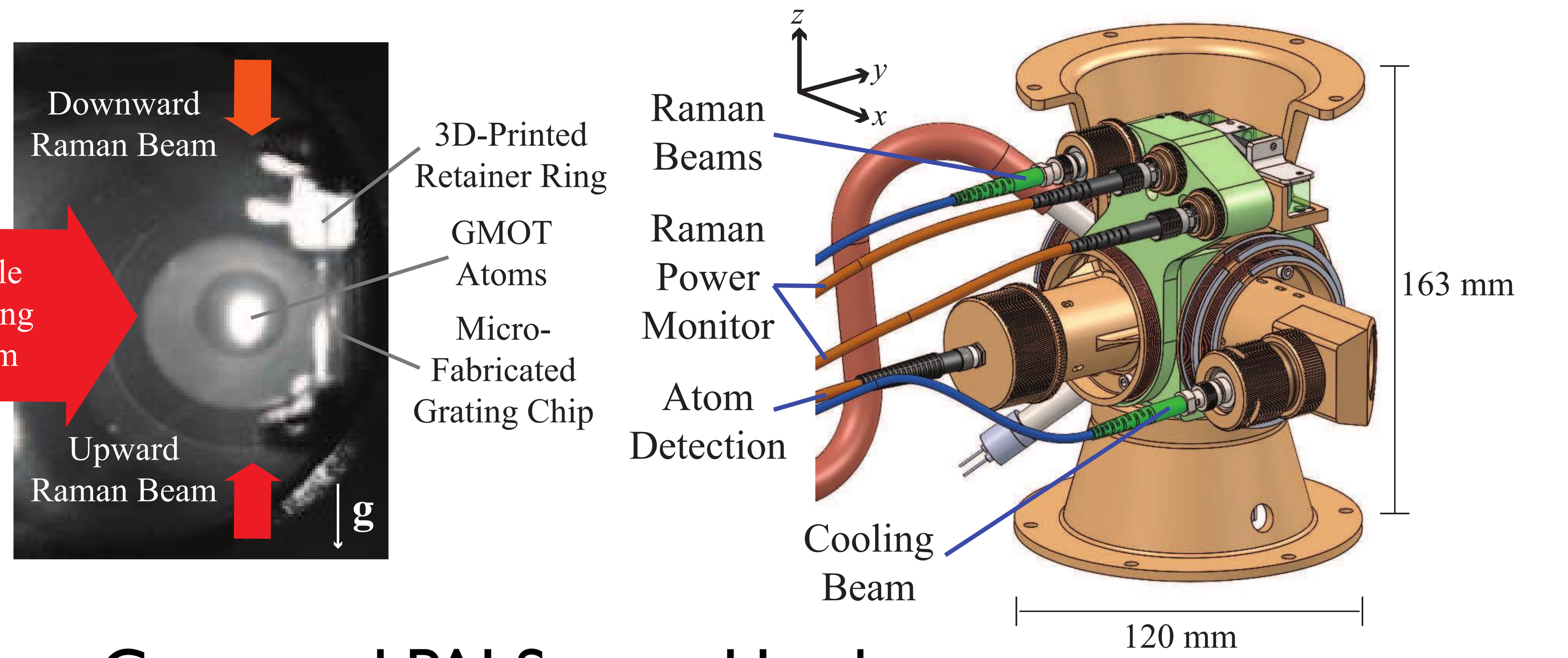
Sandia National Laboratories

A Compact Cold Atom Interferometer with a High Data Rate Grating Magneto-Optical Trap and a Photonic Integrated Circuit-Compatible Laser System

Jongmin Lee, Roger Ding, Justin Christensen, Randy R. Rosenthal, Aaron Ison, Daniel P. Gillund, David Bossert, Kyle H. Fuerschbach, William Kindel, Patrick S. Finnegan, Joel R. Wendt, Michael Gehl, Ashok Kodigala, Hayden McGuinness, Charles A. Walker, Shanalyn A. Kemme, Anthony Lentine, Grant Biedermann, Peter D. D. Schwindt
Sandia National Laboratories, Albuquerque, New Mexico, USA

Overview

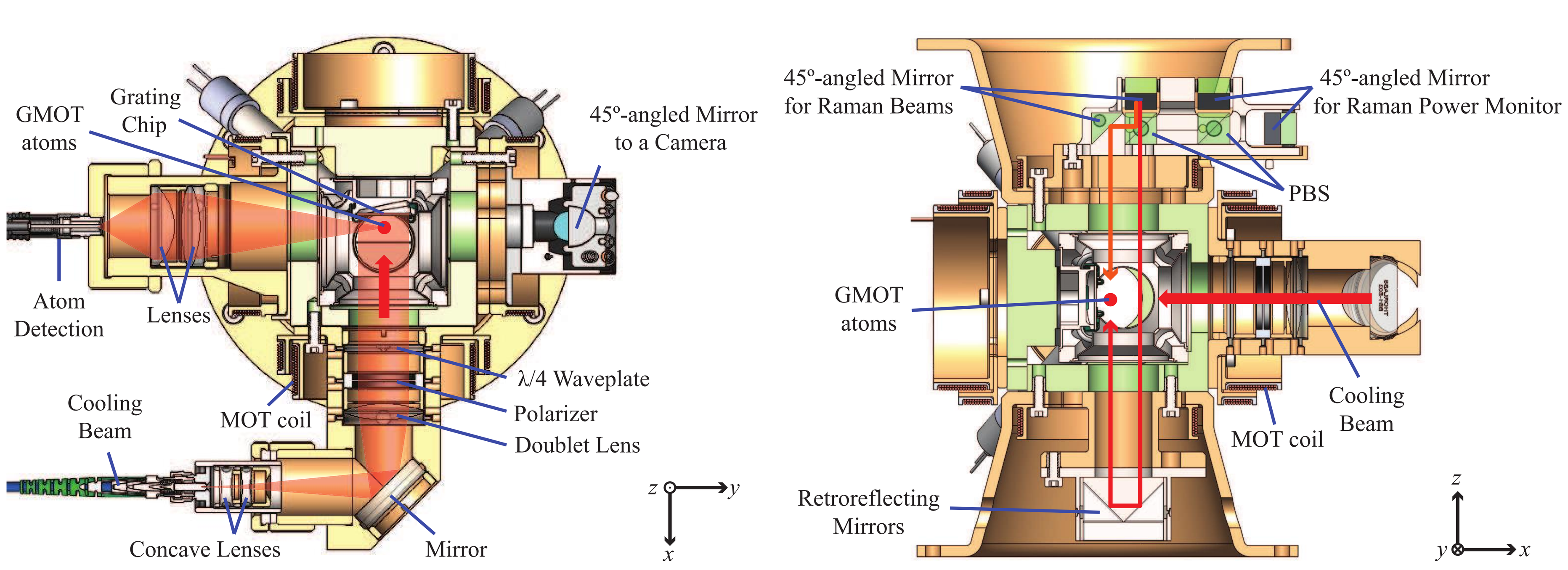
Light-pulse atom interferometers (LPAIs) have demonstrated excellent sensitivity to inertial forces in laboratory settings, and significant efforts are underway to apply them in real-world environments [1-5], but maintaining high performance in a dynamic environment is challenging. With the goal of elucidating a path towards fieldable sensors, we present a multifaceted approach based on a high data rate grating magneto-optical trap (GMOT) LPAI [6].



Prototype Compact LPAI Sensor Head

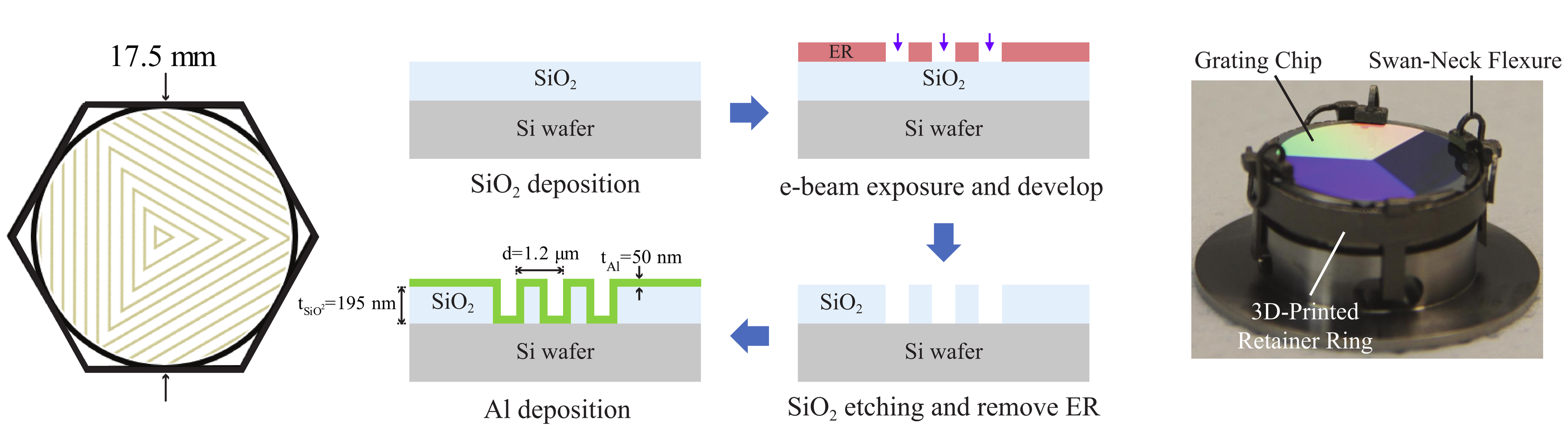
The structure was primarily designed with the goal of minimizing mechanical degrees-of-freedom while maintaining a compact formfactor. Additional considerations were taken to mitigate effects of vibrations.

- "Alignment-free" optics system with all fiber delivery of 780 nm light
- Nonconductive materials (FR4, PEEK) to reduce effects of eddy currents



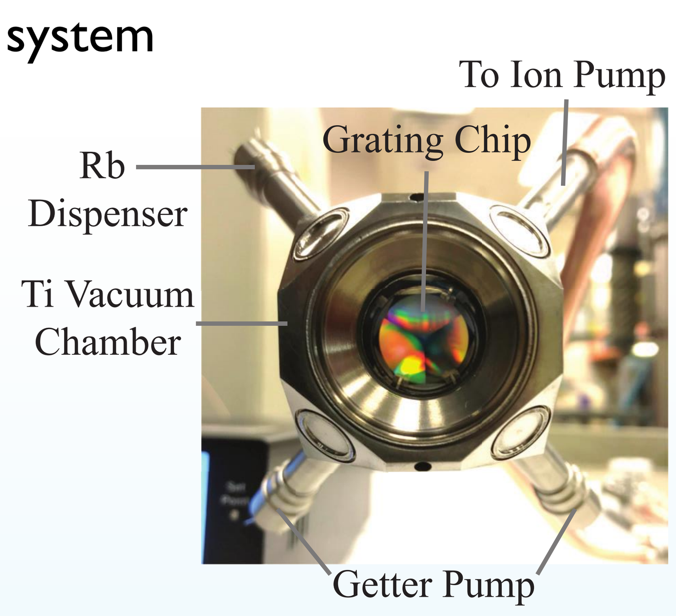
Compact Vacuum Package with Grating Chip

The sensor head is built around a custom Ti vacuum chamber and grating chip. **In-house-fabricated grating chip** is composed of three binary gratings in a triangular orientation to form a tetrahedral GMOT [7-9].



Vacuum package is similar to the passively-pumped system that has sustained a MOT for ≳2 years [10].

- Volume of about $1.6 \times 1.6 \times 1.6\ \text{in}^3$
- Internally-mounted grating chip using 3D-printed Ti swan-neck flexure mounts and retaining ring
- Includes Rb dispensers, NEGs, and AR-coated fused silica viewports ([10] used sapphire viewports)
- Assembled with laser welding



References

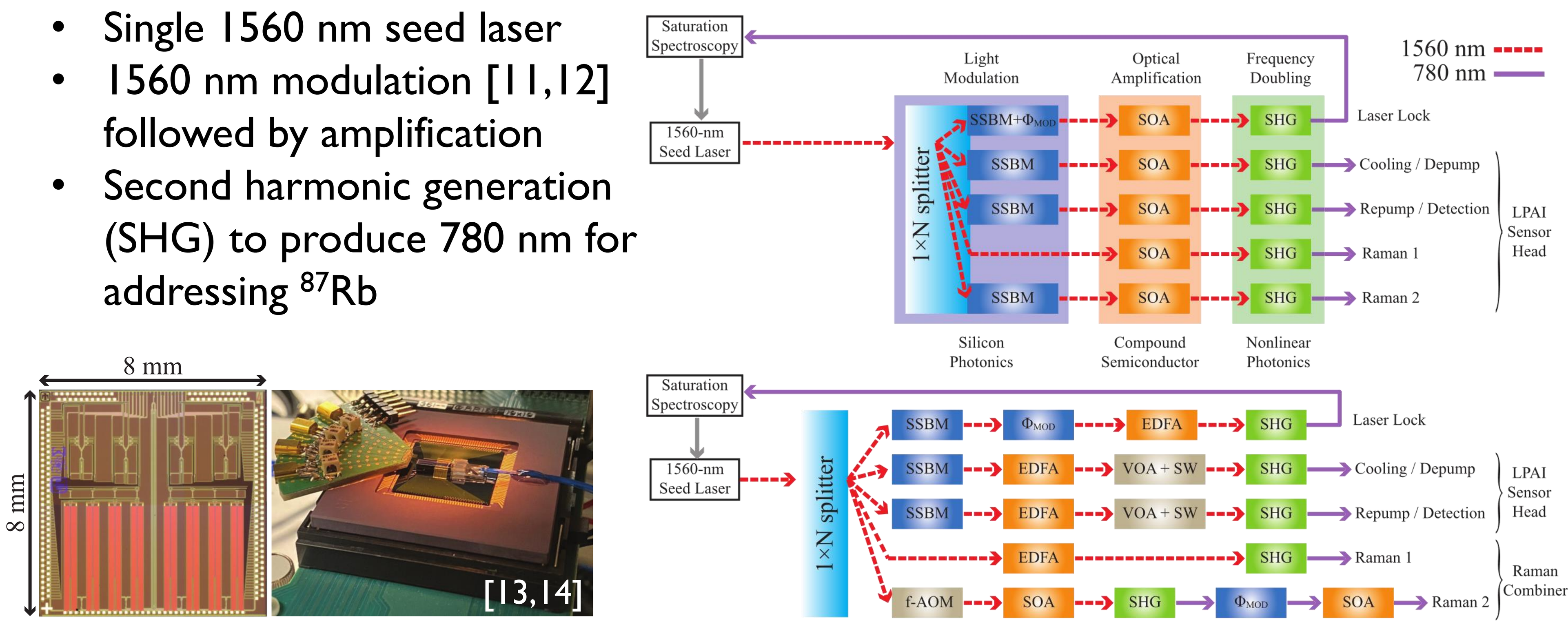
[1] V. Ménoret et al., *Sci Rep* **8**, 12300 (2018)
[2] Y. Bidel et al., *Nat Commun* **9**, 627 (2018)
[3] R. Geiger et al., Nat Commun **2**, 474 (2011)
[4] B. Barrett et al., *Nat Commun* **7**, 13786 (2016)
[5] Y. Bidel et al., *J Geod* **94**, 20 (2020)
[6] J. Lee et al., 10.48550/arXiv.2107.04792
[7] M. Vangeleyn et al., Opt. Lett. **35**, 3453-3455 (2010)
[8] C. C. Nshii et al., *Nature Nanotech* **8**, 321–324 (2013)
[9] J. P. McGilligan et al., *Sci Rep* **7**, 384 (2017)
[10] B. J. Little et al., AVS Quantum Sci. **3**, 035001 (2021)
[11] L. Zhu et al., Opt. Express **26**, 6542-6553 (2018)
[12] C. Rammeloo et al., J. Opt. Soc. Am. **B** 37, 1485-1493 (2020)
[13] A. Kodigala et al., 10.1364/CLEO_SI.2019.STh4N.6
[14] A. Kodigala et al., 10.48550/arXiv.2204.12537
[15] H. J. McGuinness et al., Appl. Phys. Lett. **100**, 011106 (2012)
[16] A. V. Rakholia et al., Phys. Rev. Applied **2**, 054012 (2014)
[17] J. P. McGilligan et al., Opt. Express **23**, 8948-8959 (2015)
[18] S. Seo et al., Opt. Express **29**, 35623-35639 (2021)
[19] N. Mielec et al., Appl. Phys. Lett. **113**, 161108 (2018)
[20] J. Lautier et al., Appl. Phys. Lett. **105**, 144102 (2014)
[21] L. Chen et al., Phys. Rev. Applied **17**, 034031 (2022)

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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.
SAND No. ____________

Photonic Integrated Circuit (PIC)-Compatible Laser System

End goal is to have all lasers, modulators, amplifiers, and nonlinear optics fabricated with photonic integrated circuit (PIC) technology to enable large-scale production. **"PIC-compatible" system** is an intermediate step to demonstrate the feasibility of the architecture using commercial-off-the-shelf components.

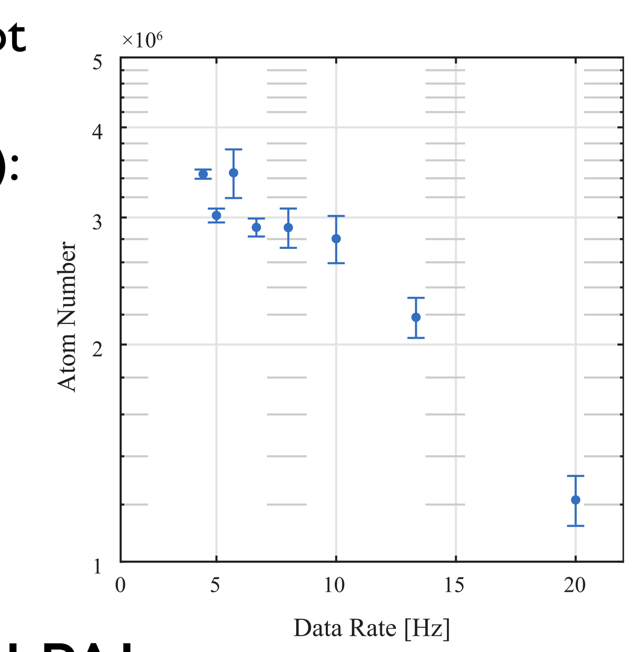
- Single 1560 nm seed laser
- 1560 nm modulation [11,12] followed by amplification
- Second harmonic generation (SHG) to produce 780 nm for addressing ^{87}Rb



Towards High Data Rate GMOT Operation

High cycle rates enable reuse of atoms from shot-to-shot and can complement conventional sensors [15,16].

- Operating with fixed 25 ms cycle time ($R = 1/T_{\text{cycle}}$):
  - MOT: $9\ \text{ms} + n(25\ \text{ms})$ where $n \in \{0,1,2,\dots\}$
  - Sub-Doppler cooling ($T \approx 15\ \mu\text{K}$): +2 ms
  - Depump atoms to $F = 1$: +1 ms
  - Perform experiment: +12 ms
  - Detect $F = 2$ and $F = 1 + 2$ populations: +1 ms
  - Recapture atoms and restart MOT loading



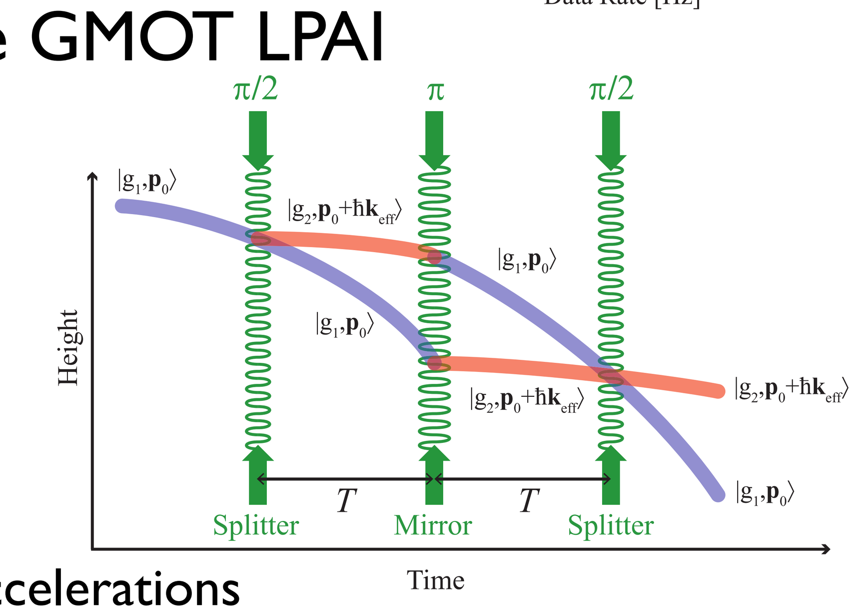
Proof-of-Concept High Data Rate GMOT LPAI

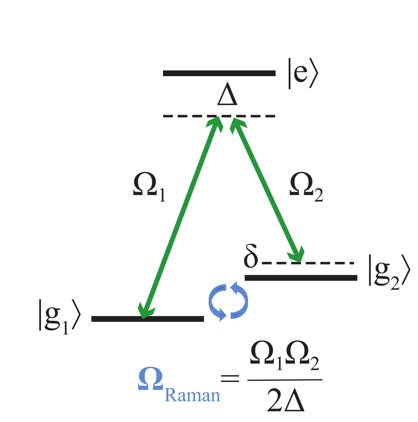
Drive coherent transitions between $|g_1\rangle = |5S_{1/2}, F = 1, m_F = 0\rangle$ and $|g_2\rangle = |5S_{1/2}, F = 2, m_F = 0\rangle$ with counterpropagating cross-linearly-polarized Raman using $\frac{\pi}{2} \to T \to \pi \to T \to \frac{\pi}{2}$ pulse sequence.

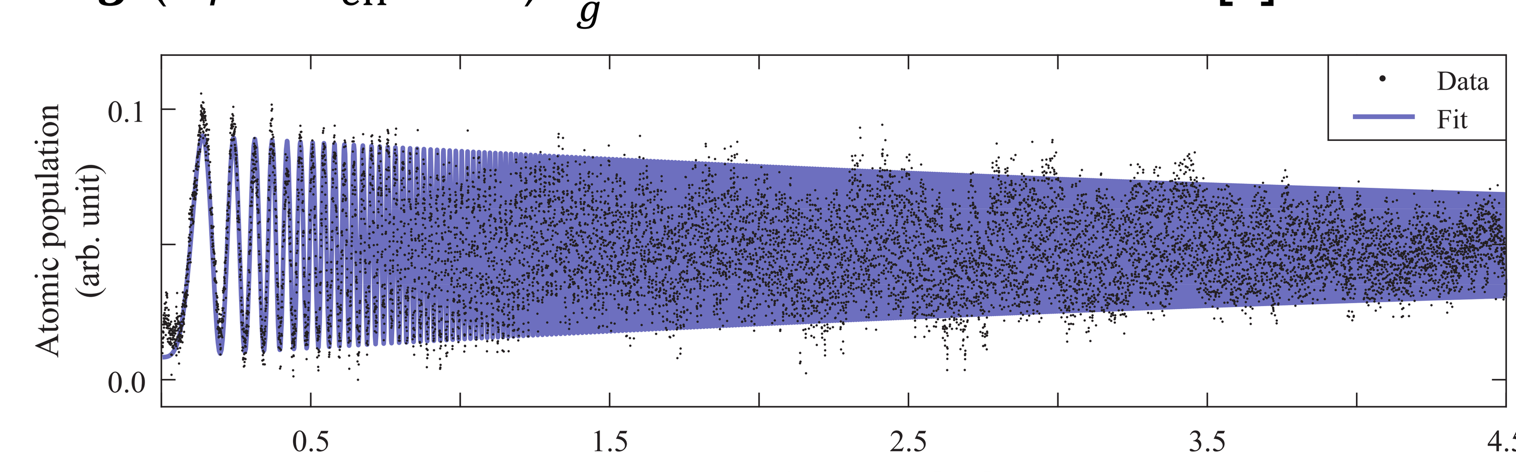
- Atomic population coherently oscillates between $|g_1\rangle$ and $|g_2\rangle$
- Interference fringe phase is sensitive to accelerations

$$\Delta\phi = \boldsymbol{k}_{\text{eff}} \cdot (\boldsymbol{a} - 2\boldsymbol{v} \times \boldsymbol{\Omega})T^2$$

- Scan T with $\mathbf{a} \parallel \boldsymbol{g}$ ($\Delta\phi = \boldsymbol{k}_{\text{eff}} \cdot \boldsymbol{a}T^2$): $\frac{\Delta g}{g} \approx 2 \times 10^{-6}$ at $R = 10$ Hz [6]







Lessons Learned

- Truncated-Gaussian "flat-top" GMOT cooling beam only delivers ~16% power out of fiber to vacuum package ($I_0 \approx 1.1\ \text{mW/cm}^2$)
  - Use 780 nm tapered amplifier to deliver $I \approx 10\ \text{mW/cm}^2$ to GMOT [17,18]
- No mechanical degrees-of-freedom made troubleshooting difficult
  - Current: replaced fixed Raman launch optics with free-space launchers
  - Next: investigate flat-top beam shapers to alleviate alignment challenges [19]
- While DPMZMs enables fast (almost) arbitrary frequency modulation, suppression of unwanted sidebands is imperfect and varies over time
  - Suspected cause of poor short term sensitivity ($\sigma \sim 10^{-5} g$)
  - Current: replace DPMZMs with AOMs
  - Next: look at alternatives (e.g., active servo control, fiber Bragg gratings)

Next Steps

- Mobile (move-stop-measure) LPAI test and rate-table test
- Hybridize with classical sensors to improve dynamic range of AI [20]
- Investigate planar MOT coils [21], alternative grating designs [8]

Sandia National Laboratories