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

Detuning

B field

$\chi''$

$\chi'$
Optical magnetometer based on Faraday effect

$^{87}\text{Rb D}_1$ line

$F'=2$

$F'=1$

$F=2$

$F=1$

$m=0$

$m=1$

$m'=-1$

$m'=0$

$m'=1$

Susceptibility vs B

$\chi''(\Delta)$

$\chi''(-\Delta)$

$\chi'(\Delta)$

$\chi'(-\Delta)$

$\sigma_+$

$\sigma_-$
Optical magnetometer based on Faraday effect

\(^{87}\text{Rb D}_1\) line

- \(F' = 2\)
- \(F' = 1\)
- \(F = 2\)
- \(F = 1\)

\[ m = 0 \quad m = 1 \quad m' = 0 \]

\[ \sigma_+ \quad \sigma_- \]

Susceptibility vs B

\[ \chi''(\pm \Delta) \]

- \(\chi''(\Delta)\)
- \(\chi''(-\Delta)\)
- \(\chi'(\Delta)\)
- \(\chi'(\Delta)\)

Detuning vs B field

\[ \text{Eugeniy E. Mikhailov (W&M)} \]

Quantum enhanced magnetometry

PQE 2013
Optical magnetometer based on Faraday effect

$^{87}\text{Rb D}_1$ line

\[
\begin{align*}
F' &= 2 \\
F' &= 1 \\
F &= 2 \\
F &= 1
\end{align*}
\]

\[
\begin{align*}
m &= -1 \\
m &= 0 \\
m &= 1
\end{align*}
\]

\[
\begin{align*}
m' &= 0
\end{align*}
\]

Susceptibility vs B

\[
\begin{align*}
\chi''(+\Delta) &\quad \chi''(-\Delta) \\
\chi'(+\Delta) &\quad \chi'(-\Delta)
\end{align*}
\]

Detuning vs $B$ field

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Optical magnetometer based on Faraday effect

$^{87}\text{Rb D}_1$ line

Susceptibility vs B

Polarization rotation vs B
Optical magnetometer based on Faraday effect

$^{87}\text{Rb } D_1$ line

Susceptibility vs B

Polarization rotation vs B
Optical magnetometer and non linear Faraday effect

Naive model of rotation

Experiment

\[
\begin{align*}
\Delta \chi' & \approx \frac{1}{2} B^2 \\
& \quad \text{for } B \ll 1 \\
\end{align*}
\]

B field

\[
\begin{align*}
\Delta \chi' & \approx \frac{1}{2} B^2 \\
& \quad \text{for } B \ll 1 \\
\end{align*}
\]

-10 -5 0 5 10

\[
\begin{align*}
\Delta \chi' & \approx \frac{1}{2} B^2 \\
& \quad \text{for } B \ll 1 \\
\end{align*}
\]

-1 -0.5 0 0.5 1

Rb Cell Rb Cell

λ/2 λ/2

SMPM FIBER

GPLENS MAGNETIC SHIELDING

PBS BPD SCOPE

LASER

Experiment

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Optical magnetometer and non linear Faraday effect

Naive model of rotation

Experiment

![Graph showing the change in susceptibility with respect to magnetic field.]

![Graphs showing rotation response for different powers: 1 mW, 2 mW, 4 mW, 6 mW, 8 mW, 12 mW.]
Shot noise limit of the magnetometer

\[ S = \left| E_p + E_v \right|^2 - \left| E_p - E_v \right|^2 \]

\[ S = 4E_p E_v \]

\[ \langle \Delta S \rangle \sim E_p \langle \Delta E_v \rangle \]
Heisenberg uncertainty principle and its optics equivalent

Heisenberg uncertainty principle
\[ \Delta p \Delta x \geq \frac{\hbar}{2} \]
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
\[ \Delta X_1 \Delta X_2 \geq \frac{1}{4} \]
Minimum uncertainty (coherent) states

Coherent state

Squeezed state

\[ \Delta X_1 \Delta X_2 \geq \frac{1}{4} \]
Minimum uncertainty (coherent) states

Coherent state

\[ X_2 \quad X_1 \quad \phi \]

Squeezed state

\[ X_2 \quad X_1 \quad \theta \]

\[ \Delta X_1 \Delta X_2 \geq 1/4 \]
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)
Setup

PBS

RB

LO

V.Sq

87RB

PBS

PBS
Maximally squeezed spectrum with $^{87}\text{Rb}$

W&M team. $^{87}\text{Rb} \; F_g = 2 \rightarrow F_e = 2$, laser power 7 mW, T=65$^\circ$ 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
Squeezed enhanced magnetometer setup

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

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Magnetometer noise floor improvements

![Graph showing noise spectral density vs. noise frequency.](image)

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Magnetometer noise spectra

- Coherent probe
- Squeezed probe
- SQL

Noise spectral density (dBm/Hz)

Frequency (kHz)

(a) (b) (c) (d) (e) (f)
Noise suppression and response vs atomic density

Noise suppression

Response
Magnetometer sensitivity vs atomic density

Sensitivity pT/√Hz vs Atomic density (atoms/cm³)

(a) Coherent probe
(b) Squeezed probe

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Squeezing vs magnetic field

Spectrum analyzer settings: Central frequency = 1 MHz, VBW = 3 MHz, RBW = 100 kHz
Squeezing vs magnetic field

Spectrum analyzer settings: Central frequency = 1 MHz, VBW = 3 MHz, RBW = 100 kHz
Group velocity measurements motivation

Light group velocity

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

Susceptibility

![Graph showing susceptibility vs detuning]
Light group velocity

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 $\tau = \frac{L}{v_g} \sim \frac{\partial n}{\partial \omega} \sim \frac{\partial R}{\partial B}$
Light group velocity

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

Delay $\tau = \frac{L}{v_g} \sim \frac{\partial n}{\partial \omega} \sim \frac{\partial R}{\partial B}$
Time advancement setup
Squeezing modulation and time advancement
Squeezing after advancement cell

![Graph showing squeezing level vs. probe power](image-url)

- **Input** (blue line)
- **Output** (green line)

Shot noise level
Advancement vs power

![Diagram showing pulse delay vs probe power with labels for coherent probe, noise trial 1, and noise trial 2.](image)

- Coherent probe
- Noise trial 1
- Noise trial 2

Pulse delay (μs) vs Probe power (mW)
Advancement vs power

![Graph showing the relationship between pulse delay and probe power, with data points for coherent probe, noise trial 1, and noise trial 2.]

- Coherent probe
- Noise trial 1
- Noise trial 2

Response slope (V/G) vs Probe power (mW)
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 $\nu_g = c/2000$ or time advancement of 0.5 $\mu$S

For more details: