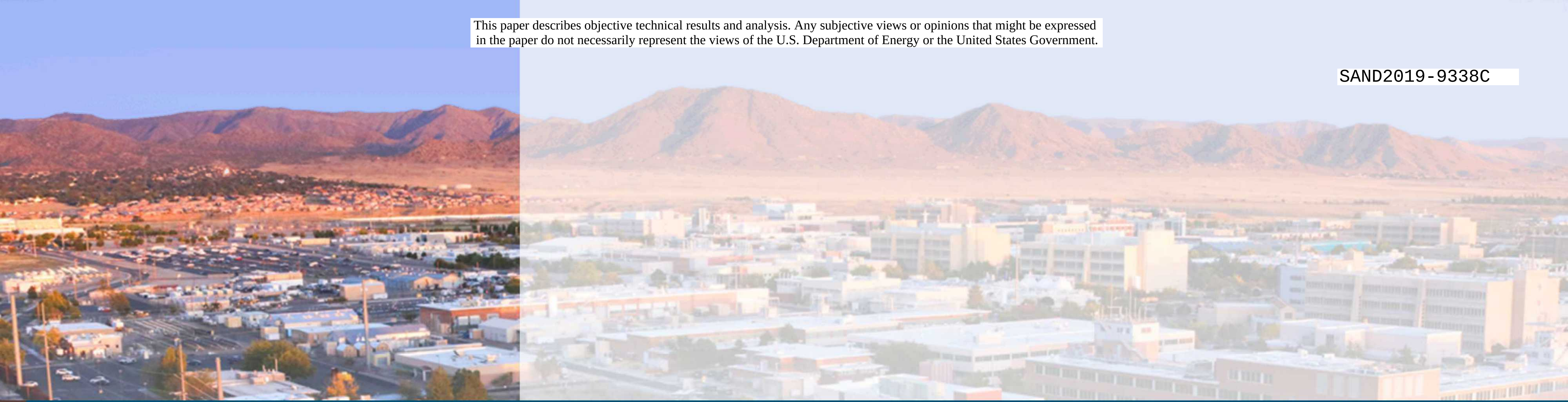
SAND2019-9338C



Towards a pulsed dead-zone free gradiometer in Earth's field

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA). The views, opinions and/or findings expressed are those of the authors and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Kaleb Campbell

Sandia National Labs, University of New Mexico
Department of Physics and Astronomy

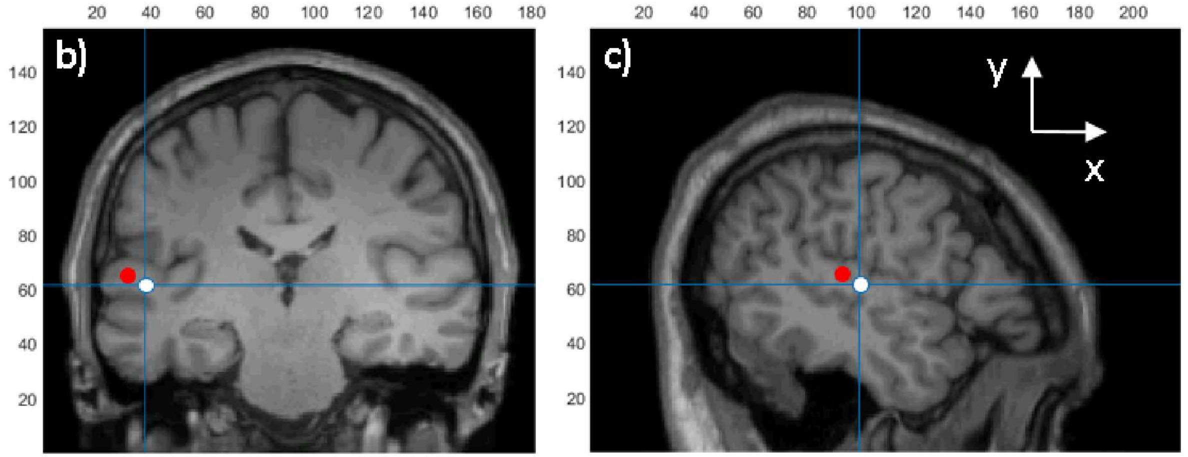
Motivation

Direct optical measurement of a magnetic field gradient

- High common mode rejection

High sensitivity in the Earth's magnetic field

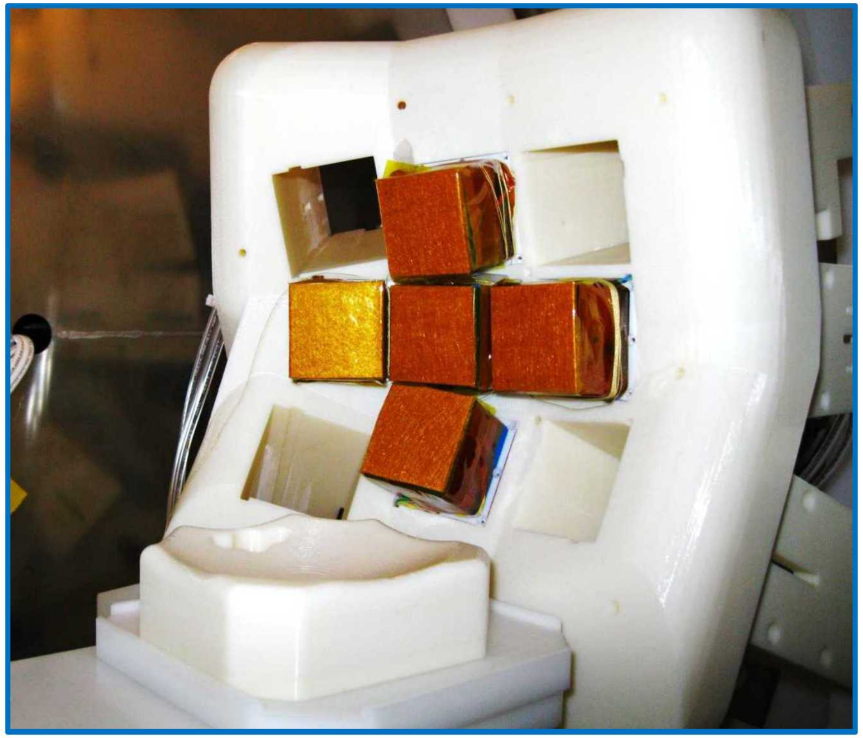
Application: magnetoencephalography and magnetocardiography



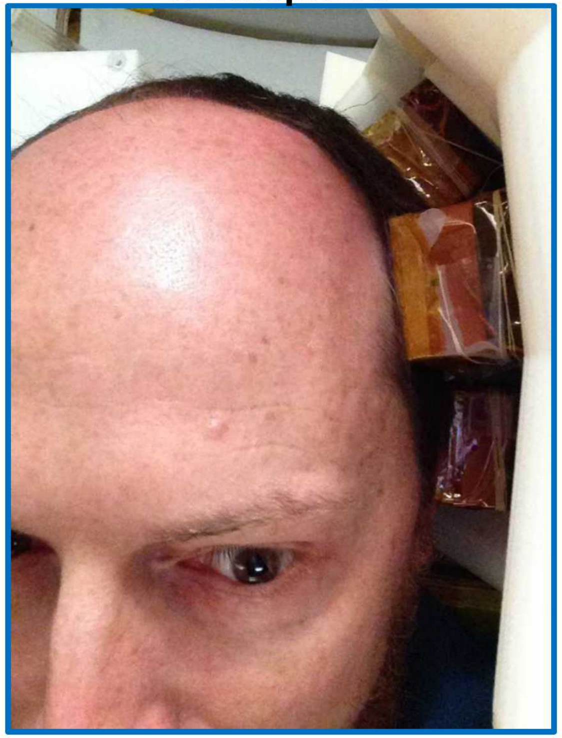
Person-Sized Magnetic Shield

Insert Person Here

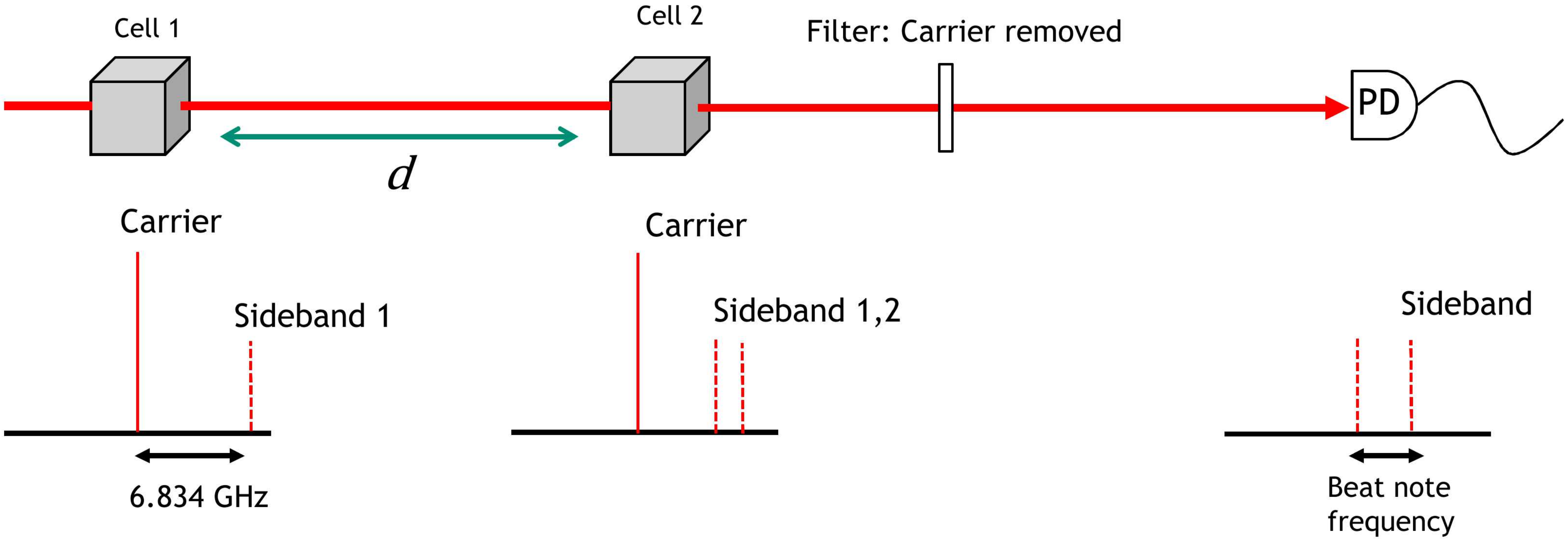
5-sensor, 20-channel array



Partially covers the left hemisphere



Basic Idea – Magnetic Gradiometer



Sideband Produced in the first cell orthogonally polarized to the carrier

Sideband Produced in the second cell orthogonally polarized to the carrier

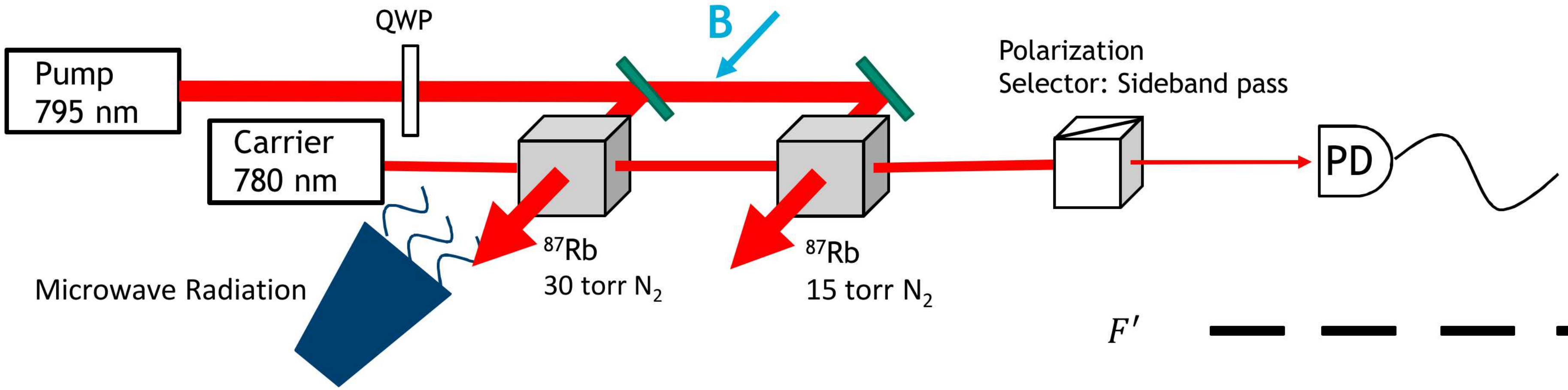
Carrier removed and sidebands beat together

$$f_B \propto \frac{\Delta B}{d}$$

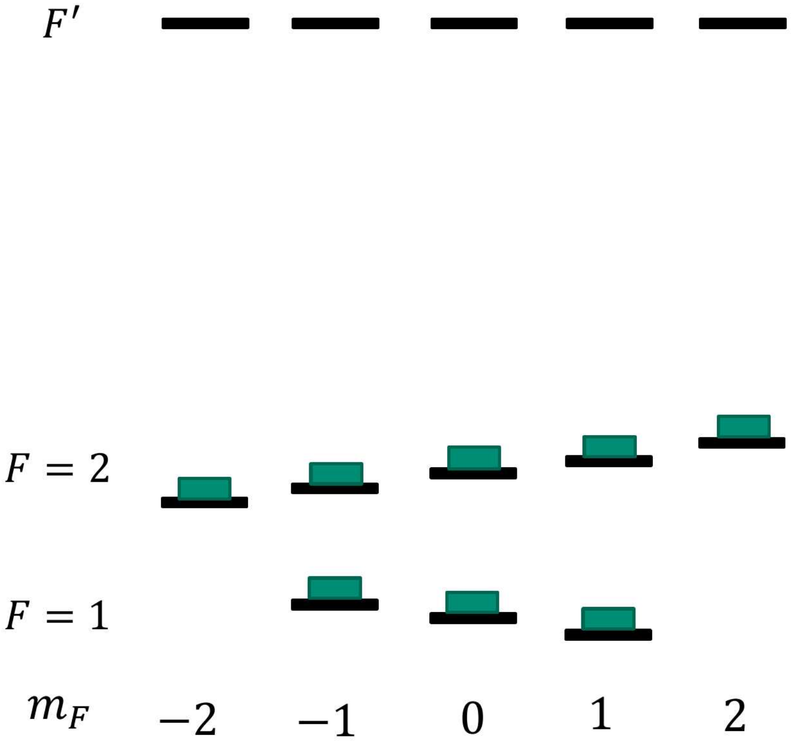
*__Henry Tang__, *Parametric Frequency Conversion of Resonance Radiation in Optically Pumped ^{87}Rb Vapor*. Phys. *Rev. A* **7**, 2010 (1973).

*Vishal Shah, *System and Method for Measuring a Magnetic Gradient Field*. Patent. US10088535 (2018)

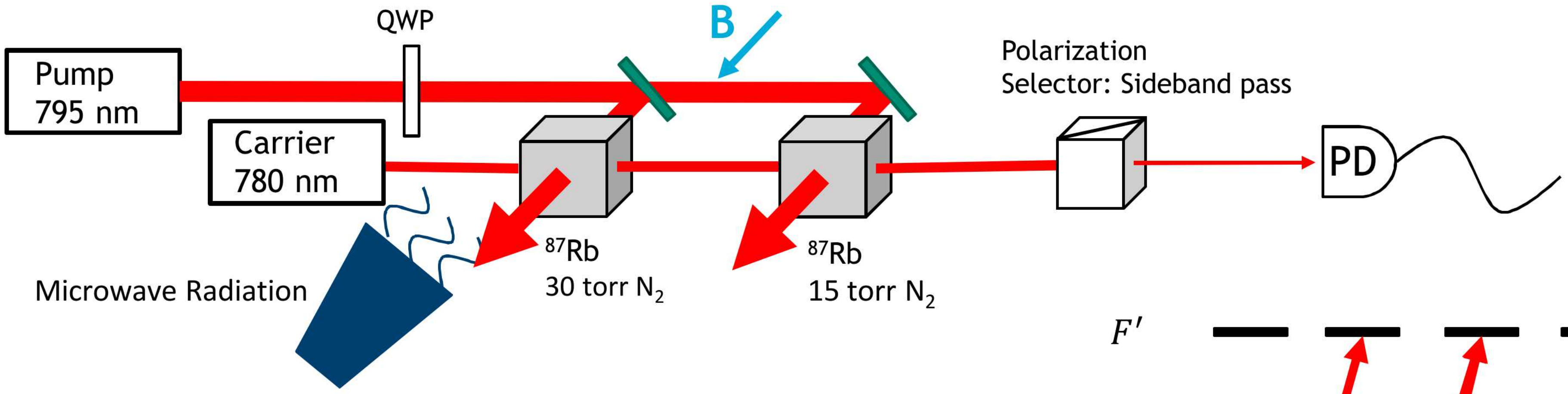
More detailed description

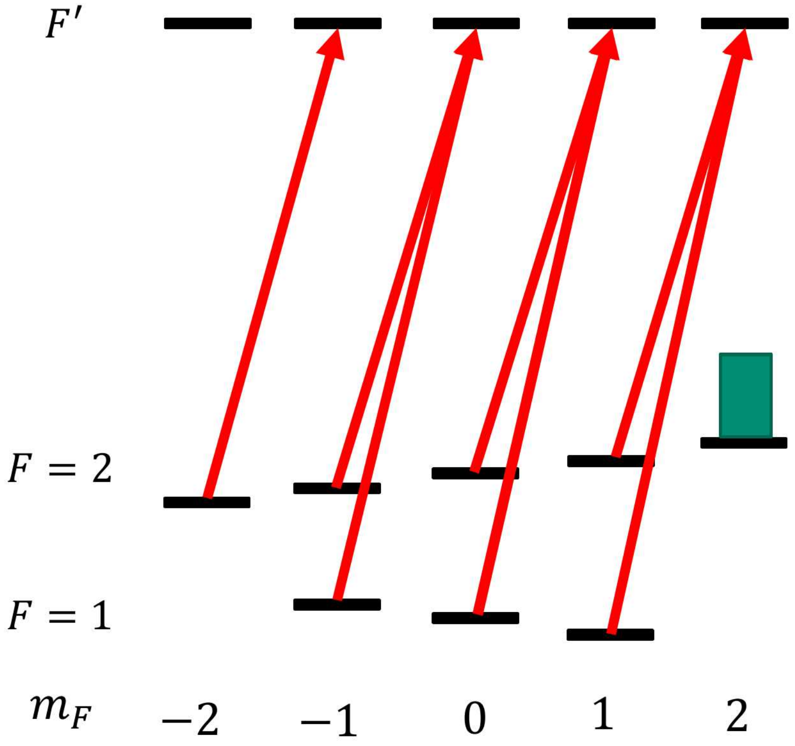


Gradiometer Process



More detailed description

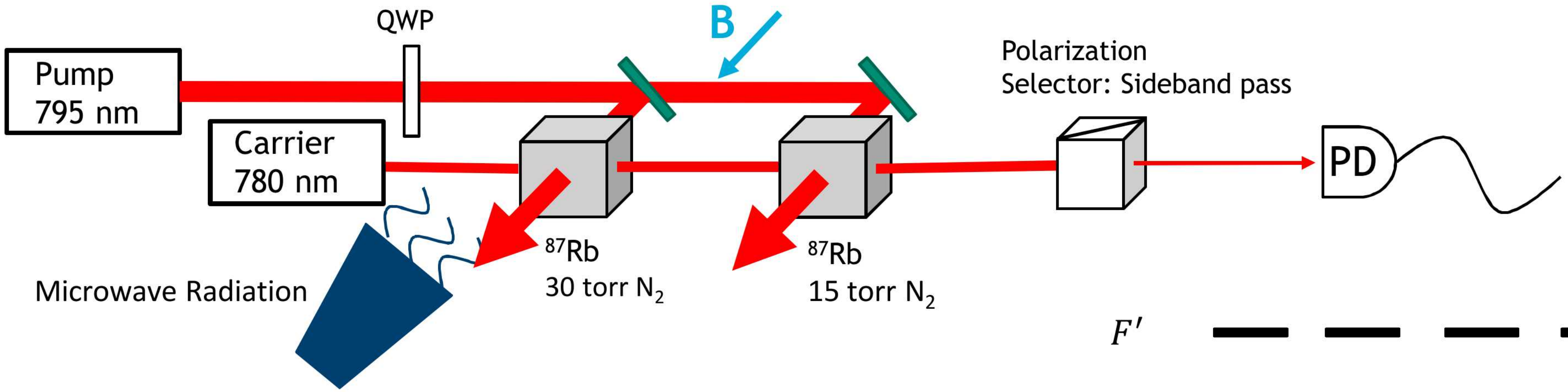




Gradiometer Process

1) Pump atoms to the end-state

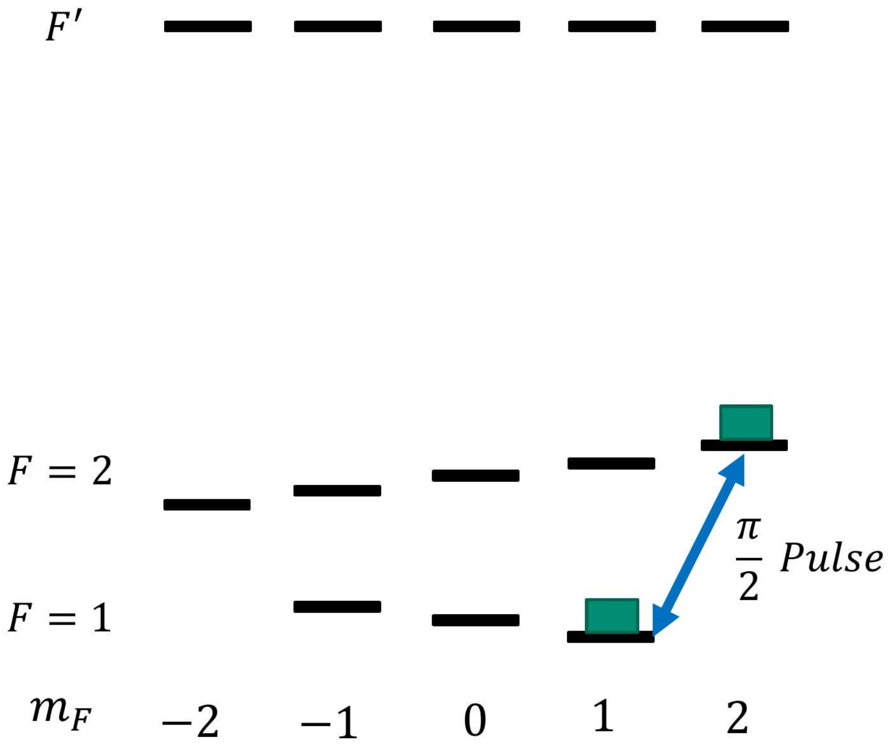
More detailed description



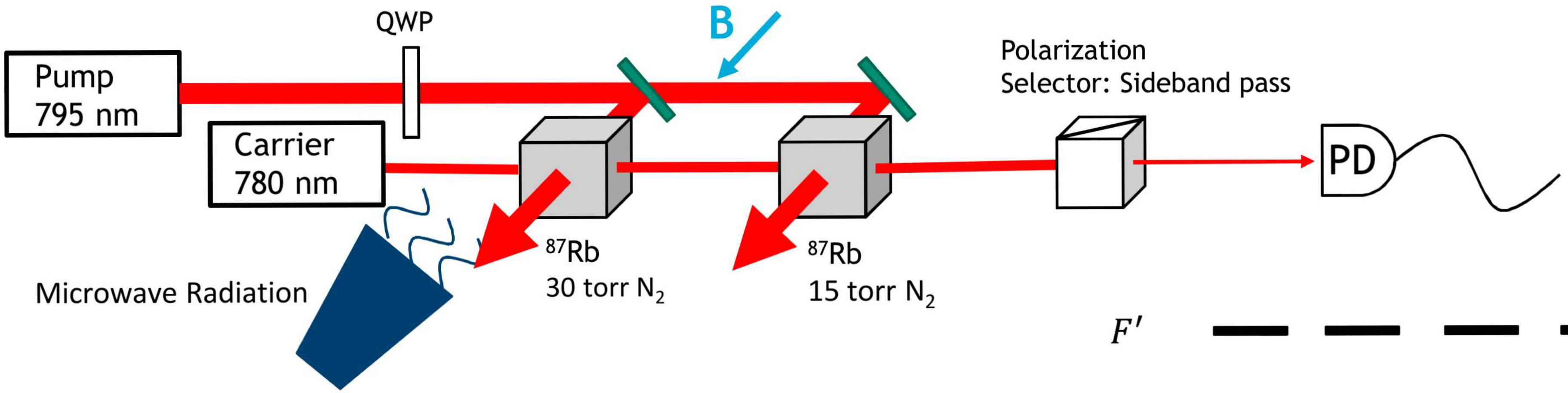
Gradiometer Process

1) Pump atoms to the end-state

2) Apply a $\frac{\pi}{2}$ pulse of magnetic energy to put the atoms in a coherent superposition

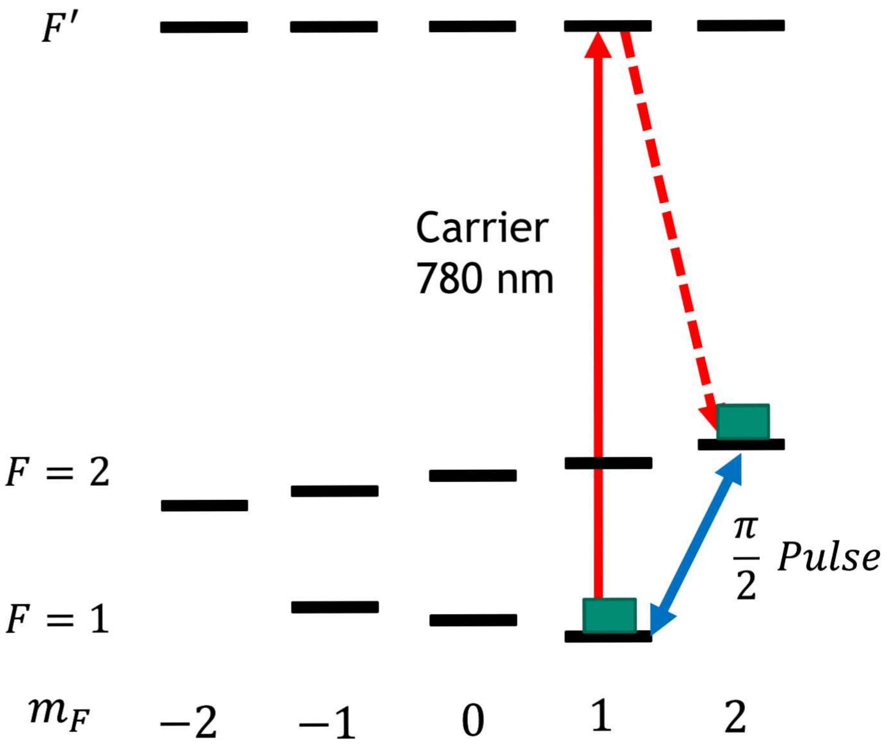


More detailed description

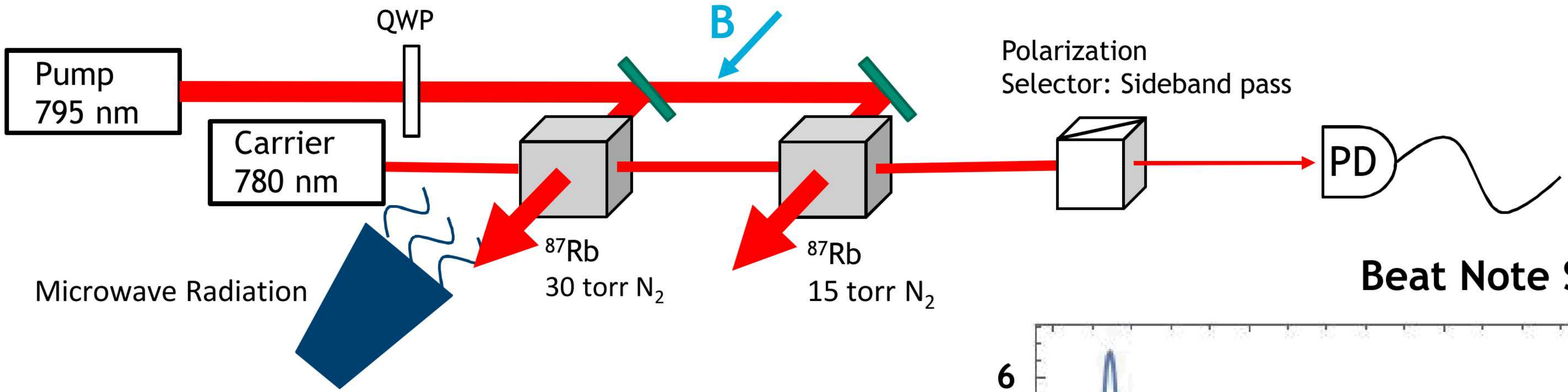


Gradiometer Process

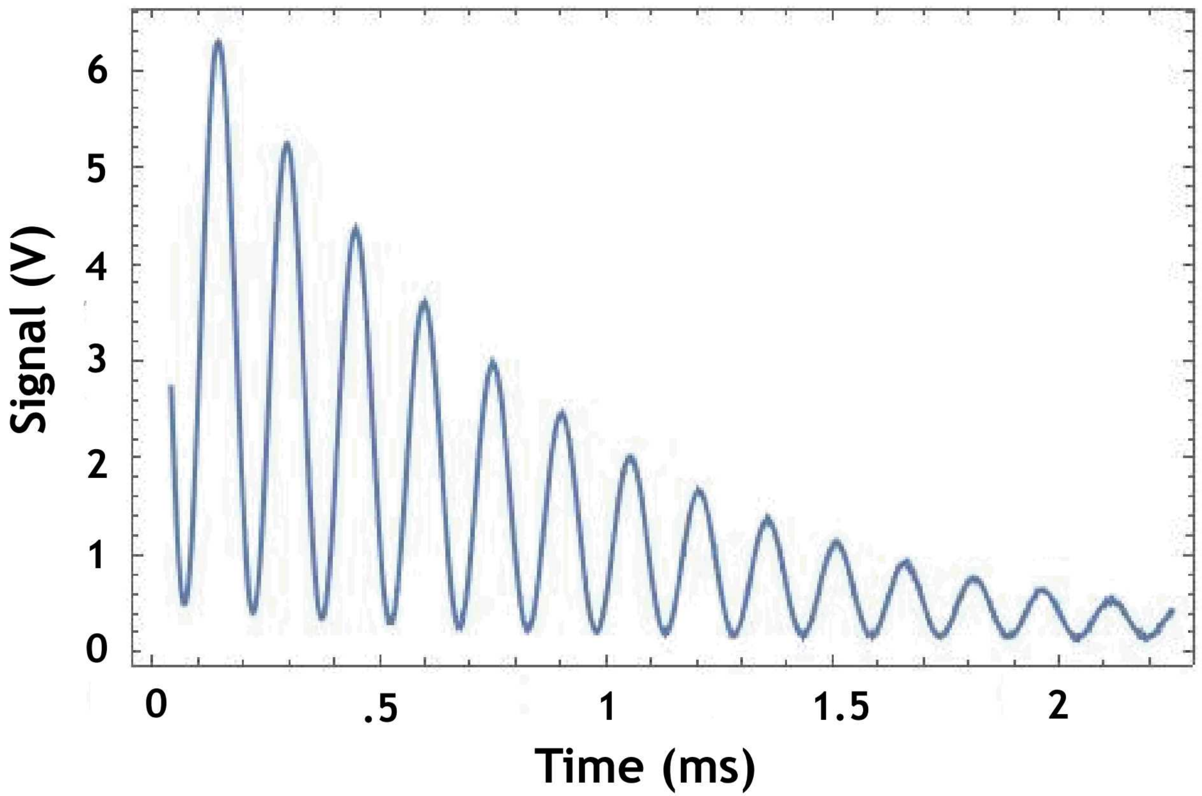
1) Pump atoms to the end-state
2) Apply a $\frac{\pi}{2}$ pulse of magnetic energy to put the atoms in a coherent superposition
3) Send in Carrier light to generate a sideband in each cell



More detailed description



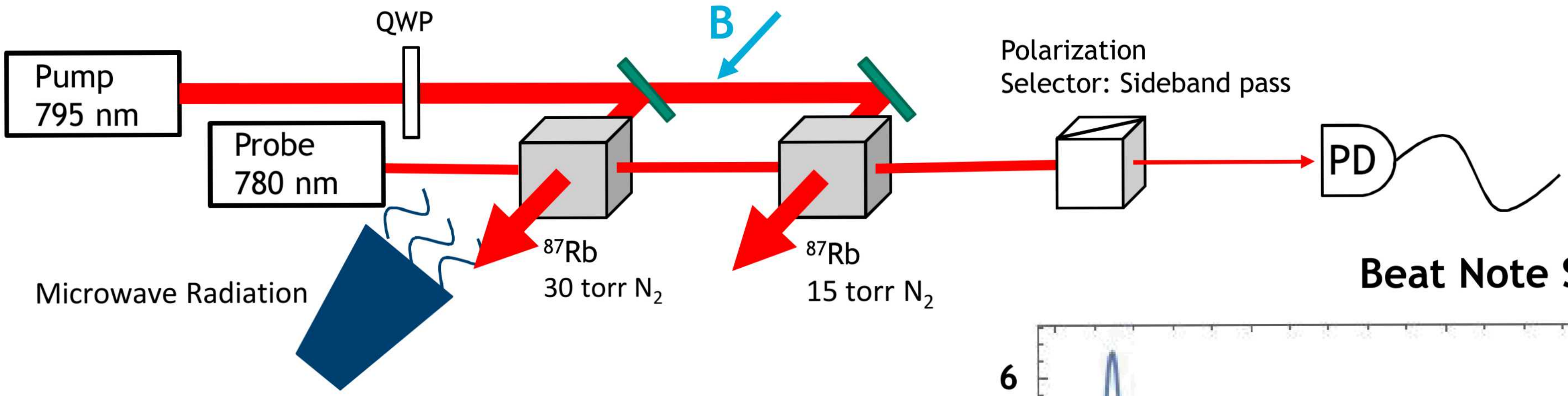
Beat Note Signal



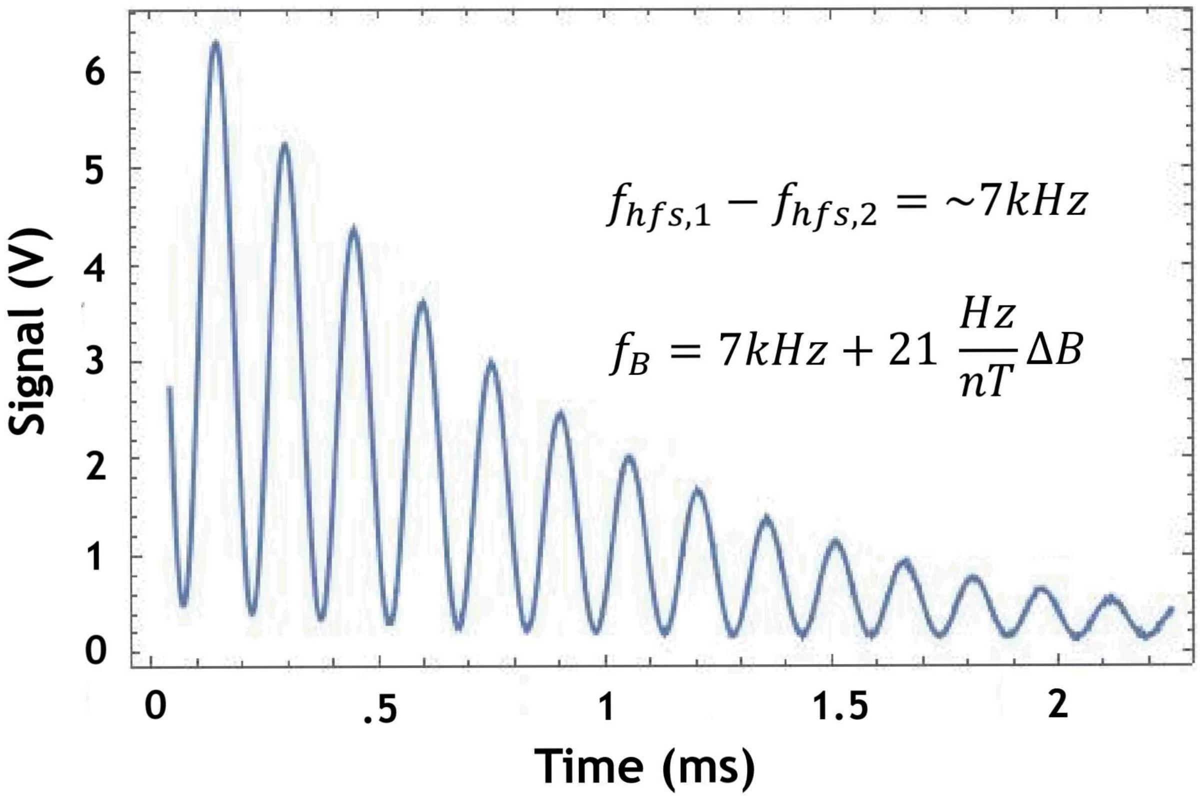
Gradiometer Process

1) Pump atoms to the end-state
2) Apply a $\frac{\pi}{2}$ pulse of magnetic energy to put the atoms in a coherent superposition
3) Send in Carrier light to generate a sideband in each cell
4) Beat the sidebands together to produce a beat note

More detailed description



Beat Note Signal



$$f_{hfs,1} - f_{hfs,2} = \sim 7kHz$$

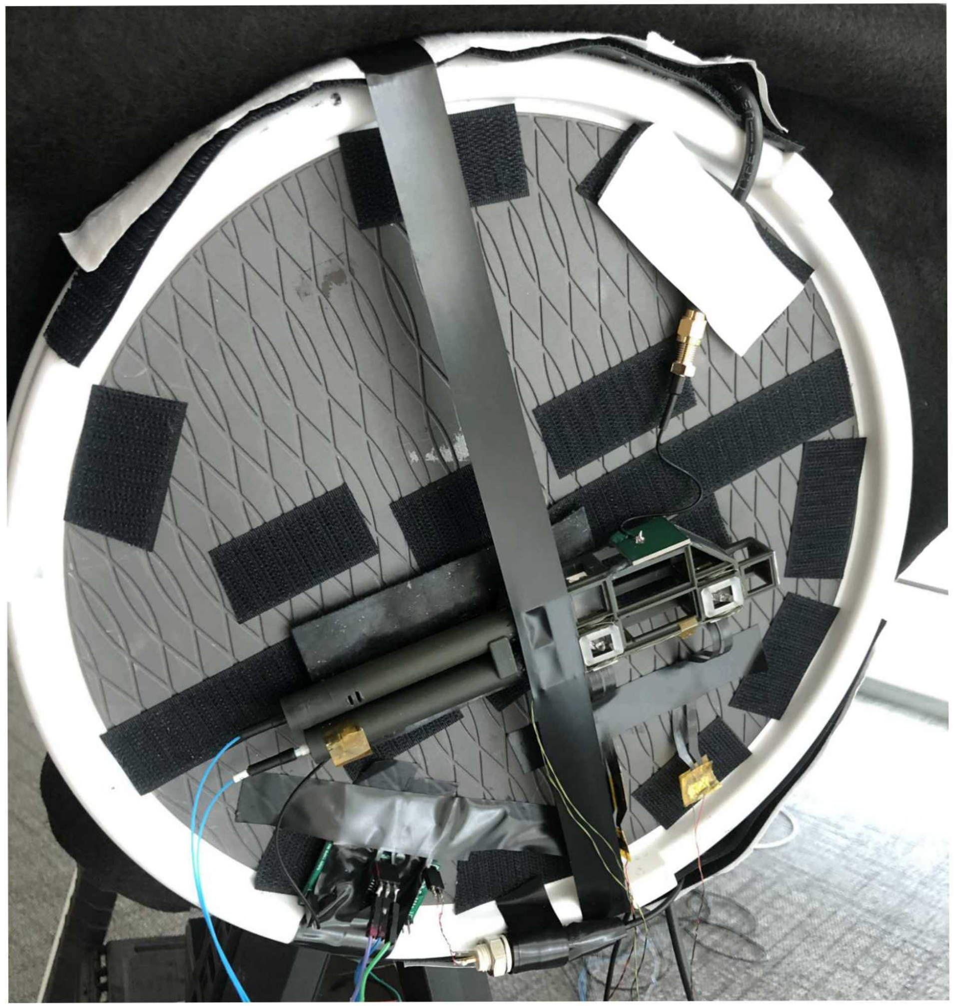
$$f_B = 7kHz + 21\,\frac{Hz}{nT}\Delta B$$

Gradiometer Process

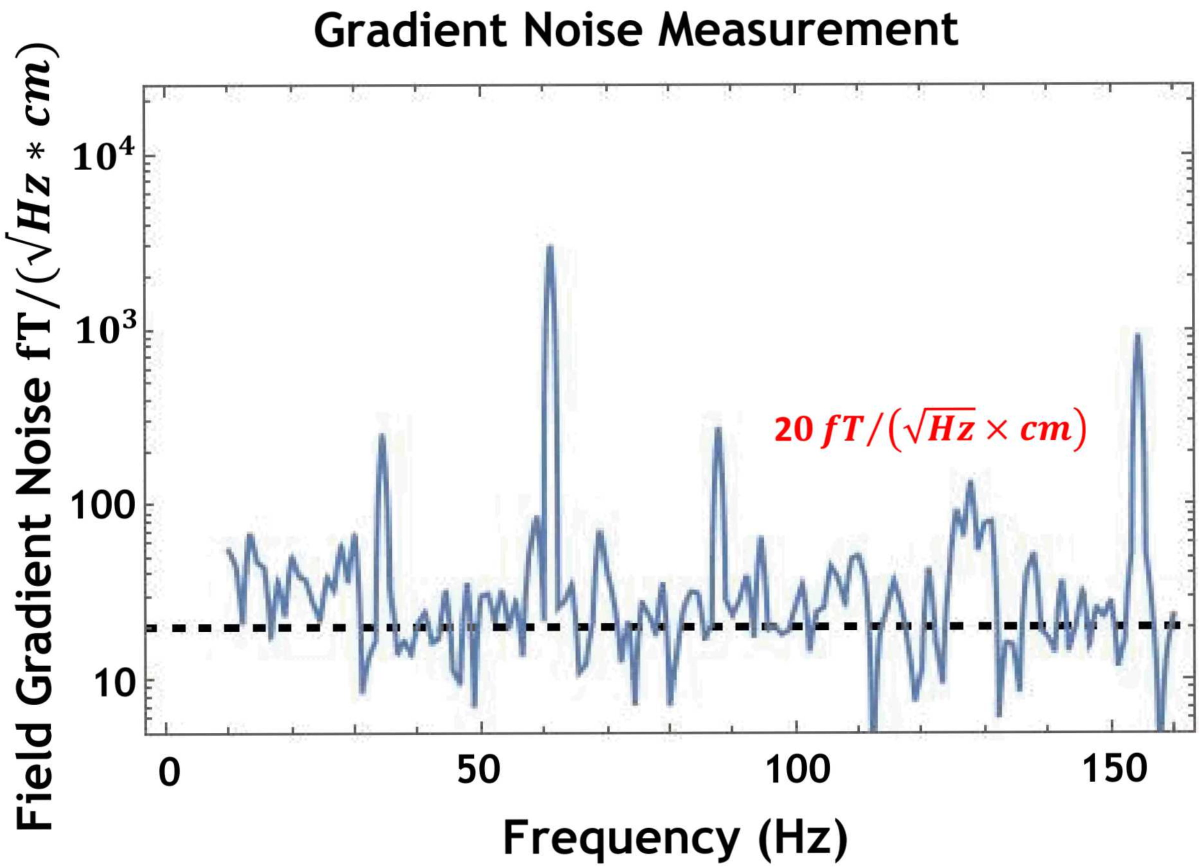
1) Pump atoms to the end-state
2) Apply a $\frac{\pi}{2}$ pulse of magnetic energy to put the atoms in a coherent superposition
3) Send in Probe light to generate a sideband in each cell
4) Beat the sidebands together to produce a beat note
5) Measure the frequency of the beat note to determine the magnetic gradient between the cells

Results

In Earth's Field



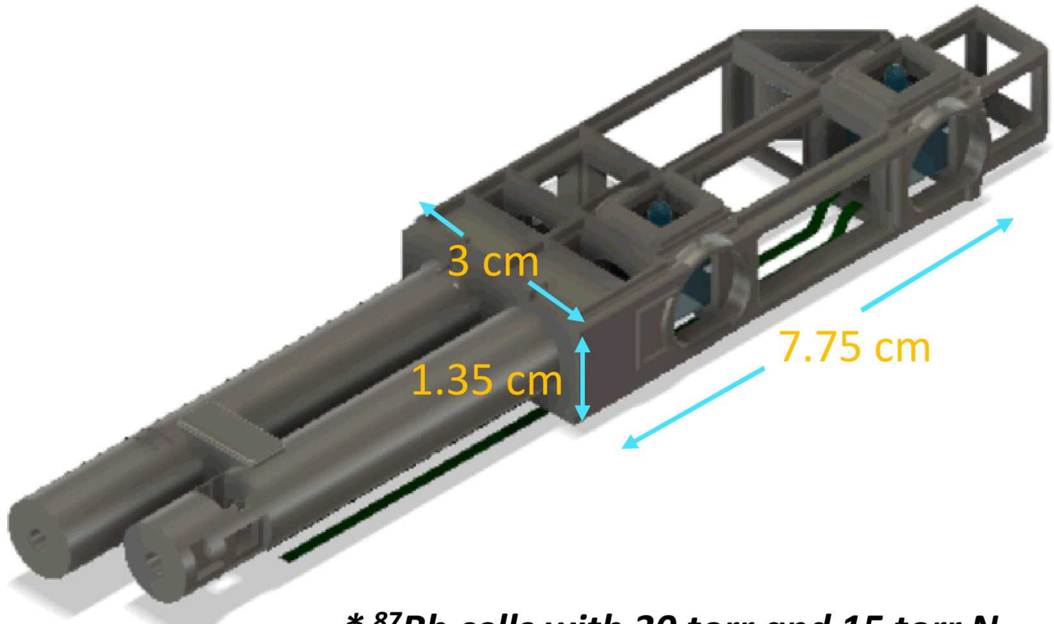
^{87}Rb cells with 30 torr N_2 and 15 torr N_2
Separation: 4.4 cm



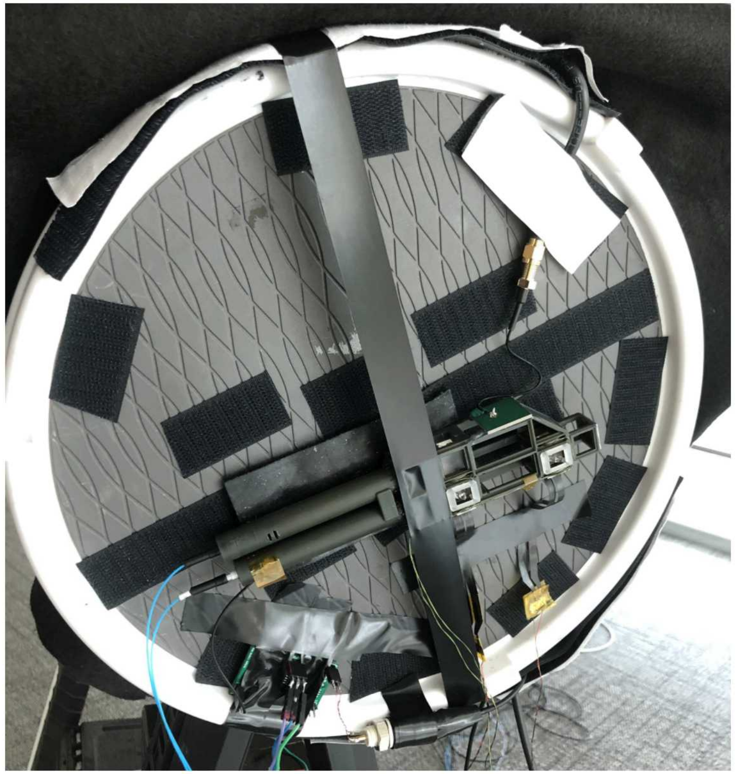
Photon Shot Noise: ~6 fT/cm/rt-Hz

Data and photo courtesy of QuSpin

Final Package Design for Phase I Prototype



** ^{87}Rb cells with 30 torr and 15 torr N_2*

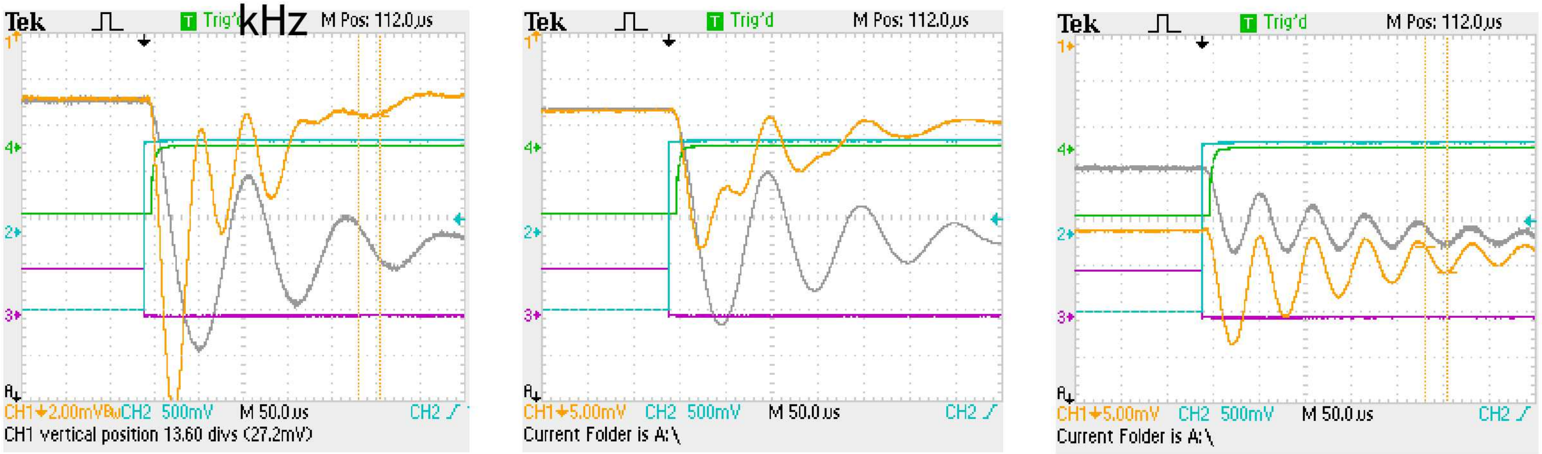


- All components are dropped-in design. Requires minimum alignment.
- Improved gradient cancellation coil design.

Evidence sideband is generated from coherence.

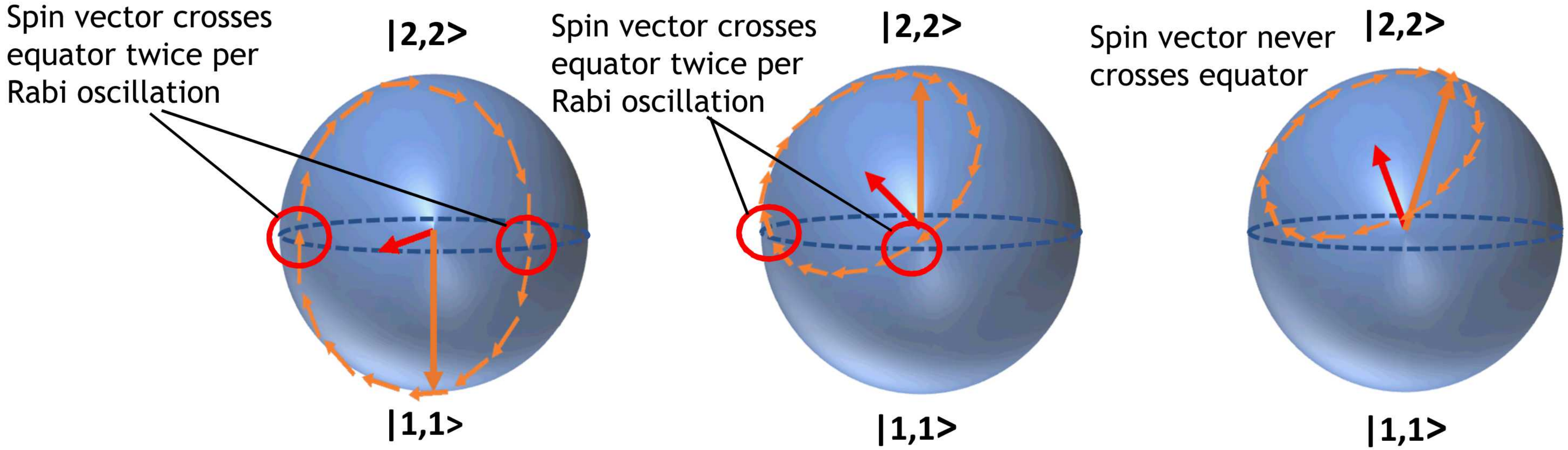
Microwave optical double resonance (MODR) signal oscillates at the Rabi frequency, Ω. Sideband signal oscillates at 2Ω on resonance. This shows the sidebands are due to coherence between the |1,1> and |2,2> states.

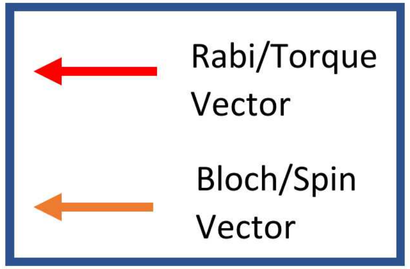
Detuning: 0 kHz | 3 kHz | 14 kHz



Gray: MODR signal/parallel polarizers

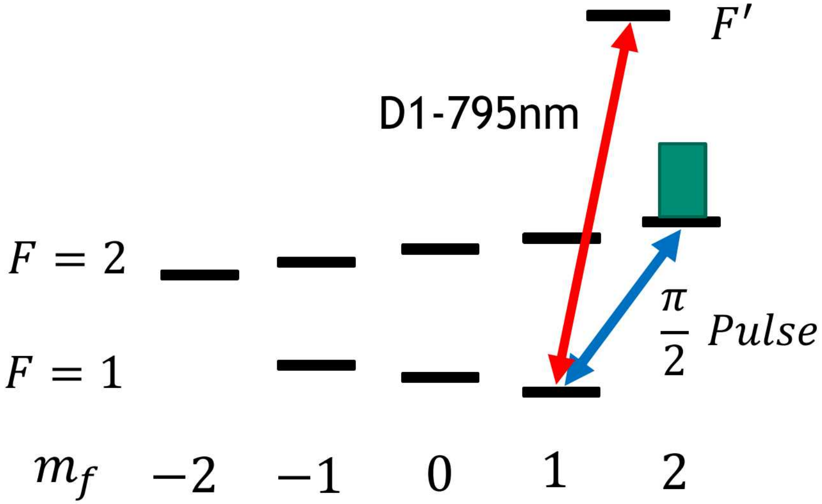
Orange: Sideband signal (inverted)/ crossed polarizers

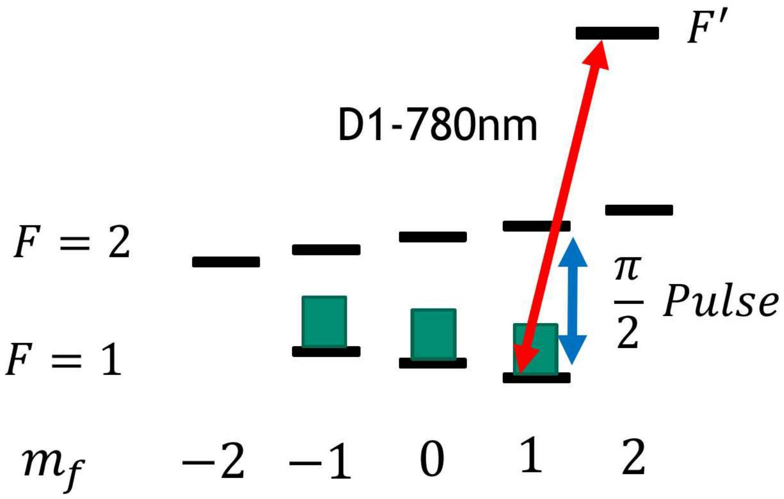


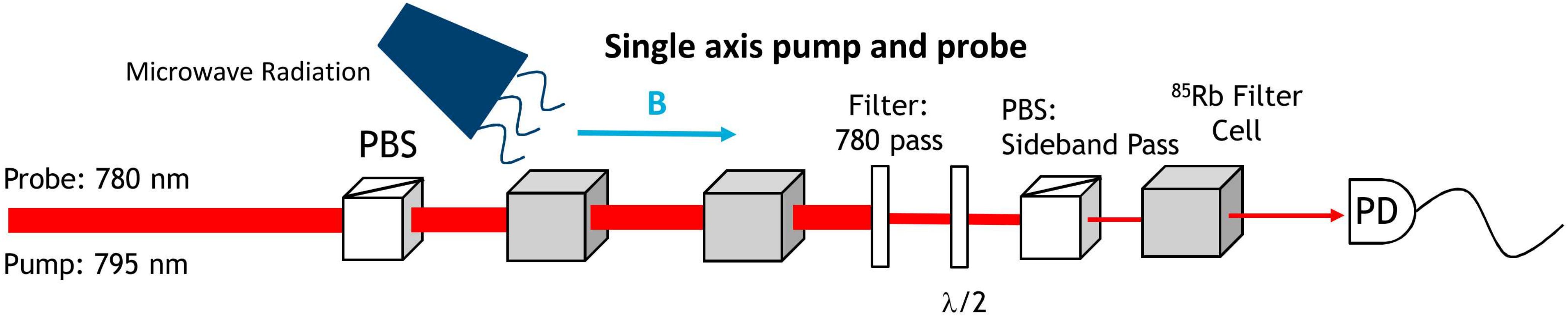


Can we make the sensor more compact?

- Pump and Carrier along the same axis?
- Selection rules prohibit sideband generation on the |F=1, m_f = 1> to |F=2, m_f = 2> transition.
- Selection rules allow only $\Delta m_F = 0$ transitions.

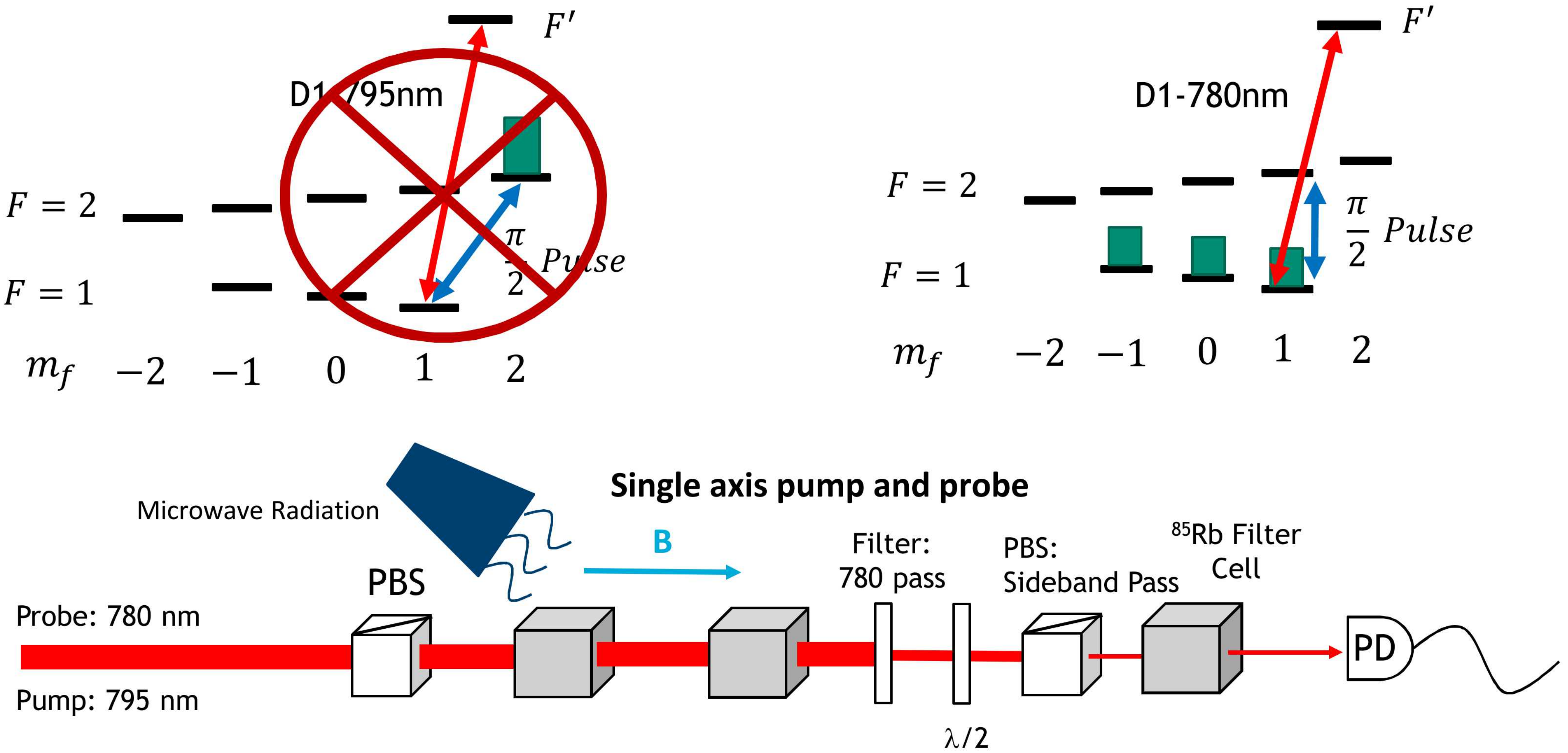






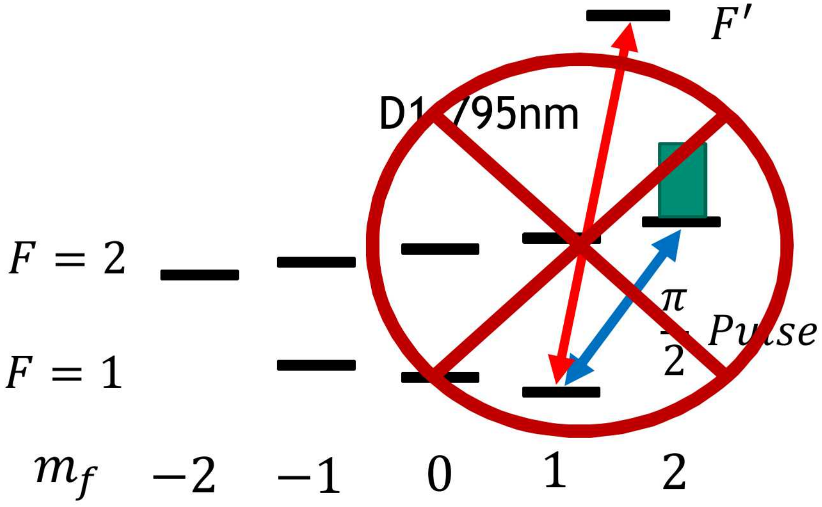
Can we make the sensor more compact?

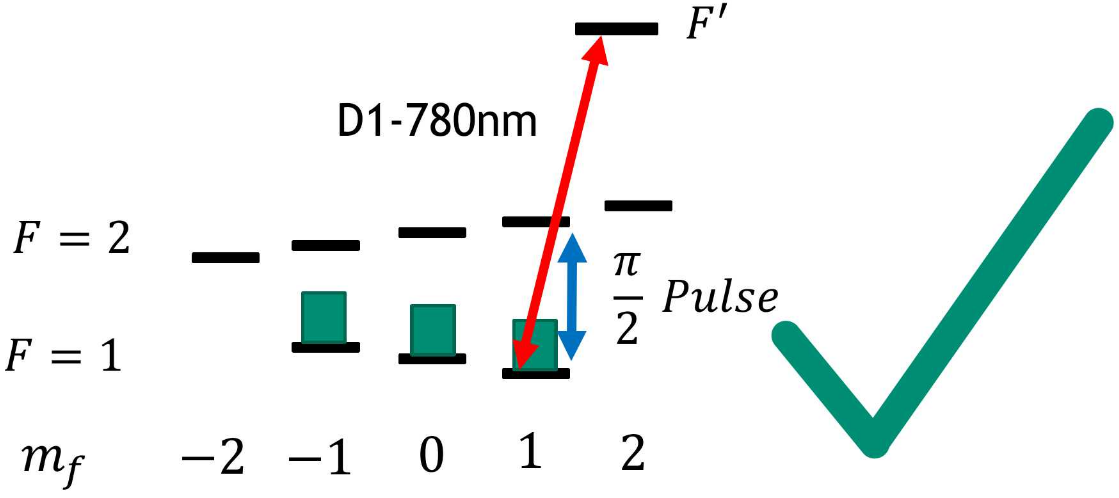
- Pump and Carrier along the same axis?
- Selection rules prohibit sideband generation on the |F=1, m_f = 1> to |F=2, m_f = 2> transition.
- Selection rules allow only $\Delta m_F = 0$ transitions

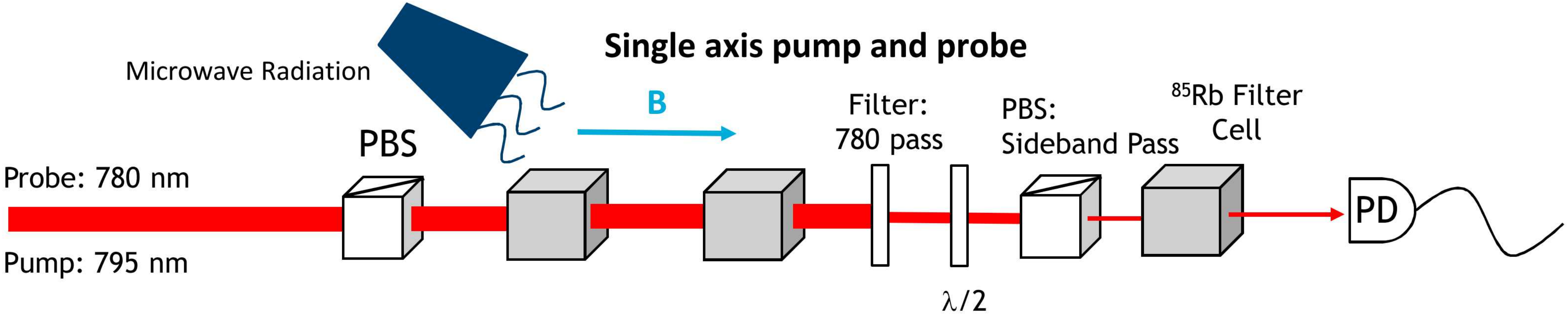


Can we make the sensor more compact?

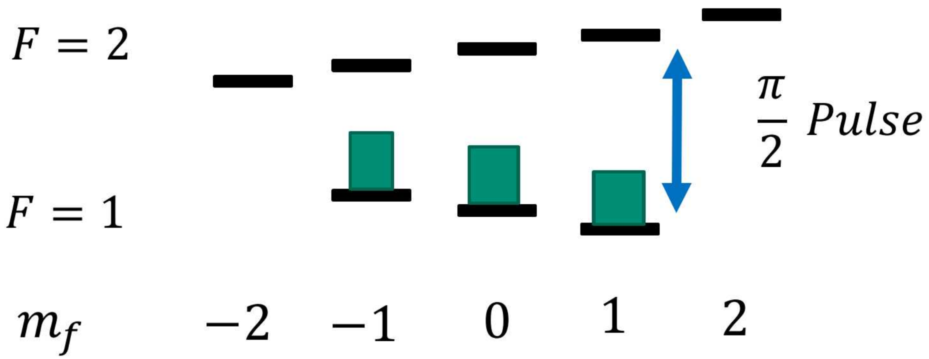
- Pump and Carrier along the same axis?
- Selection rules prohibit sideband generation on the |F=1, m_f = 1> to |F=2, m_f = 2> transition.
- Selection rules allow only $\Delta m_F = 0$ transitions







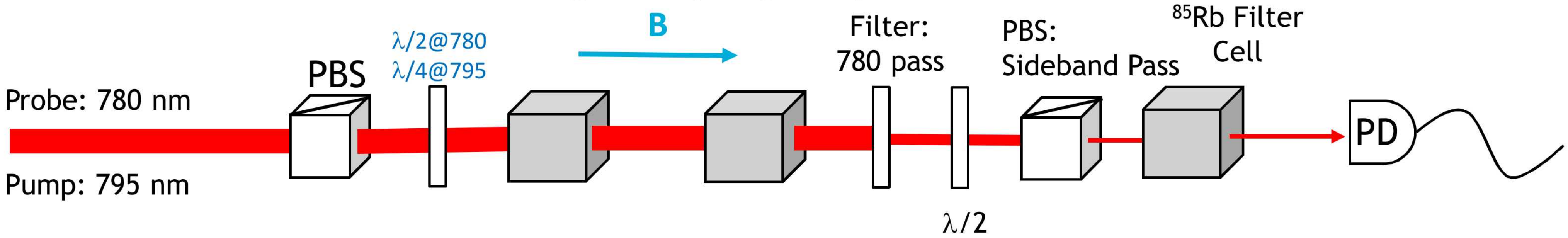
Problems with this orientation



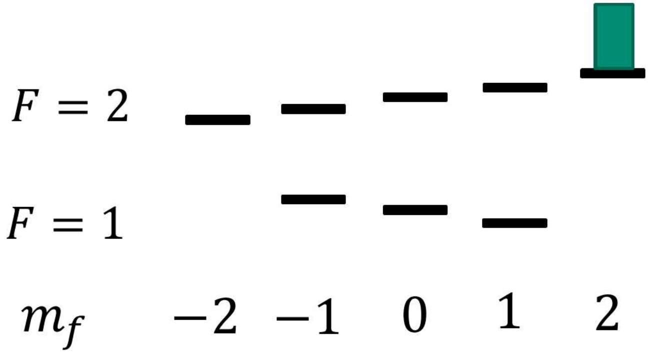
- We can only pump the atoms to a single ground state, not an individual Zeeman sublevel
- Reduced sideband amplitude

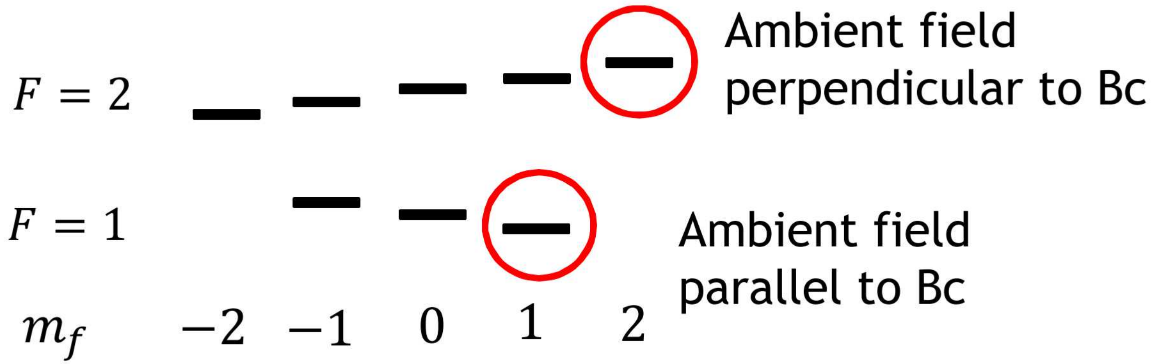
Solutions?

Single axis pump and probe



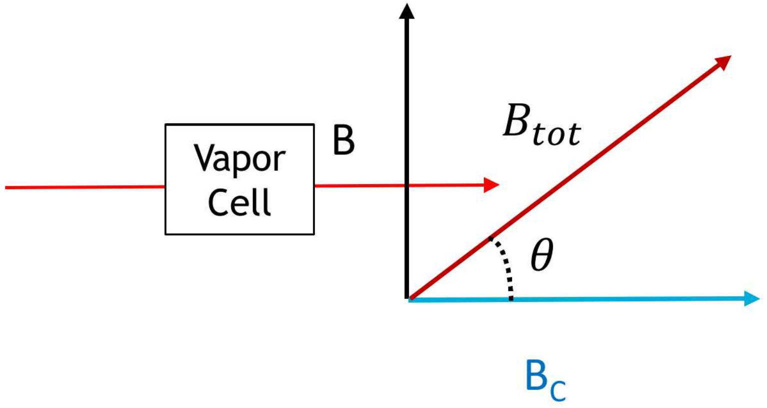
Atoms optically pumped to the end-state

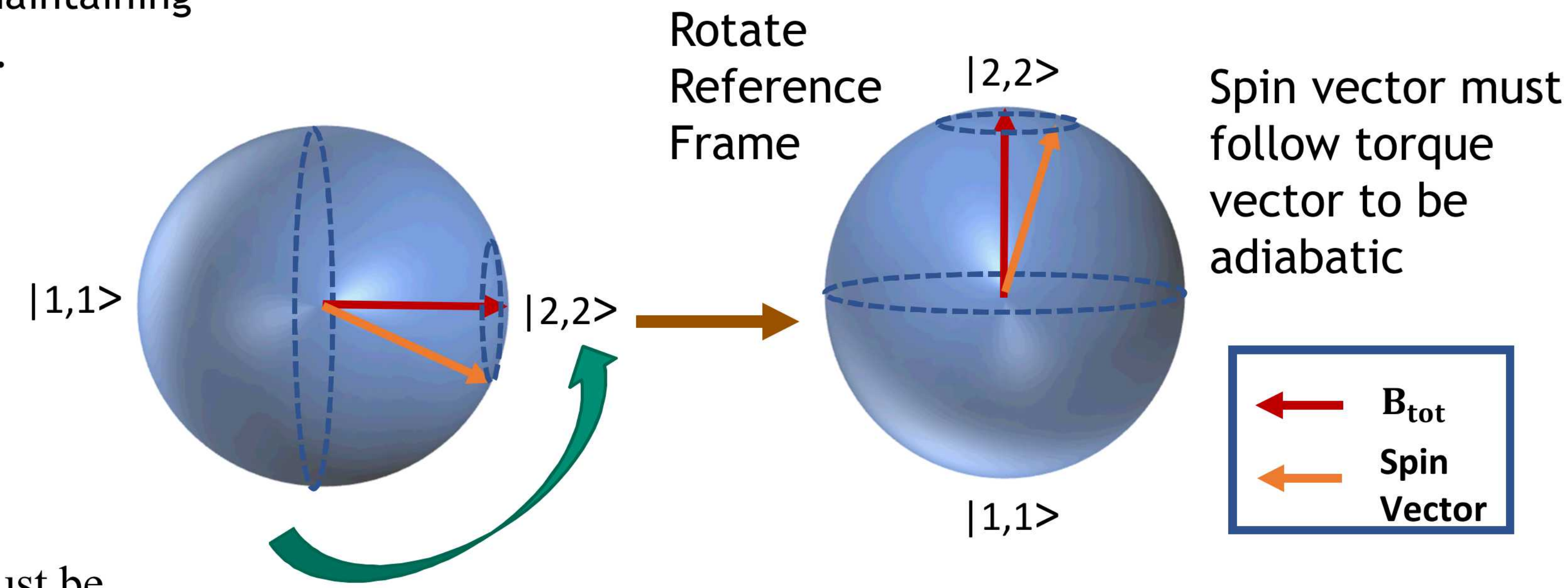




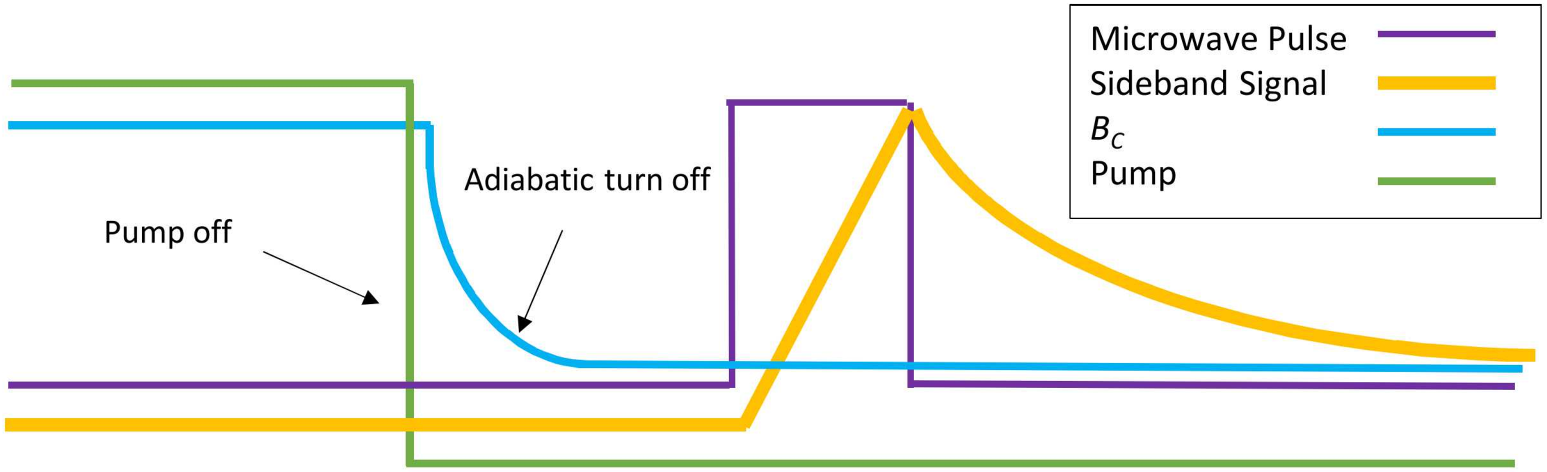
Case 1: Ambient field perpendicular to the laser axis

We rotate the quantization axis, while maintaining the atomic population in the |2,2> state.

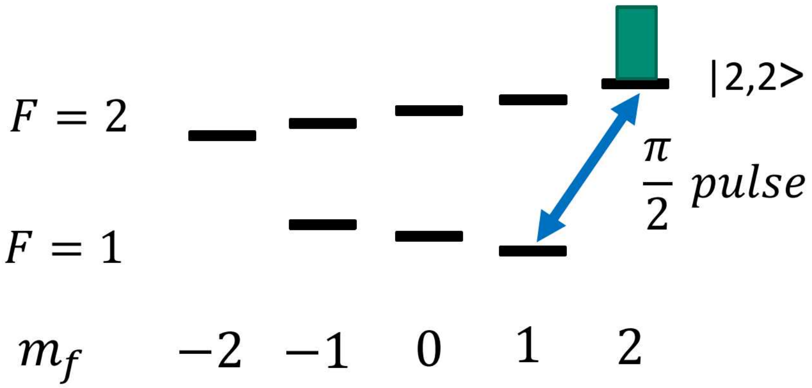




To be adiabatic, the rotation rate of the field must be less than the Larmor precession frequency $\frac{d\theta}{dt} << \omega_L$.



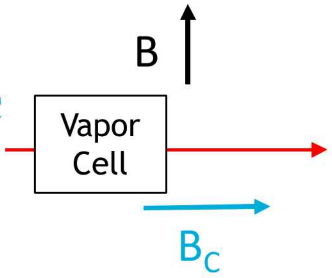
Selection rules now allow Δm_F = 1 transitions

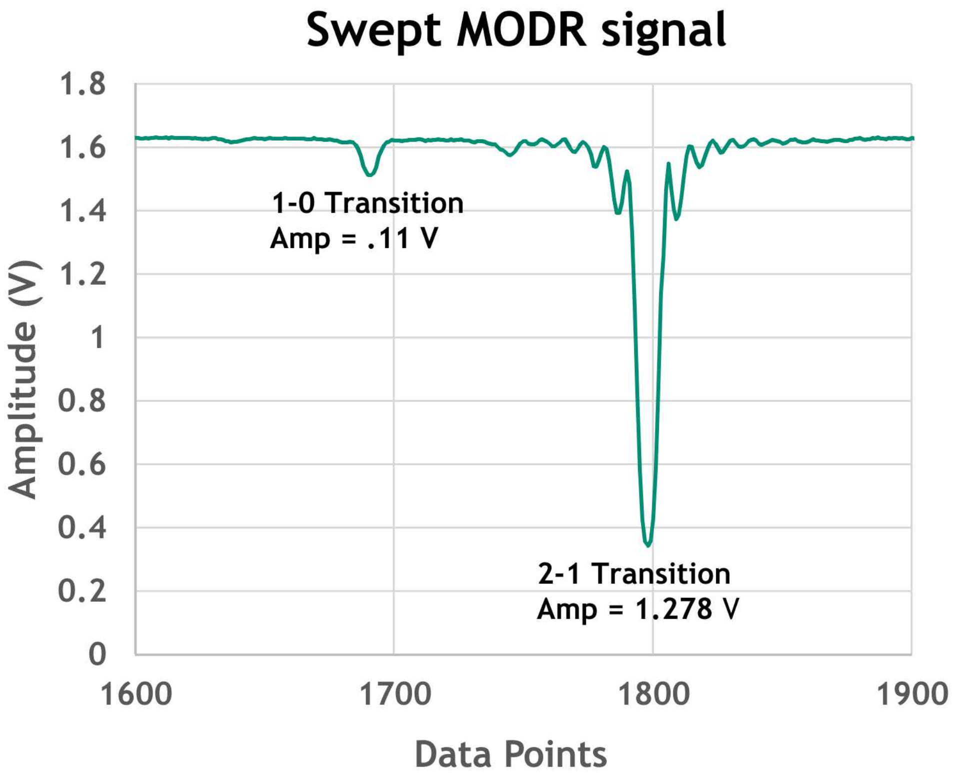


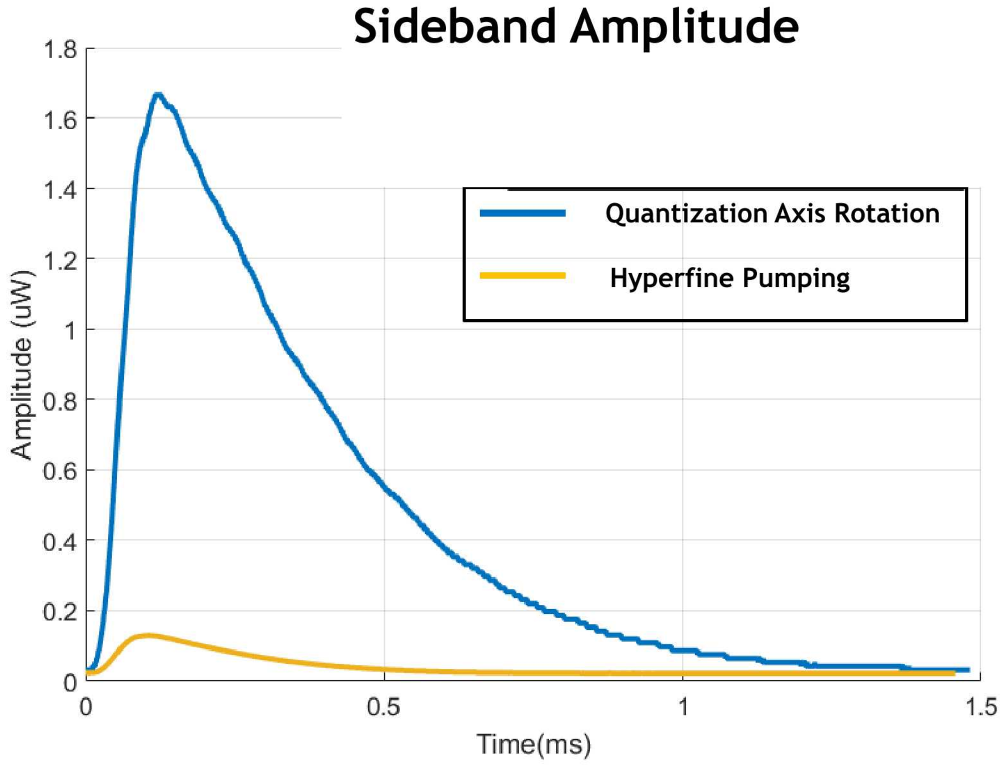
Case 1: Results

Compare adiabatic field switching to the old method of hyperfine pumping.

- Observe ~90% in the |2,2> state with optical pumping: expect improvement with lager B_C
- Adiabatic switch does not degrade populations
- See a 10x improvement in sideband size



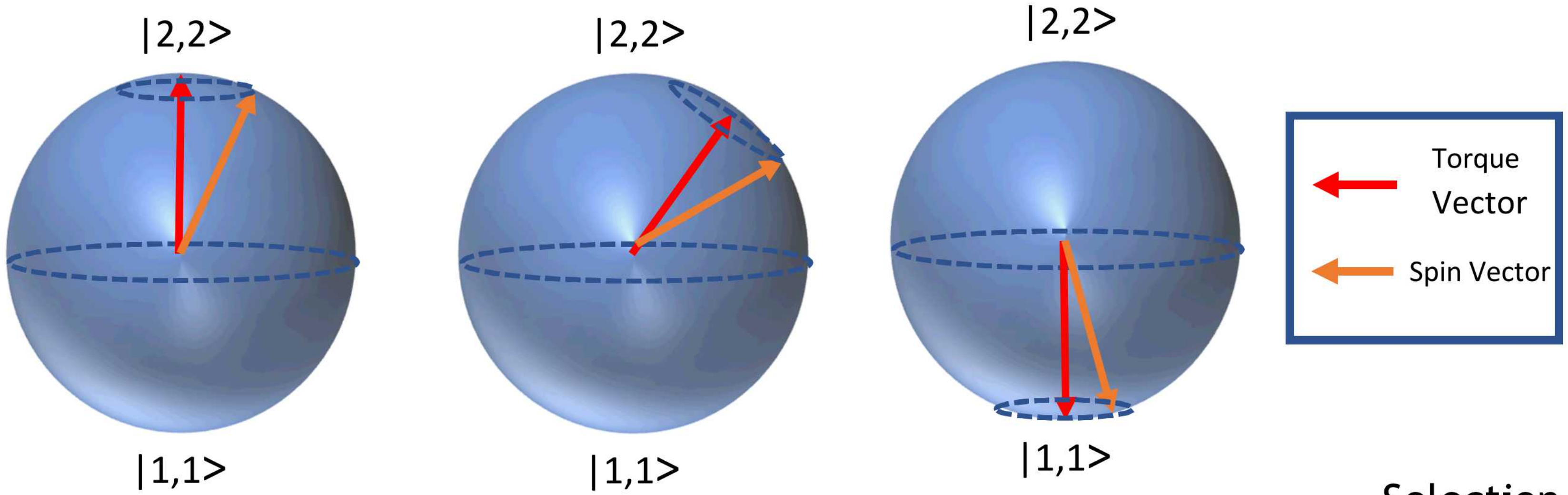




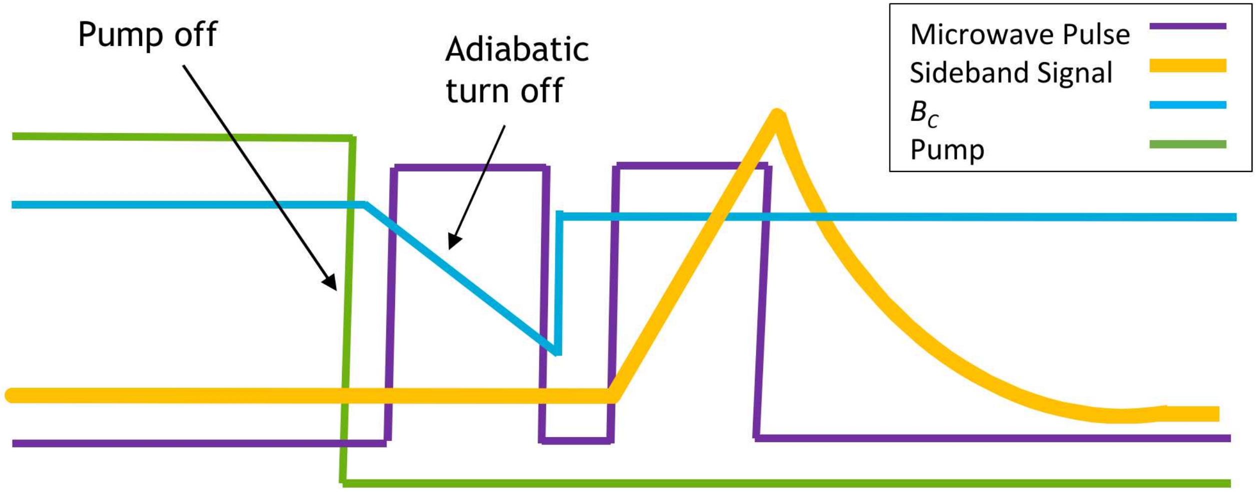
Probe Power = ~20 μW; Detuning near F = 1; Useing Rb-85 filter cell; Buffer gas: 30 Torr N2; Cell Temp = 98 °C;

Case 2: Ambient field parallel to the laser axis

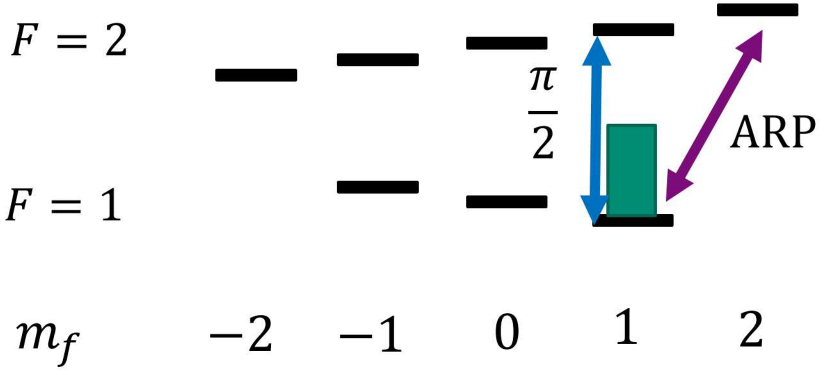
- We perform adiabatic rapid passage to transfer the population from the |2,2> state to the |1,1> state.
- We use a magnetic field ramp to simplify microwave and cover both cells.



Magnetic field must be ramped slow enough that the Spin vector follows the Torque vector



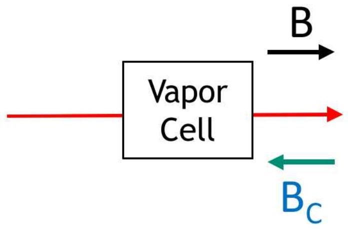
Selection rules allow $\Delta m_F = 0$ transitions

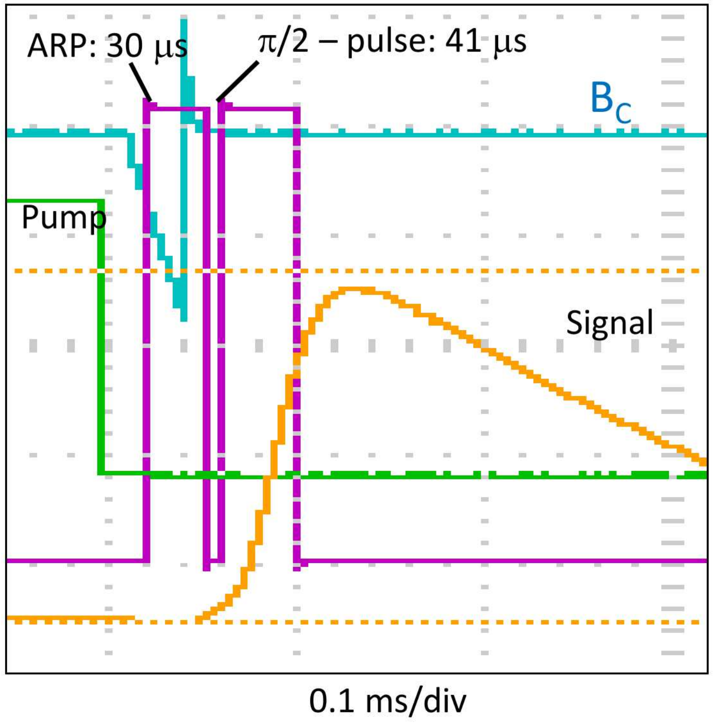


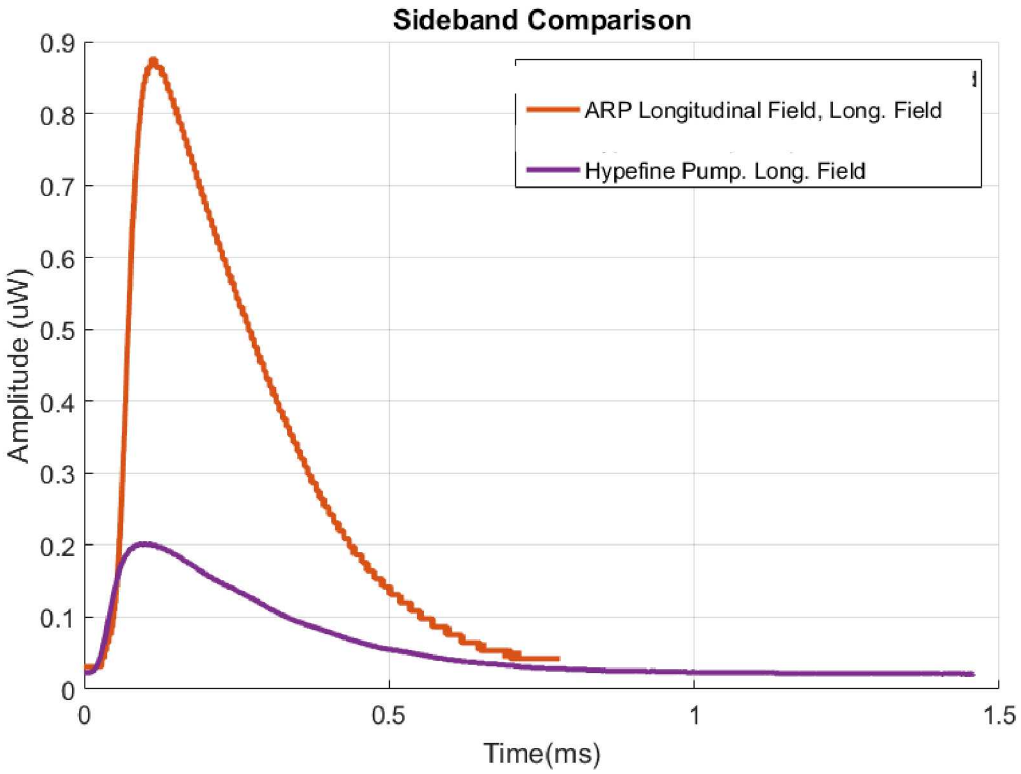
Field parallel to the laser axis

Compare adiabatic field switching to the old method of hyperfine pumping.

- Observe ARP from |2,2> to |1,1>
  - Use a single microwave synthesizer
  - The percentage of the transfer uncertain
- See a 4x improvement in sideband size on the |1,1> to |2,1> transition.



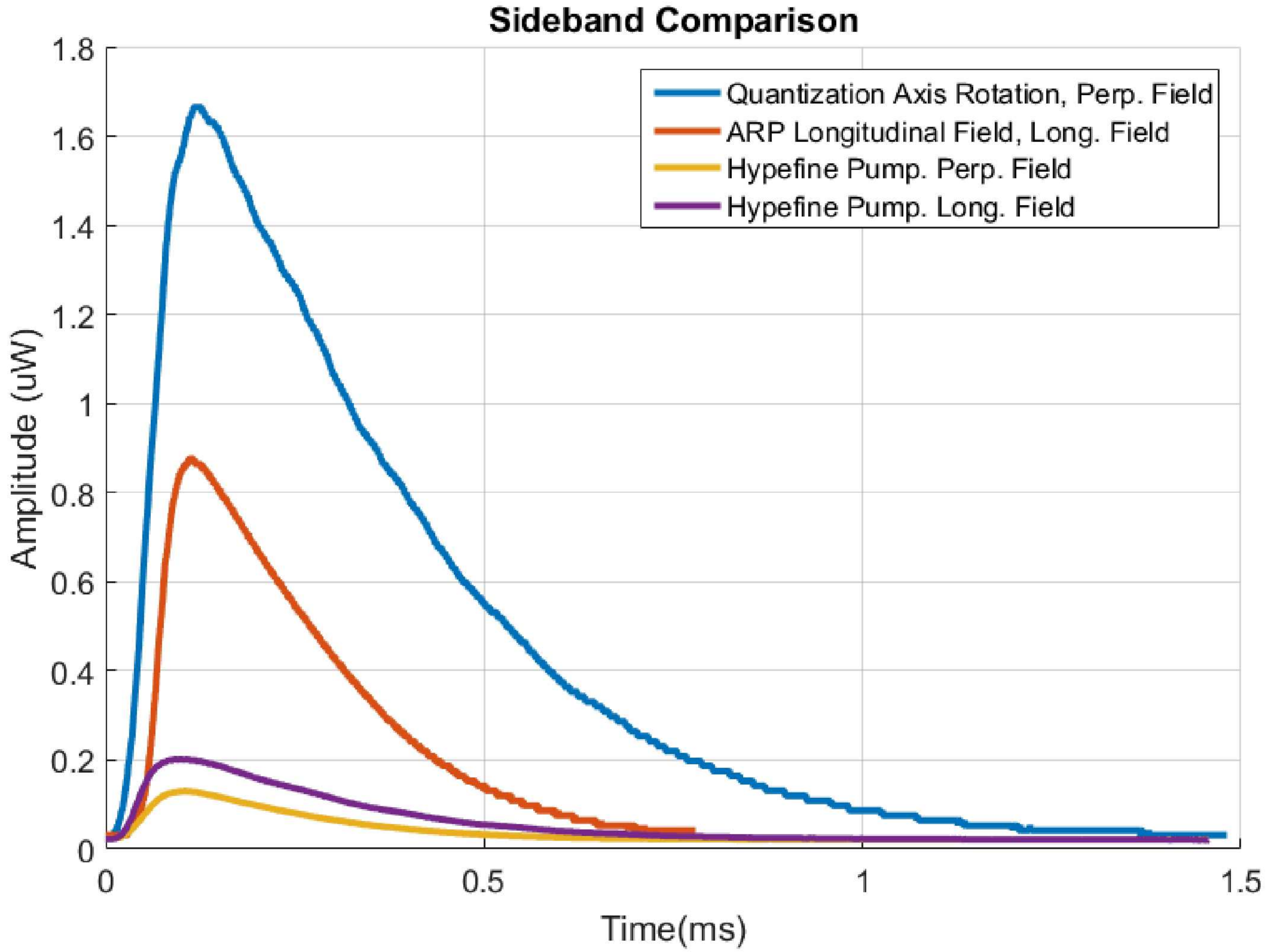




Comparison of four experiments

Quantization axis rotation currently working better than microwave ARP

- Why is this?



Can we work towards dead-zone free operation?

Minimum field

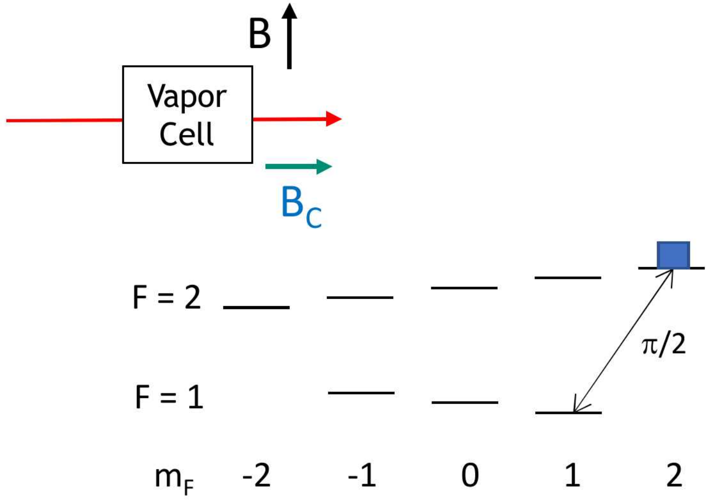
- $f_{1\to 2} - f_{1\to 1} \gg \frac{1}{2\pi\, T_{\pi/2}}$
- For $T_{\pi/2} = 0.1$ ms, $B_{min} \gg 230$ nT

How to switch between the two schemes

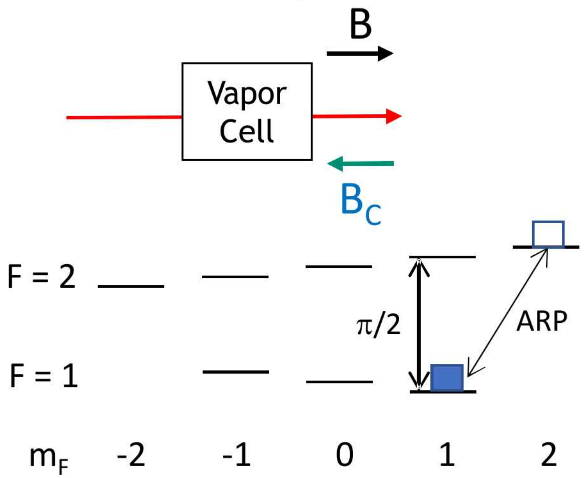
- Start up:
  1. Determine ambient field and direction using a field zeroing scheme
  2. Select scheme, microwave frequency, and direction of B_C
  3. Begin operation.
- Continuous operation:
  1. Monitor signal size
  2. If signal size drops below threshold, switch scheme.
     1. If this fails, re-zero field.

Need to understand better how to ramp Bc for ARP

Quantization axis rotation



ARP with longitudinal field



Conclusion

- We detail a new gradiometer in Earth's field based on the hyperfine splitting and demonstrate sensitivity as low as $\frac{20\ fT}{\sqrt{Hz}*cm}$.
- We work towards dead-zone free operation of the gradiometer, and show how we can make the setup more compact with parallel pump and carrier.
- We experimentally show that our ARP and quantization axis rotation method produces sidebands 4-10X larger in amplitude than sidebands from hyperfine pumping.

- Next steps:
  - Understand sideband amplitude discrepancy between ARP and QA rotation methods.
  - Continue working towards deadzone-free operation

Acknowledgements

Experiment

Sandia National Laboratories

-Kaleb Campbell
-Peter D.D Schwindt

QUSPIN

-Ying-Ju Wang
-Vishal Shah-PI

Theory

Los Alamos National Laboratory

-Igor Savukov

Funding

DARPA -Atomic Magnetometer for Biological Imaging In Earth's Native Terrain (AMBIIENT)

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA). The views, opinions and/or findings expressed are those of the authors and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Abstract

Towards a pulsed dead-zone free gradiometer in earth's field

Kaleb Campbell[1,2], Ying-Ju Wang [3], Igor Savukov[4], Peter D.D Schwindt[1], Vishal Shah[3]

- *Sandia National Laboratory, 1515 Eubank SE, 87123 Albuquerque, USA*
- *Department of Physics and Astronomy, University of New Mexico, 1919 Lomas Blvd NE, Albuquerque, USA*
- *QuSpin Inc., 331 S 104th St Unit 130, 80027 Louisville, USA*
- *Los Alamos National Laboratory, 87545 Los Alamos, USA*

•Measuring ambient magnetic field gradients in a single device is an important problem in atomic magnetometry. We report on the development of an atomic gradiometer based on the hyperfine splitting in two vapor cells of warm ^{87}Rb atoms. By applying a π/2 pulse of microwave magnetic energy, we maximize the coherence between disparate energy levels, producing a sideband at the frequency of the coupling microwave radiation [1]. By beating together the sidebands from each vapor cell, we measure the beat frequency and thus the magnetic field gradient between the cells [2]. For a practical gradiometer, it is important to be able to measure the gradient regardless of the direction of the ambient magnetic field $\mathbf{B_A}$, either perdendicular or parallel to the laser beam propagation axis. For the perpendicular case, we first apply a magnetic field $\mathbf{B_C}$ collinear to the laser beams so that a circularly polarized Pump beam at 795 nm can optically pump the atoms to the |F=2, m_F=2> state. To obey selection rules for sideband generation on the |1, 1> and |2, 2> states, we quickly turn off the pump, and adiabatically turn off $\mathbf{B_C}$ to rotate the quantization axis to be along $\mathbf{B_A}$. Then, the microwave π/2 pulse is applied, the Carrier is applied, and the beat note of the sidebands is detected. For the other case, if the ambient field is along the direction of the laser beams, we turn off the pump, and then use adiabatic rapid passage (ARP) to transfer the atomic population from the |2, 2> to the |1, 1> state, with the experiment proceeding as before. Experimental details for each case will be provided. We report preliminary noise sensitivities as low as *30fTHz*cm* with magnetic shielding and *65fTHz*cm* for measurements performed in the Earth's field.

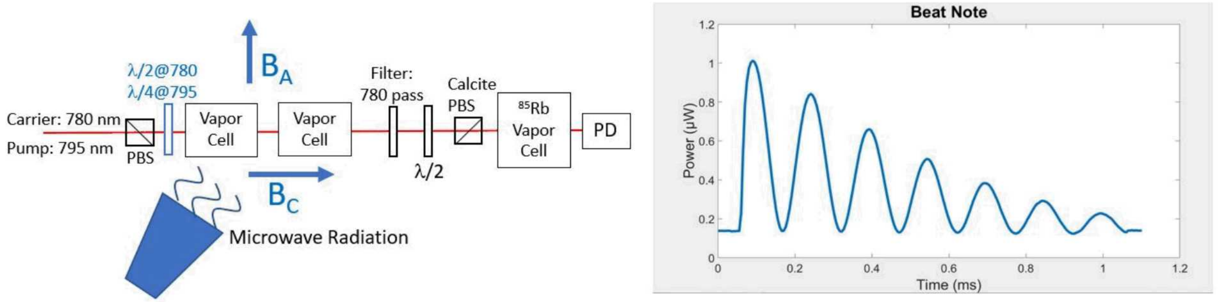


Fig. 1 (Left) Experimental gradiometer setup with collinear Pump and Carrier beams [2]. For this case, we assume the ambient field, *BA*, is perpendicular to the Carrier direction. The sideband is orthogonally polarized to the carrier, so the beat note can be picked off using a polarizing beam splitter (PBS). (Right) An example of the beat note data.

References

[1]**Henry Tang**, *Parametric Frequency Conversion of Resonance Radiation in Optically Pumped ^{87}Rb Vapor*. Phys. *Rev. A* **7**, 2010 (1973).

[2] Vishal Shah, *System and Method for Measuring a Magnetic Gradient Field*. Patent. US10088535 (2018)