Precision measurements assisted by Rb vapor

Eugeniy E. Mikhailov[2]

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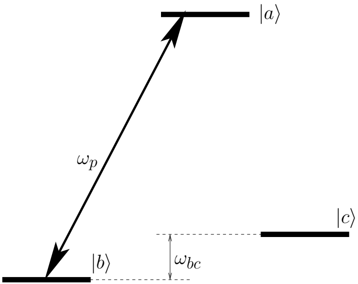
WILLIAM & MARY
CHARTERED 1693

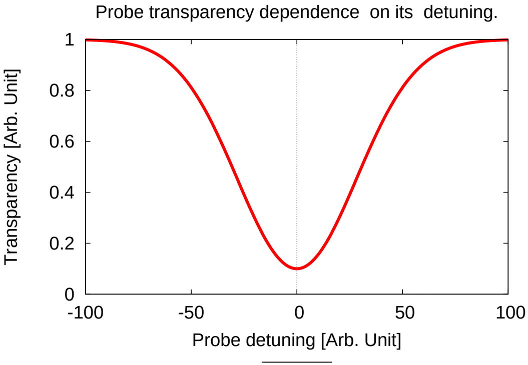
About William & Mary

Outline

- Magnetic compass
- Quantum noise imaging

Electromagnetically Induced Transparency (EIT)





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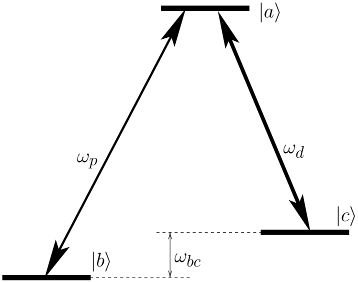

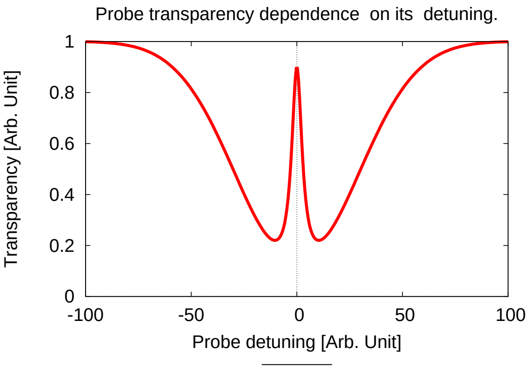

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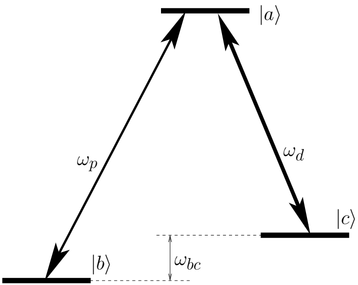
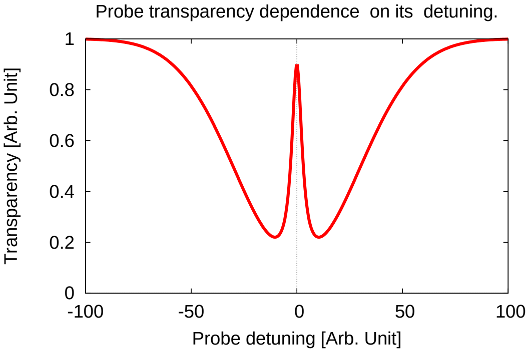


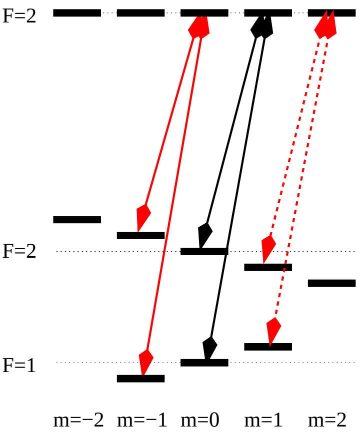


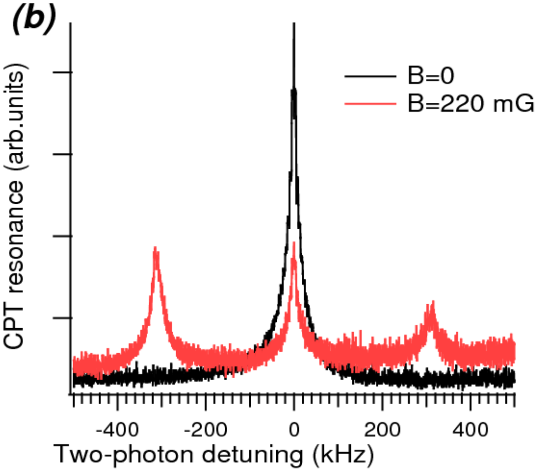
Coherent Population Trapping

- Dark $|D\rangle = \Omega_d|b\rangle - \Omega_p|c\rangle$ and Bright $|B\rangle = \Omega_d|c\rangle + \Omega_p|b\rangle$ states
- resonance width ($\sim$ 10kHz) much smaller then natural line width

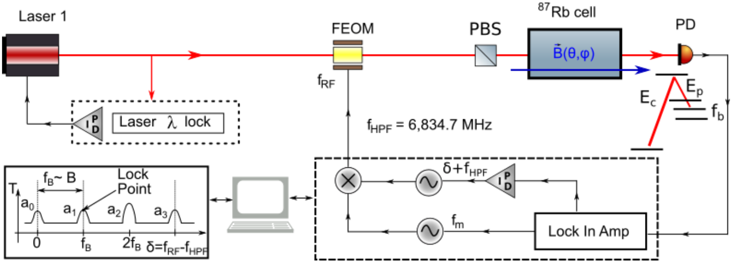
Simple EIT magnetometer

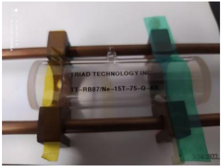
EIT with circularly polarized light

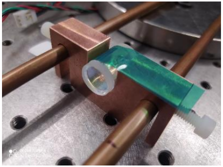


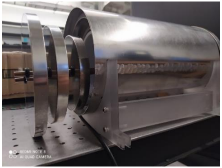


Conceptual design

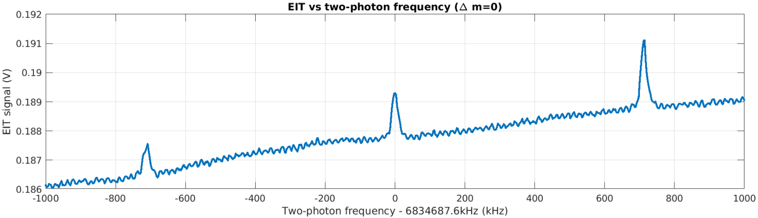








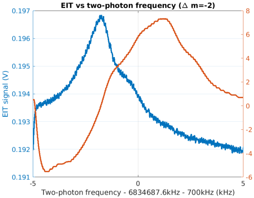
EIT signals vs two-photon detuning. B=50μT, $f_{center} = 6'834'687.6$kHz

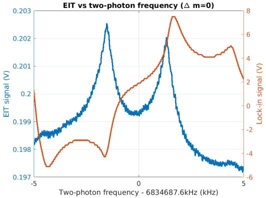


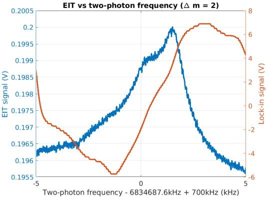
$\Delta m = -2$, $f_{center} - 700$kHz

$\Delta m = 0$, f_{center}

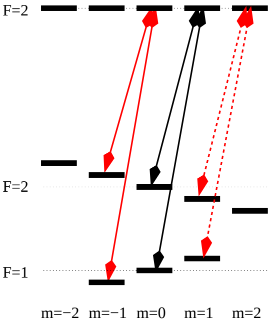
$\Delta m = 2$, $f_{center} + 700$kHz

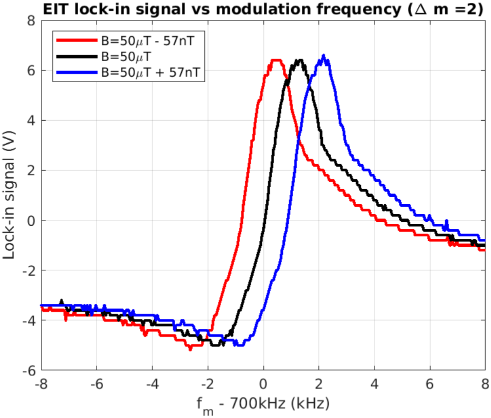




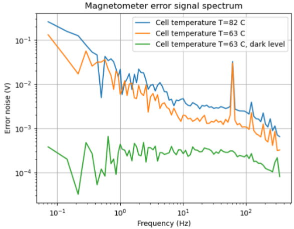


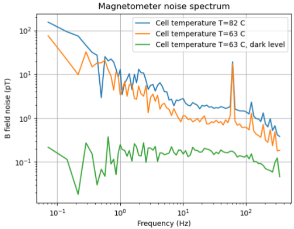
Shift by ± 57nT magnetic field change

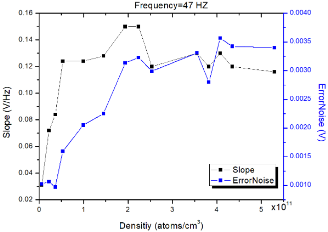


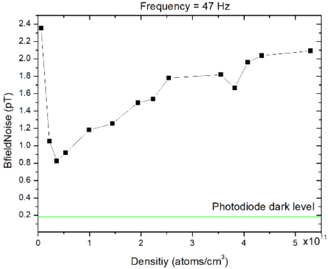


Signal to noise optimization

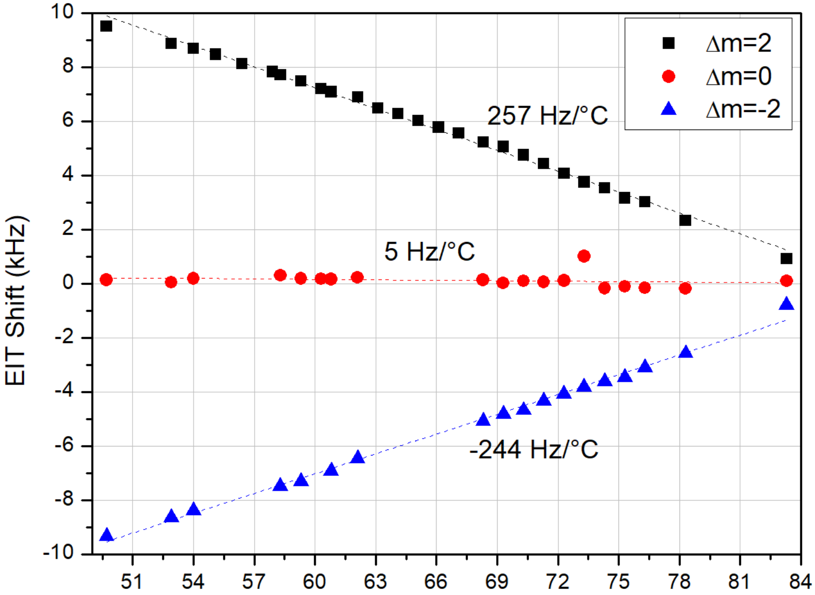




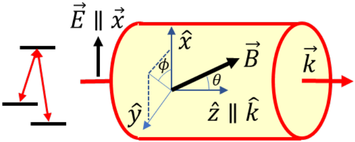


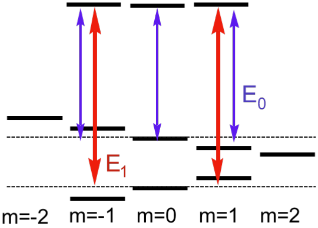


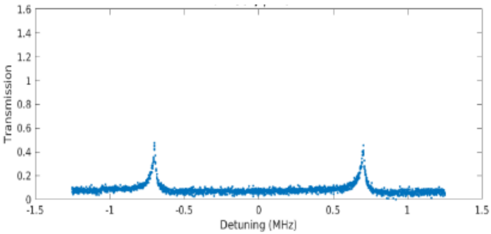
EIT shift vs temperature



Compass idea







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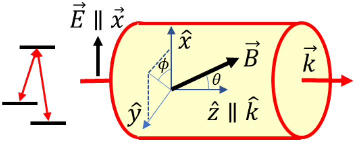

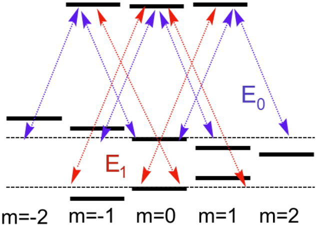

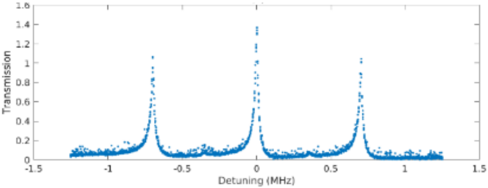

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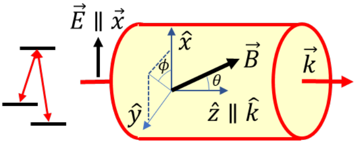
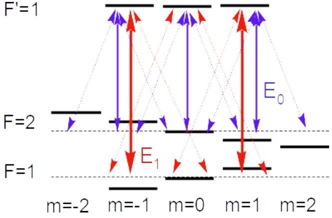
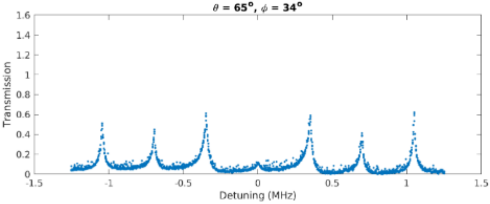
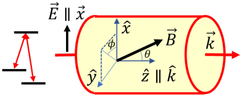
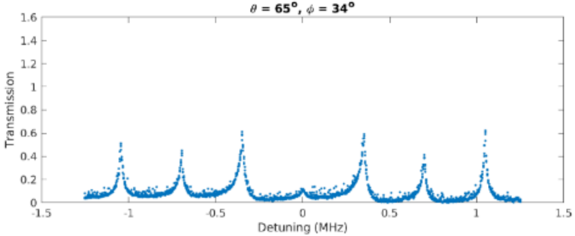




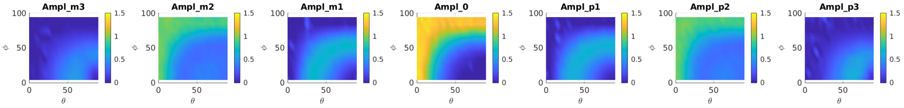






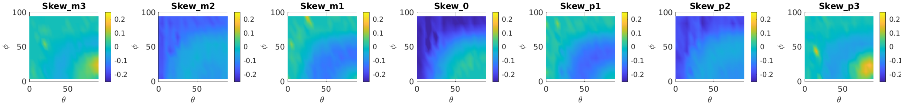
Amplitude

EIT parameter for linear polarization

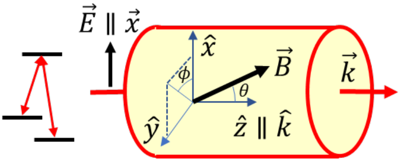


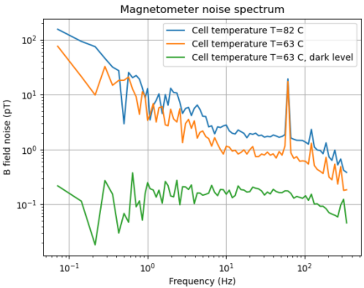
Skew

EIT parameter for linear polarization



Compass summary





- measures B-field vector
- can operate at the Earth magnetic field
- sub-pT sensitivity

Transition from classical to quantum field

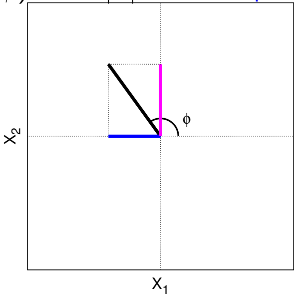
Classical analog

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

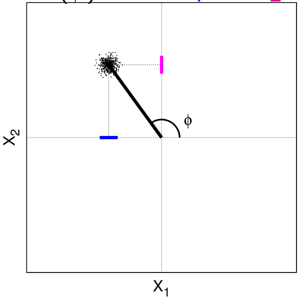
Quantum approach

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

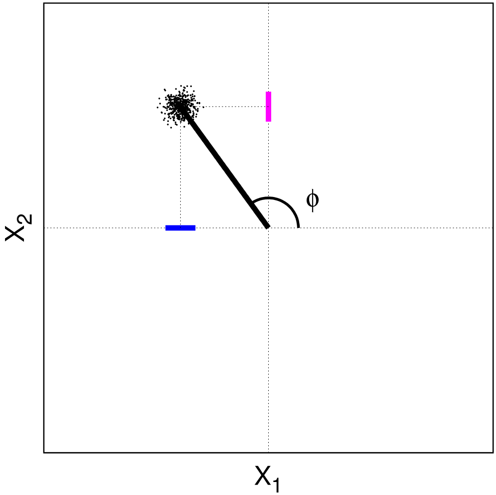
$$E(\phi) = |a|e^{-i\phi} = X_1 + iX_2$$



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



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

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Optics equivalent

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

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

Heisenberg uncertainty principle and its optics equivalent

Heisenberg uncertainty principle

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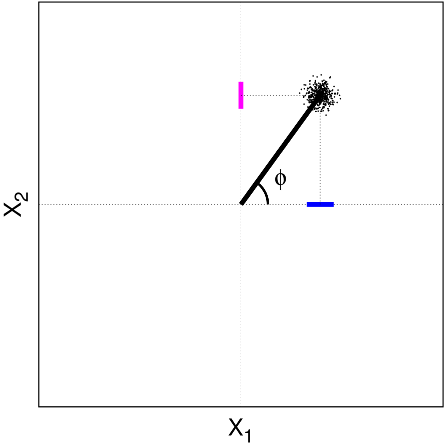
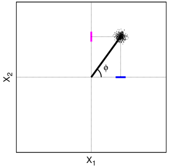
Optics equivalent strict definition

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

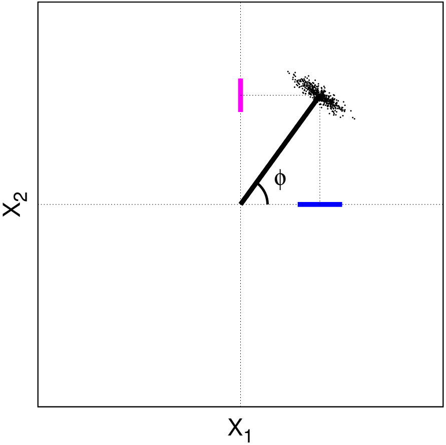
Squeezed quantum states zoo



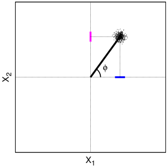
Unsqueezed
coherent



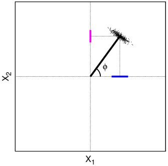
Squeezed quantum states zoo



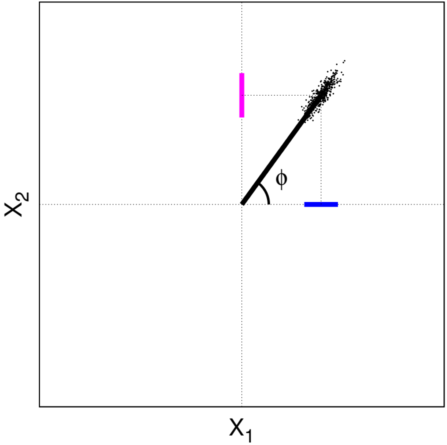
Unsqueezed coherent



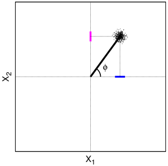
Amplitude squeezed



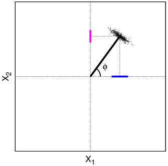
Squeezed quantum states zoo



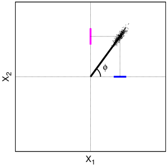
Unsqueezed coherent



Amplitude squeezed



Phase squeezed



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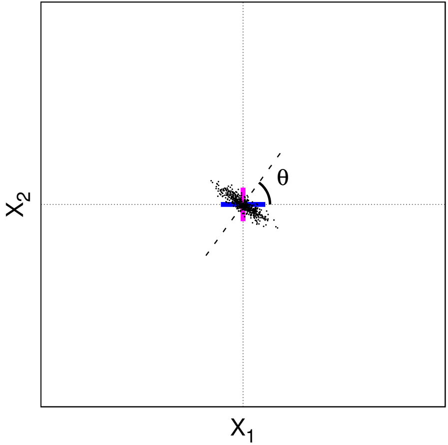
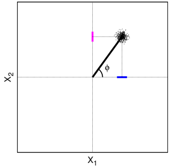
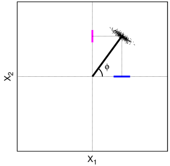


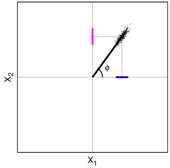
Unsqueezed coherent



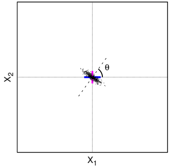
Amplitude squeezed



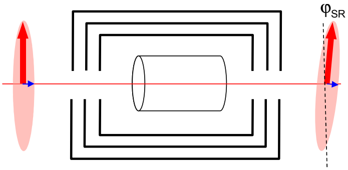
Phase squeezed

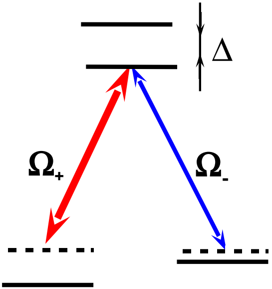


Vacuum squeezed



Self-rotation of elliptical polarization in atomic medium

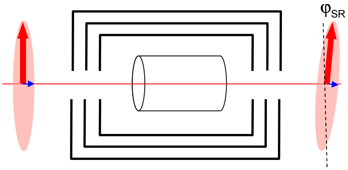


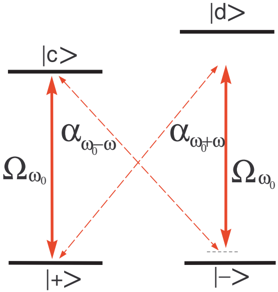


A. B. Matsko, I. Novikova, G. R. Welch, D. Budker, D. F. Kimball, and S. M. Rochester, PRA 66, 043815 (2002):
theoretical prediction of 4–6 dB noise suppression

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

Self-rotation of elliptical polarization in atomic medium





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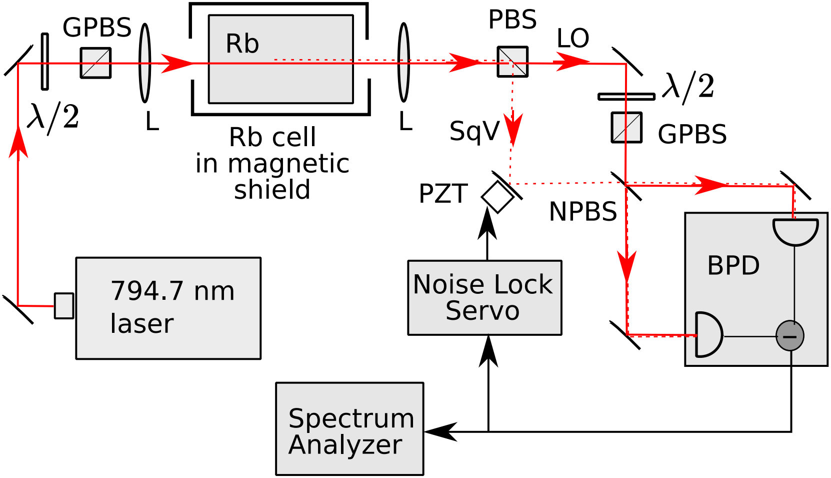
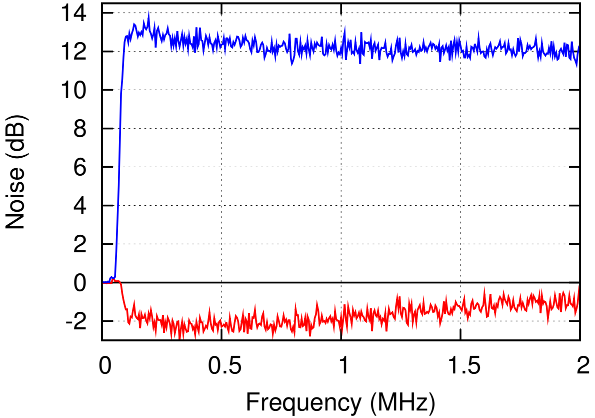
Setup


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

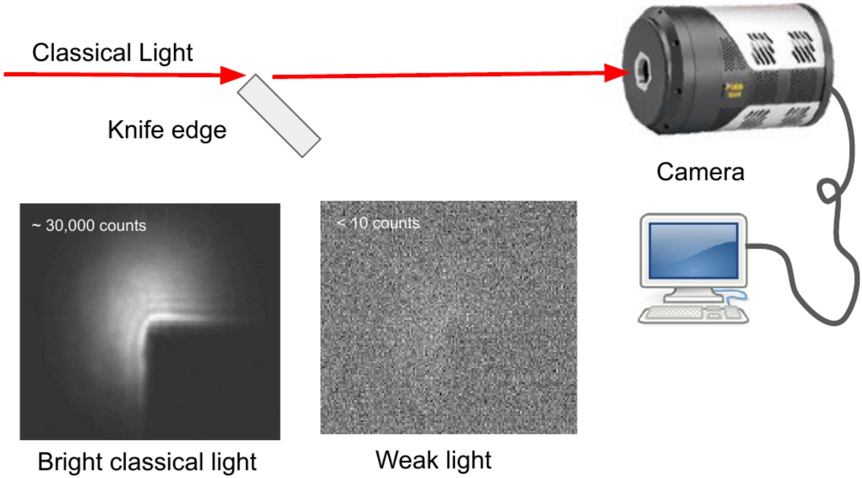
Maximally squeezed spectrum with ^{87}Rb

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)

From bright to low light imaging



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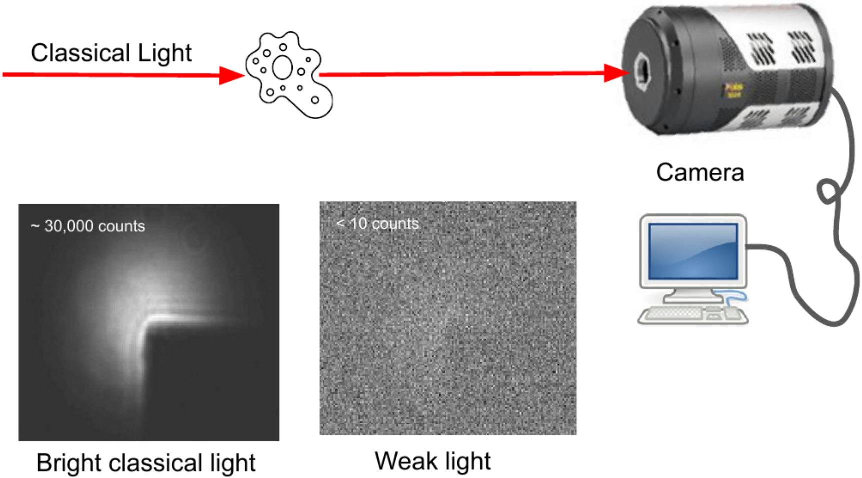
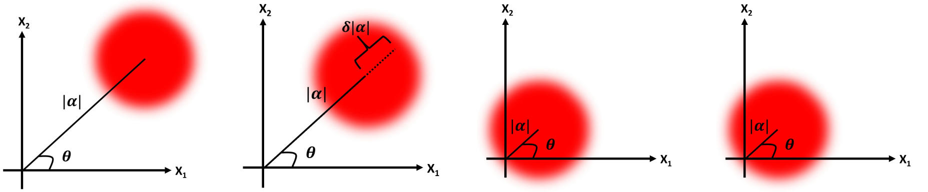
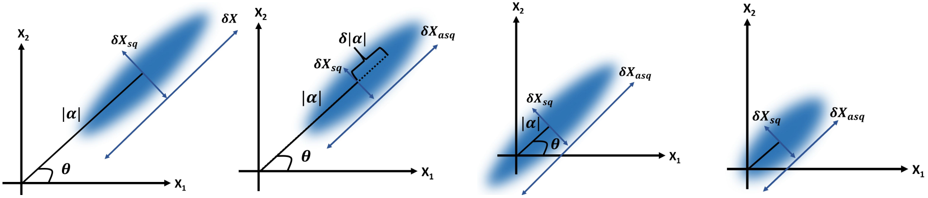


Let's look at quantum picture

Bright state in Bright state out Low-light state in Low-light out

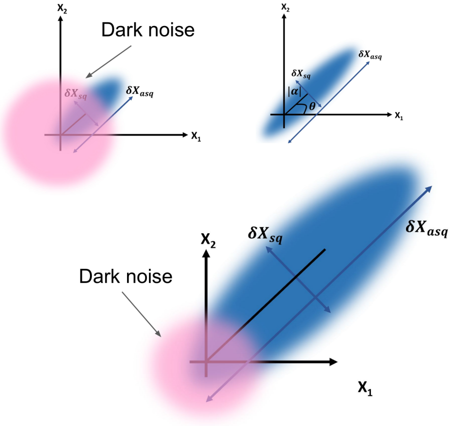


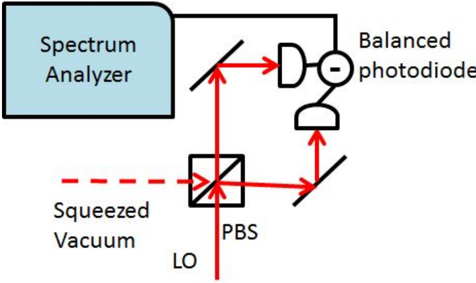
$$\alpha_{out}^2 = \alpha_{in}^2 T$$



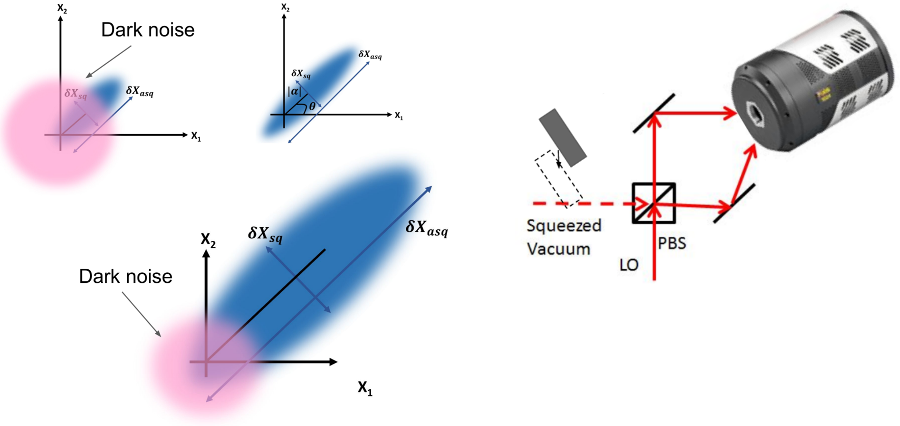
$$V = 1 + (\delta X_{sq/asq}^2 - 1)|\mathcal{O}|^2 T$$

Detector dark noise



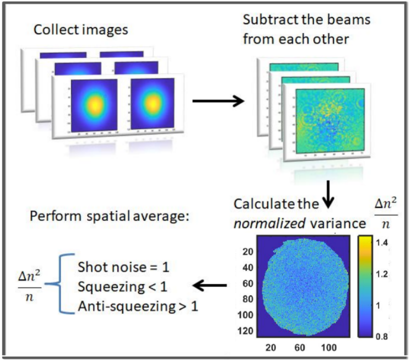


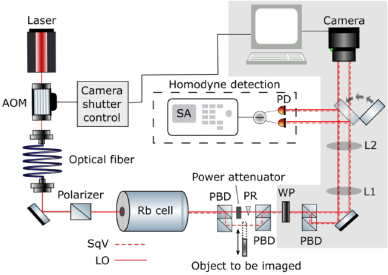
Detector dark noise



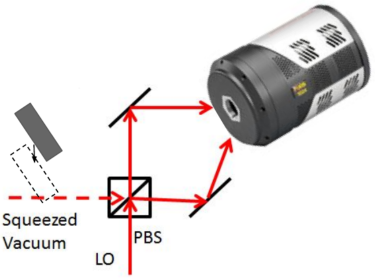
“Quantum-Limited Squeezed Light Detection with a Camera”, Phys. Rev. Lett. **125**, 113602

Imaging quantum noise



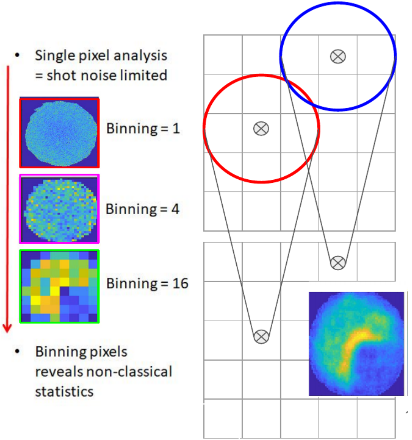


Imaging quantum noise with binning



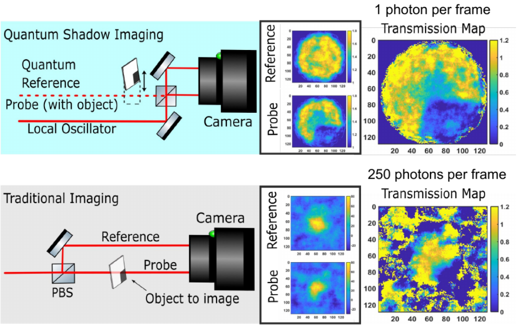
$$V = 1 + (\delta X^2_{sq/asq} - 1)|\mathcal{O}|^2 T$$

- Single pixel analysis = shot noise limited



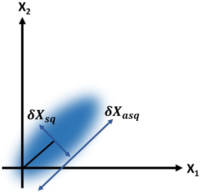
- Binning pixels reveals non-classical statistics

Shadow imaging



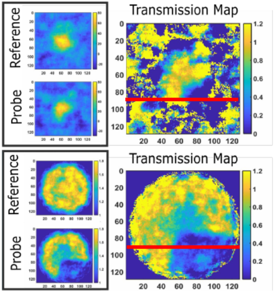
$$V_{pr} = 1 + (\delta X_{ref}^2 - 1)|\mathcal{O}|^2 T$$

$$T = \frac{V_{pr} - 1}{V_{ref} - 1}$$

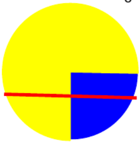


$$T = \frac{|\alpha_{pr}|^2}{|\alpha_{ref}|^2} = \frac{N_{pr}}{N_{ref}}$$

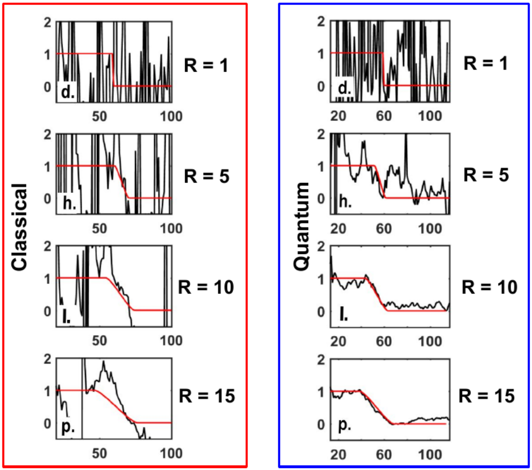
Similarity Parameter



Ideal case: T_o



Transmission Map Cross-section

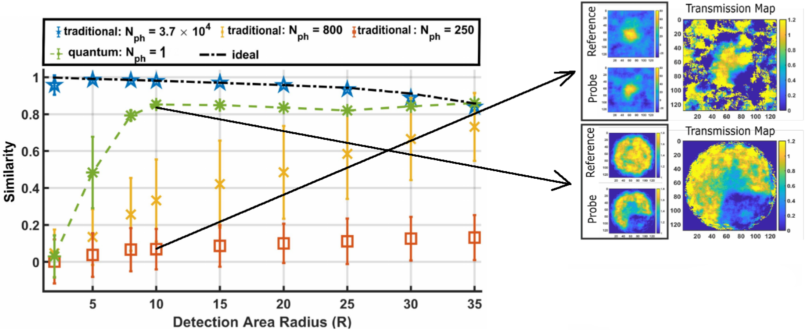


$$S = \frac{\sum T_{exp} T_o}{\sqrt{\sum T_{exp}^2 \sum T_o^2}}$$

Similarity Parameter

$$S = \frac{\sum T_{exp} T_o}{\sqrt{\sum T_{exp}^2 \sum T_o^2}}$$

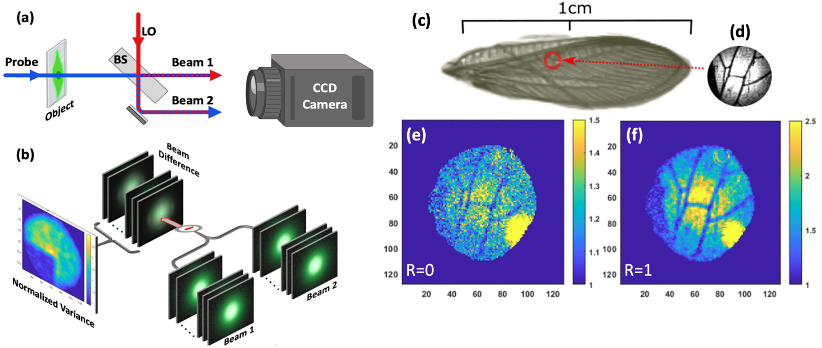
Savannah Couzzo



“Low-Light Shadow Imaging using Quantum-Noise Detection with a Camera”
`https://arxiv.org/abs/2106.00785`

Imaging with thermal light

Ziqi Niu



Structural light imaging: single pixel camera

Single-pixel imaging 12 years on: a review

GRAHAM M. GIBSON,[1,2] STEVEN D. JOHNSON,[1,3] AND MILES J. PADGETT[1,4]

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[2] graham.gibson@glasgow.ac.uk
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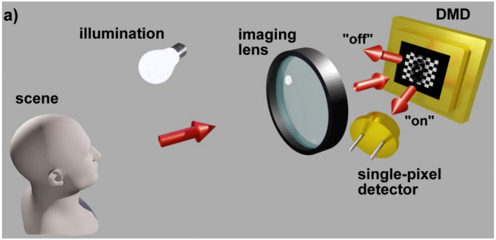
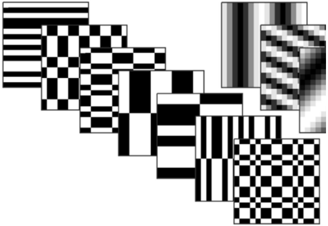
[4] miles.padgett@glasgow.ac.uk
https://www.gla.ac.uk/schools/physics/ourresearch/groups/optics/

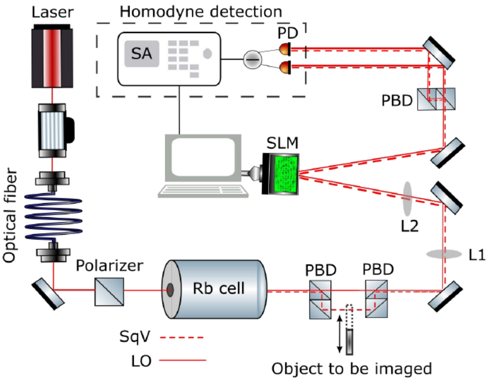


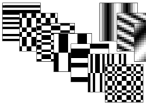


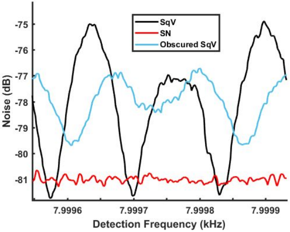
Reconstructed object

$$Ob(x,y) = \frac{1}{M} S_m P_m(x,y)$$

Structural light imaging with quantum noise





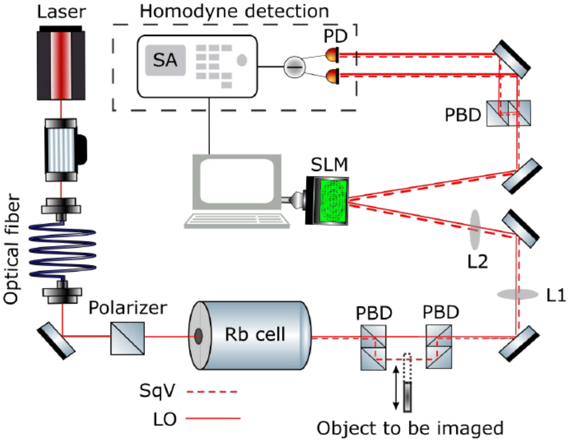


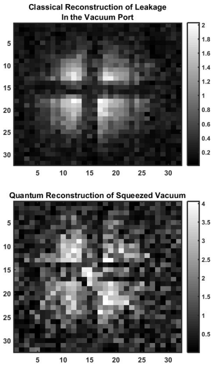
$$V_m = 1 + (\delta X^2_{sq/asq} - 1)|\mathcal{O}_m|^2$$

$$\mathcal{O}_m = \int_A P_m u_{lo} u_q^* T dA$$

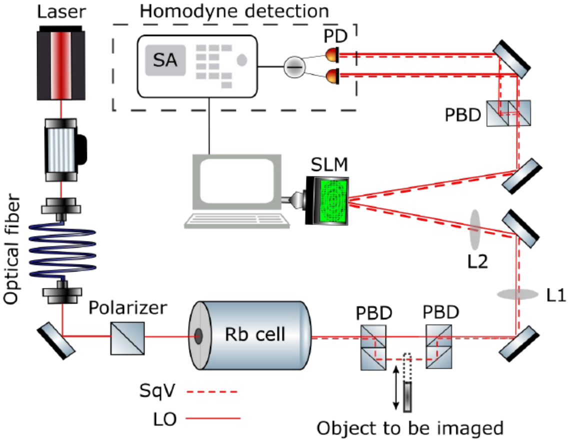
$$u_{lo} u_q^* T = \frac{1}{M} \sum \mathcal{O}_m P_m(x, y)$$

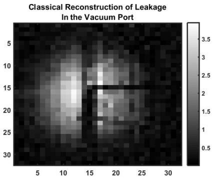
Structural light imaging with quantum noise

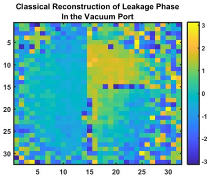




Structural light imaging with quantum noise





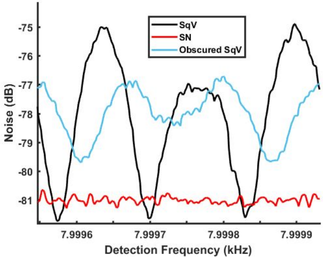


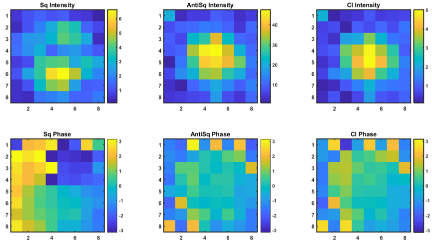
Structural light using different quadratures

$$V_m = 1 + (\delta X^2_{sq/asq} - 1)|\mathcal{O}_m|^2$$

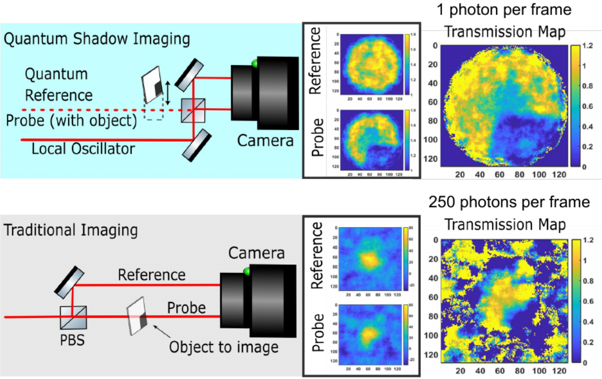
$$\mathcal{O}_m = \int_A P_m u_{lo} u_q^* T dA$$

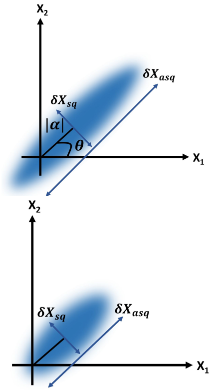
$$u_{lo} u_q^* T = \frac{1}{M} \sum \mathcal{O}_m P_m(x,y)$$





Summary

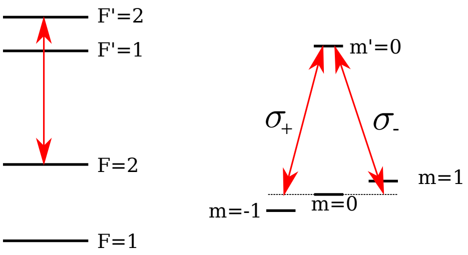




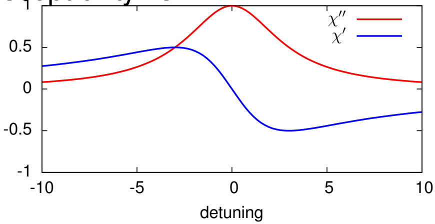
“Low-Light Shadow Imaging using Quantum-Noise Detection with a Camera” `https://arxiv.org/abs/2106.00785`

Optical magnetometer based on Faraday effect

^{87}Rb D_1 line

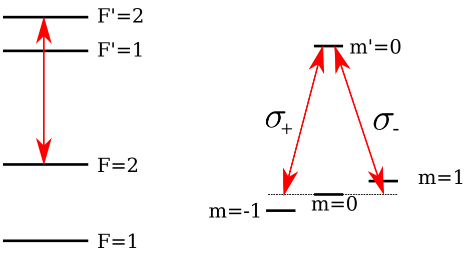


Susceptibility vs B

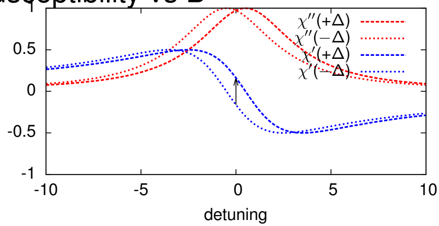


Optical magnetometer based on Faraday effect

^{87}Rb D_1 line

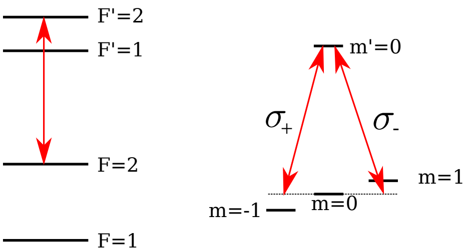


Susceptibility vs B

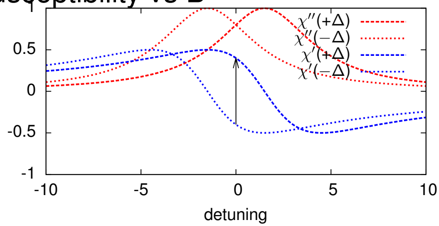


Optical magnetometer based on Faraday effect

^{87}Rb D_1 line

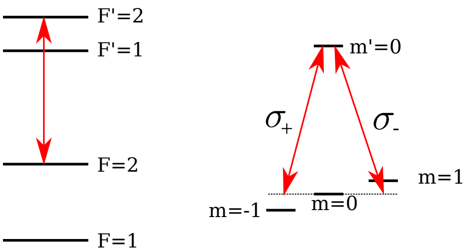


Susceptibility vs B

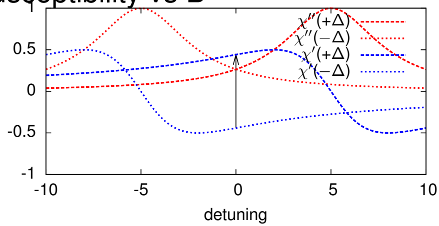


Optical magnetometer based on Faraday effect

^{87}Rb D$_1$ line

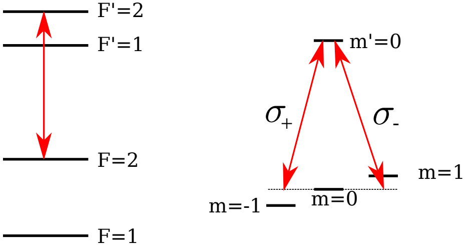


Susceptibility vs B

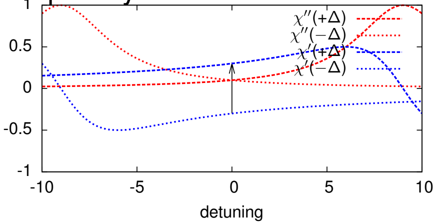


Optical magnetometer based on Faraday effect

^{87}Rb D_1 line

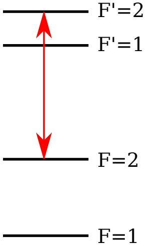


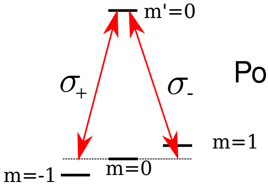
Susceptibility vs B



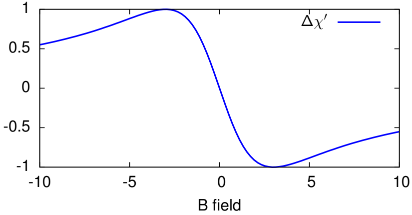
Optical magnetometer based on Faraday effect

^{87}Rb D_1 line

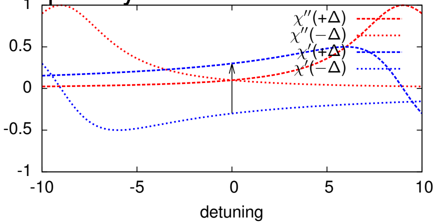




Polarization rotation vs B

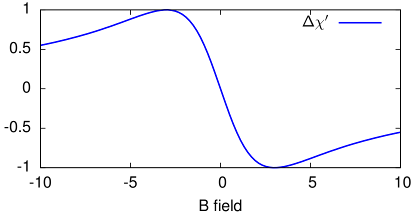


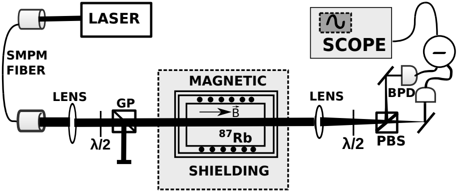
Susceptibility vs B



Optical magnetometer and non linear Faraday effect

Naive model of rotation

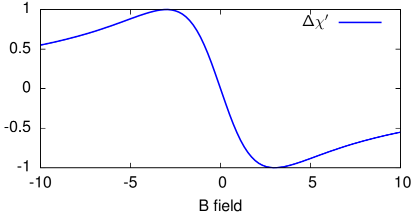


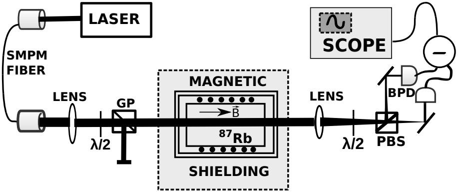


Experiment

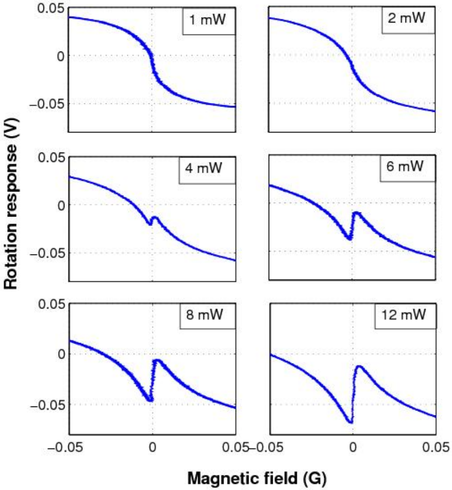
Optical magnetometer and non linear Faraday effect

Naive model of rotation

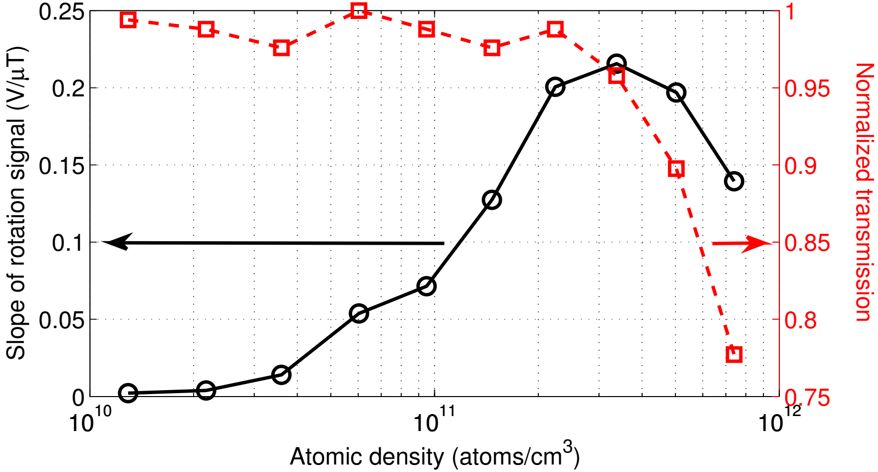




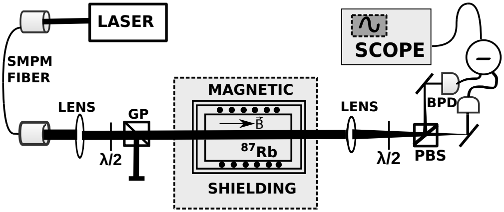
Experiment

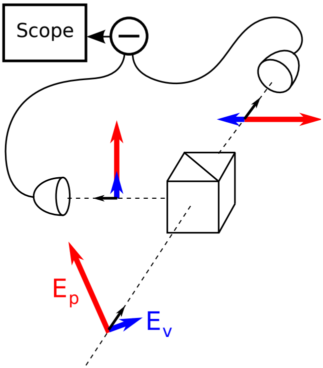


Magnetometer response vs atomic density



Shot noise limit of the magnetometer



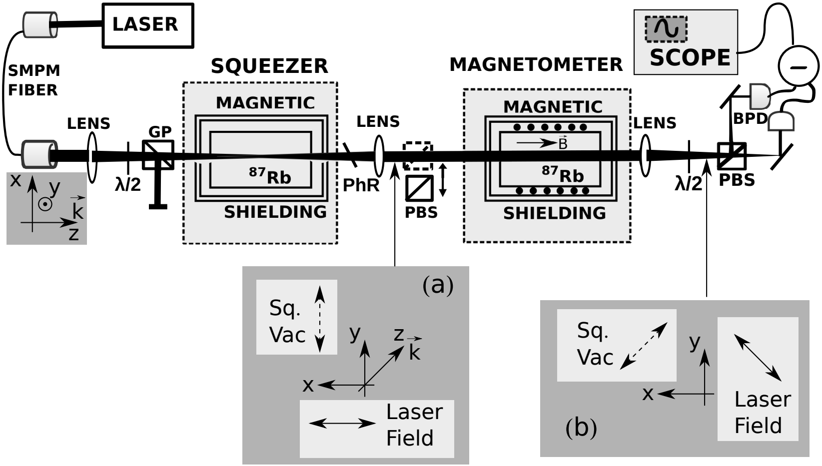


$$S = |E_p + E_v|^2 - |E_p - E_v|^2$$

$$S = 4E_pE_v$$

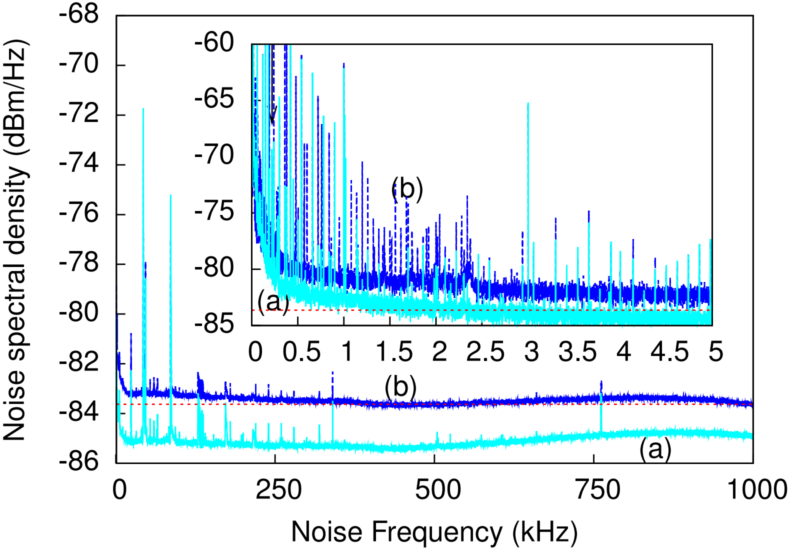
$$< \Delta S > \sim E_p < \Delta E_v >$$

Squeezed enhanced magnetometer setup

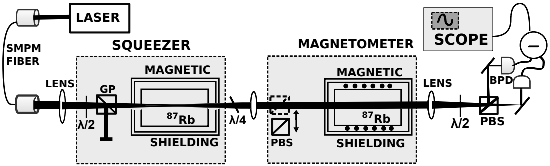


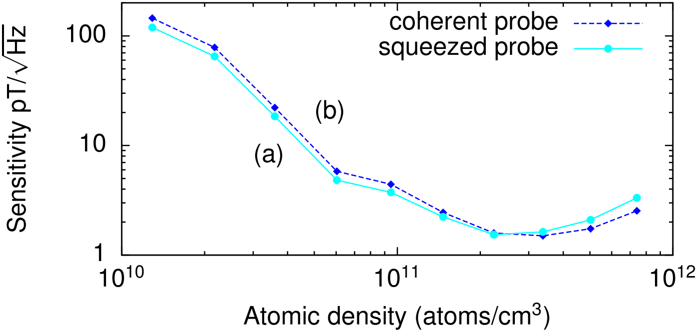
Note: Squeezed enhanced magnetometer was first demonstrated by Wolfgramm *et. al* Phys. Rev. Lett, **105**, 053601, 2010.

Magnetometer noise floor improvements



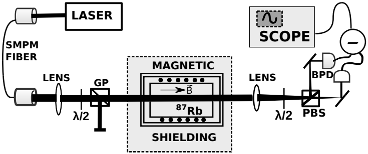
Magnetometer with squeezing enhancement

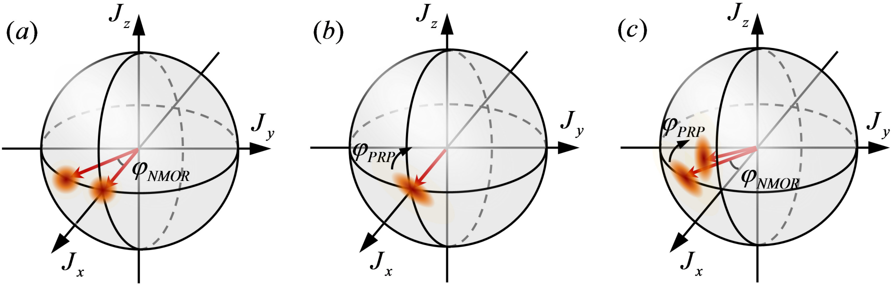




T. Horrom, et al. **PRA**, 86, 023803, (2012).

Self-squeezed magnetometry





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