Quantum enhanced magnetometry and resonant squeezing interaction with atoms

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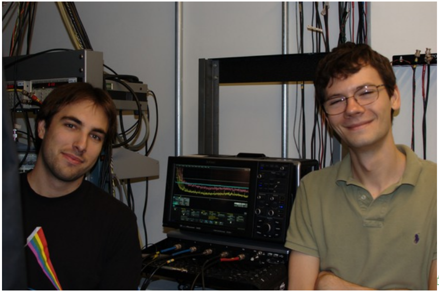
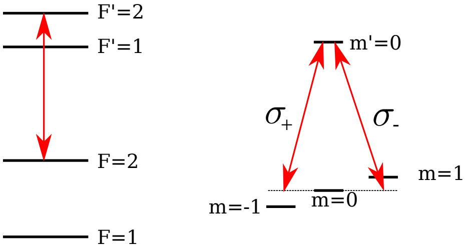
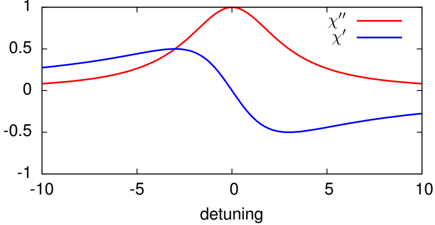


Optical magnetometer based on Faraday effect

^{87}Rb D_1 line



Susceptibility vs B



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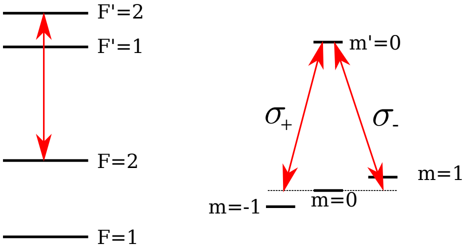

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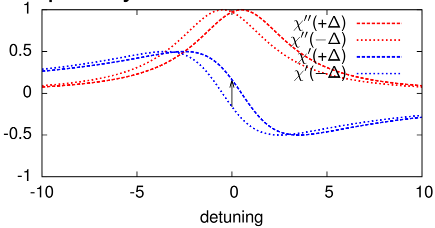

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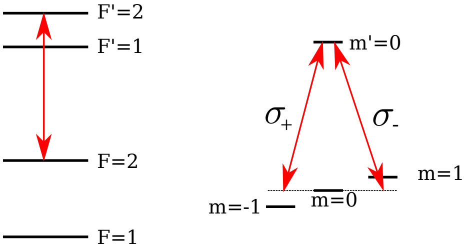

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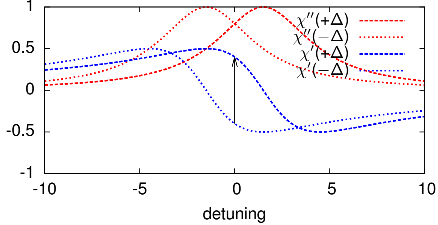

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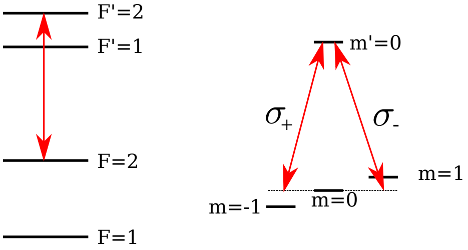

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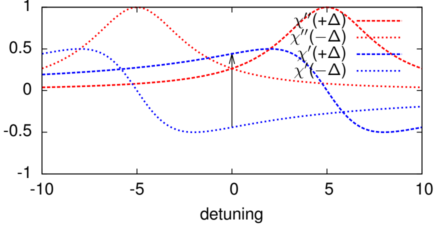

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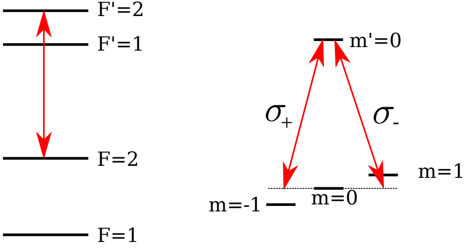

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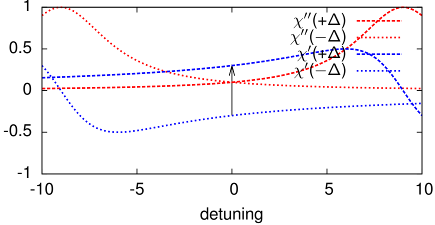

Optical magnetometer based on Faraday effect

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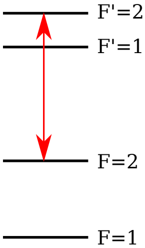
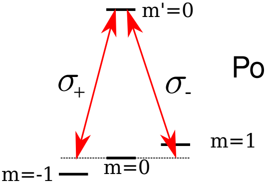
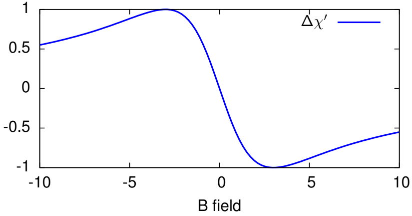
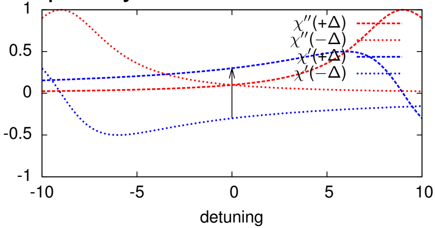




Polarization rotation vs B



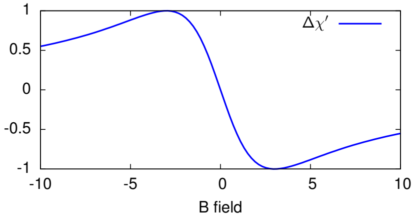
Susceptibility vs B

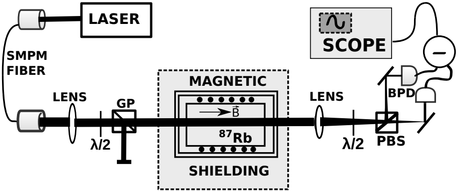


Optical magnetometer and non linear Faraday effect

Naive model of rotation

Experiment





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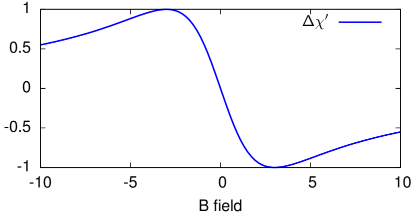
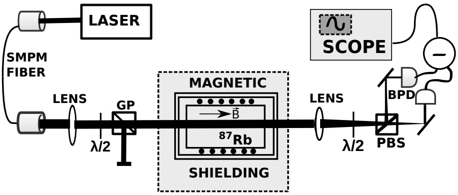
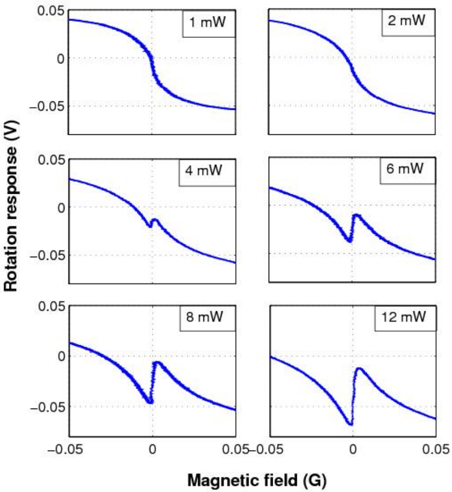
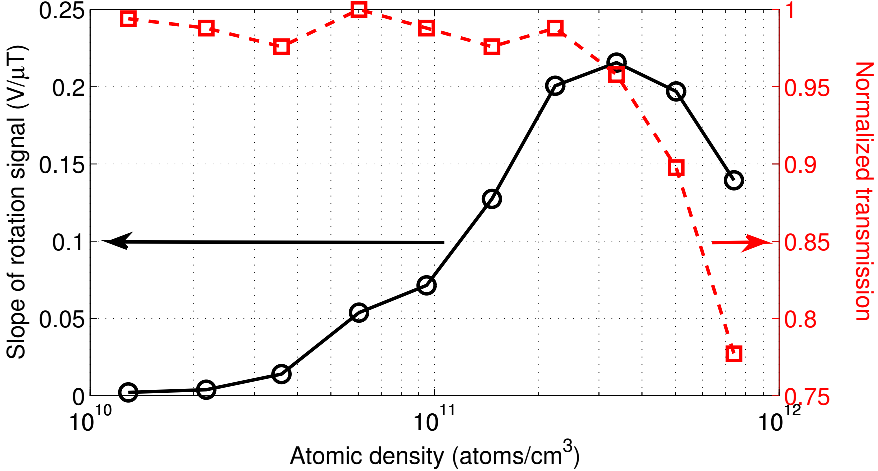




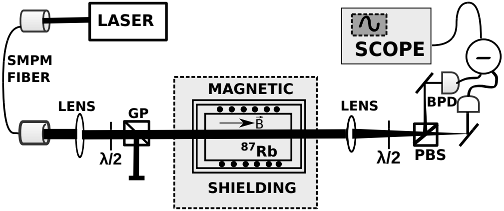
Experiment

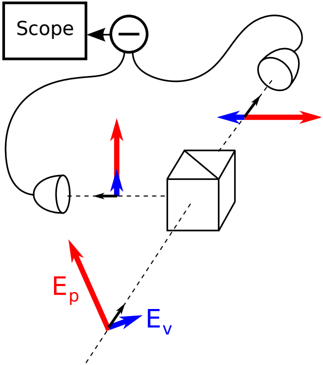


Magnetometer response vs atomic density



Shot noise limit of the magnetometer





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

$$S = 4E_pE_v$$

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

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

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

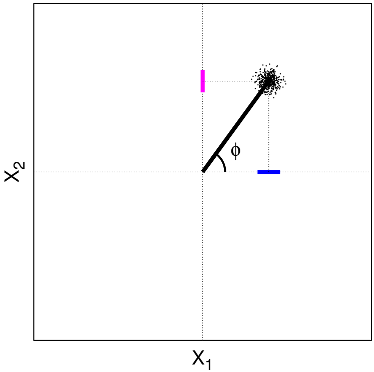
The more precisely the PHASE is determined, the less precisely the AMPLITUDE is known, and vice versa

Optics equivalent strict definition

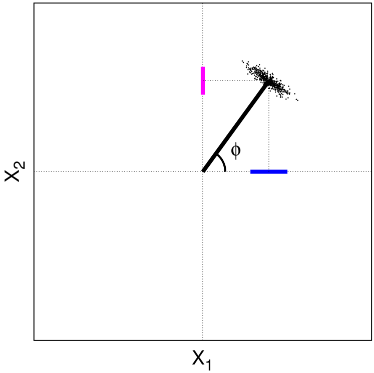
$\Delta X_1 \Delta X_2 \geq 1/4$

Minimum uncertainty (coherent) states

Coherent state



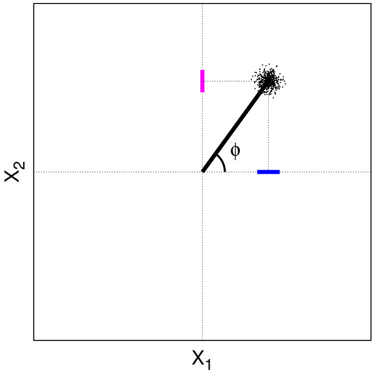
Squeezed state



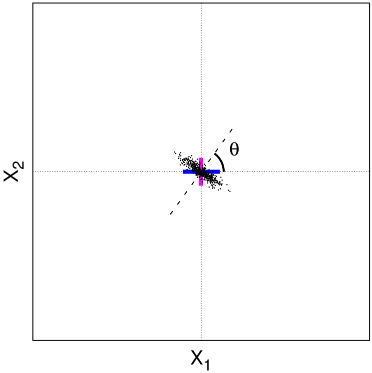
$$\Delta X_1 \Delta X_2 \geq 1/4$$

Minimum uncertainty (coherent) states

Coherent state

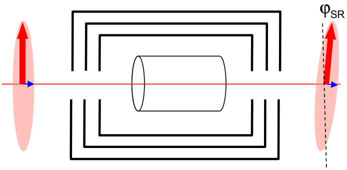


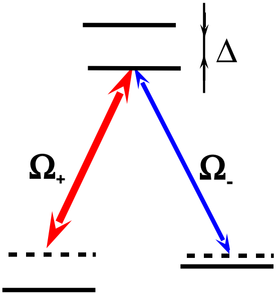
Squeezed state



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

Self-rotation of elliptical polarization in atomic medium

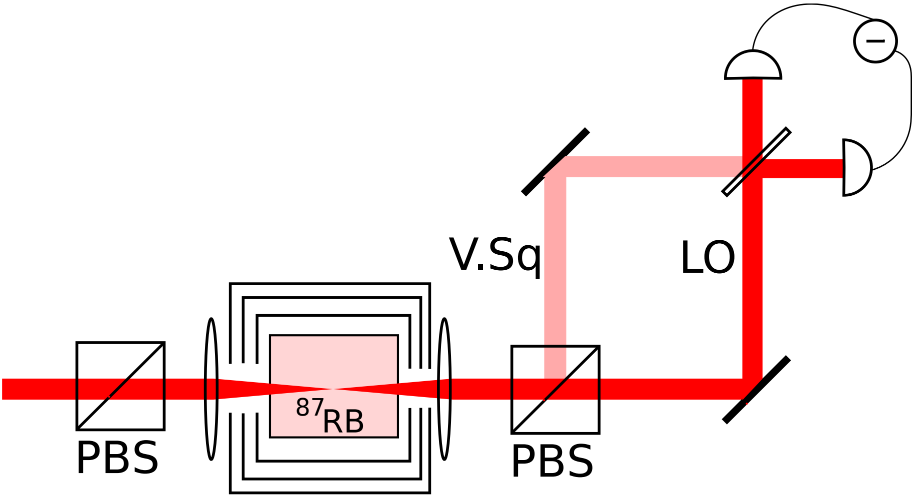




$$a_{out} = a_{in} + \frac{igL}{2}(a_{in}^{\dagger} - a_{in})$$

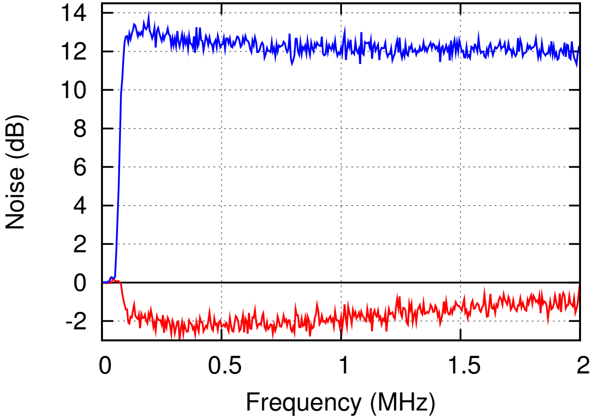
- **theory :** A.B. Matsko et al., PRA 66, 043815 (2002)
- **experiment:** J. Ries, B. Brezger, and A. I. Lvovsky, Experimental vacuum squeezing in rubidium vapor via self-rotation, PRA **68**, 025801 (2003).

Setup



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



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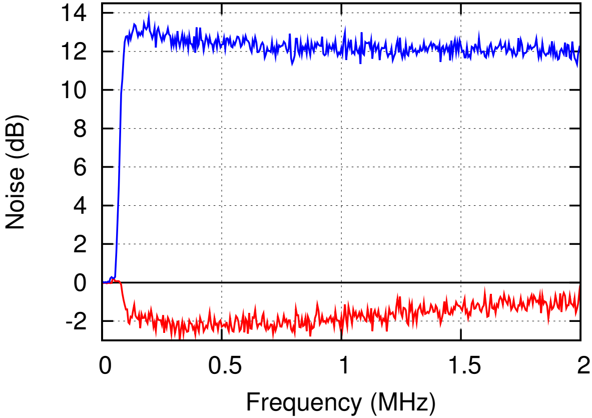
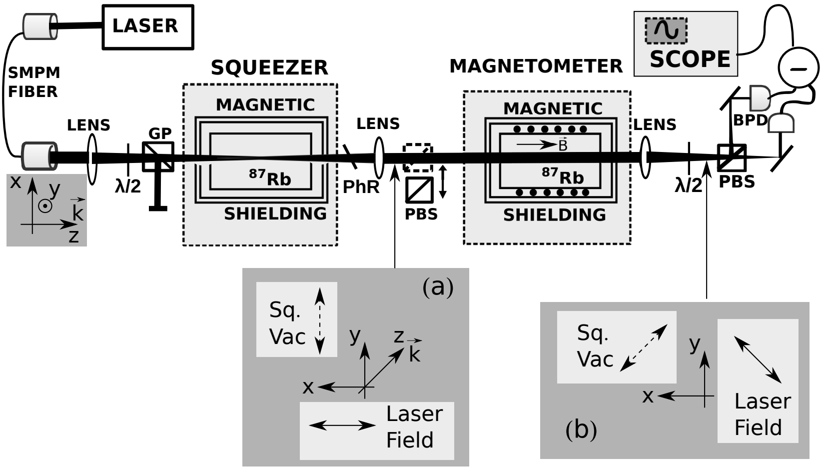


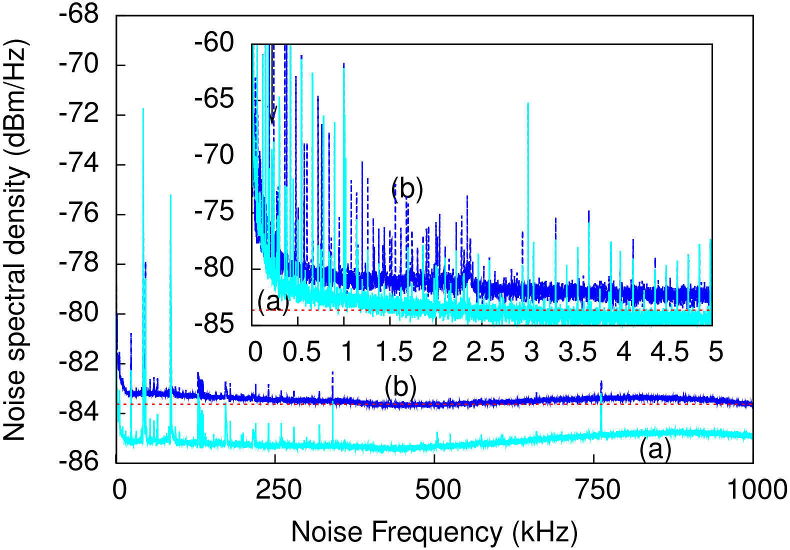
Lezama et.al report 3 dB squeezing in similar setup
Phys. Rev. A 84, 033851 (2011)

Squeezed enhanced magnetometer setup

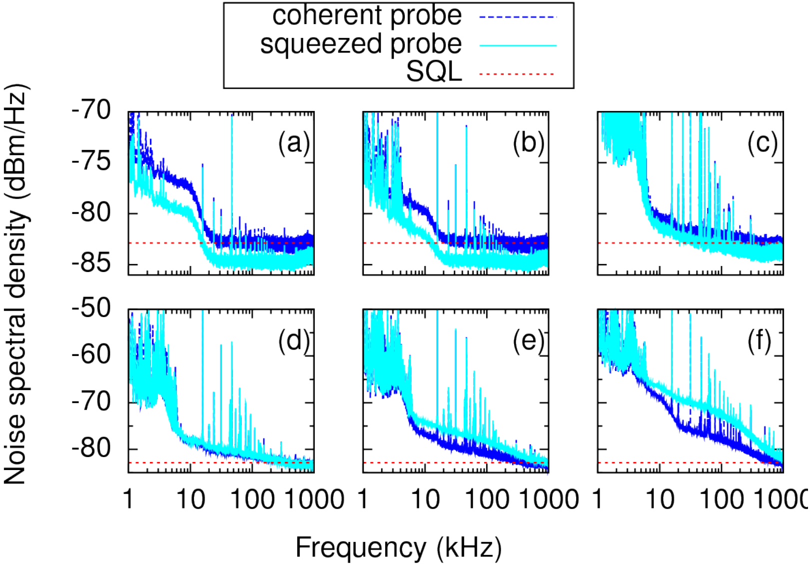


Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al* Phys. Rev. Lett, **105**, 053601, 2010.

Magnetometer noise floor improvements

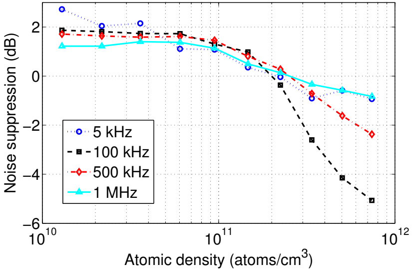


Magnetometer noise spectra

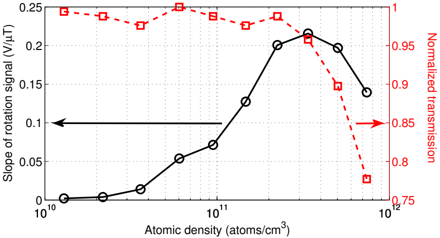


Noise suppression and response vs atomic density

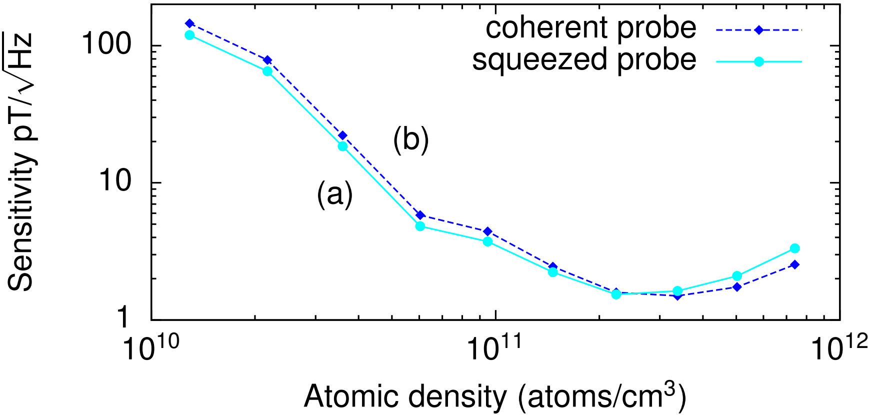
Noise suppression



Response

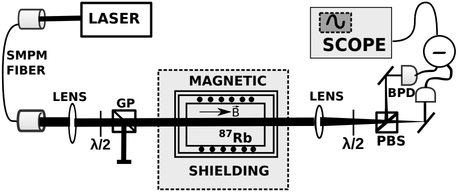


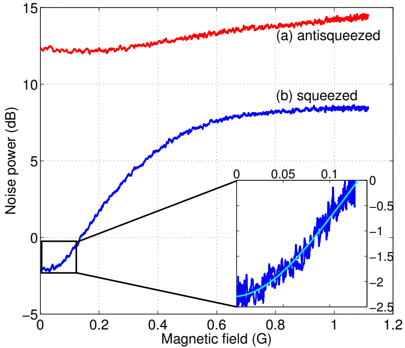
Magnetometer sensitivity vs atomic density



Squeezing vs magnetic field

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





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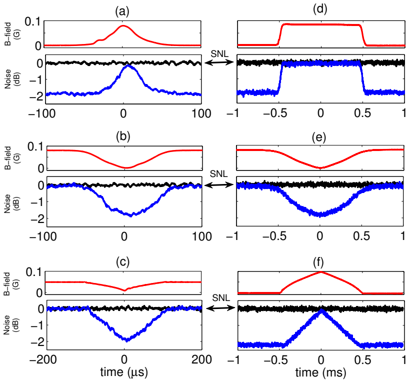
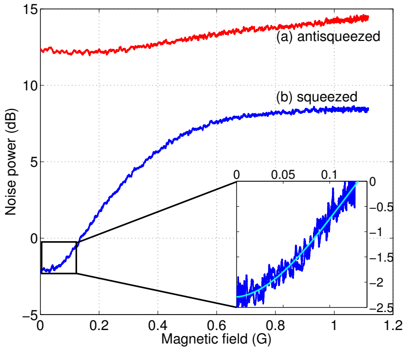




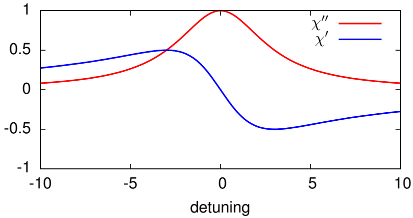
Group velocity measurements motivation

- 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.
- Yakir Aharonov, et al. “Quantum Limitations on Superluminal Propagation”, Phys. Rev. Lett. 81, 2190 (1998)

Light group velocity

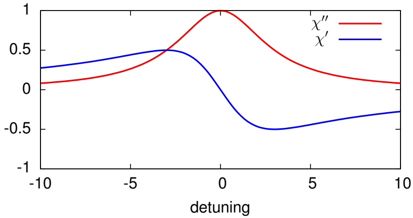
Group velocity $v_g = \frac{c}{\omega \frac{\partial n}{\partial \omega}}$

Susceptibility

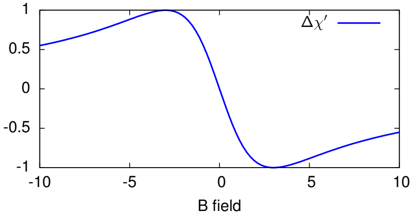


Group velocity $v_g = \frac{c}{\omega \frac{\partial n}{\partial \omega}}$

Susceptibility



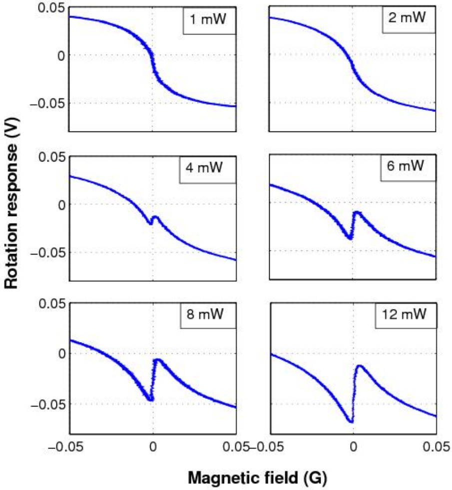
Rotation vs B field



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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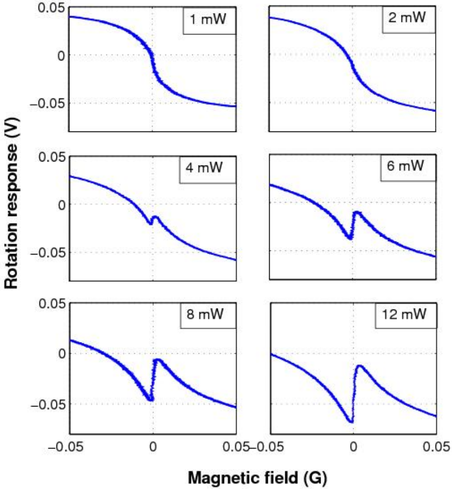
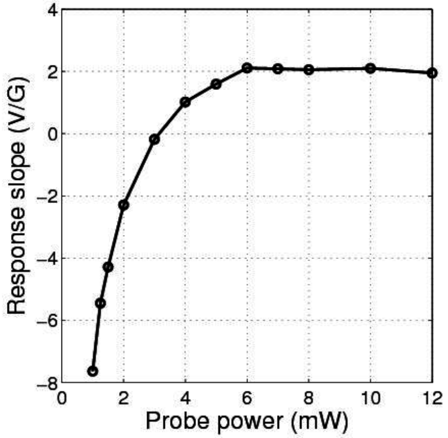
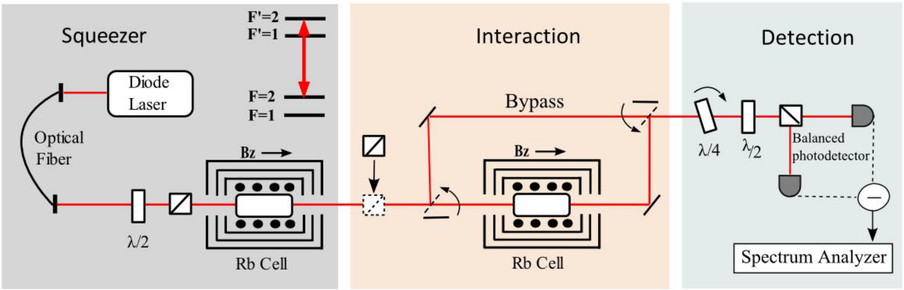
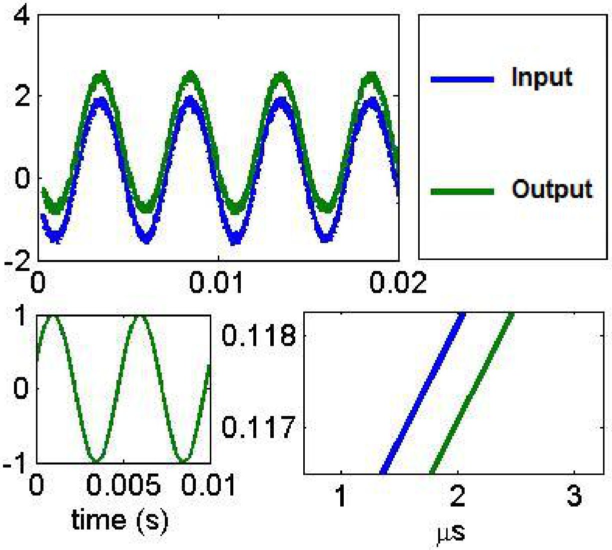




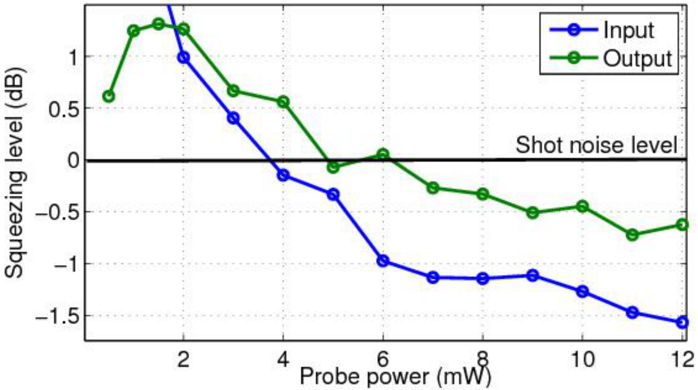
Time advancement setup



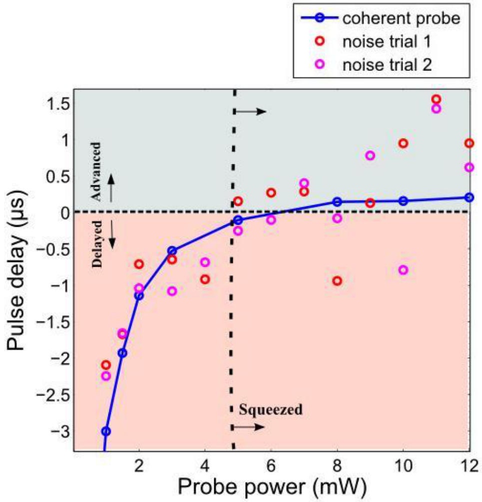
Squeezing modulation and time advancement



Squeezing after advancement cell



Advancement vs power



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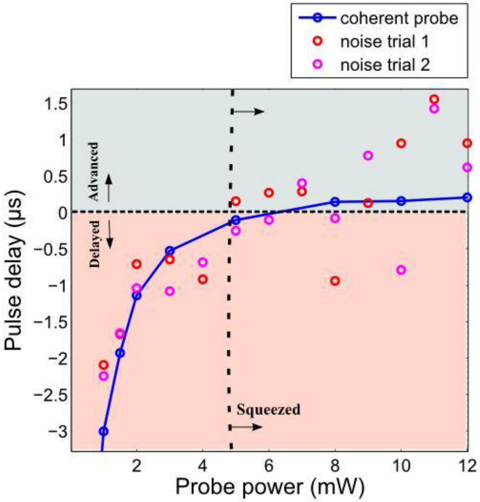

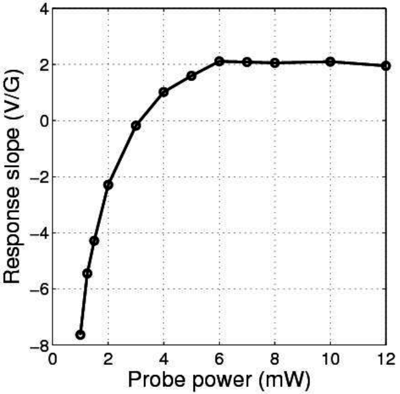

Summary

- We demonstrate fully atomic squeezed enhanced magnetometer
- Magnetometer noise floor lowered in the range from several kHz to several MHz
- Demonstrated sensitivity as low as 1 pT/$\sqrt{\text{Hz}}$ in our particular setup
- First demonstration of superluminal squeezing propagation with $v_g = c/2000$ or time advancement of 0.5 μS

For more details:

- T. Horrom, et al. "Quantum Enhanced Magnetometer with Low Frequency Squeezing", **PRA**, 86, 023803, (2012).