Frequency Tunable Atomic Magnetometer based on an Atom Interferometer

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Blaubeuren Quantum Optics Summer School

29 July 2013

Also thanks to S. A. DeSavage, R. Forster and Z. Switzer

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The Lincoln Laboratory portion of this work is sponsored by the Assistant Secretary of Defense for Research & Engineering under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the authors and are not necessarily endorsed by the United States Government.
Outline

- Magnetometry / Gradiometry Motivation
  - Gradiometry

- Atom Interferometer Magnetometer
  - Atom Interferometer Concept
  - NMR Pulse Sequences for Atoms

- Experimental Results
  - Clock Transition
  - Ramsey vs. Hahn Echo
Airborne Magnetic Noise

Spectral Density (nT/Hz^{0.5}) vs Frequency (Hz)

- MAD
- ELF
- Geology
- Shallow
- Buffeting
- Platform Maneuver
- Geomagnetic
- Swell
- Dipole
- CPA=2000 ft
- CPA=1000 ft
- 3 \times 10^6 \text{nT-ft}^3
- ASQ-208
- P-2000
- MAD ELF

NIST
Welch
Budker
Romalis

\sim fT/Hz^{1/2}
Motivation:
(classical) gradiometer example

P2000 Gradiometer Test
Memorial Airfield, Chandler AZ
April 27 2003

Even an Admiral can see this!

AI Gradiometer Sensitivity: 0.2 pT/m
Atom Interferometry Applications

- **Clocks**
  - Frequency standards
  - Navigation, communication, synchronization

- **Magnetometers**
  - Magnetic anomaly detection (i.e. submarines, unexploded ordinance, mines), detection of dangerous liquids and uranium, biomagnetics, navigation

- **Accelerometers, Gyroscopes**
  - Arrayed for differential acceleration, gravimeters, etc
  - Navigation, seismology, mass anomaly detection (minerals, bunkers, natural resources)
  - Fundamental laws of physics

Language is common to the worlds of NMR and quantum computing
Cannot remove magnetic noise in remote sensing

1. Filter out of band noise
2. Measure magnetic field gradient
   (Gradients used for object location)
• Magnetometry / Gradiometry Motivation
  – Gradiometry

• Atom Interferometer Magnetometer
  – Atom Interferometer Concept
  – NMR Pulse Sequences for Atoms

• Experimental Results
  – Clock Transition
  – Ramsey vs. Hahn Echo
Two level atom reminder

Powerbroadened Linewidth

Natural Linewidth

\[ \hbar \omega_0 \quad \hbar \omega_L \]
Raman Resonances

Now controlled by ground state decoherence time which can be made very small \[ \Delta \nu \sim \frac{1}{T_{\text{pulse}}} \]
Atom Interferometer:

Time Domain

\[ \Delta \phi = -\left( k_1 + k_2 \right) g T^2 \]

\[ + \frac{\mu_B}{\hbar} \left( g_F m_F - g_F m_F \right) \left[ \int_0^{T/2} B(t) \, dt - \int_{T/2}^{T} B(t) \, dt \right] \]

\[ \omega_2 \]

\[ \Delta \nu_{HF} \]

Co-propagating Raman beams: Doppler-free

Pseudospin Representation:

\[ |1\rangle \]

\[ \pi/2 \]

\[ |2\rangle \]

\[ \pi \]

\[ |3\rangle \]
Magnetic Gradient (spin echo) Interferometer...not quite
Ramsey \((\pi/2-\pi/2)\)
Spin Echo \((\pi/2-\pi-\pi/2)\)
(Unbalanced) Spin echo \( (\frac{\pi}{2} - \pi - \frac{\pi}{2}) \)
Atom Interferometer:
Frequency Domain

Pulse sequence controls interferometer sensitivity to noise

Scanning number of pulses can map out magnetic noise spectral density

\[ \Delta \phi = \frac{\mu_B}{\hbar} (g_F m_F - g_F m_F) \left( \int_0^T B(t)\,\text{d}t - \int_0^{2T} B(t)\,\text{d}t \right) \]
Filter Functions Frequency Domain

$g_N(\omega, T)$

- $N = 0$
- $N = 1$
- $N = 5$
- $N = 10$

$T = 1 \text{ ms}$

- Hahn Echo
  - $N = 1$
  - $T = 1000 \text{ us}$
  - $T = 500 \text{ us}$
  - $T = 250 \text{ us}$

- $T = 1 \text{ ms}$

$\frac{\pi}{2}$

$\frac{3\pi}{2}$

$\pi$
State preparation
✓ well defined qubit ✓ initialization

- Gradient coils
  - 10 G/cm

- Trapping lasers:
  - Amplified (TA7613) New Focus StableWave 7013
  - 2.5 cm beam

Unshielded environment and in a metal canister!
Apparatus

- Trapping Setup
- Raman Lasers
Timing sequence

85Rb \( \sim 10^7 \) atoms; \( \sim 300 \mu K; F = 2 \)

Trapping B-Field

Repump Field

Trapping Field

Well-defined coherent qubit

Initialize

Gate operations

Readout

Time [ms]

-20 -15 -10 -5 0 5

-20 -15 -10 -5 0 5

-20 -15 -10 -5 0 5

-20 -15 -10 -5 0 5

-20 -15 -10 -5 0 5
A real atom: $^{85}\text{Rb}$

11 different Raman resonances!
Raman spectra (arbitrary field)

\[ \delta f = g_F m_F \frac{\mu_B B}{h} \approx 466.5 m_F \text{kHz/G} \]

\[ 5^2 S_{1/2} \]

\[ 5^2 P_{3/2} \]

F = 2

F' = 4

F' = 3

F' = 2

F' = 1

85Rb \sim 10^7 \text{ atoms}

\sim 300 \mu K

F = 2

\Delta \nu = \frac{1}{T_{puls}}
Use to “zero” field around atoms

Field 1

Field 2

Field 3
Single Peak
Selection Rules

• “Even” transitions driven by:
  - $\hat{x} - \hat{y}$ polarization
  - $\hat{\sigma}^+ - \hat{\sigma}^-$ polarization
  - $\Delta m = 0$

• “Odd” transitions driven by:
  - $\hat{\sigma}^+ - \hat{z}$, $\hat{\sigma}^- - \hat{z}$, $\hat{x} - \hat{z}$, $\hat{y} - \hat{z}$ polarization
  - $|\Delta m| = 1$

• Here, $\hat{z}$ is defined by the direction of the magnetic field
• $g$ factor between ground states changes sign
Six Peaked Spectrum

![Graph showing a six-peaked spectrum with frequency (Freq) on the x-axis and intensity (arb. units) on the y-axis. Peaks are centered around 0 Hz with symmetrical peaks on either side.]
Five Peaked Spectrum

\[ \sum_{\theta=3} \rho_{\theta} \] (arb. units)

Freq (kHz)
Effect of pulse shape
Hybrid Pulse
Crude Magnetometer

10 min of data @ 0.25Hz

Now can do up to 10 Hz
Rabi cycling: $m=0$ to $m'=0$ transition

- Universal gates
- Ability to read out

$5^2P_{3/2}$

$5^2S_{1/2}$

$F = 3$

$F = 2$

$F' = 4$

$F' = 3$

$F' = 2$

$F' = 1$

$\pi$

$\pi/2$

$T_{\text{Raman}}$

Readout

Time

$\nu = \frac{1}{T_{\text{pulse}}}$

Two photon detuning

$\nu_{HF}/2$

$\pm$ AOM
Ramsey interference

\[
\sum_{\ell=3}^{\infty} \rho_{\ell\ell}(\text{arb. units})
\]

\[\delta_{2\nu}(kHz)\]
• As time between pulses is lengthened, Ramsey interference disappears.
Atom Interferometer Clock Transition

Two-Photon Detuning [kHz]

\[ \Delta \nu_{HF} \]

\[ |1\rangle \quad |2\rangle \quad |3\rangle \]

\[ \omega_1 \quad \omega_2 \]

Double Delay [$\mu$s]

100

150

200

\[ \Delta m = -1 \quad \Delta m = 0 \quad \Delta m = +1 \]
Atom Interferometer
Magnetometer

Double Delay [µs]

Two Photon Detuning [kHz]

$\Delta = -10 \text{ kHz}$

Ramsey Frequency

$10^4$
Atom Interferometer Magnetometer

- **Ramsey (Magnetic)**

  - \(\pi/2\)
  - \(\pi/2\)
  - \(\Delta = -141 \text{kHz}\)
  - \(T_2^* \approx 55 \text{ us}\)

- **Spin Echo (Magnetic)**

  - \(\pi/2\)
  - \(\pi\)
  - \(\pi/2\)
  - \(\Delta = 144 \text{kHz}\)
  - \(T_{2e} \approx 55 \text{ us}\)
**Conclusions**

- Magnetometry is useful for a broad range of applications from biomagnetics to remote detection.
- Atom Interferometry allows NMR like pulse control sequences as a lock-in-amplifier for magnetic signals.
- Using these techniques combined with gradiometry, we can detect signals in a magnetically noisy environment.
Thank you for your attention!

Questions?
Other experiments-then

“…could be interesting. But it’s not fundamental enough” → maybe

Photo courtesy J. Mandel

Leonard Mandel
1927-2001
Bonus Material
Multiple Pulse Interferometer Sequences

\[ \frac{\pi}{2} \rightarrow \pi \rightarrow \frac{\pi}{2} \]

\[ \frac{\pi}{2} \rightarrow \pi \rightarrow \pi \rightarrow \frac{\pi}{2} \]

\( g(\omega) \)

- **N = 1**
- **N = 3**

Frequency [kHz]

Two Photon Detuning [kHz]

NMR: Carr Purcell *PR* 94 630 (1954)
Atoms: Davidson *PRL* 105,053201 (2010)
NV Centers: Lukin, Rugar, Cappellaro …
Rabi cycling: $m' = 0$ to $m' = 0$ transition

- Universal gates
- Ability to read out

$5^2P_{3/2}$
- $F' = 4$
- $F' = 3$
- $F' = 2$
- $F' = 1$

$5^2S_{1/2}$
- $F = 3$
- $F = 2$

Two photon detuning

$$\Delta \nu = \frac{1}{T_{\text{pulse}}}$$

AOM

$\nu_{HF}/2$

$T_{\text{Raman}}$

Readout

Time

Blaubeuren Summer School
July 29, 2013
Atom Interferometer

\[ \Delta \phi = -\left( \vec{k}_1 - \vec{k}_2 \right) g T^2 \]

\[ + \mu_B (g_F m_F - g_F m_F) \left[ \int_0^{T/2} B(t) \, dt - \int_{T/2}^T B(t) \, dt \right] \]

\[ \Delta \nu_{HF} \]

\[ \omega_1 \]

\[ \omega_2 \]

\[ |1\rangle \]

\[ |2\rangle \]

\[ |3\rangle \]

\[ x \]

\[ y \]

\[ z \]

\[ \pi/2 \]

\[ \pi \]

\[ \pi/2 \]

\[ 0 \]

\[ T/2 \]

\[ T \]


Zhou et al. *PRA* 82 061602 (2010)
Magnetically sensitive Ramsey interferometer

\[ \frac{\pi}{2} \quad \text{(Double Delay)} \quad \frac{\pi}{2} \]

\[ g(\omega, \tau) = \text{sinc}^2 \left( \frac{\omega \tau}{2} \right) \]

- Frequency [kHz]
- Two-photon Detuning [kHz]
- Double Delay [us]
• Rabi flopping in a magnetically noisy environment:
Sensitivity

$$\Delta \phi = -\frac{\mu_B}{\hbar} \left( m_{F'} g_{F'} - m_F g_F \right) \frac{dB(r_\circ)}{dr} \Delta r T$$

$$\sigma_\phi = \frac{1}{C} \sqrt{\frac{1}{N}}$$

For $\text{SNR}=1$ we have $\sigma_\phi = \Delta \phi$

$$\left( \frac{dB}{dr} \right)_{\text{min}} = \frac{1}{C \sqrt{N}} \cdot \frac{1}{\mu_B/\hbar} \cdot \frac{1}{(m_{F'} g_{F'} - m_F g_F)} \cdot \frac{1}{\sqrt{T^2}}$$

$$= \frac{2}{\sqrt{10^9}} \cdot \frac{1G}{8.8 \times 10^6 \text{ Hz}} \cdot \frac{1T}{10^4 G} \cdot \frac{1}{2/3} \cdot \frac{1}{(50 \text{ m/s})(10^{-2} \text{ sec})^2}$$

$$= .2pT/m$$
Filter Functions Time / Frequency Domain

T = 1 ms

Hahn Echo
N = 1

T = 0.25 ms  T = 0.5 ms  T = 1 ms

T = 1000 µs  T = 500 µs  T = 250 µs
Cannot remove magnetic noise in remote sensing

1. Filter out of band noise
2. Measure magnetic field gradient
   (Gradients used for object location)
The complete solution, after the double integration over the filter function, is quite formidable. Here, we present the answer in the long time limit ($\sigma t \gg 1$):

$$
\int_0^{+\infty} dt' \int_0^{+\infty} dt'' f(t + \tau - t') f(t + \tau - t'') (\dot{E}(-)(t') \dot{E}(+(t')) \dot{E}(+(t'')) \dot{E}(+(t)))
$$

$$
= |K|^4 \left( \mathcal{R}_3(\infty) \right) + \frac{1}{2} \left\{ \frac{1}{8} |A|^2 e^{-2\sigma t} + \frac{1}{4} |A|^2 (1 - e^{-\sigma t}) \left( \frac{1}{2} + e^{-\sigma t} \right) + \frac{1}{4} \sum_{i=1}^{3} \frac{\sigma^2 C_i A_i^*}{\sigma + p_i} e^{-\sigma t} + \frac{1}{2} \sum_{i=1}^{3} \frac{\sigma AC_i^*}{\sigma - p_i} e^{-\sigma t} + \frac{1}{4} \sum_{i=1}^{3} \frac{\sigma (D + \frac{1}{2}) B_i^* e^{-\sigma t}}{\sigma - p_i^*} + \frac{1}{4} \sum_{i=1}^{3} \frac{\sigma^2 (D + \frac{1}{2}) B_i^* e^{-(\sigma + p_i^*) t}}{(\sigma + p_i^*)^2} \right\} + c.c. \ (S.61)
$$
Bulletin of the American Physical Society

2013 Joint Meeting of the APS Division of Atomic, Molecular & Optical Physics and the CAP Division of Atomic, Molecular & Optical Physics, Canada
Volume 58, Number 6
Monday–Friday, June 3–7, 2013; Quebec City, Canada

Session K1: Poster Session II (4:00 - 6:00PM)
4:00 PM–4:00 PM, Wednesday, June 5, 2013
Room: 400A

Abstract: K1.00030 : Optical Coherence of the Fluorescence of a Driven Single-Atom with Slow and Fast Light Media

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“...could be interesting. But it’s not fundamental enough”
Definition of $\pi$ pulse
Definition of $\pi/2$ pulse

A graph showing a plot of fluorescence intensity against time. The graph indicates a vertical shift at $\pi/2$.

- **Time (\mu sec)**: The x-axis represents time in microseconds, ranging from 0 to 200.
- **Fluorescence (a.u.)**: The y-axis represents fluorescence intensity in arbitrary units, ranging from 0 to 1.

The graph visualizes the temporal evolution of fluorescence intensity, with a marked vertical transition at $\pi/2$. This corresponds to the point where the fluorescence intensity changes, marking the $\pi/2$ pulse.