Squeezing vacuum with Rb atoms: quantum enhanced magnetometry and competition of spatial modes.

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WILLIAM & MARY
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CICESE, August 20, 2018

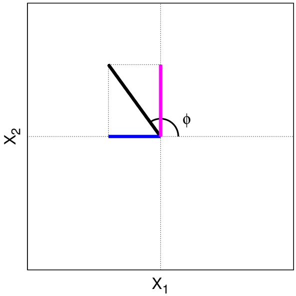
About College of William and Mary

Transition from classical to quantum field

Classical analog

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

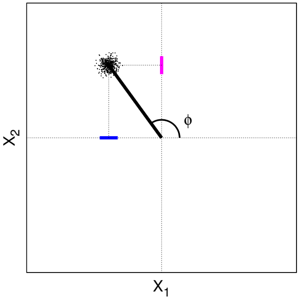
$$E(\phi) = |a|e^{-i\phi} = X_1 + iX_2$$



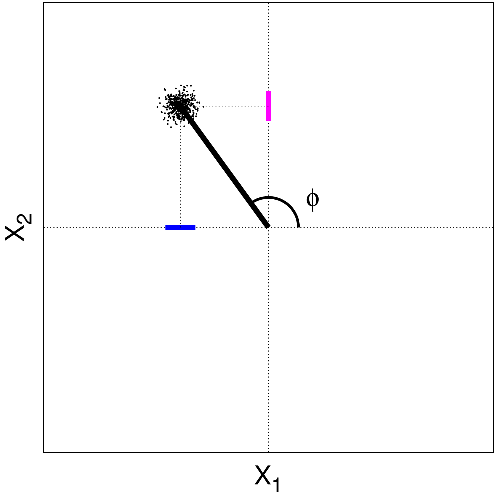
Quantum approach

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

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



Quantum optics summary



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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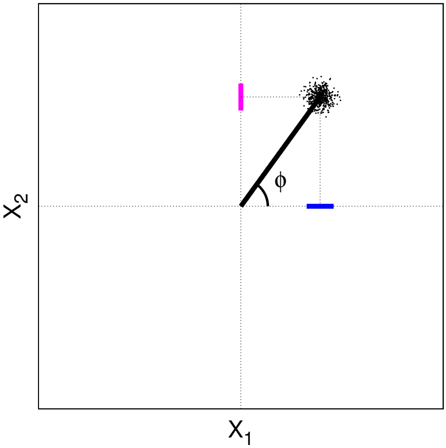
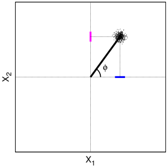
Optics equivalent strict definition

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

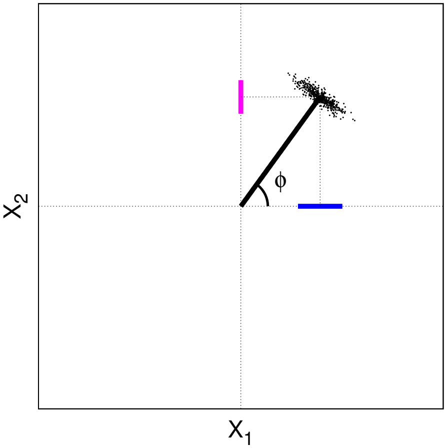
Squeezed quantum states zoo



Unsqueezed coherent



Squeezed quantum states zoo



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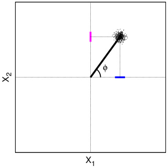
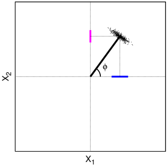
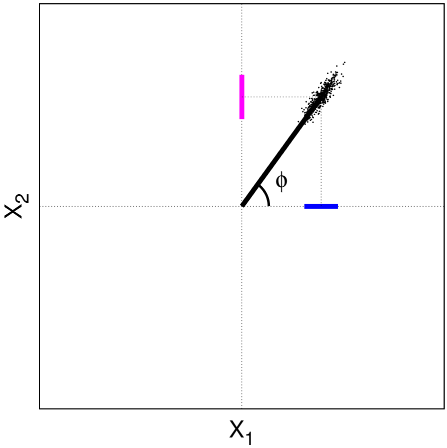


Amplitude squeezed



Squeezed quantum states zoo



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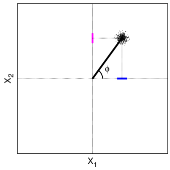
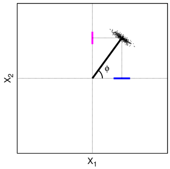
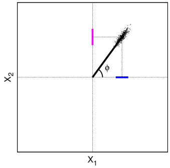


Amplitude squeezed



Phase squeezed



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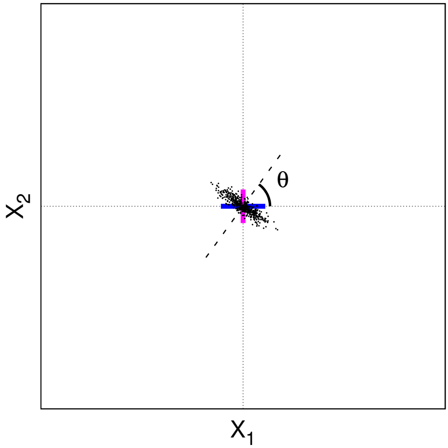
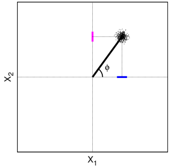


Unsqueezed coherent



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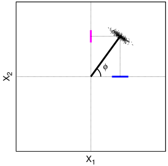
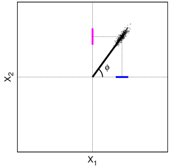
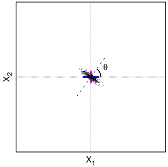


Phase squeezed

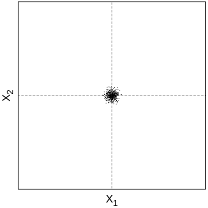


Vacuum squeezed



Squeezed field generation recipe

Take a vacuum state $|0>$



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

Squeezed field generation recipe

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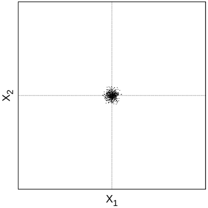
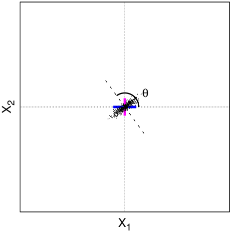


$$H = \frac{1}{2}$$

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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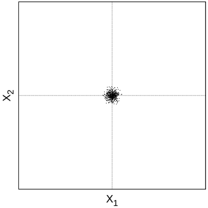
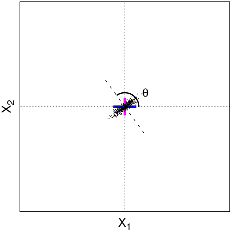


$$H = \frac{1}{2}$$

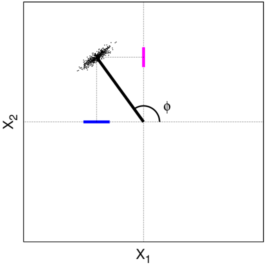
Apply squeezing operator $|\xi >= \hat{S}(\xi)|0>$

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



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

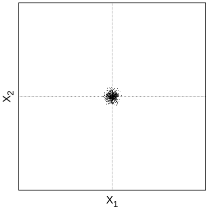
$$\hat{D}(\alpha) = e^{\alpha a^\dagger - \alpha^* a}$$



$$\begin{aligned} <\alpha, \xi | X_1 | \alpha, \xi > &= Re(\alpha), \\ <\alpha, \xi | X_2 | \alpha, \xi > &= Im(\alpha) \end{aligned}$$

Squeezed field generation recipe

Take a vacuum state $|0>$

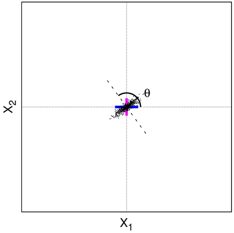


$$H = \frac{1}{2}$$

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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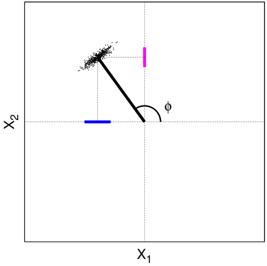
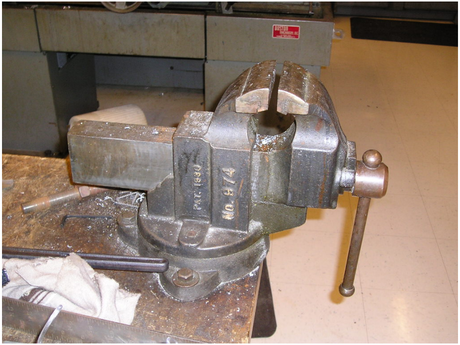


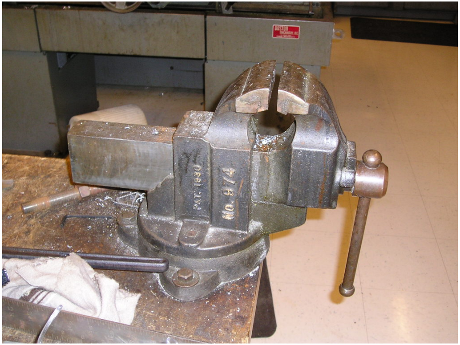
$$< \alpha, \xi | X_1 | \alpha, \xi > \;=\; Re(\alpha),$$
$$< \alpha, \xi | X_2 | \alpha, \xi > \;=\; Im(\alpha)$$

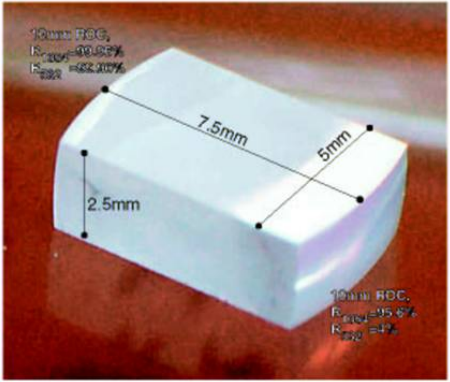
Tools for squeezing

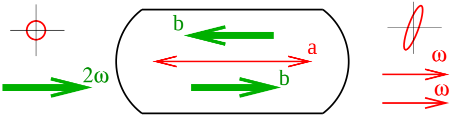
Tools for squeezing



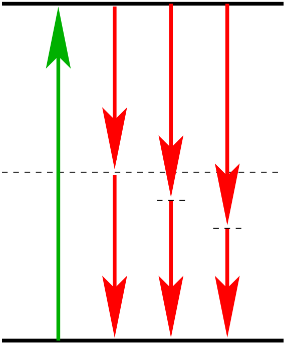
Tools for squeezing







Two photon squeezing picture

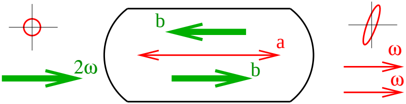


Squeezing operator

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

Parametric down-conversion in crystal

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



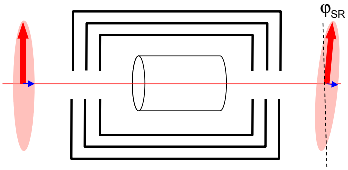
Squeezing

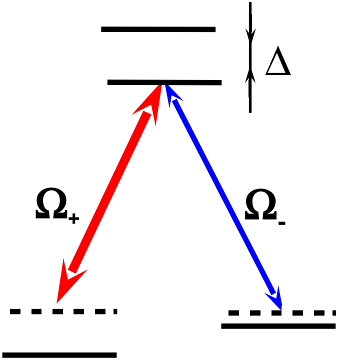
maximum squeezing value detected 15 dB at 1064 nm
Henning Vahlbruch, Moritz Mehmet, Karsten Danzmann, and Roman Schnabel Phys. Rev. Lett **117**, 110801 (2016)

Possible squeezing applications

- shot noise limited optical sensors enhancements
- noiseless signal amplification
- 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

Self-rotation of elliptical polarization in atomic medium

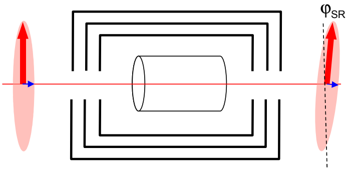


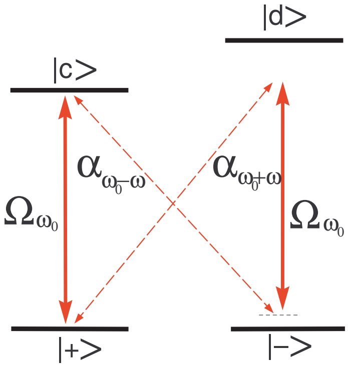


A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

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

Self-rotation of elliptical polarization in atomic medium





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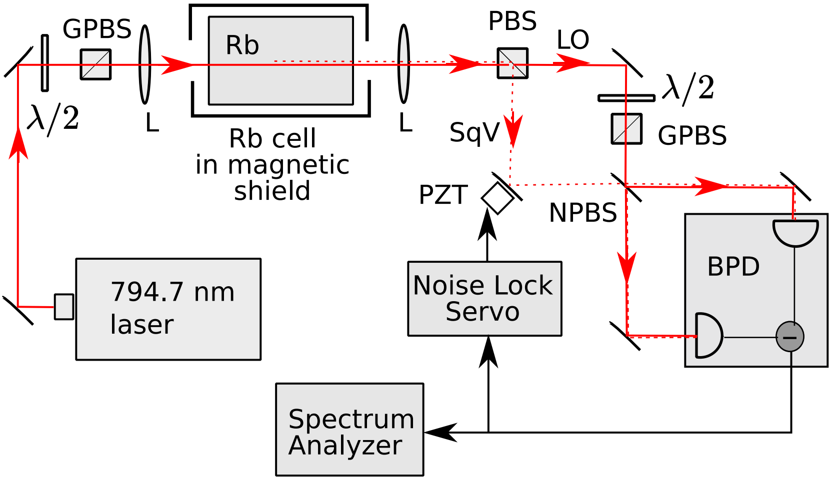
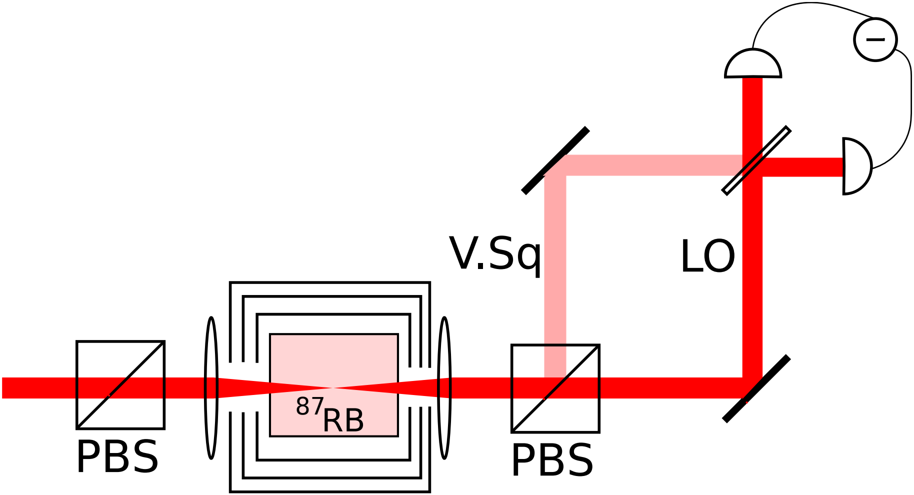
$$a_{out} = a_{in} + \frac{igL}{2}(a_{in}^{\dagger} - a_{in})$$

Setup



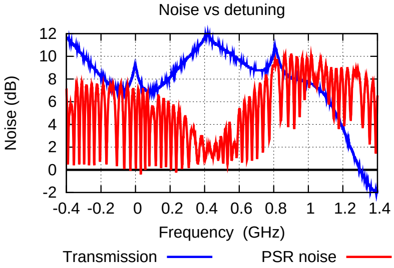
GPBS
Rb
PBS
LO
$\lambda/2$
$\lambda/2$
L
Rb cell
in magnetic
shield
L
SqV
GPBS
PZT
NPBS
BPD
794.7 nm
laser
Noise Lock
Servo
Spectrum
Analyzer

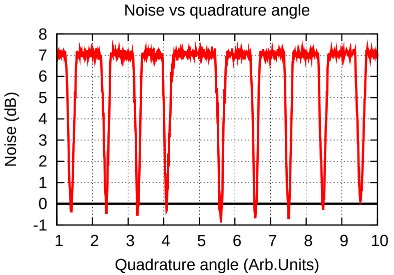
Setup



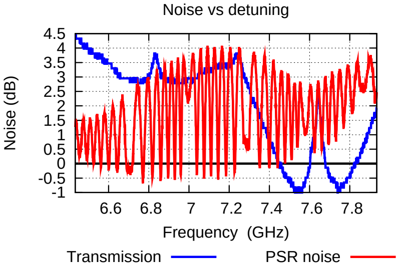
Noise contrast vs detuning in hot ^{87}Rb vacuum cell

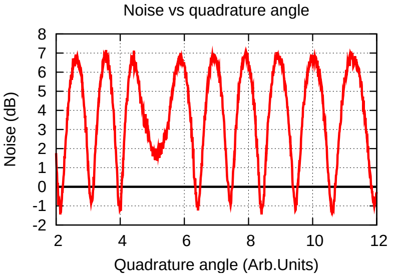
$F_g = 2 \rightarrow F_e = 1, 2$





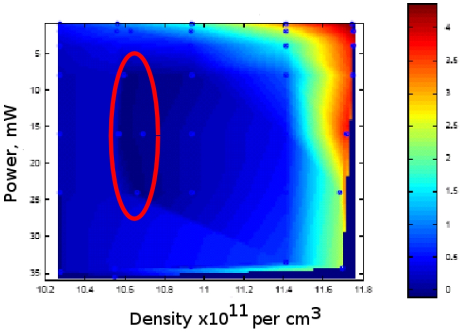
$F_g = 1 \rightarrow F_e = 1, 2$



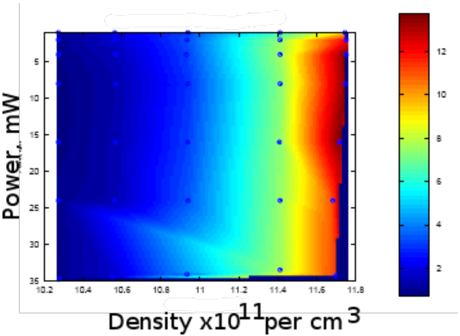


Squeezing region

Squeezing



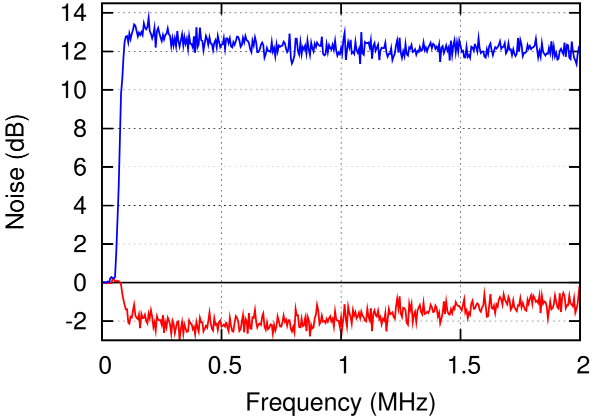
Anti-squeezing



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

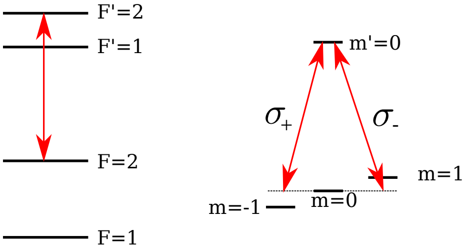
W&M team. ^{87}Rb $F_g = 2 \rightarrow F_e = 2$, laser power 7 mW, T=65° C



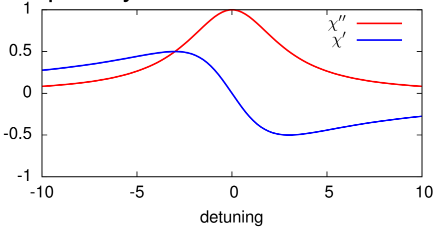
Lezama et.al report 3 dB squeezing in similar setup
Phys. Rev. A 84, 033851 (2011)

Optical magnetometer based on Faraday effect

^{87}Rb D_1 line



Susceptibility vs B



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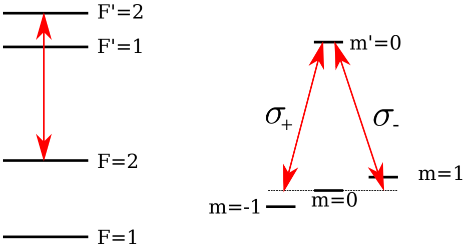

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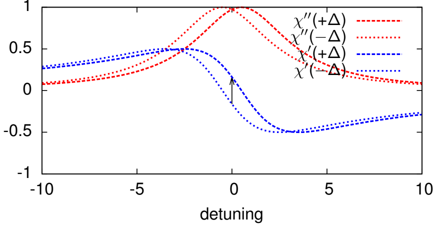

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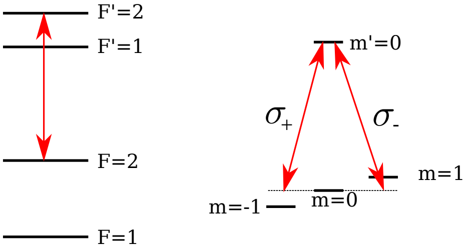

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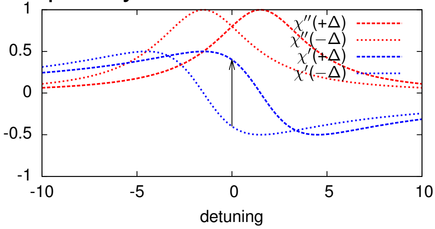
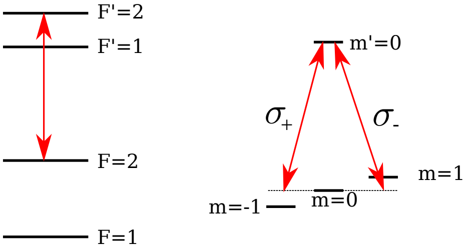


Optical magnetometer based on Faraday effect

^{87}Rb D_1 line



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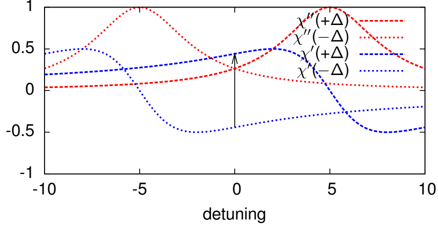

Optical magnetometer based on Faraday effect

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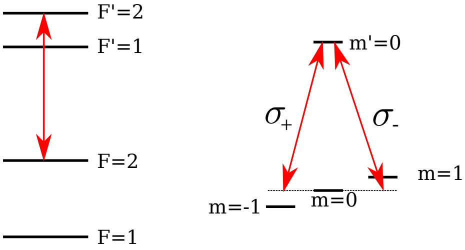

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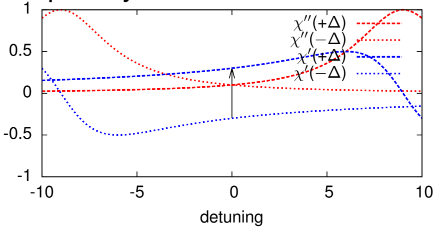

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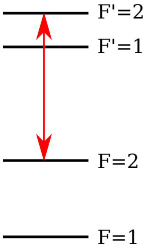
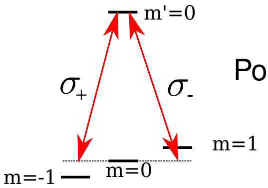
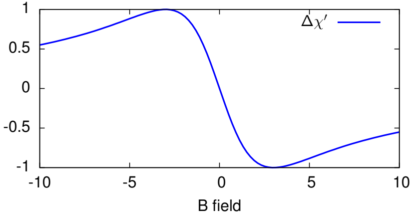
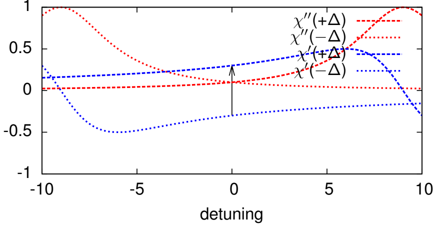




Polarization rotation vs B

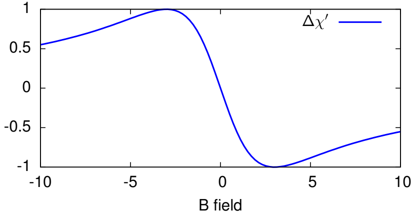


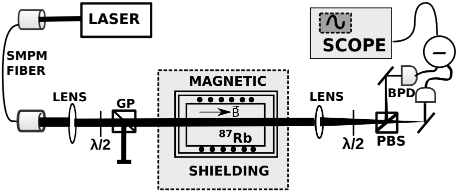
Susceptibility vs B



Optical magnetometer and non linear Faraday effect

Naive model of rotation

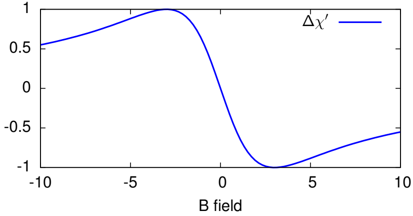


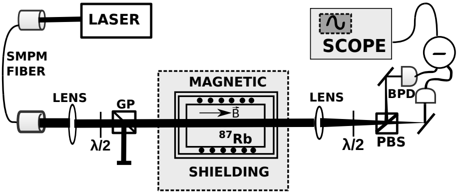


Experiment

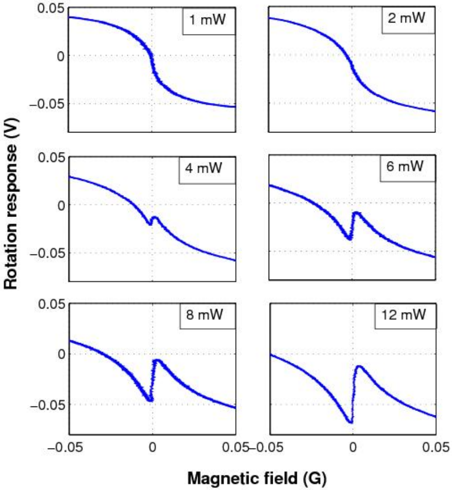
Optical magnetometer and non linear Faraday effect

Naive model of rotation

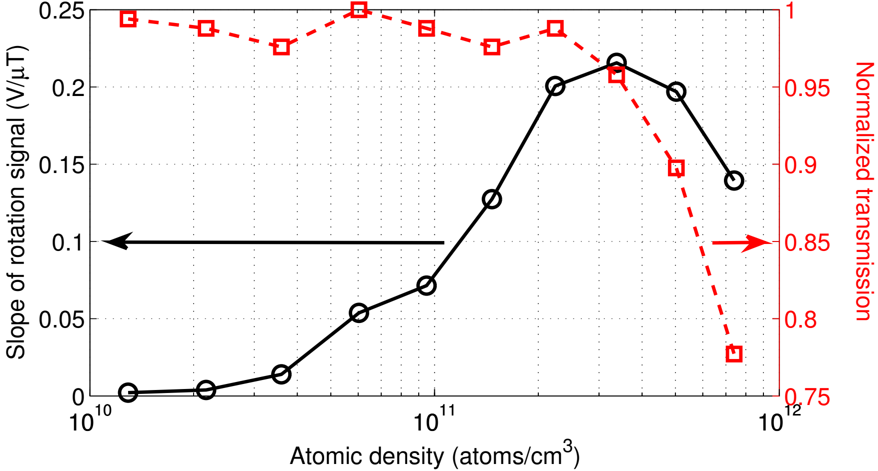




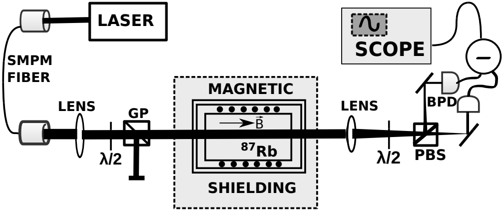
Experiment

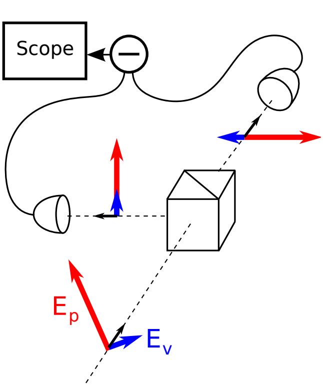


Magnetometer response vs atomic density



Shot noise limit of the magnetometer



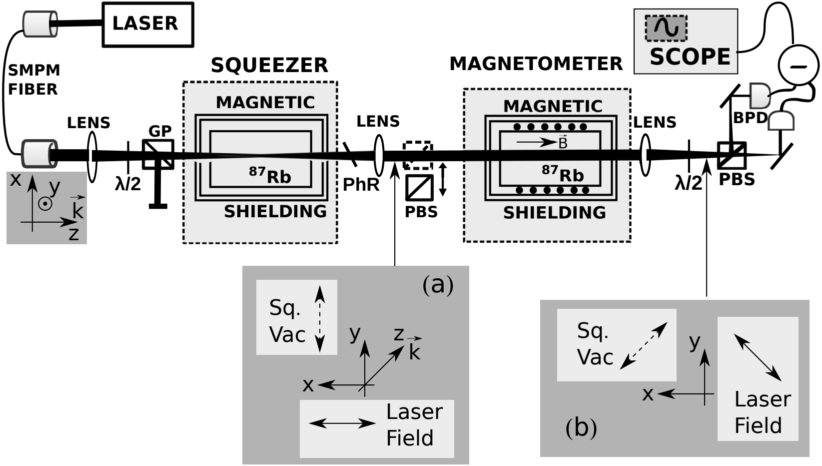


$$S = |E_p + E_v|^2 - |E_p - E_v|^2$$

$$S = 4E_pE_v$$

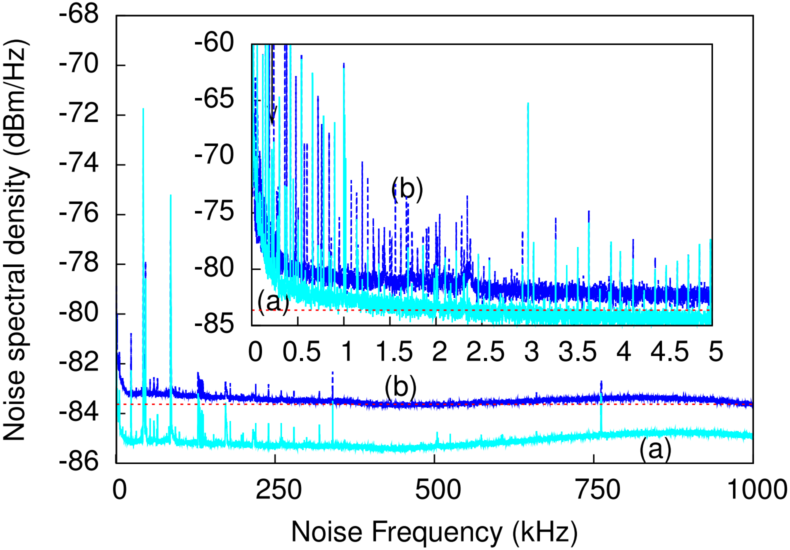
$$< \Delta S > \sim E_p < \Delta E_v >$$

Squeezed enhanced magnetometer setup

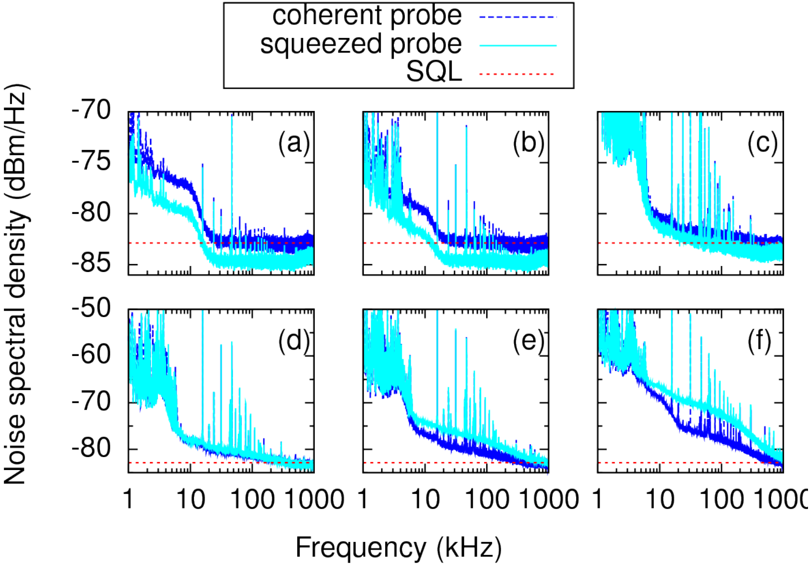


Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al* Phys. Rev. Lett, **105**, 053601, 2010.

Magnetometer noise floor improvements

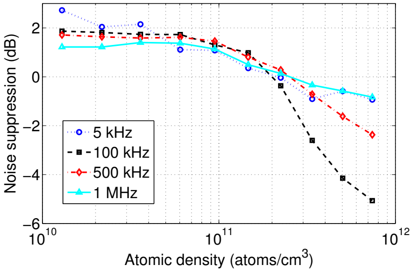


Magnetometer noise spectra

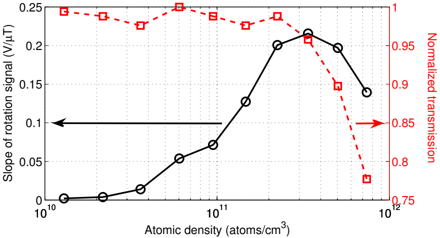


Noise suppression and response vs atomic density

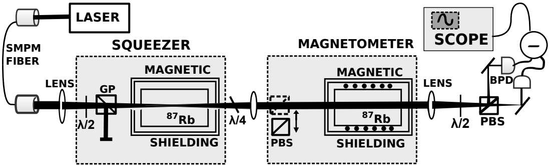
Noise suppression

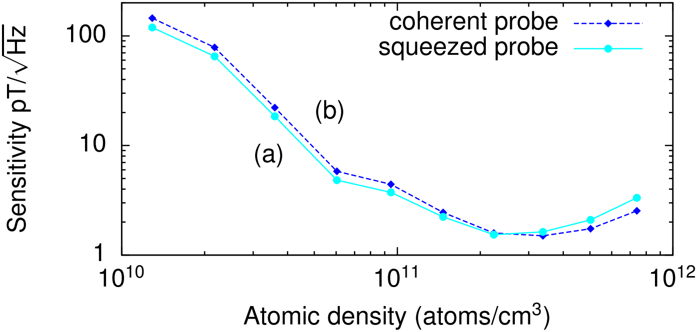


Response



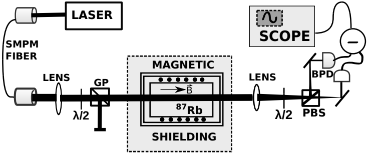
Magnetometer with squeezing enhancement

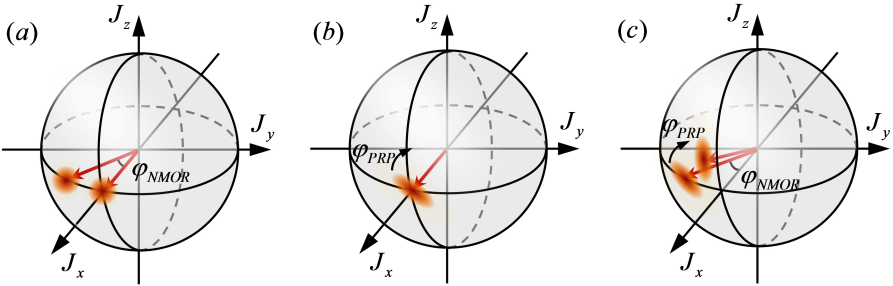




T. Horrom, et al. **PRA**, 86, 023803, (2012).

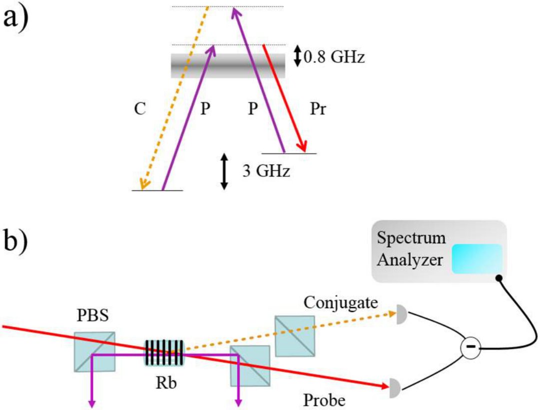
Self-squeezed magnetometry





Irina Novikova, Eugeniy E. Mikhailov, Yanhong Xiao, "Excess optical quantum noise in atomic sensors", Phys. Rev. A, **91**, 051804(R), (2015)

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



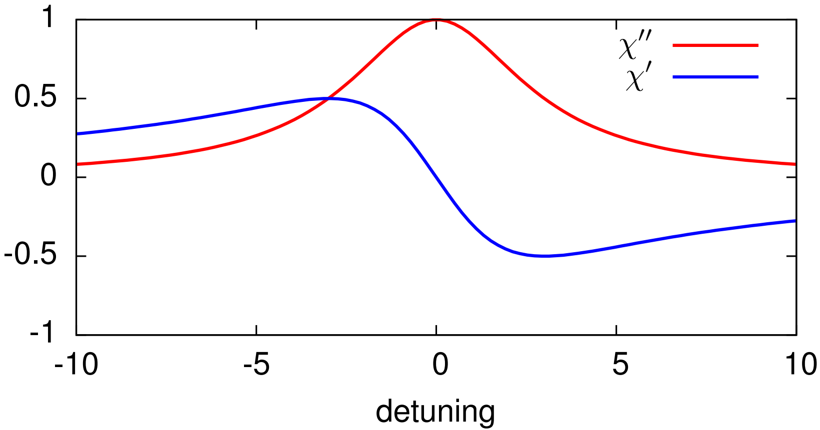
N. Otterstrom, R. C. Pooser, and B. J. Lawrie, “Nonlinear optical magnetometry with accessible in situ optical squeezing”, Optics Letters, **39**, Issue 22, pp. 6533-6536 (2014)

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).

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

Susceptibility



Susceptibility and non linear Faraday effect

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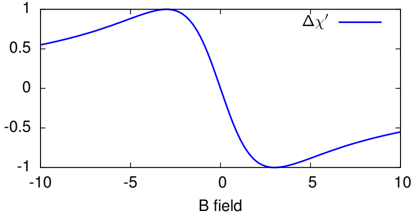
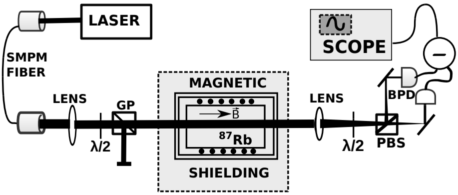
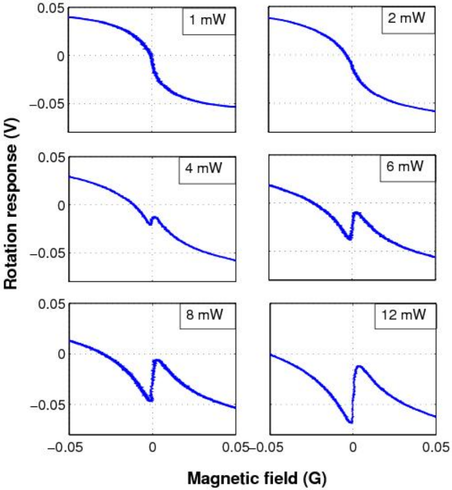




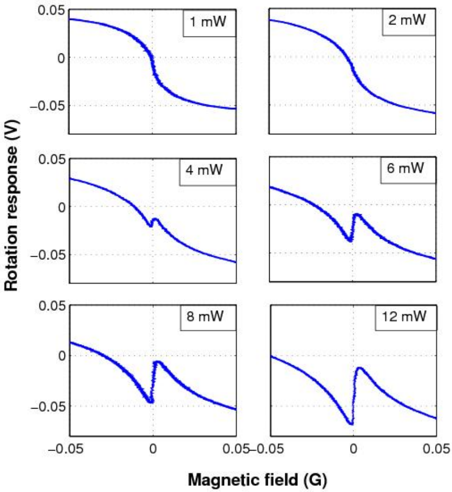
Experiment



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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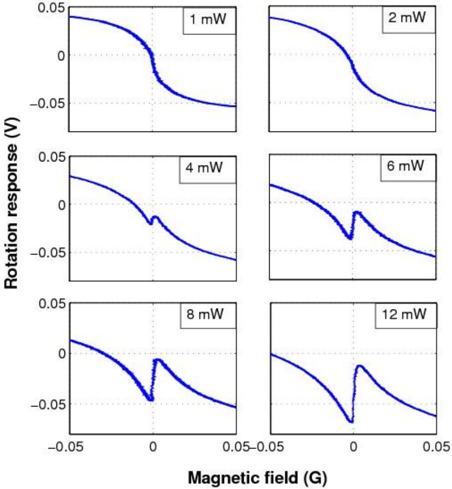
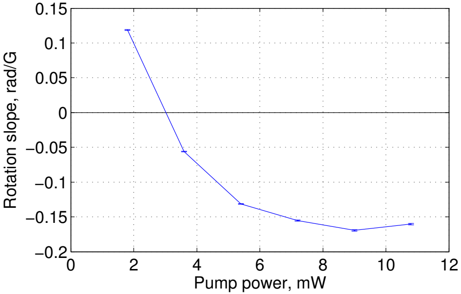
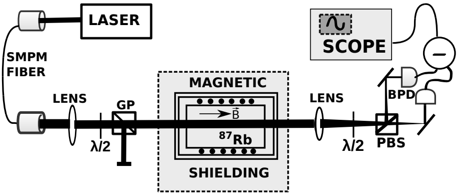
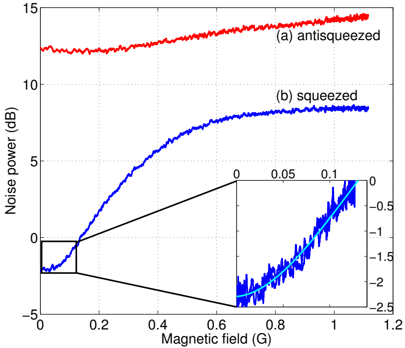




Squeezing vs magnetic field

Spectrum analyzer settings: Central frequency = 1 MHz, VBW = 3 MHz, RBW = 100 kHz

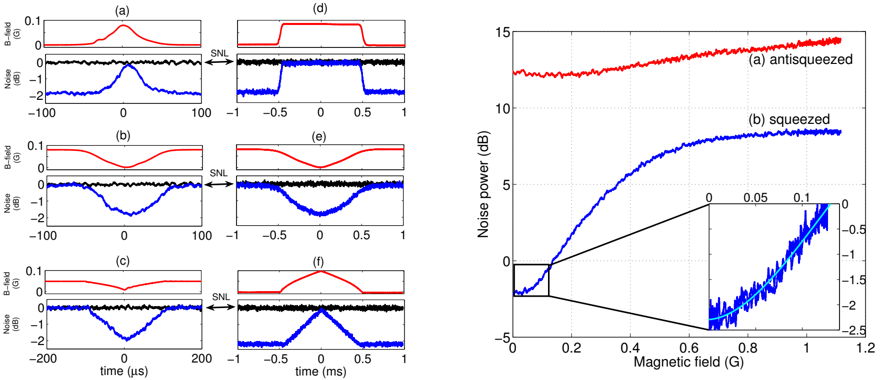




Travis Horrom et al. "All-atomic source of squeezed vacuum with full pulse-shape control", Journal of Physics B: Atomic, Molecular and Optical Physics, Issue 12, 45, 124015, (2012).

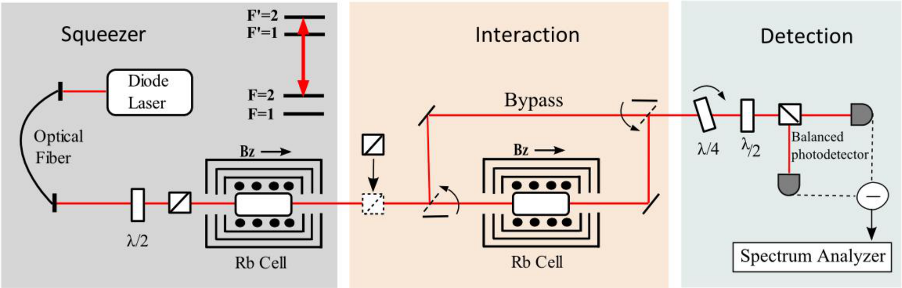
Squeezing vs magnetic field

Spectrum analyzer settings: Central frequency = 1 MHz, VBW = 3 MHz, RBW = 100 kHz

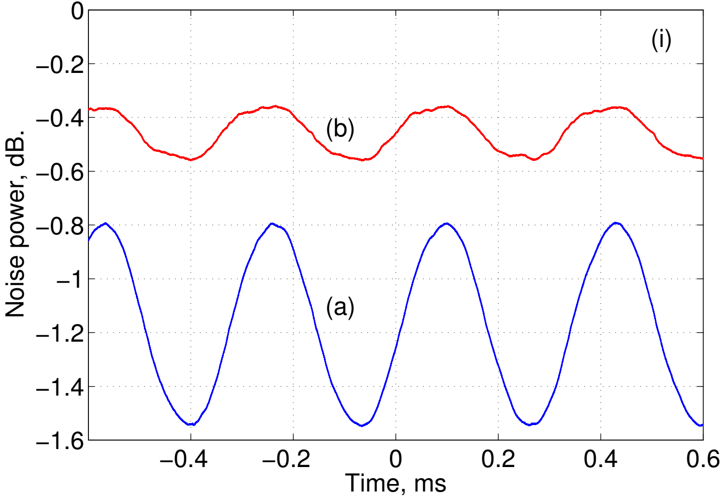


Travis Horrom et al. "All-atomic source of squeezed vacuum with full pulse-shape control", Journal of Physics B: Atomic, Molecular and Optical Physics, Issue 12, 45, 124015, (2012).

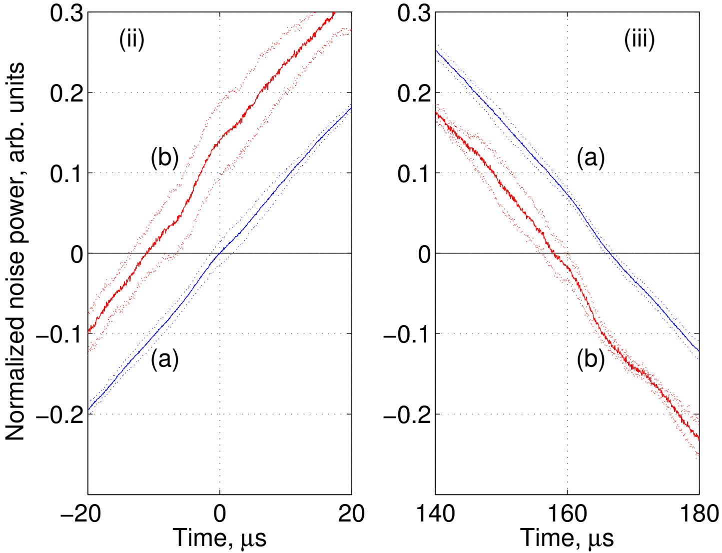
Time advancement setup



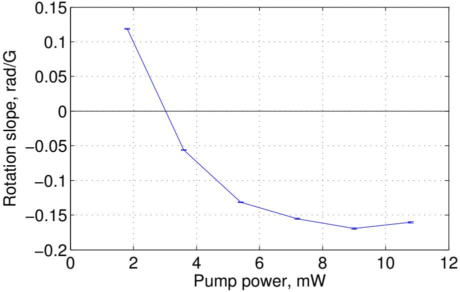
Squeezing modulation and time advancement



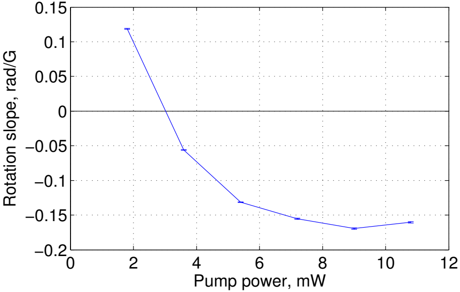
Squeezing modulation and time advancement

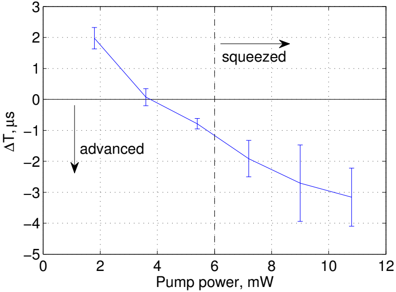


Advancement vs power

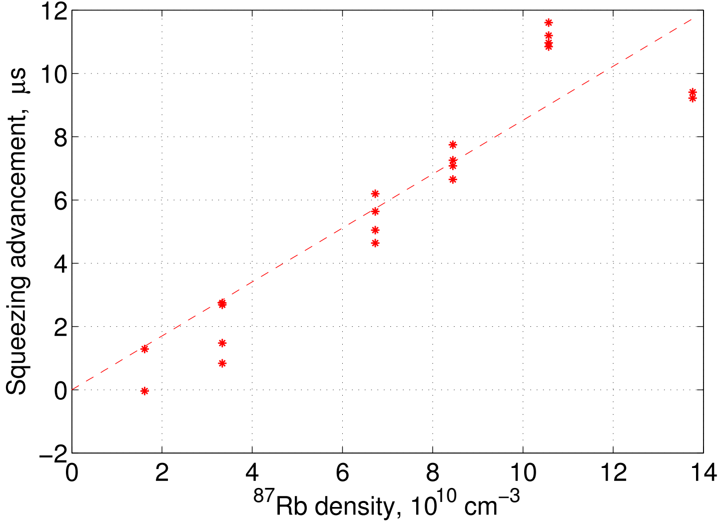


Advancement vs power





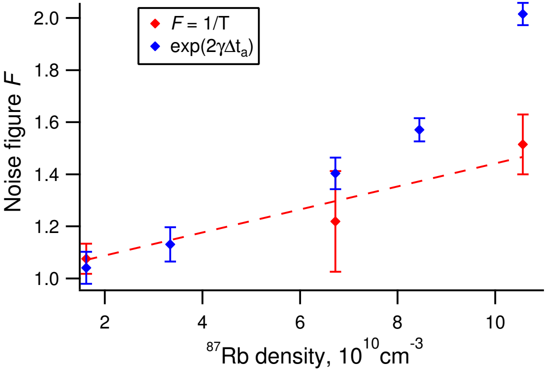
Squeezing advancement vs atomic density

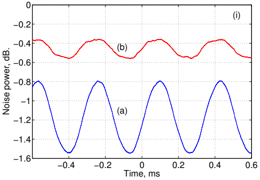


G. Romanov, et al. Optics Letters, Issue 4, 39, 1093-1096, (2014).

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

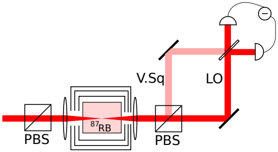
$$F = \frac{SNR_{in}}{SNR_{out}} = 1/T = e^{2\gamma\Delta t_a}$$



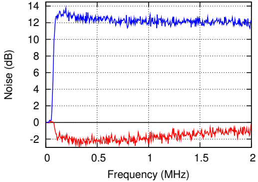


Polarization self-rotation (PSR) squeezing

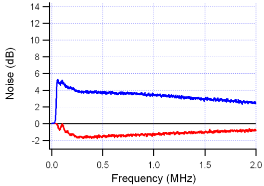
Setup



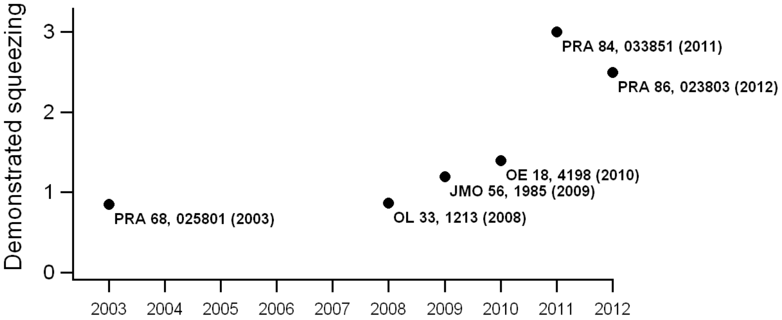
Vacuum cell



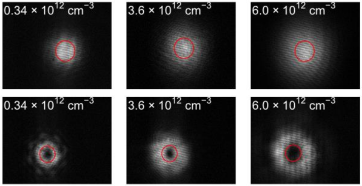
Coated cell

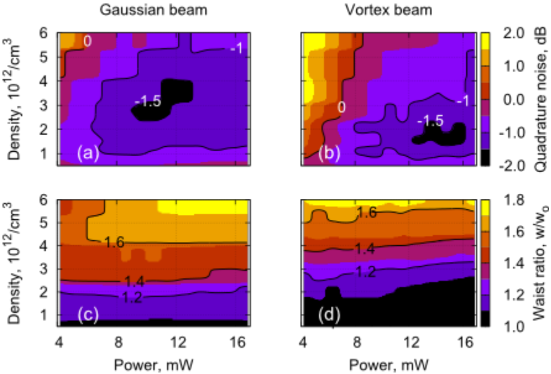


A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression



Output beam shapes





Beam expansion caused by self-defocusing seems to be decoupled from measured squeezing amount variation.

Mi Zhang, Joseph Soultanis, Irina Novikova, and Eugeniy E. Mikhailov, “Generating squeezed vacuum field with nonzero orbital angular momentum with atomic ensembles”, Optics Letters, Vol. 38, Issue 22, pp. 4833-4836 (2013)

Beer-Lambert law

$$dI = -NI\alpha dz$$

$$I = I_0 exp(-\tau)$$

where τ is optical depth

$$\tau = \alpha NL$$

Beer-Lambert law

$$dI = -NI\alpha dz$$

$$I = I_0 exp(-\tau)$$

where τ is optical depth

$$\tau = \alpha NL$$

Will we get equivalent result for the following cases?

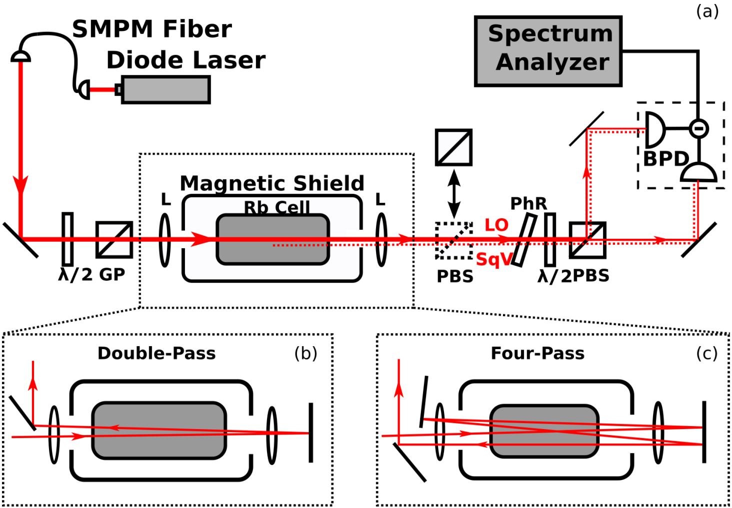
double the medium length

$$\tau = \alpha N(2L)$$

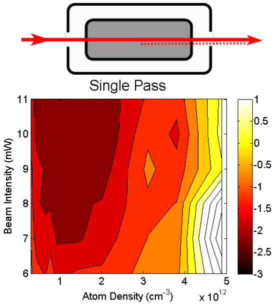
double the medium density

$$\tau = \alpha(2N)L$$

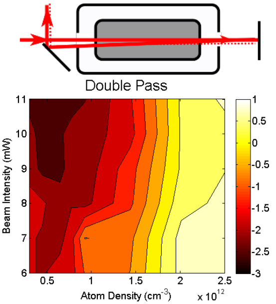
Multipass setup



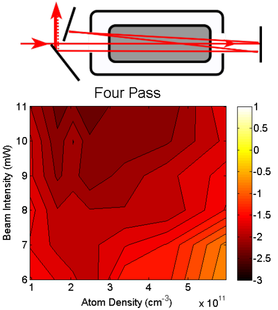
Optical depth dependence



$P = 11$ mW
$N = 9.3 \times 10^{11}$ cm^{-3}
Squeezing = -2.0 dB



$P = 11$ mW
$N = 4.3 \times 10^{11}$ cm^{-3}
Squeezing = -2.6 dB

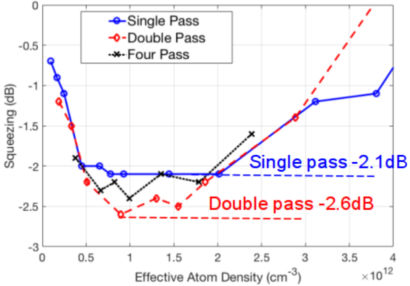


$P = 11$ mW
$N = 2.4 \times 10^{11}$ cm^{-3}
Squeezing = -2.2 dB

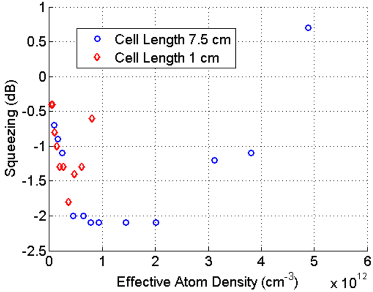
Mi Zhang, Melissa A. Guidry, R. Nicholas Lanning, Zhihao Xiao, Jonathan P. Dowling, Irina Novikova, Eugeniy E. Mikhailov, "Multi-pass configuration for Improved Squeezed Vacuum Generation in Hot Rb Vapor", Physical Review A, 96, 013835, (2017)

Squeezing vs effective optical depth

Long cell

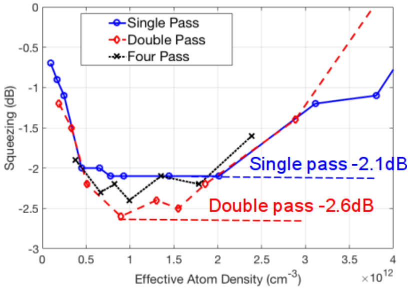


Long vs short cell

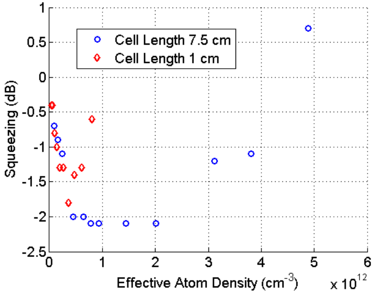


Squeezing vs effective optical depth

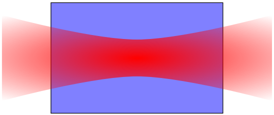
Long cell



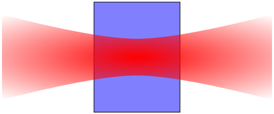
Long vs short cell



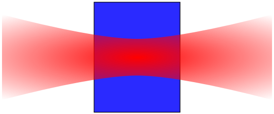
Cell length doubled



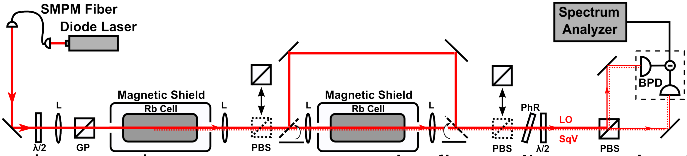
Reference



Atomic density doubled



Double cell setup: atomic density optimization



+: combined squeezing

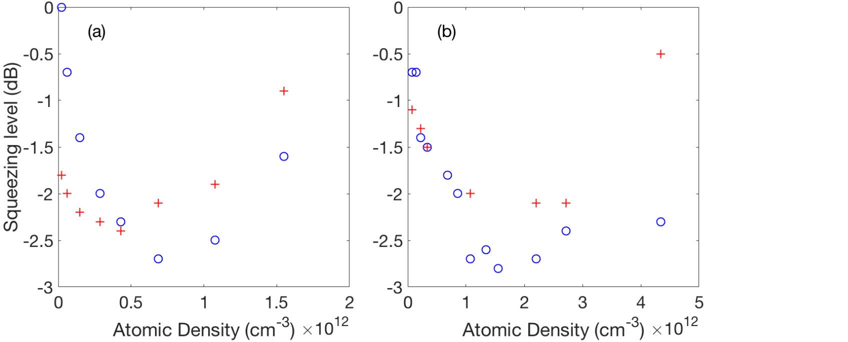
1st cell atomic density

$N_1 = 9.3 \times 10^{11}\ \mathrm{cm}^{-3}$

o: the first cell squeezing filtered

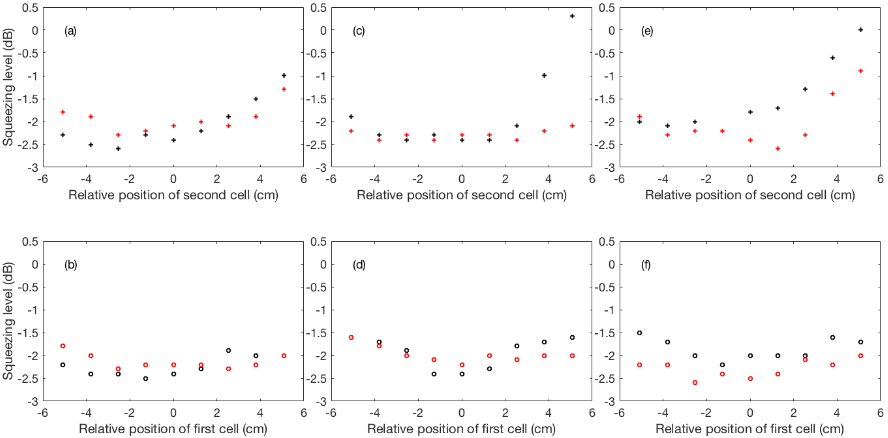
1st cell atomic density

$N_1 = 4.3 \times 10^{11}\ \mathrm{cm}^{-3}$



Double cell setup: position optimization

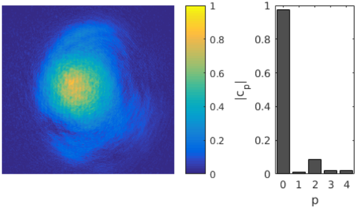
atomic densities:	atomic densities:	atomic densities:
$N_1 = 4.3 \times 10^{11}$ cm^{-3}	$N_1 = 4.3 \times 10^{11}$ cm^{-3}	$N_1 = 9.3 \times 10^{11}$ cm^{-3}
$N_2 = 4.3 \times 10^{11}$ cm^{-3}	$N_2 = 9.3 \times 10^{11}$ cm^{-3}	$N_2 = 9.3 \times 10^{11}$ cm^{-3}



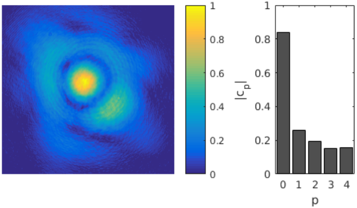
+/o: combined squeezing; +/o: the first cell squeezing filtered

Multimode pump output

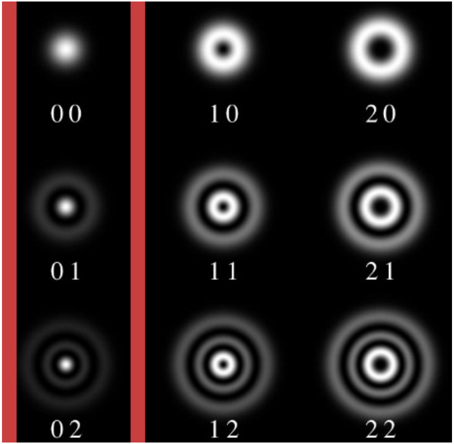
T=26 °C

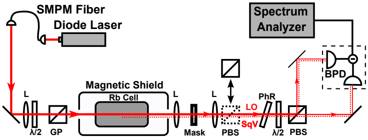


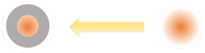
T=91 °C

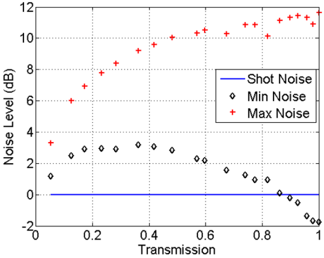


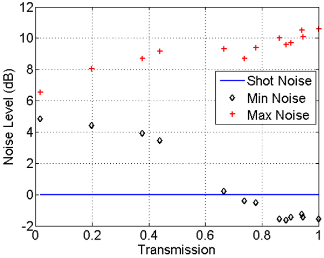
Laguerre-Gaussian modes basis







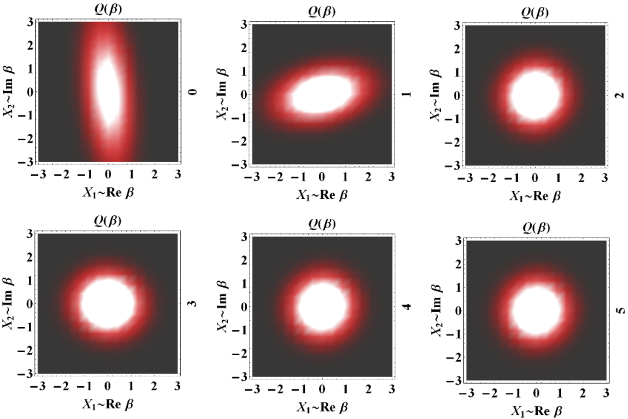


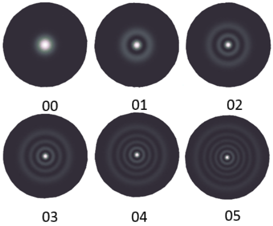


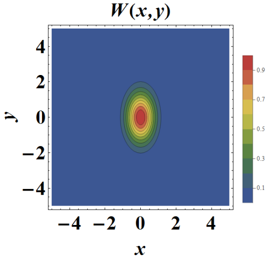
Mi Zhang, R. Nicholas Lanning, Zhihao Xiao, Jonathan P. Dowling, Irina Novikova, Eugeniy E. Mikhailov, “Spatial multimode structure of atom-generated squeezed light”, Phys. Rev. A, 93, 013853, (2016).
Zhihao Xiao, R. Nicholas Lanning, Mi Zhang, Irina Novikova, Eugeniy E. Mikhailov, Jonathan P. Dowling, “Why a hole is like a beam splitter–a general diffraction theory for multimode quantum states of light”, Phys. Rev. A, **96**, 023829, (2017).

Multimode squeezing decomposition

$$\hat{S}(\xi) = \exp\left[\sum_{l,p} \frac{1}{2}(\xi^*_{l,p}\ \hat{a}^2_{l,p} - \xi_{l,p}\ \hat{a}^{\dagger 2}_{l,p})\right]$$







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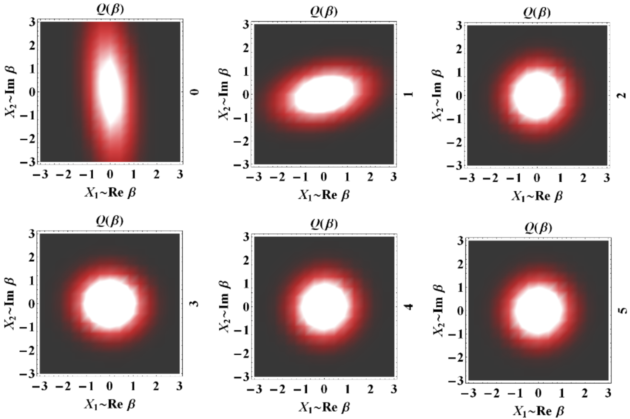

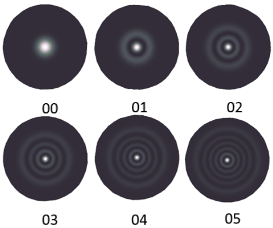

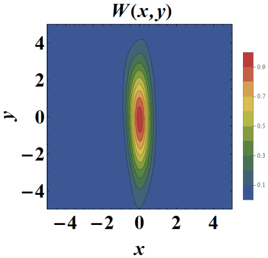

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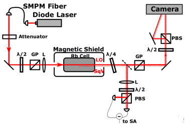
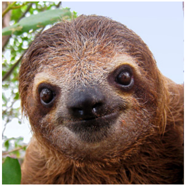
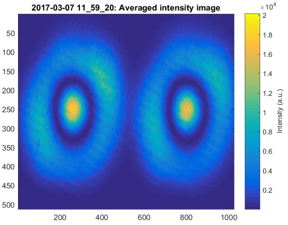
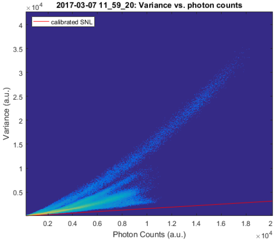
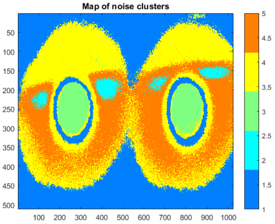
Quantum imaging effort: from owl to sloth

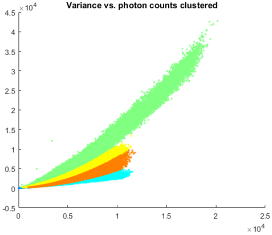










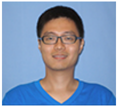


People

WM: Mi Zhang, Demetrious T. Kutzke, Melissa A. Guidry, Irina Novikova, Gleb Romanov, Travis Horrom

LSU:
R. Nicholas Lanning

Zhihao Xiao



Jonathan P. Dowling

Summary

- fully atomic squeezed enhanced magnetometer
  with sensitivity as low as 1 pT/$\sqrt{\text{Hz}}$
- superluminal squeezing propagation
  with $v_g \approx -7'000$ m/s $\approx -c/43'000$ or time advancement of 11 μS
- We were able to improve squeezing by multipass configuration
- Our squeezed state is a set of competing multimodes
- We are working on quantum modes extraction and imaging

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