Quantum-enhanced measurements and fast squeezing with atomic vapor

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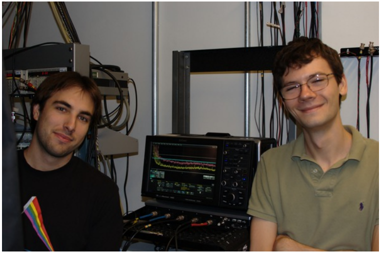
Travis Horrom, Gleb Romanov, and Irina Novikova

The College of William & Mary, USA

SPIE, Febrary 03, 2014

People

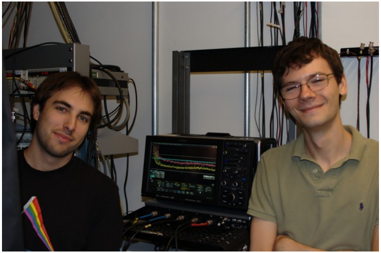
Travis Horrom and Gleb Romanov



Irina Novikova

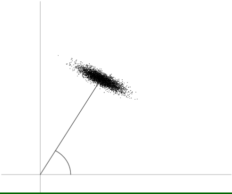
People

Travis Horrom and Gleb Romanov



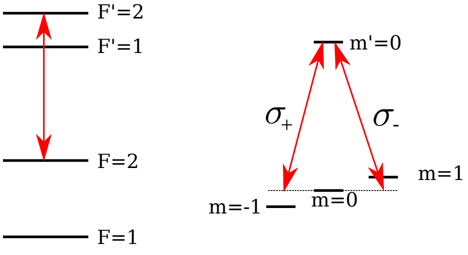
Irina Novikova

Squeezed state

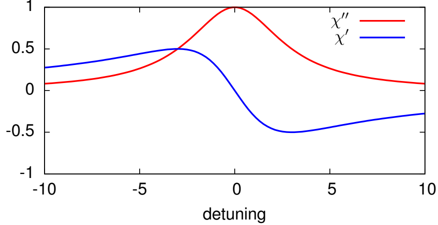


Optical magnetometer based on Faraday effect

^{87}Rb D_1 line



Susceptibility vs B



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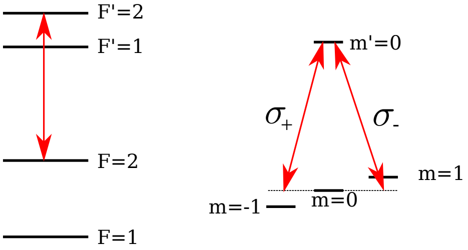

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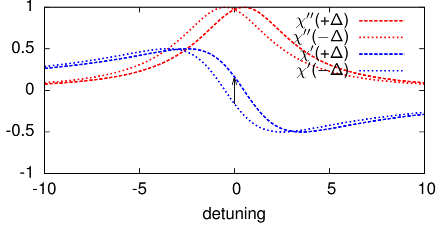

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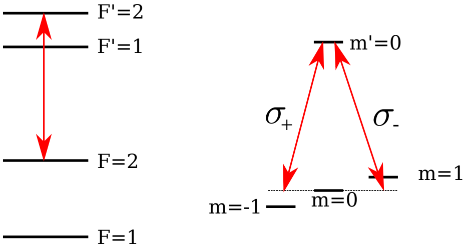

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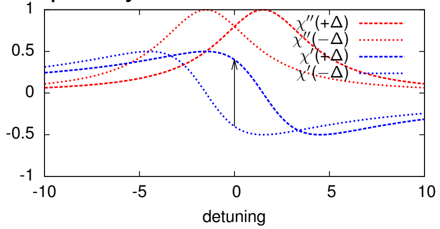

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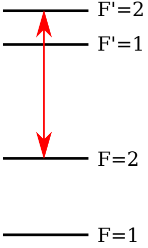

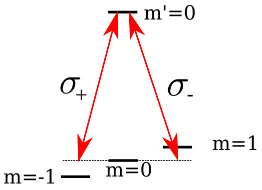

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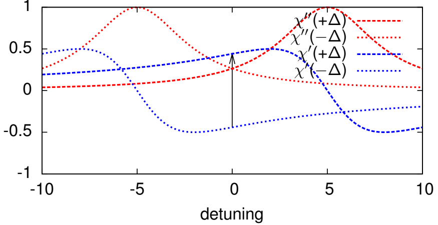

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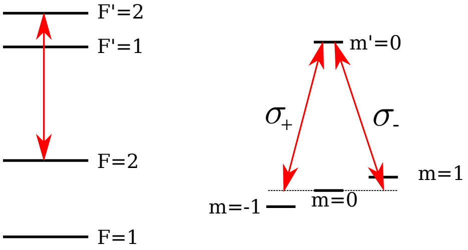

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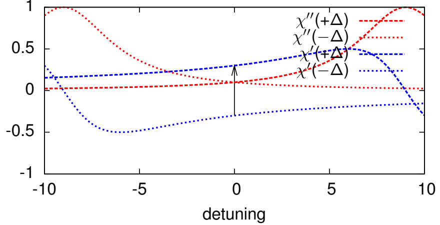

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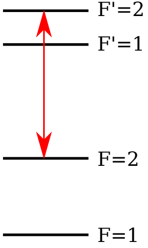
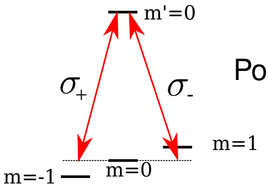
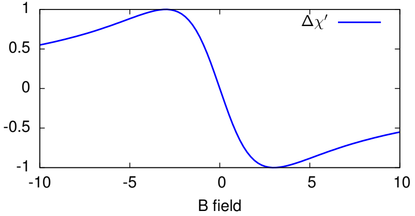
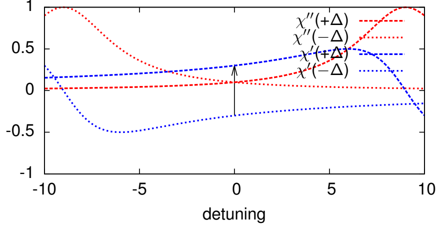




Polarization rotation vs B

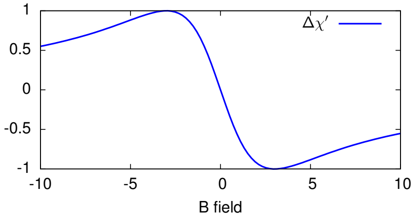


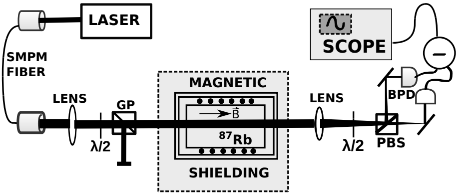
Susceptibility vs B



Optical magnetometer and non linear Faraday effect

Naive model of rotation





Experiment

Optical magnetometer and non linear Faraday effect

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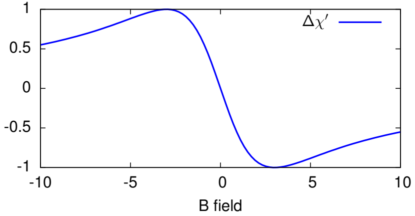

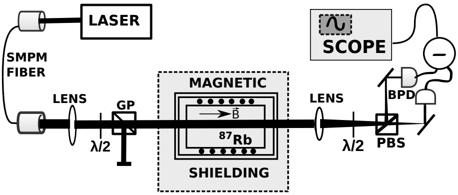

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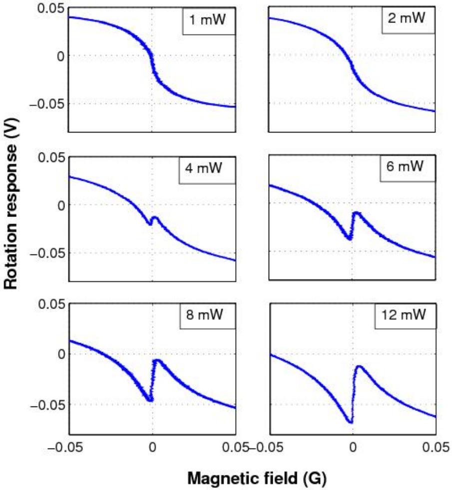
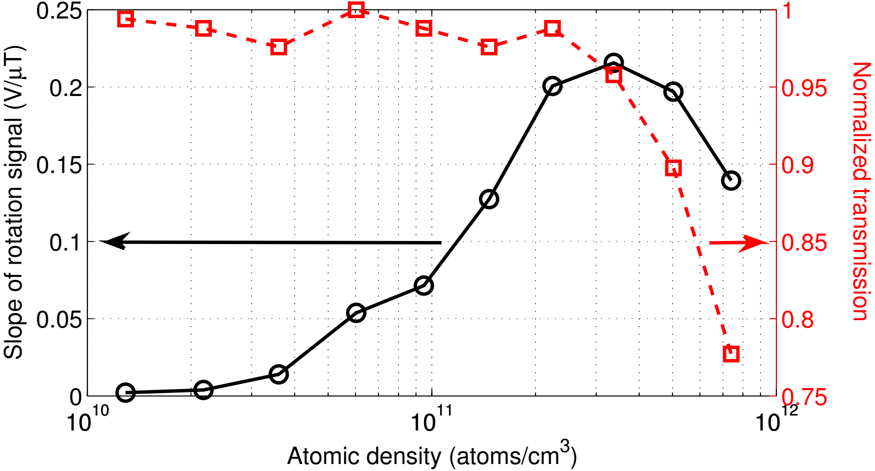
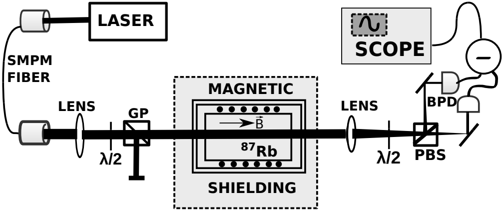
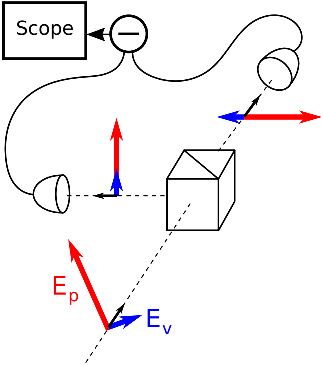


Magnetometer response vs atomic density



Shot noise limit of the magnetometer





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

$$S = 4E_pE_v$$

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

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

$\Delta \phi \Delta N \geq 1$

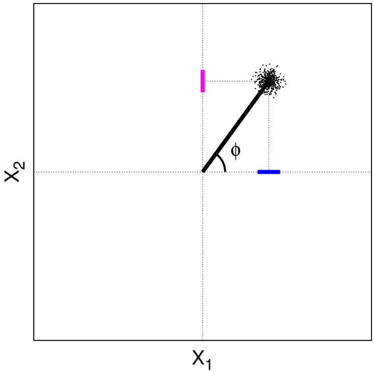
The more precisely the PHASE is determined, the less precisely the AMPLITUDE is known, and vice versa

Optics equivalent strict definition

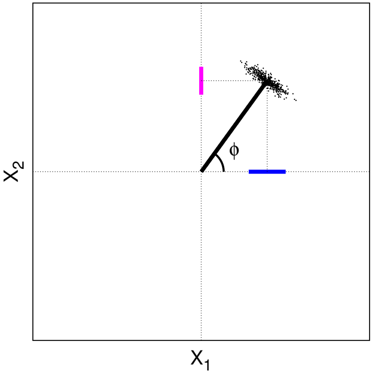
$\Delta X_1 \Delta X_2 \geq 1/4$

Minimum uncertainty (coherent) states

Coherent state



Squeezed state



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

Minimum uncertainty (coherent) states

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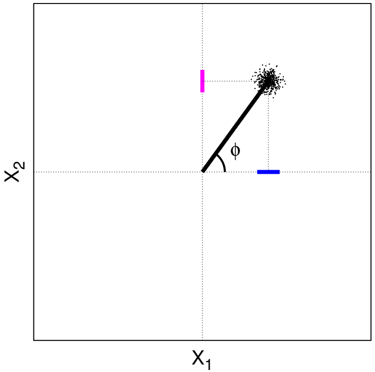
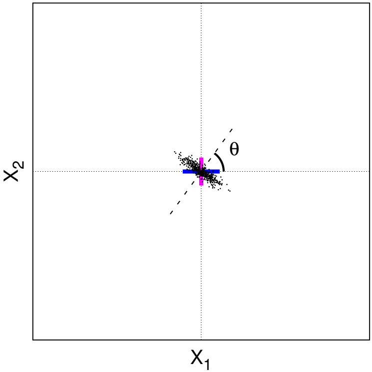
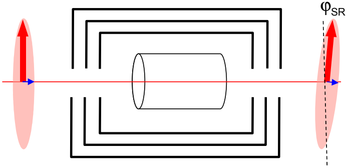


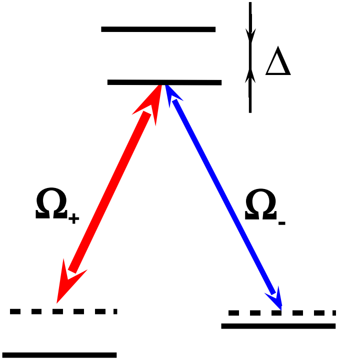
Squeezed state



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

Self-rotation of elliptical polarization in atomic medium

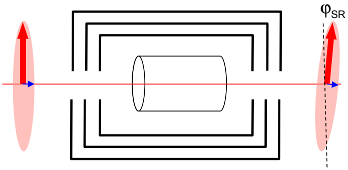


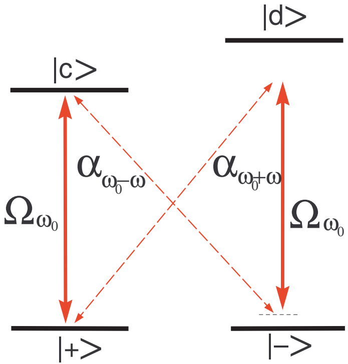


A.B. Matsko et al., PRA 66, 043815 (2002): theoretically prediction of 4-6 dB noise suppression

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

Self-rotation of elliptical polarization in atomic medium





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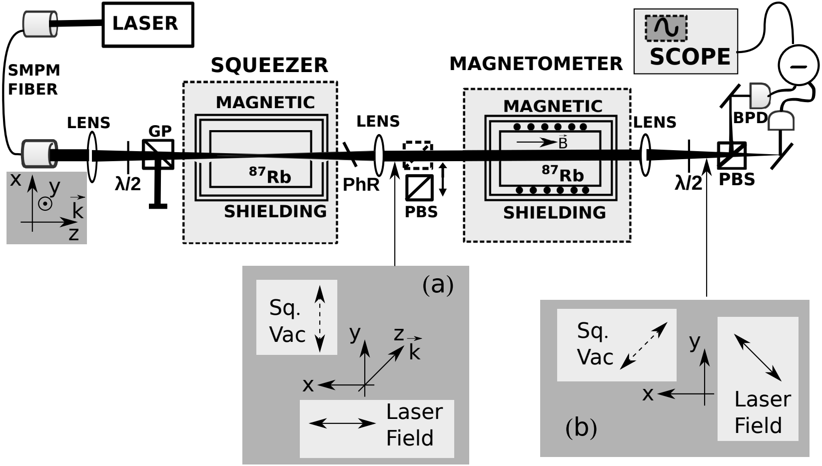
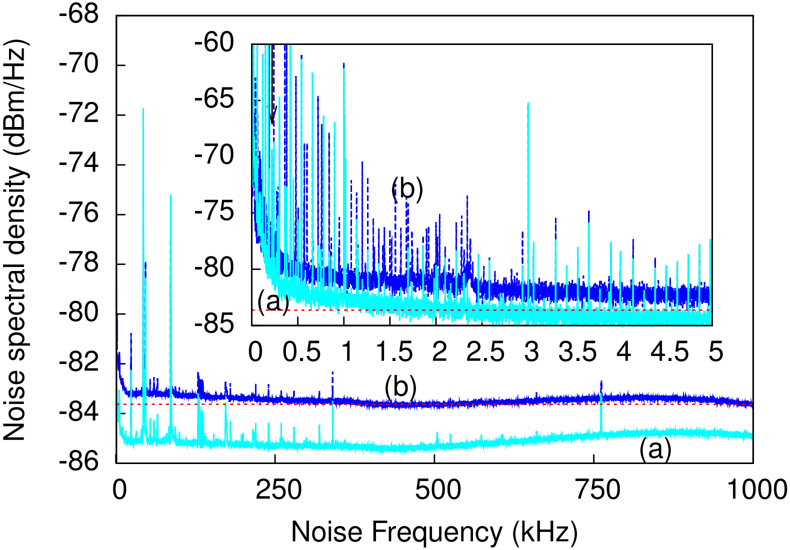
Squeezed enhanced magnetometer setup

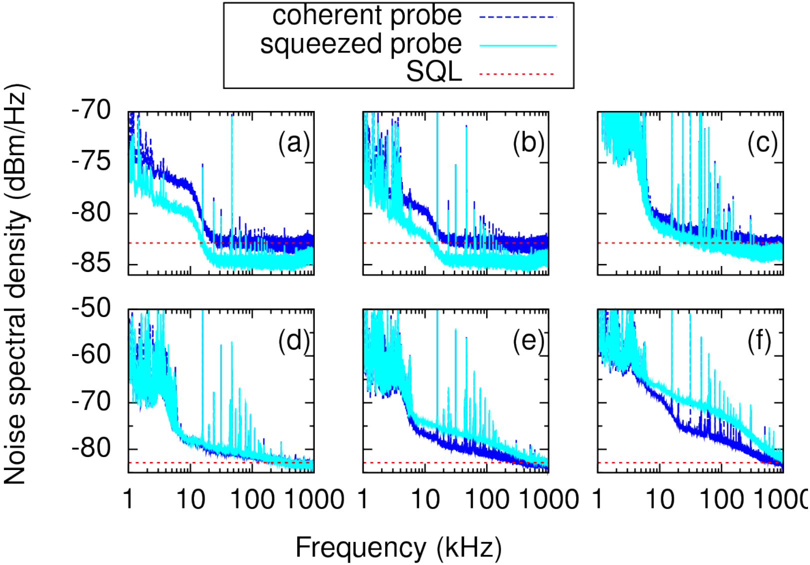


Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al* Phys. Rev. Lett, **105**, 053601, 2010.

Magnetometer noise floor improvements

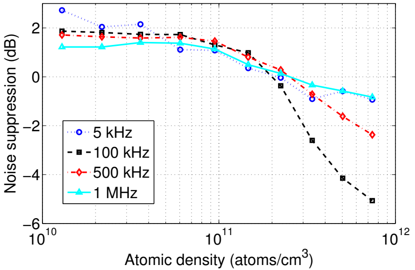


Magnetometer noise spectra

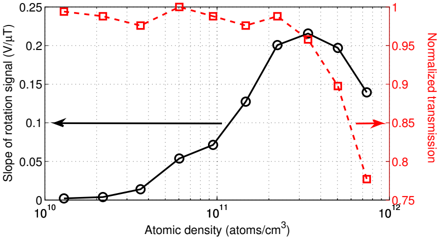


Noise suppression and response vs atomic density

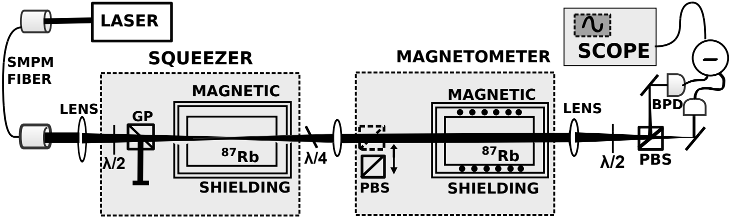
Noise suppression

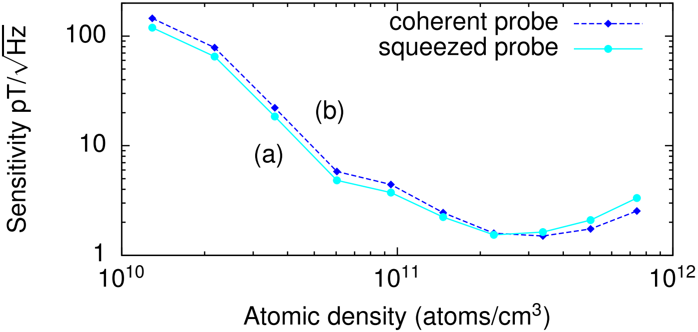


Response



Magnetometer with squeezing enhancement





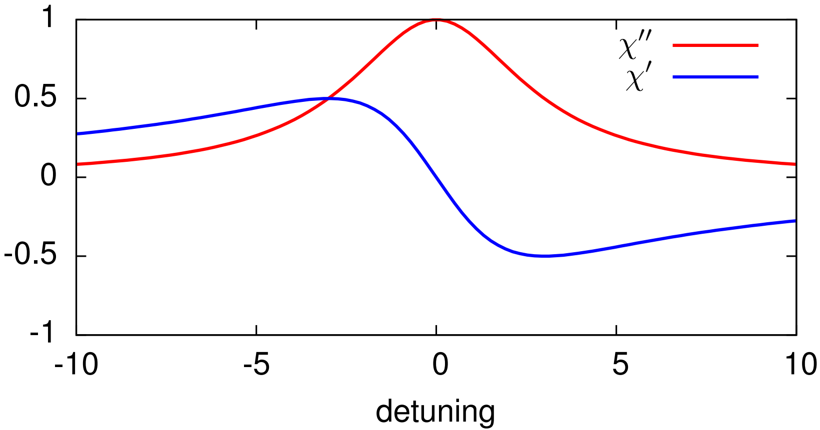
Why superluminal squeezing?

- 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



Susceptibility and non linear Faraday effect

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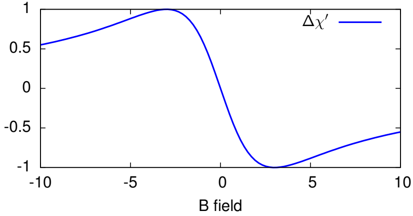

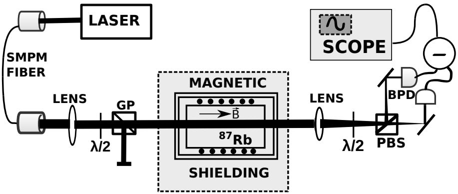

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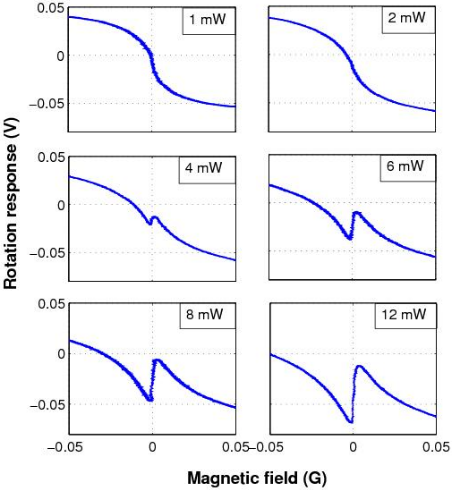

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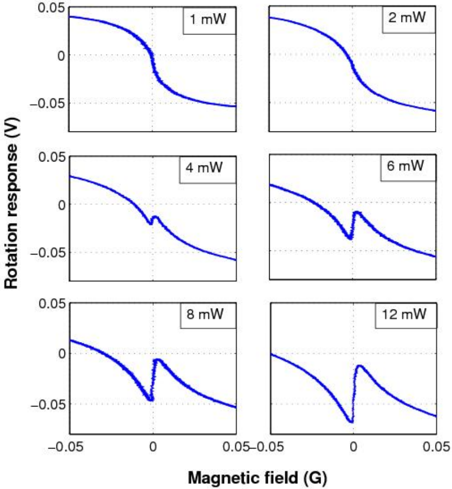
Group velocity $v_g = \frac{c}{\omega \frac{\partial n}{\partial \omega}}$

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



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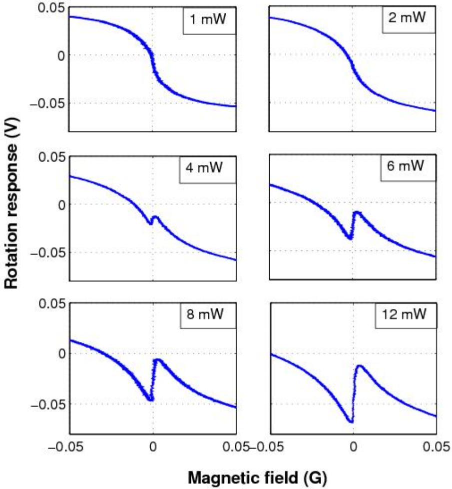
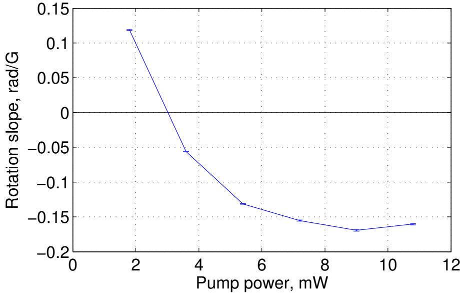
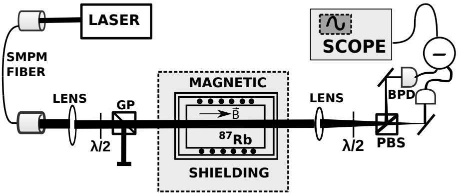
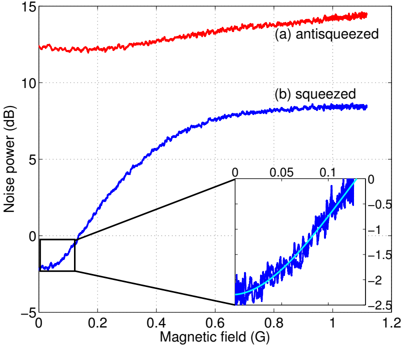




Squeezing vs magnetic field

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).

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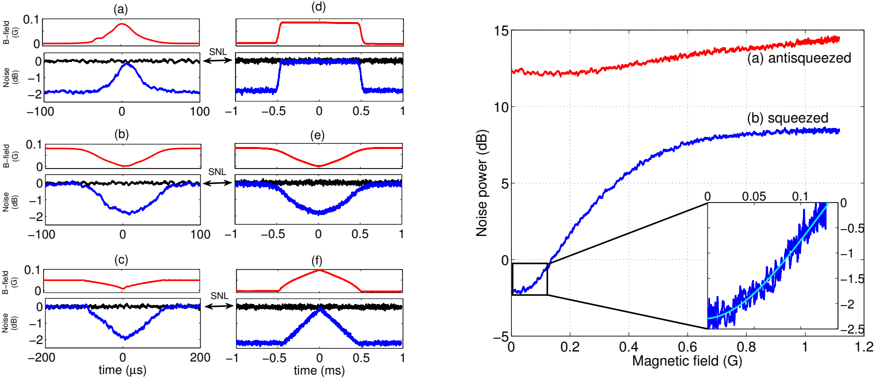

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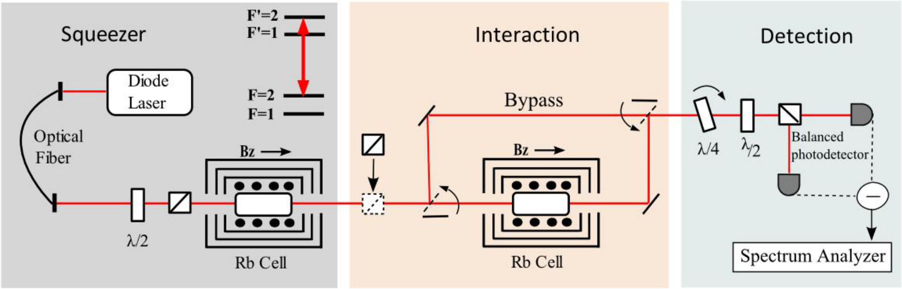
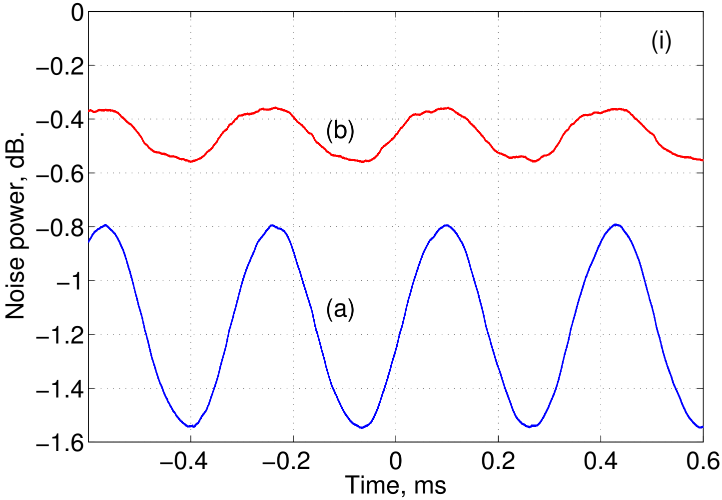
Time advancement setup



Squeezing modulation and time advancement



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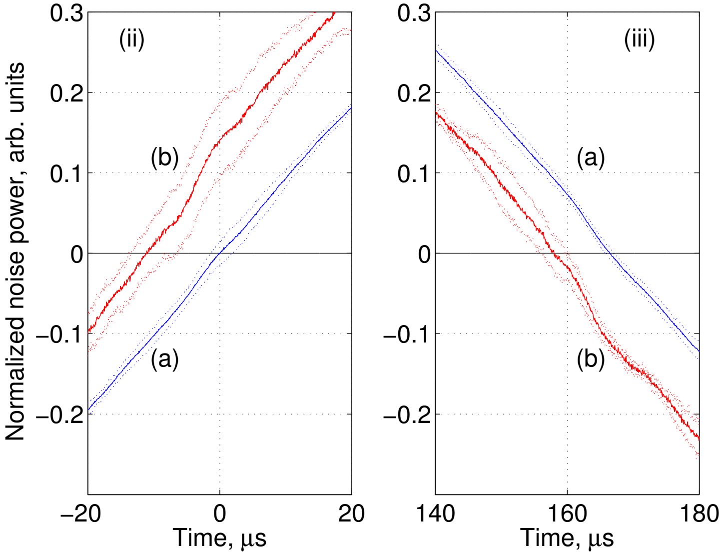
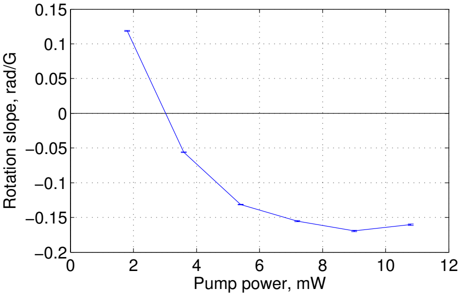


Advancement vs power



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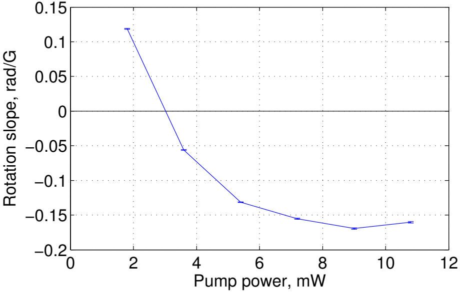
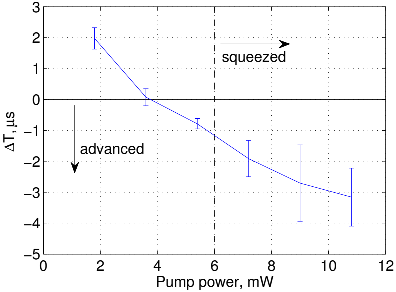
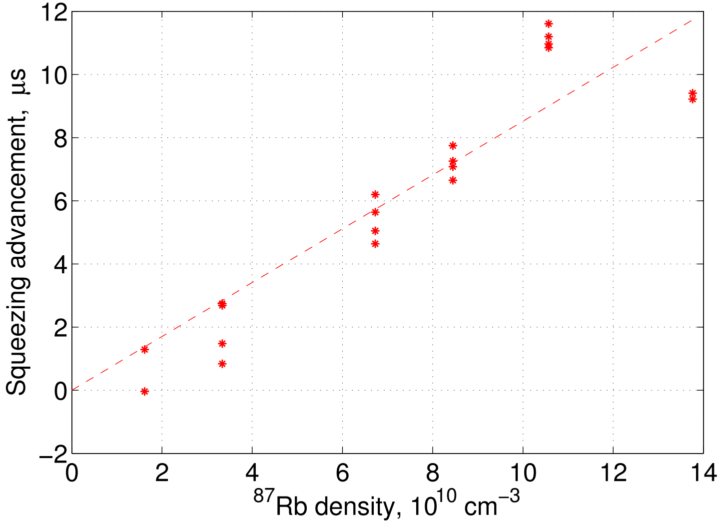




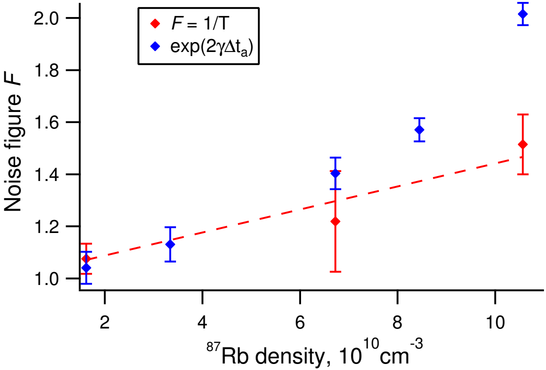
Squeezing advancement vs atomic density

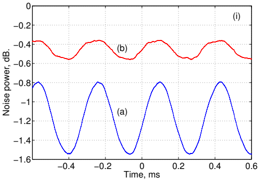


Noise figure and advancement

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

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





Summary

- We demonstrate 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

For more details:

- T. Horrom, et al. “Quantum Enhanced Magnetometer with Low Frequency Squeezing”, **PRA**, 86, 023803, (2012).
- G. Romanov, et al. “Propagation of a squeezed optical field in a medium with superluminal group velocity”, arXiv:1310.4815, (2013). *To appear in Optics Letters*

Support from NSF AFOSR