All atomic generation and manipulation of squeezed light with Rb atoms

Eugeniy E. Mikhailov,
Travis Horrom, Gleb Romanov, Irina Novikova

The College of William & Mary, USA

January 4, 2012
PQE

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

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

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

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

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

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

Transition from classical to quantum field

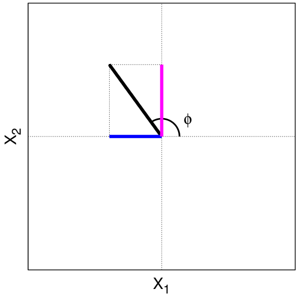
Classical analog

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

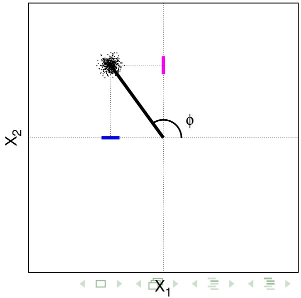
Quantum approach

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

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

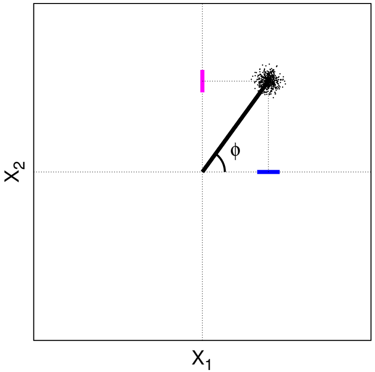


$$\hat{E}(\phi) = \hat{X}_1 + i\hat{X}_2$$

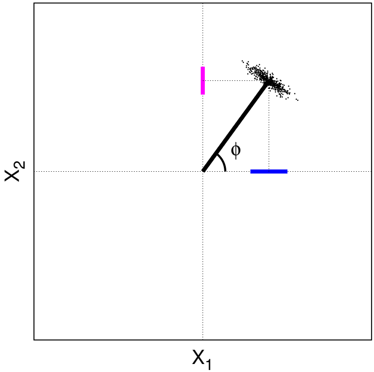


Minimum uncertainty (coherent) states

Coherent state



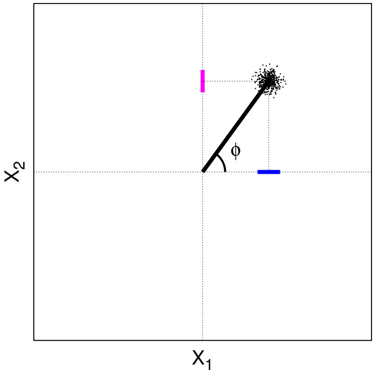
Squeezed state



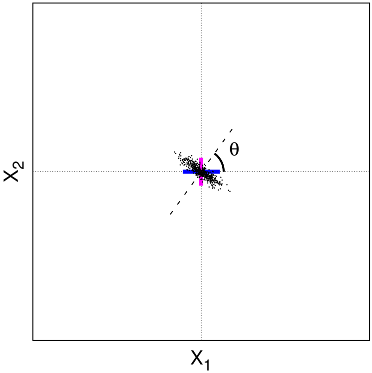
$$\Delta X_1 \Delta X_2 \geq 1/4$$

Minimum uncertainty (coherent) states

Coherent state

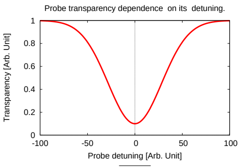


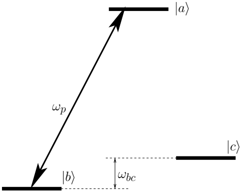
Squeezed state



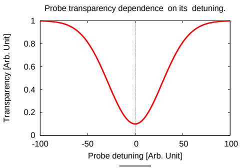
$$\Delta X_1 \Delta X_2 \geq 1/4$$

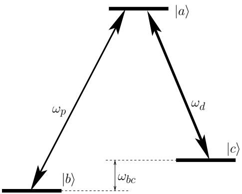
Quantum memory with atomic ensembles

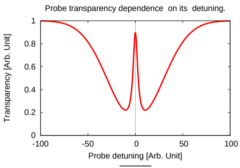




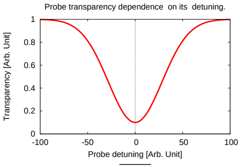
Quantum memory with atomic ensembles

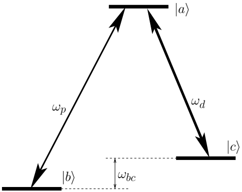


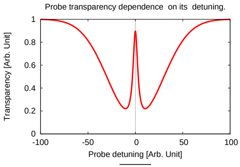




Quantum memory with atomic ensembles



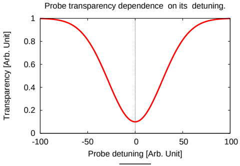


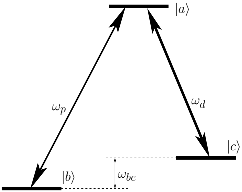


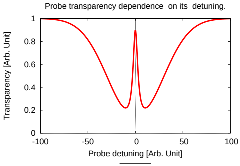
Storage and retrieval

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

Quantum memory with atomic ensembles







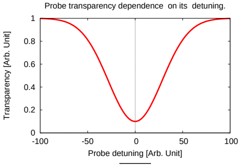
Storage and retrieval

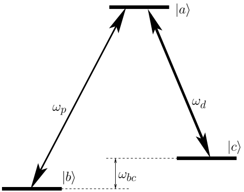
- single photon
- squeezed state (Furusawa and Lvovsky PRL **100** 2008)

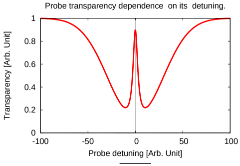
Squeezed state requirements for a quantum memory probe

- squeezing carrier at atomic wavelength (780nm, 795nm)
- squeezing within narrow resonance window at frequencies($<$100kHz)

Quantum memory with atomic ensembles







Storage and retrieval

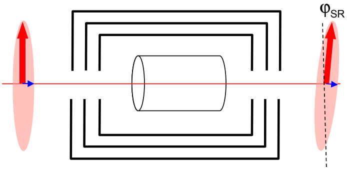
- single photon
- squeezed state (Furusawa and Lvovsky PRL **100** 2008)

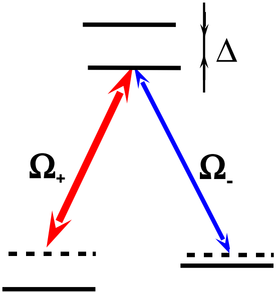
Squeezed state requirements for a quantum memory probe

- 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 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

$$a_{out} = a_{in} + \frac{igL}{2}(a_{in}^{\dagger} - a_{in}) \quad (1)$$

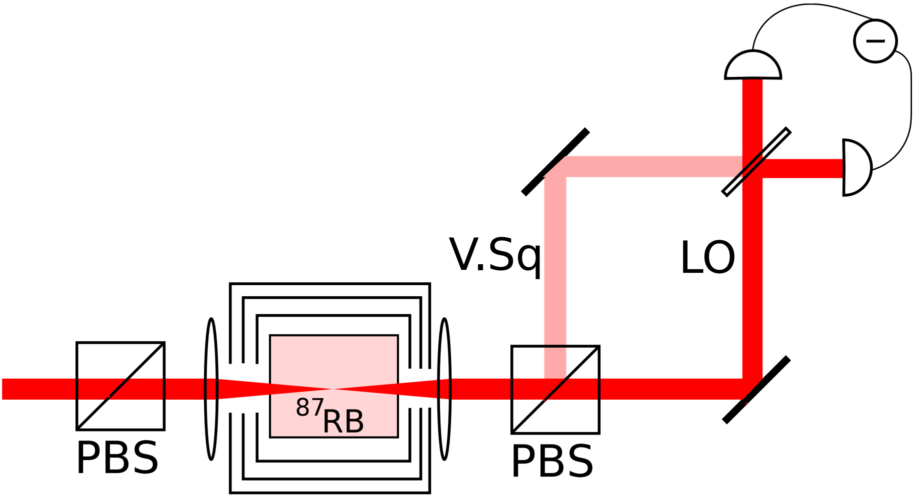
Will something so simple work?

- 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

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
- Possible. Arturo Lezama et al., PRA **77**, 013806 (2008).
- Definitely Eugeniy E. Mikhailov et al. Optics Letters, Issue 11, **33**, 1213-1215, (2008).
- Definitely Eugeniy E. Mikhailov et al. JMO , Issues 18&19, **56**, 1985-1992, (2009).
- Definitely Philippe Grangier et al. Optics Express, **18**, Issue 5, pp. 4198-4205 (2010)
- Definitely Arturo Lezama et al., PRA **84**, 033851 (2011).
  - 3 dB of squeezing

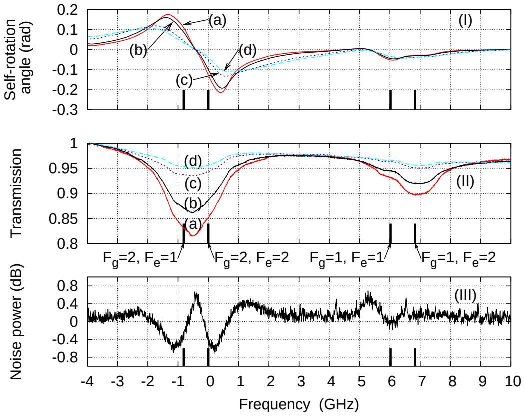
Setup



Squeezing vs laser detuning in ^{87}Rb at 795 nm

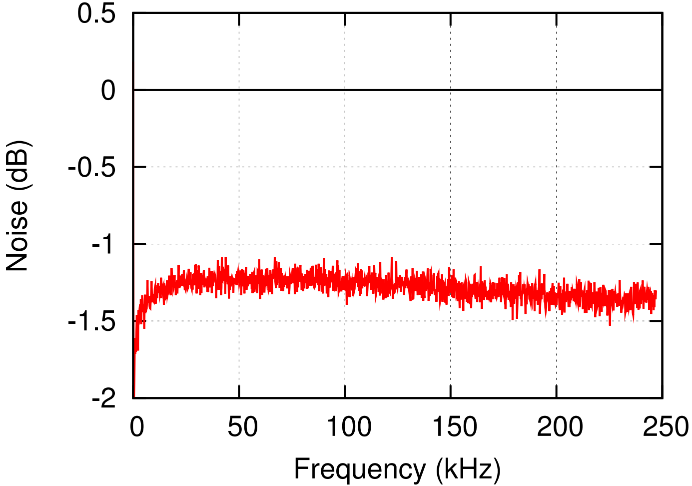
^{87}Rb cell + 2.5Torr Ne

(a) P=1.0 mW, (b) P=1.5 mW, (c) P=4.2 mW, (d) P=6.6 mW



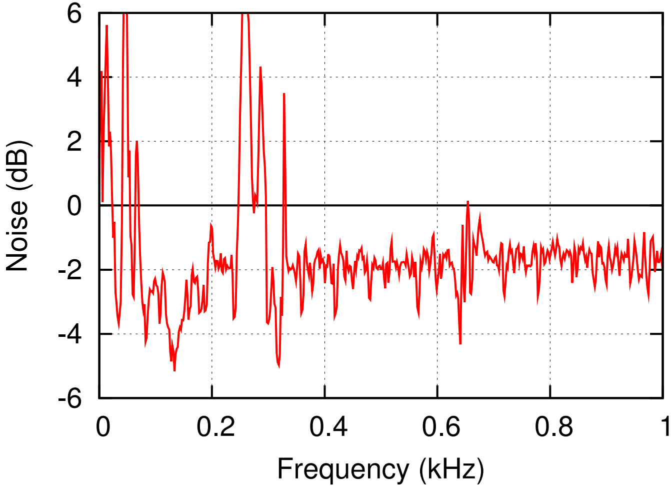
Low frequency squeezing spectrum in ^{87}Rb at 795 nm

$F_2 = 2 \rightarrow F_2 = 2$ transition ^{87}Rb cell + 2.5Torr Ne, T=63°C P=5 mW



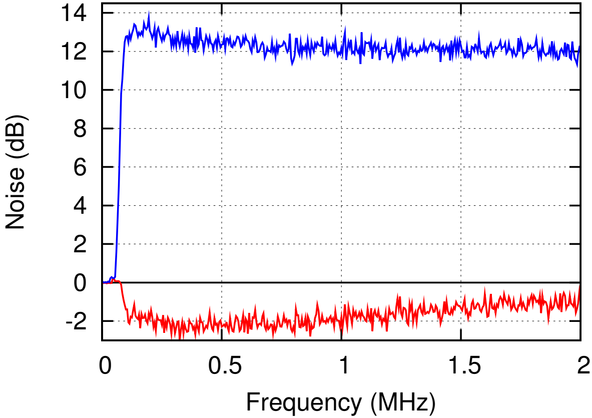
Low frequency squeezing spectrum in ^{87}Rb at 795 nm

$F_2 = 2 \rightarrow F_2 = 2$ transition ^{87}Rb cell + 2.5Torr Ne, T=63°C P=5 mW



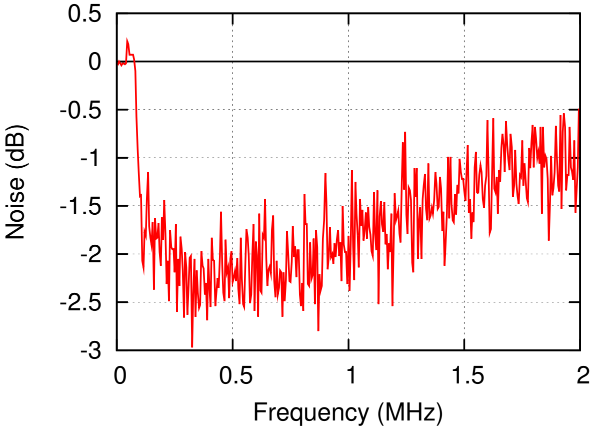
Maximally squeezed spectrum with ^{87}Rb

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



Maximally squeezed spectrum with ^{87}Rb

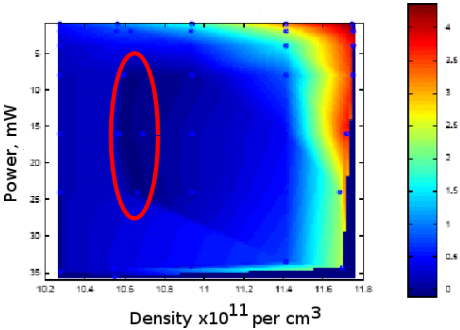
W&M team. ^{87}Rb $F_g = 2 \rightarrow F_e = 2$, laser power 7 mW, T=65° C



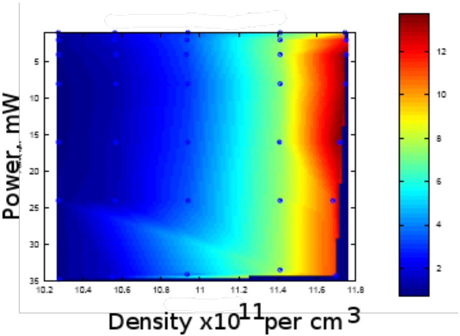
Lezama et.al report 3 dB squeezing in similar setup
Phys. Rev. A 84, 033851 (2011)

Squeezing region

Squeezing



Anti-squeezing

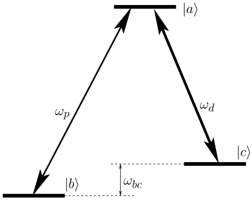


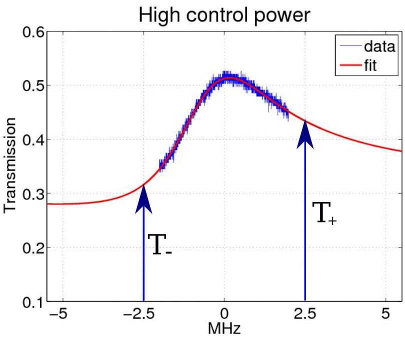
Observation of reduction of quantum noise below the shot noise limit is corrupted by the excess noise due to atomic interaction with atoms.

Squeezing and EIT filter

$$\varphi_\pm = \frac{1}{2}(\Theta_+ \pm \Theta_-)$$

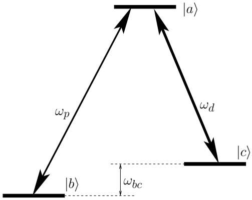
$$A_\pm = \frac{1}{2}(T_+ \pm T_-)$$

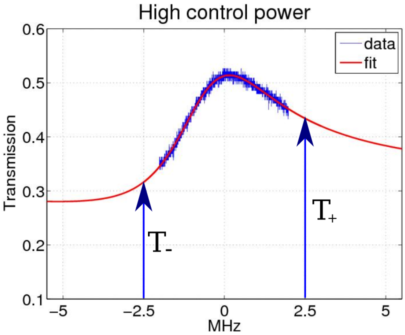




Squeezing and EIT filter

$$\varphi_\pm = \frac{1}{2}(\Theta_+ \pm \Theta_-)$$
$$A_\pm = \frac{1}{2}(T_+ \pm T_-)$$



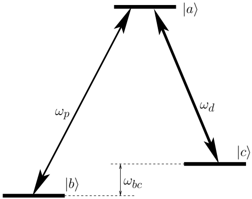


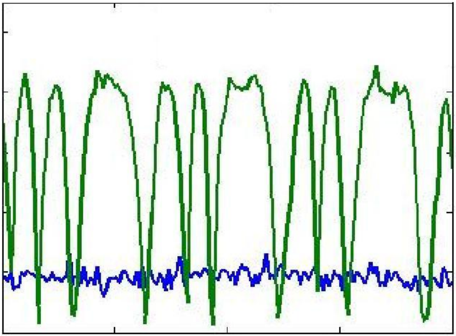
$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

Eugeniy E. Mikhailov et al. Physical Review A, 73, 053810, (2006).

Squeezing and EIT filter

$$\varphi_\pm = \frac{1}{2}(\Theta_+ \pm \Theta_-)$$
$$A_\pm = \frac{1}{2}(T_+ \pm T_-)$$



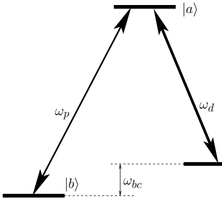


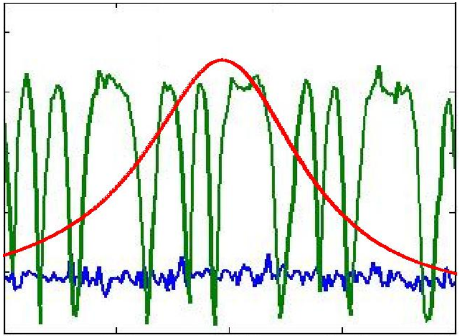
$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

Eugeniy E. Mikhailov et al. Physical Review A, 73, 053810, (2006).

Squeezing and EIT filter

$$\varphi_\pm = \frac{1}{2}(\Theta_+ \pm \Theta_-)$$
$$A_\pm = \frac{1}{2}(T_+ \pm T_-)$$



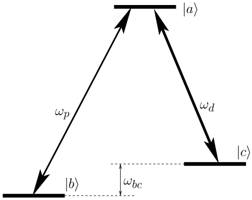


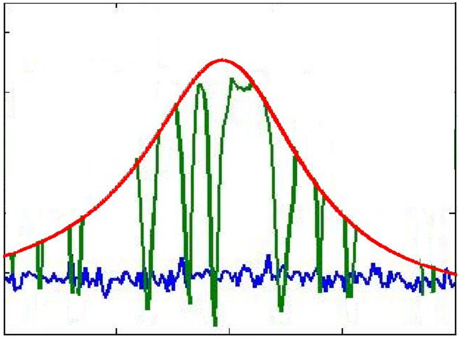
$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

Eugeniy E. Mikhailov et al. Physical Review A, 73, 053810, (2006).

Squeezing and EIT filter

$$\varphi_\pm = \frac{1}{2}\left(\Theta_+ \pm \Theta_-\right)$$
$$A_\pm = \frac{1}{2}\left(T_+ \pm T_-\right)$$





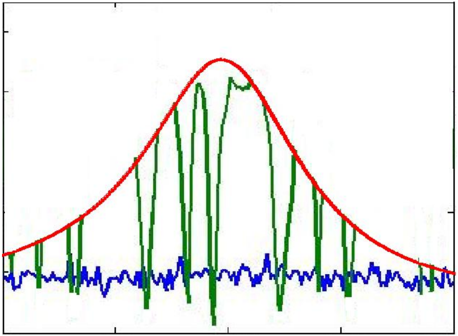
$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

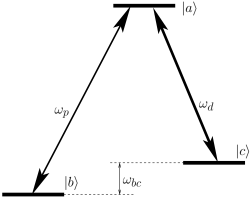
Eugeniy E. Mikhailov et al. Physical Review A, 73, 053810, (2006).

Squeezing and the simplest symmetric filter

Simple case $T_+ = T_- = T$

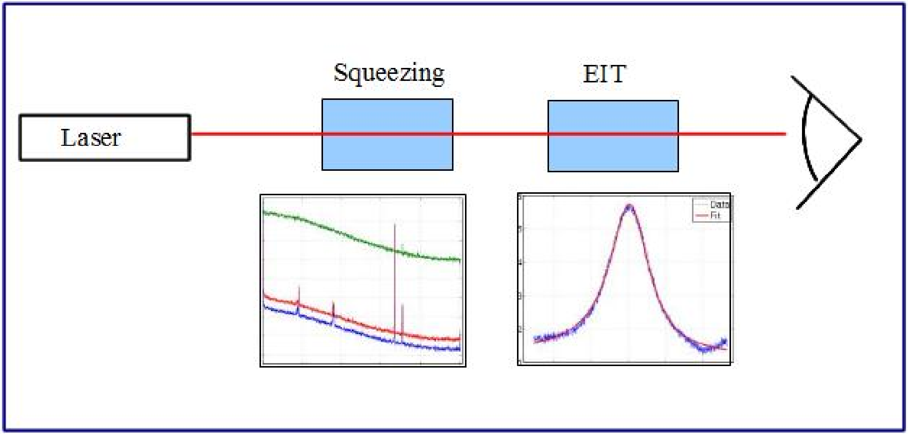
$$\varphi_\pm = 0$$
$$A_+ = T$$
$$A_- = 0$$



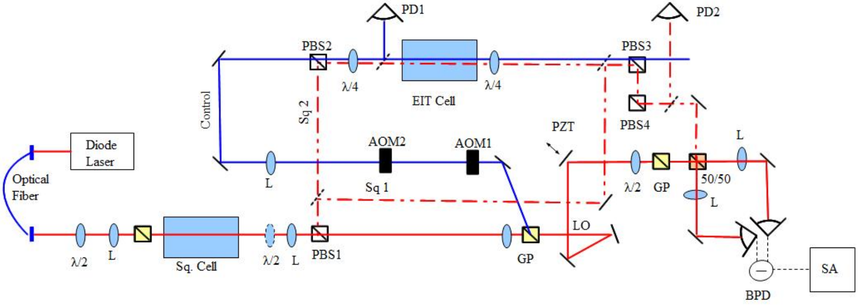


$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} T^2 & 0 \\ 0 & T^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - T^2\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

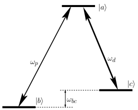
Squeezing and EIT filter setup

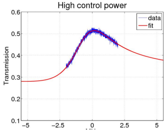


Squeezing and EIT filter setup

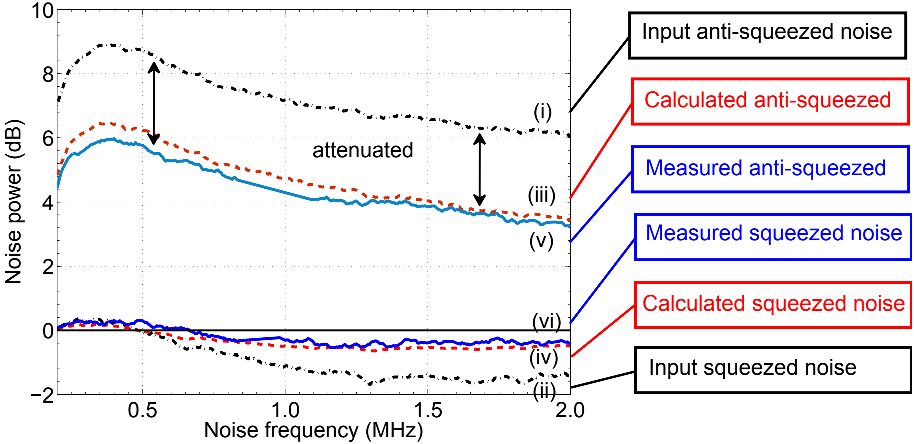


Wide EIT filter and squeezing

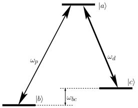


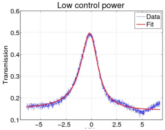


- Peak transmission = 52%
- FWHM= 4MHz

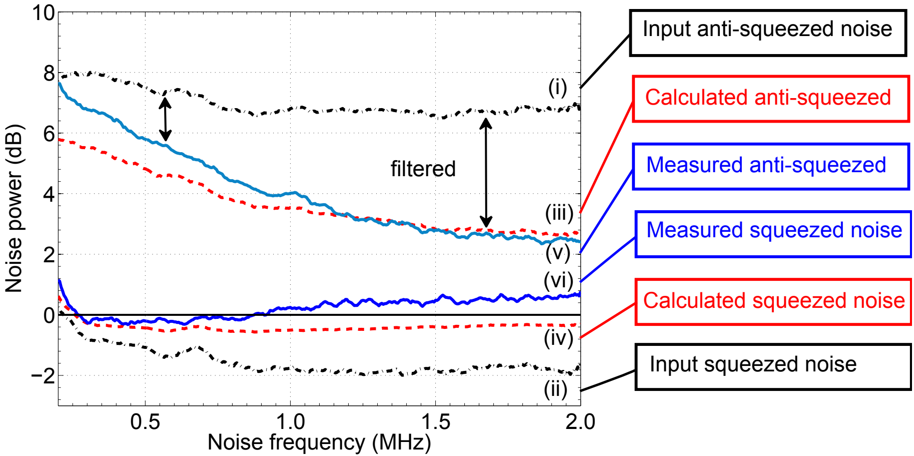


Narrow EIT filter and squeezing

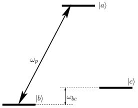


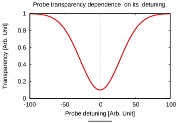


- Peak transmission = 50%
- FWHM= 2MHz

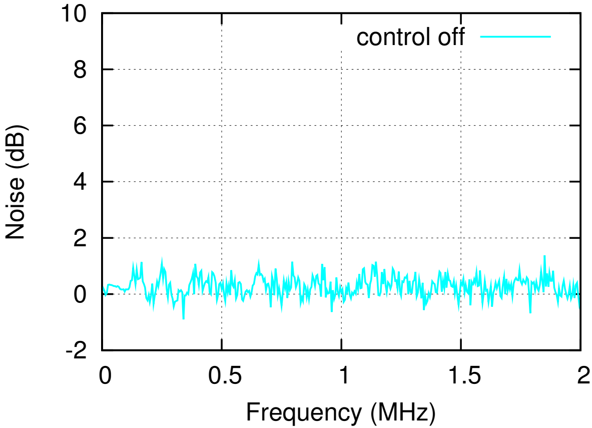


Control off no EIT and no squeezing at the output

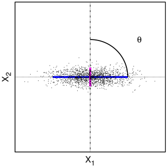


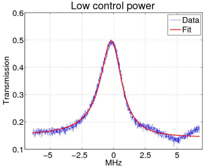


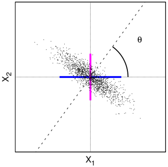
- Peak transmission = 0%



Squeezing angle rotation

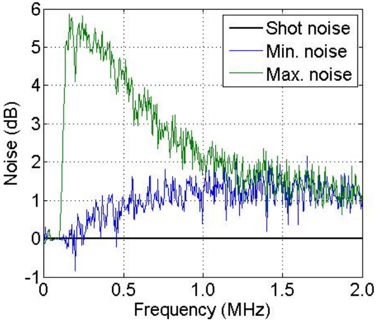




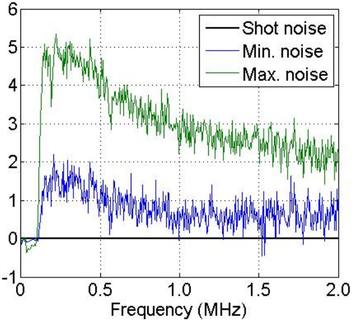


$$\begin{pmatrix} V_1^{out} \\ V_2^{out}\end{pmatrix} = \begin{pmatrix}\cos^2\varphi_+ & \sin^2\varphi_+ \\ \sin^2\varphi_+ & \cos^2\varphi_+\end{pmatrix}\begin{pmatrix}A_+^2 & A_-^2\\ A_-^2 & A_+^2\end{pmatrix}\begin{pmatrix}V_1^{in}\\ V_2^{in}\end{pmatrix} + \left[1-\left(A_+^2+A_-^2\right)\right]\begin{pmatrix}1\\ 1\end{pmatrix}$$

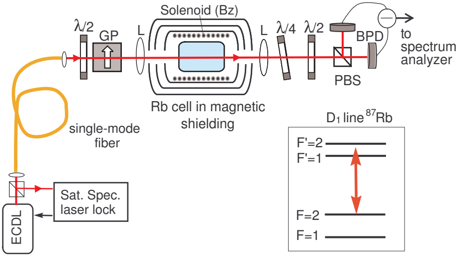
Locked at 300kHz

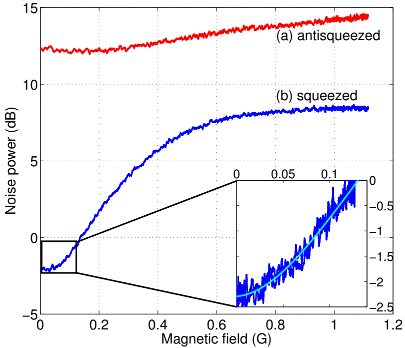


Locked at 1200kHz



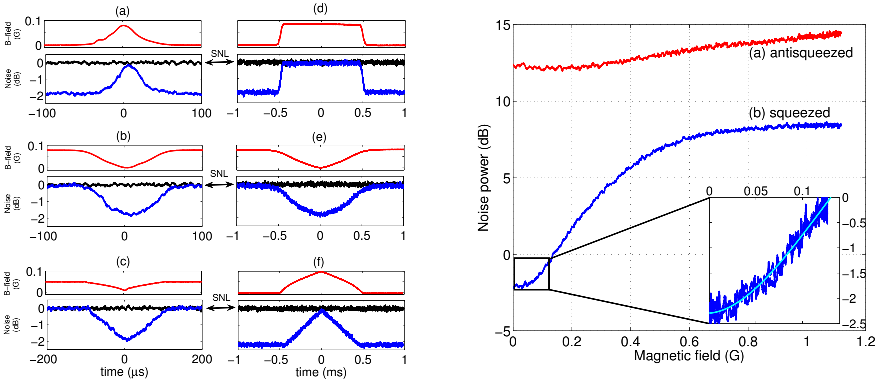
Spectrum analyzer settings: Central freq = 1 MHz, VBW = 3 MHz, RBW = 100 kHz



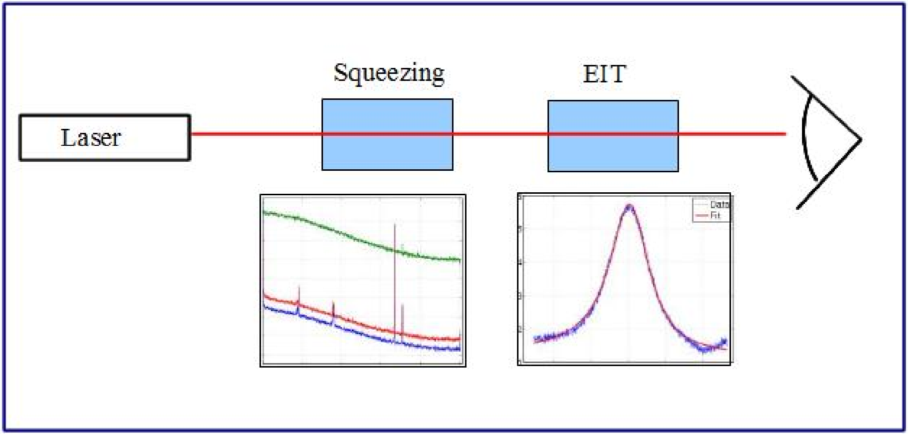


Squeezing vs magnetic field

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

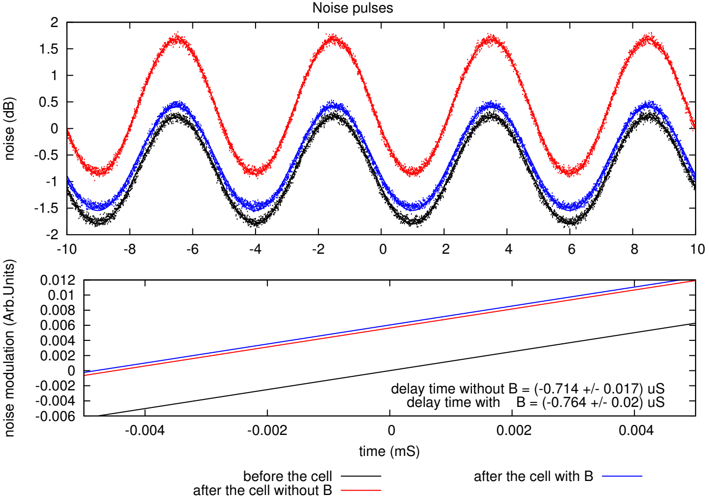


Delay/advancement measurement setup

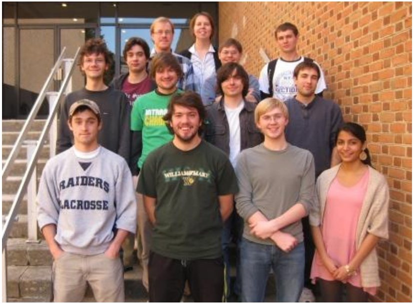


Fast squeezed light

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



People



Support from NSF

Summary

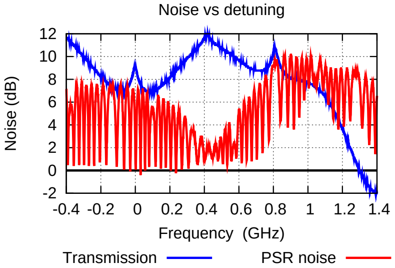
- We demonstrate fully atomic generation and manipulation of squeezing
- Squeezing is generated in the range from 100 Hz to several MHz

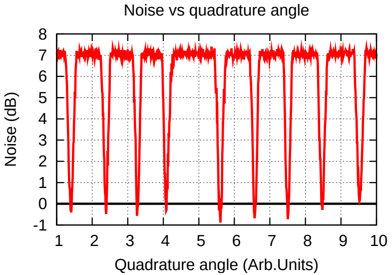
Advantages of the PSR squeezing

- Requires very little optical power (< 100 mW)
- Generated at atomic transition wavelength
- Potentially can be generated at any wavelength where the suitable transition exists
  - think blue or even ultraviolet

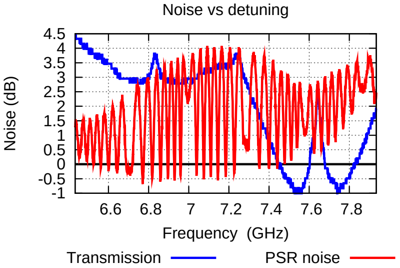
Noise contrast vs detuning in hot ^{87}Rb vacuum cell

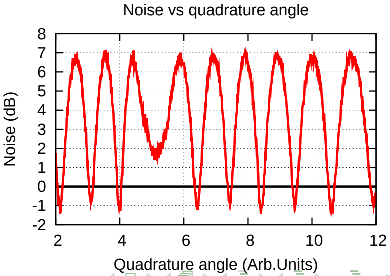
$F_g = 2 \rightarrow F_e = 1, 2$





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

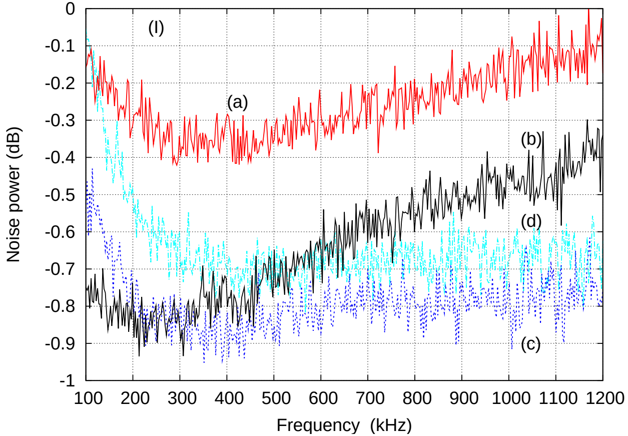




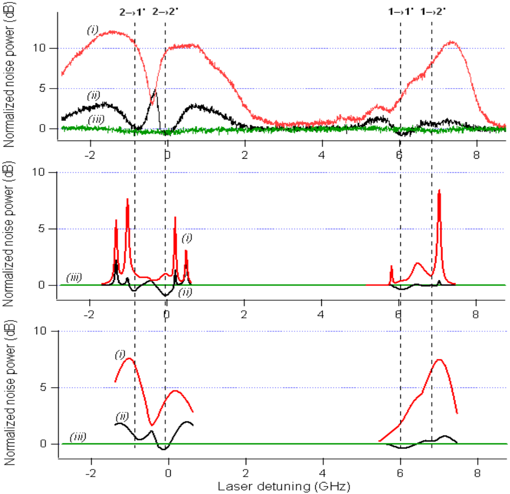
Squeezing spectrum vs pump power in ^{87}Rb

^{87}Rb cell + 2.5Torr Ne, T=63.3°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, J. Mod. Opt. **56**, 1985 (2009).