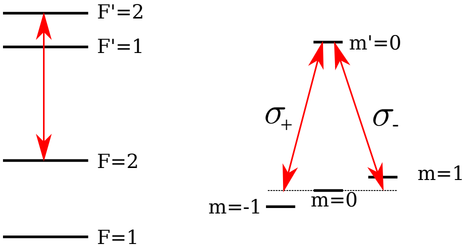
^{87}Rb D_1 line



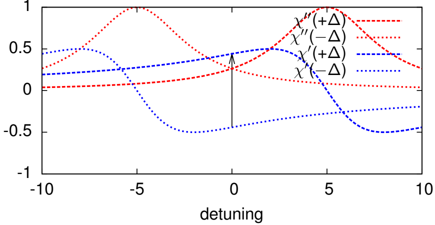
Susceptibility vs B



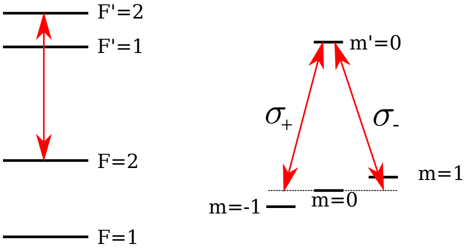
^{87}Rb D$_1$ line



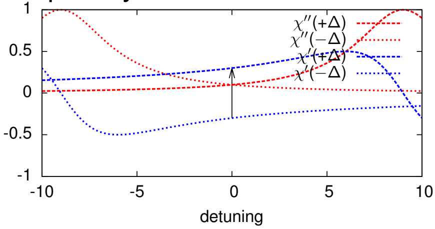
Susceptibility vs B



^{87}Rb D_1 line

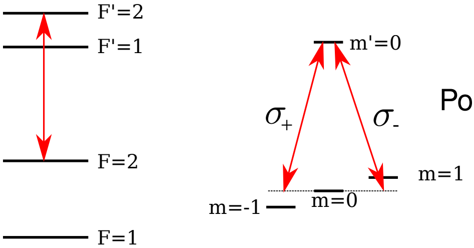


Susceptibility vs B

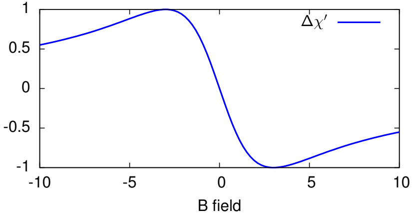


Optical magnetometer based on Faraday effect

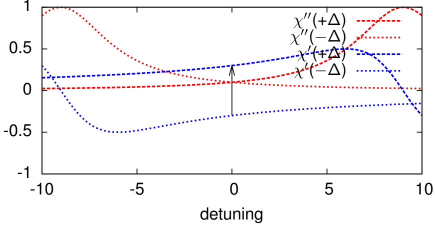
^{87}Rb D_1 line



Polarization rotation vs B

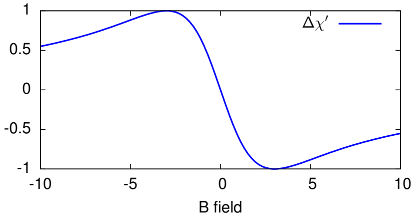


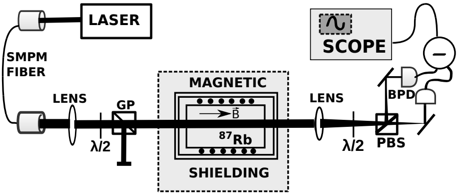
Susceptibility vs B



Optical magnetometer and non linear Faraday effect

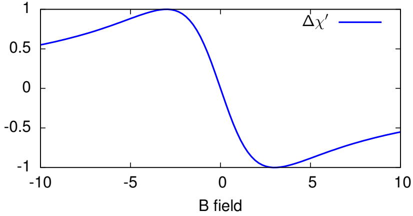
Naive model of rotation

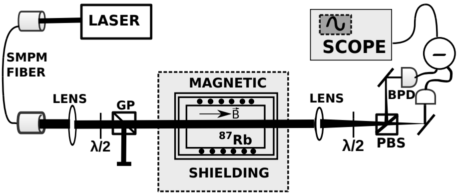




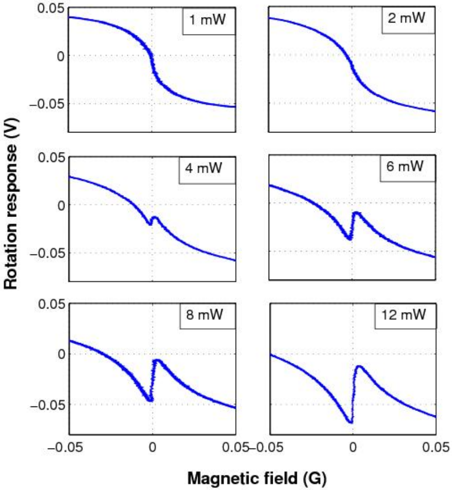
Experiment

Naive model of rotation

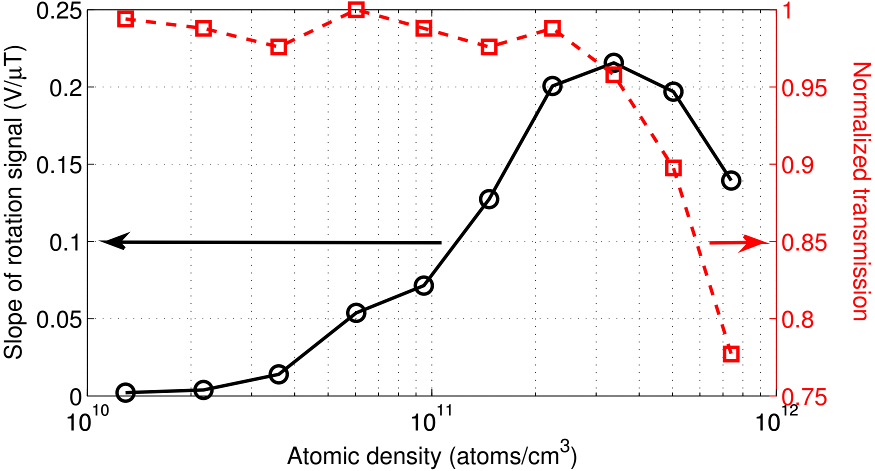




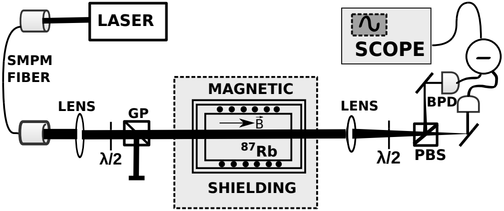
Experiment

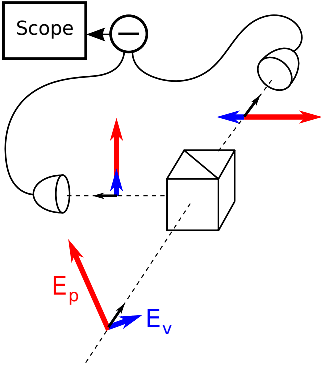


Magnetometer response vs atomic density



Shot noise limit of the magnetometer



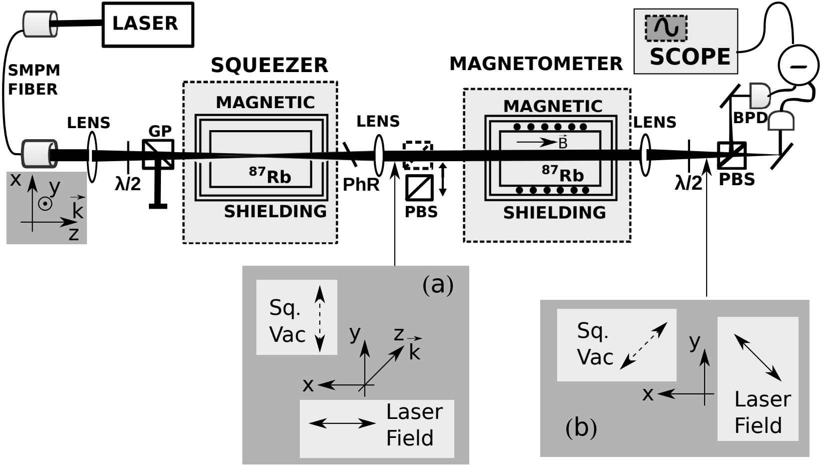


$$S = |E_p + E_v|^2 - |E_p - E_v|^2$$

$$S = 4E_pE_v$$

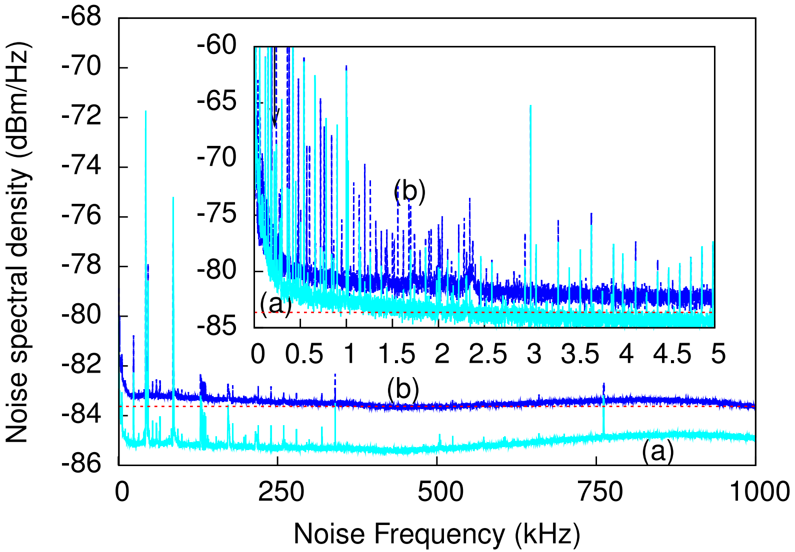
$$< \Delta S > \sim E_p < \Delta E_v >$$

Squeezed enhanced magnetometer setup

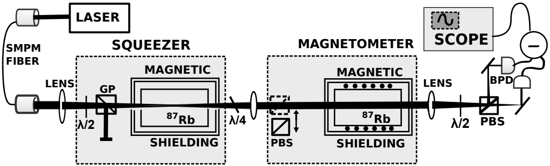


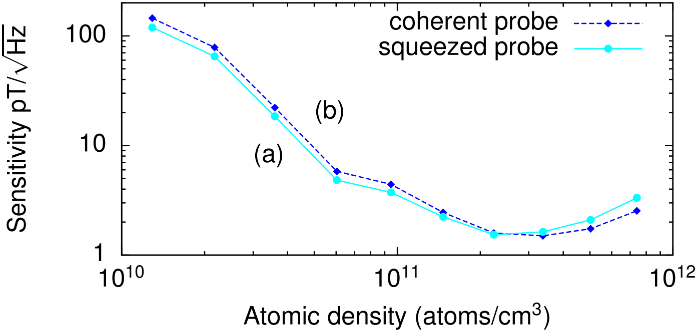
Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al* Phys. Rev. Lett, **105**, 053601, 2010.

Magnetometer noise floor improvements



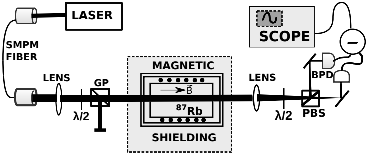
Magnetometer with squeezing enhancement

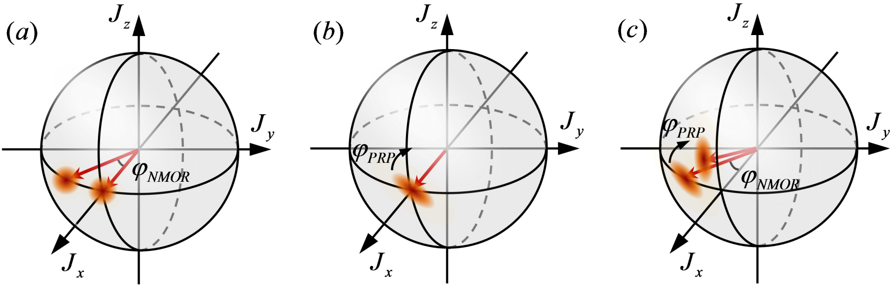




T. Horrom, et al. **PRA**, 86, 023803, (2012).

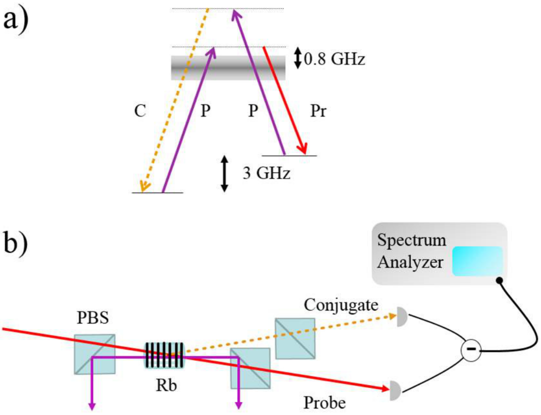
Self-squeezed magnetometry





Irina Novikova, Eugeniy E. Mikhailov, Yanhong Xiao, “Excess optical quantum noise in atomic sensors”, arXiv:1410.3810, (2014).

20 pT$/\sqrt{\mathrm{Hz}}$ self-squeezed magnetometry with 4WM



N. Otterstrom, R. C. Pooser, and B. J. Lawrie, "Nonlinear optical magnetometry with accessible in situ optical squeezing", Optics Letters, **39**, Issue 22, pp. 6533-6536 (2014)

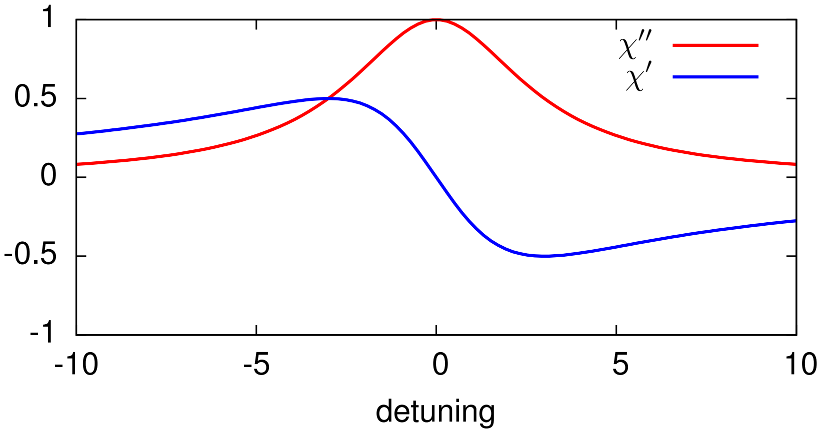
Why superluminal squeezing?

- Quantum memories
- M. S. Shahriar, et al. “Ultrahigh enhancement in absolute and relative rotation sensing using fast and slow light”, Phys. Rev. A 75(5), 053807, 2007.
- R. W. Boyd, et al. “Noise properties of propagation through slow- and fast- light media”, Journal of Optics **12**, 104007 (2010).

Light group velocity

Group velocity $v_g = \frac{c}{\omega \frac{\partial n}{\partial \omega}}$

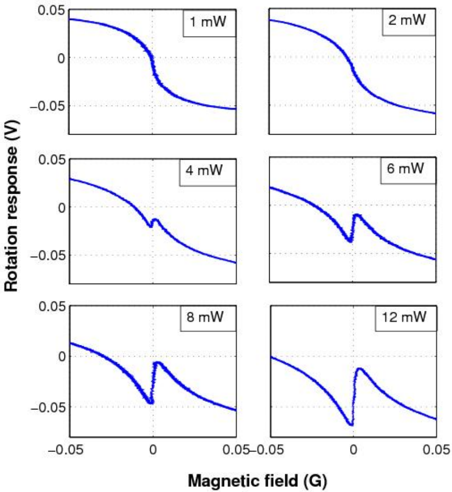
Susceptibility



Light group velocity

Group velocity $v_g = \frac{c}{\omega \frac{\partial n}{\partial \omega}}$

Delay $\tau = \frac{L}{v_g} \sim \frac{\partial n}{\partial \omega} \sim \frac{\partial R}{\partial B}$



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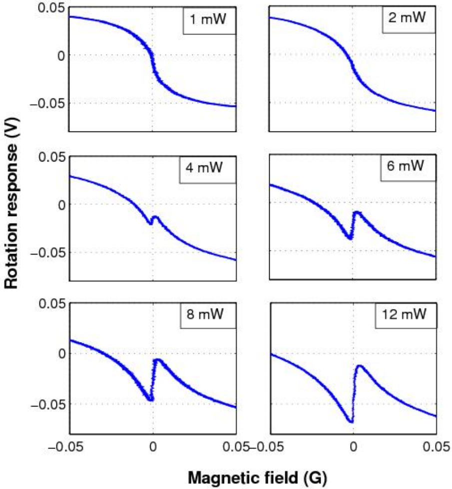
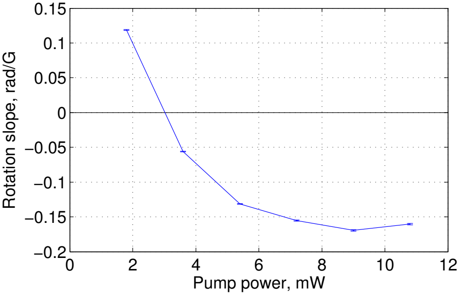
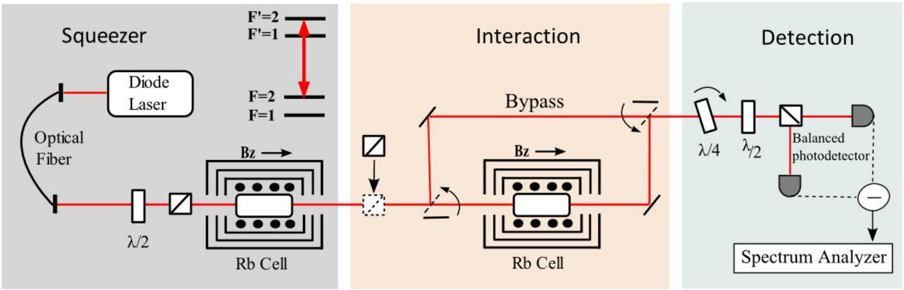
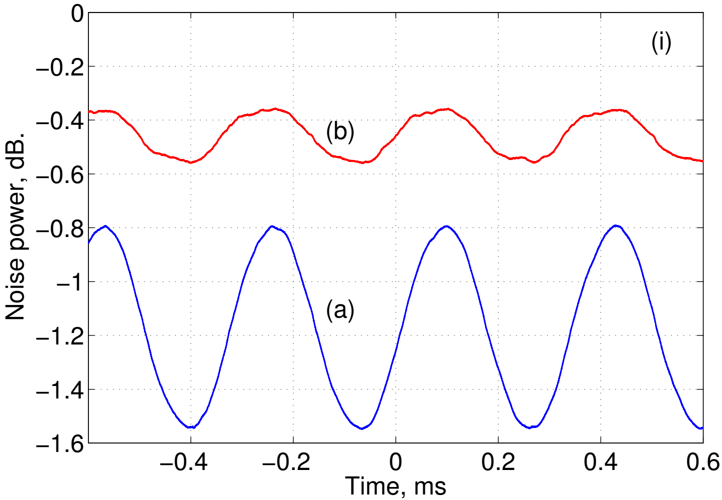




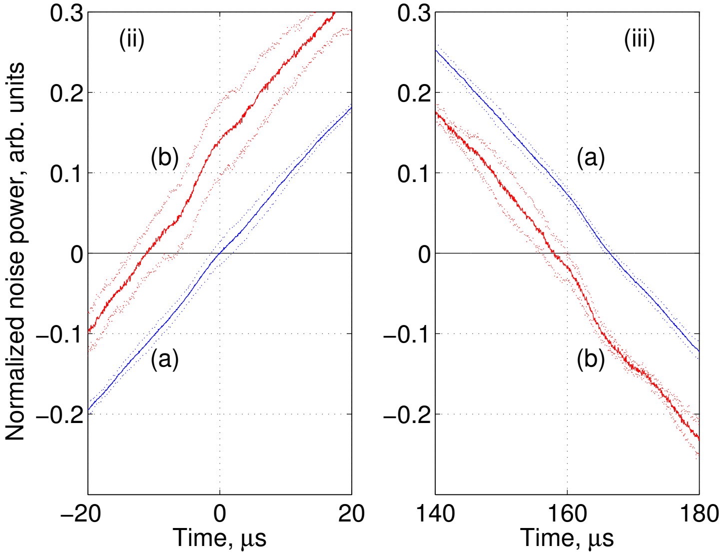
Time advancement setup



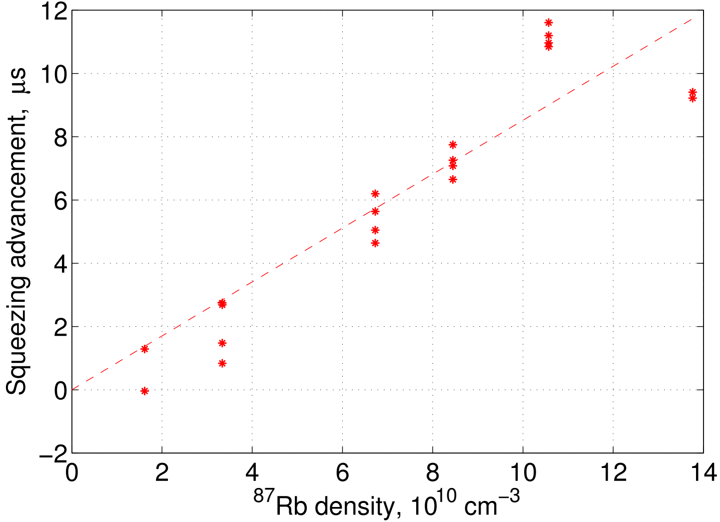
Squeezing modulation and time advancement



Squeezing modulation and time advancement



Squeezing advancement vs atomic density

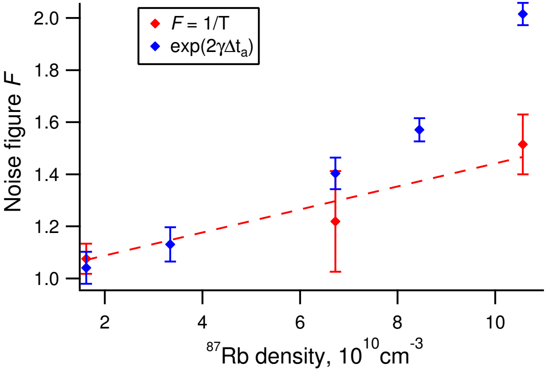


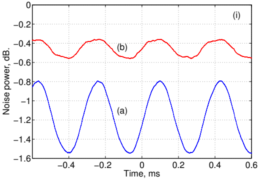
G. Romanov, et al. Optics Letters, Issue 4, 39, 1093-1096, (2014).

Noise figure and advancement

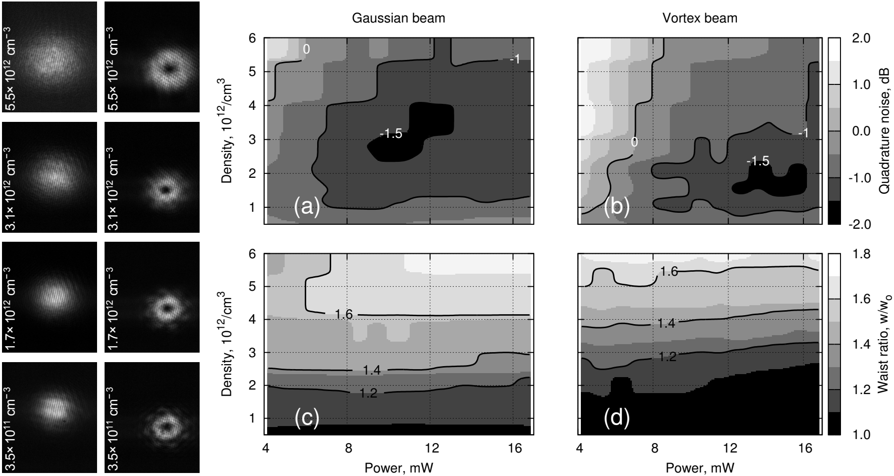
R. W. Boyd, et al. “Noise properties of propagation through slow- and fast- light media”, Journal of Optics **12**, 104007 (2010).

$$F = \frac{SNR_{in}}{SNR_{out}} = 1/T = e^{2\gamma \Delta t_a}$$



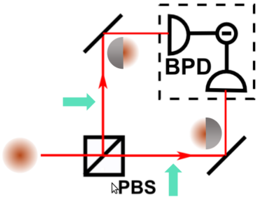


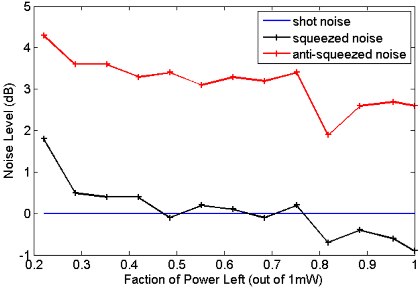
Squeezing and self-focusing



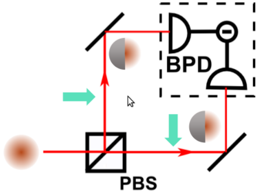
Mi Zhang, et al., Optics Letters, Issue 22, 38, 4833-4836, (2013).

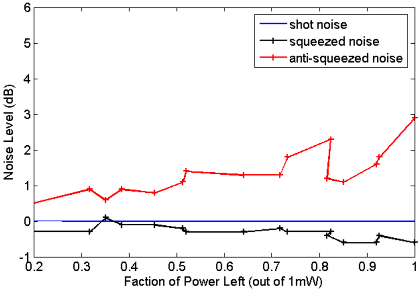
Same side cut (= before BS)



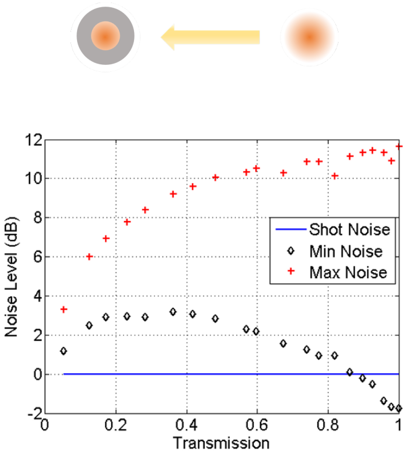


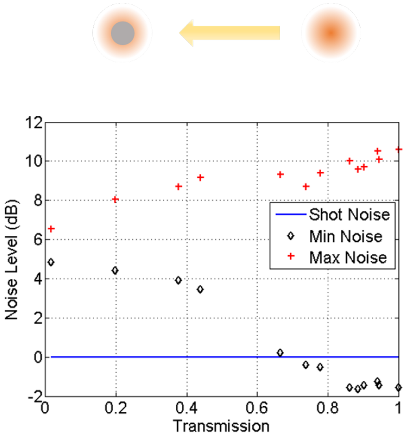
Opposite sides cut



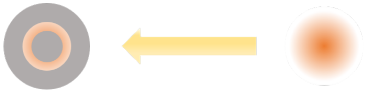


Simple round mask

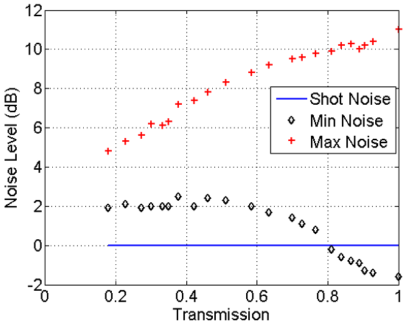




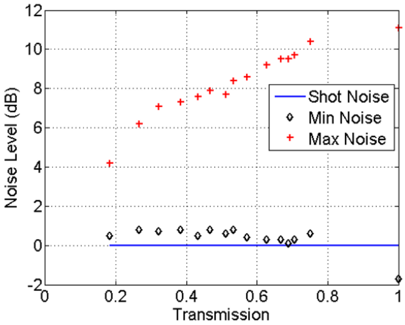
Transmissive ring mask



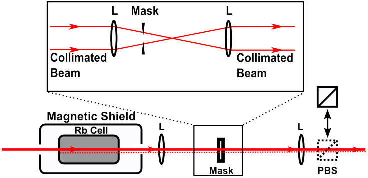
8% blocking disk

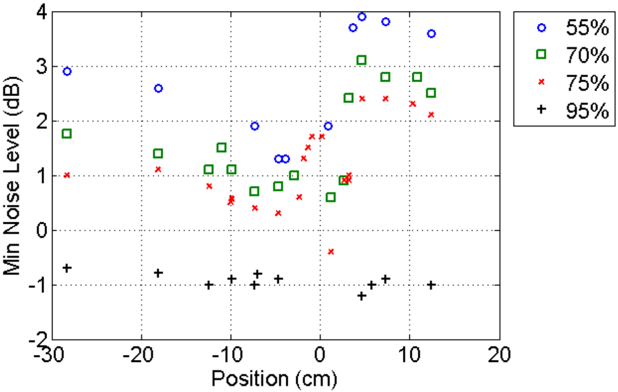


25% blocking disk

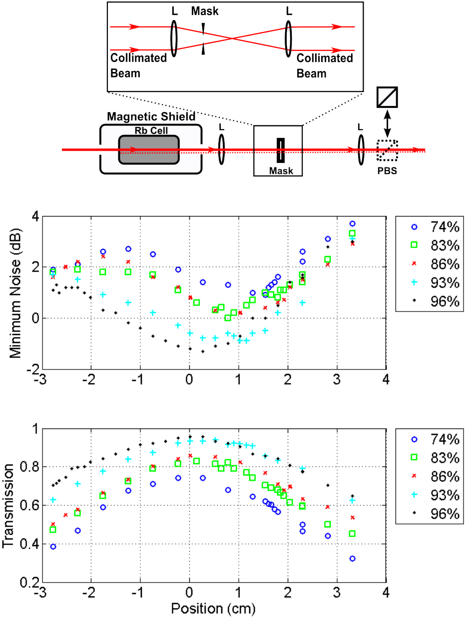


Constant transmission map





Constant iris size map



People

Irina Novikova, Mi Zhang, Gleb Romanov and Travis Horrom (NIST), LSU group of Jonathan P. Dowling, Yanhong Xiao (Fudan, China) and Arturo Lezama (Instituto de Física, Uruguay)