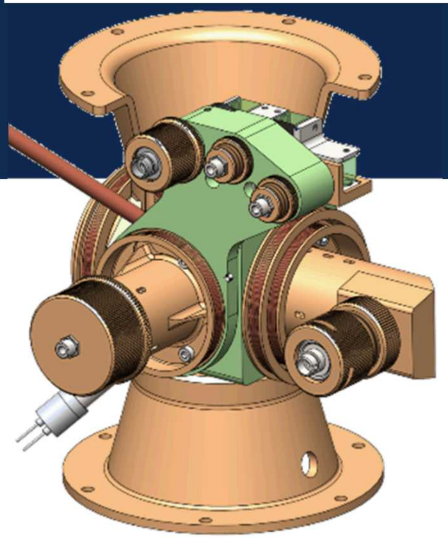
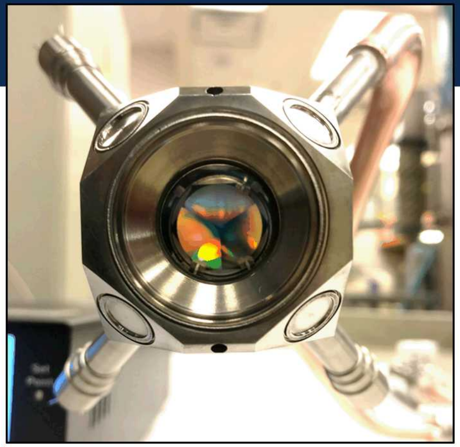
SAND2020-9489C

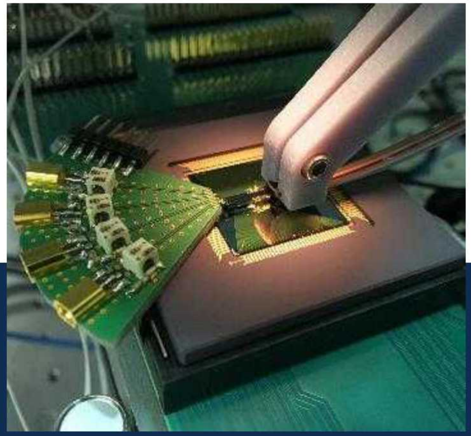
Strategic Inertial Guidance with MAtterwaves (ΣΙΓΜΑ)





Deployable Cold Atom Interferometry Sensor Platforms Based On Diffractive Optics and Integrated Photonics

Jongmin Lee



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Outline

- Motivation for a compact atom interferometer (AI)
- Sandia Development in SIGMA Grand Challenge (GC)
- Passively pumped vacuum package
- Integrated photonics platform
- AI demonstration with compact sensor head and diffractive optics
- Conclude

Motivation

- Atom interferometers (AIs) are excellent inertial sensors
  - Exciting candidate for inertial navigation under GPS-denied environments
- Can an atom interferometer be substantially miniaturized while maintaining high performance?
  - Research the technologies that enable miniaturization of an AI.

	Navigation Grade (HG9900)	Atom interferometer (Lab demos)	SIGMA Goals (1-axis accel)
Accel Bias (1σ) $[\mu g]$	< 25	$< 10^{-4}$	<0.25
Accel SF (1σ) $[PPM]$	< 100	$< 10^{-4}$	1
Accel Random Walk $[\mu g/\sqrt{Hz}]$	not reported QA ~ 10	10^{-5}	<1
Gyro Bias (1σ) $[\deg/hr]$	< 0.003	$< 7 \times 10^{-5}$	
Gyro SF $[PPM]$	< 5	< 5	
Gyro Random Walk (1σ) $[\deg/\sqrt{hr}]$	< 0.002	2×10^{-6}	

QA: Quartz Accelerometer
RLG: Ring Laser Gyroscope

≈6”

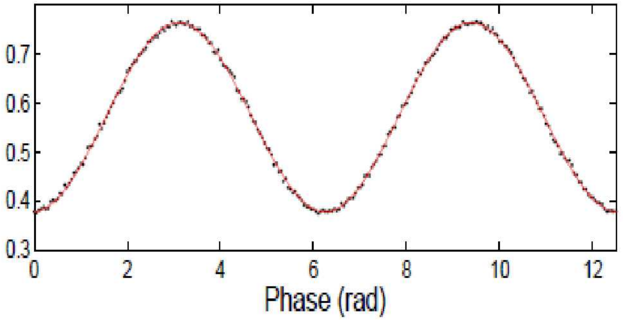
QA (x3) & RLG (x3)

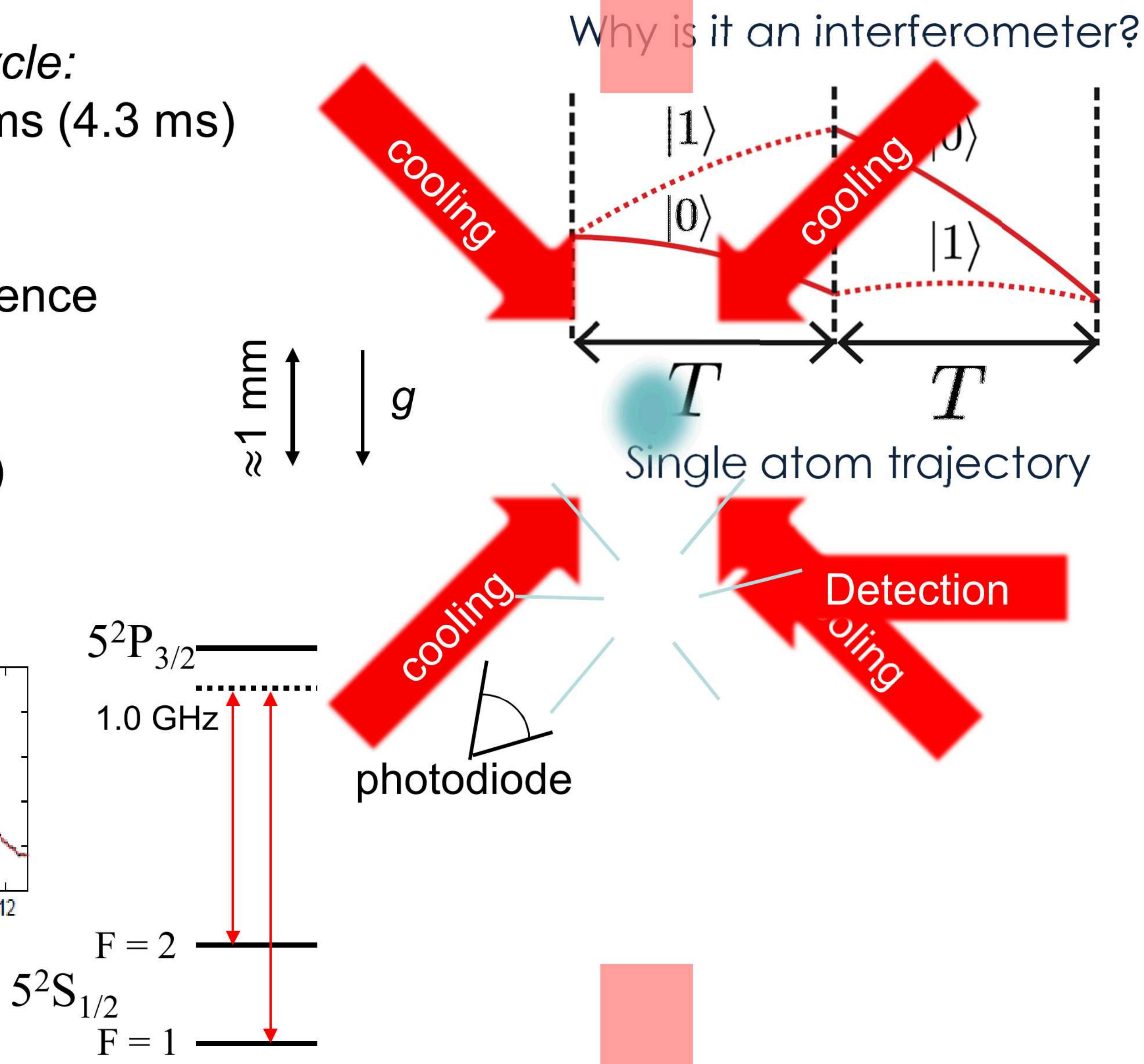
One measurement cycle

Example, (40 Hz)$^{-1}$ cycle:

- Laser cool 10^6 atoms (4.3 ms)
  - $T \approx 15\ \mu K$
- Release atoms
- Raman pulse sequence (14 ms, T = 7 ms)
- Detect
- Recapture (1.7 ms)

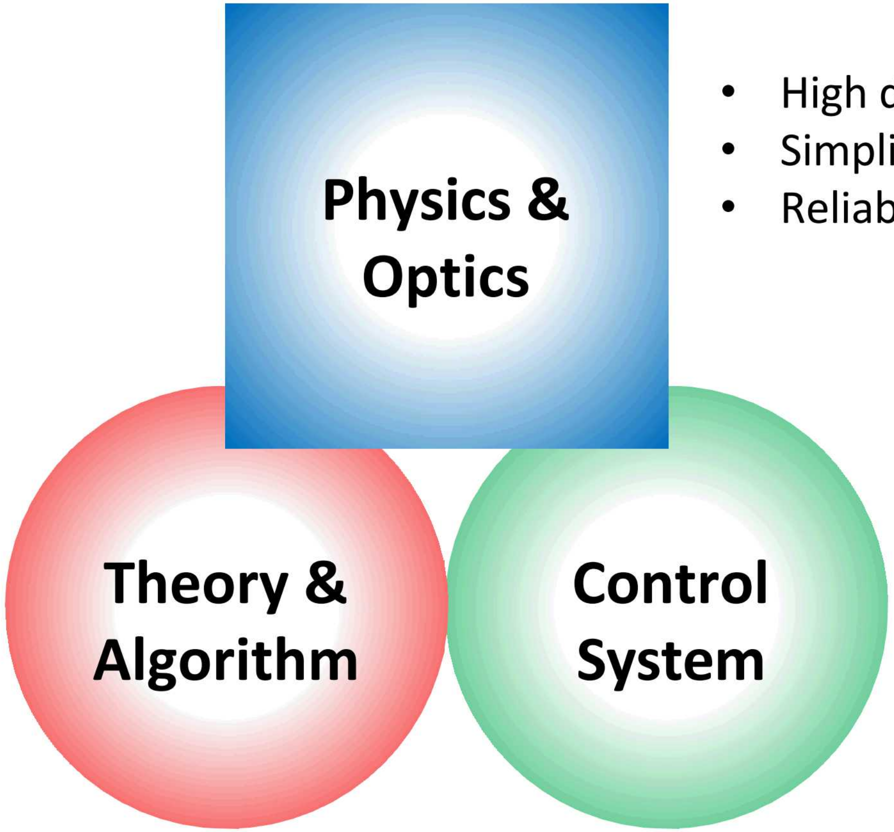
Acceleration →





H. J. McGuinness, et al., Appl Phys Lett **100**, 011106 (2012).

Three Key Components toward Deployable Cold Atom Inertial Navigation Sensors



Physics & Optics
- High data-rate AI operation
- Simplified laser architecture
- Reliable and compact optomechanical structure

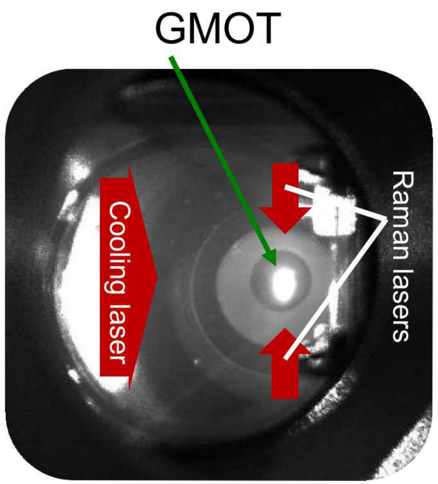
Theory & Algorithm
- Complete AI physics model
- IMU cosensor inputs
- AI feedforward algorithm

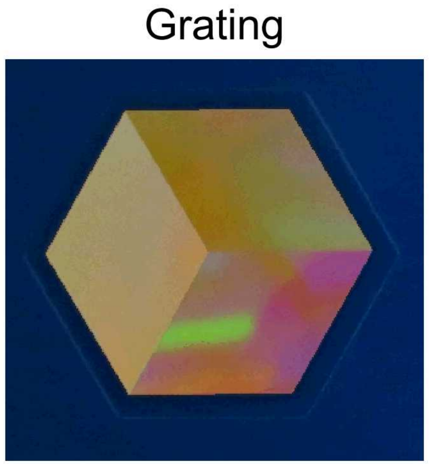
Control System
- Reliable AI control electronics
- Real-time AI feedforward processor
- Self-calibration/optimization

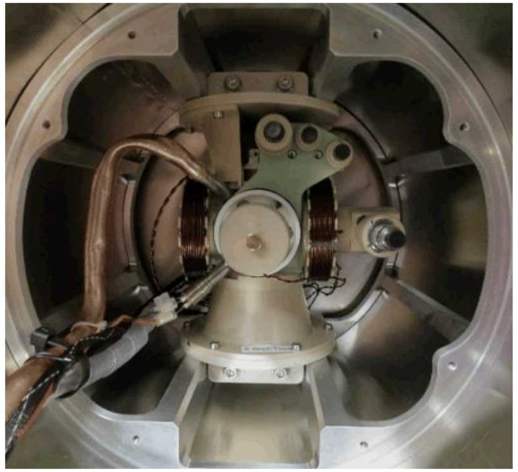
AI: Atom Interferometer
IMU : Inertial Measurement Unit

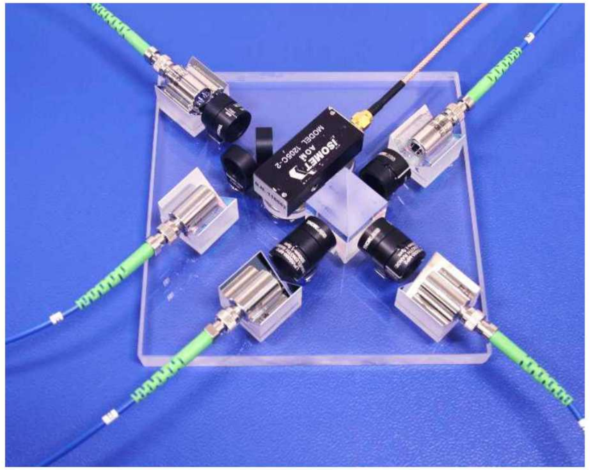
Sandia Development in SIGMA GC

- Atom interferometer prototype

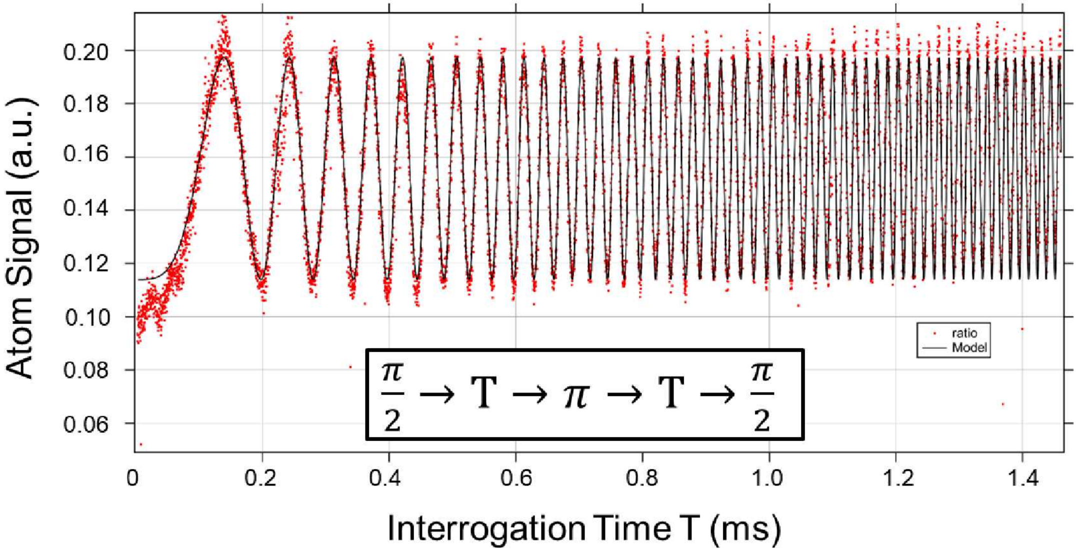






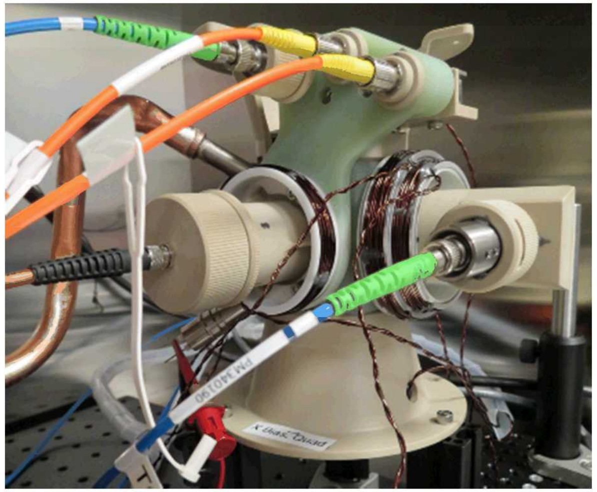


Gravimeter Signal

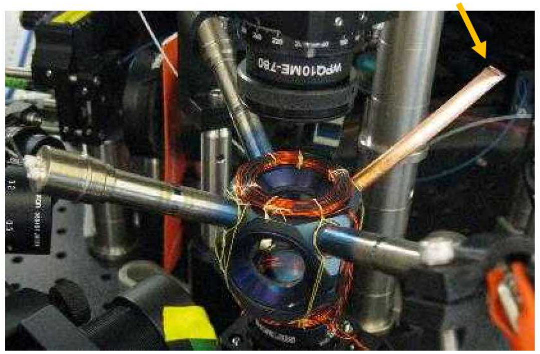


Sandia Development in SIGMA GC

- Alignment-free AI sensor head designs

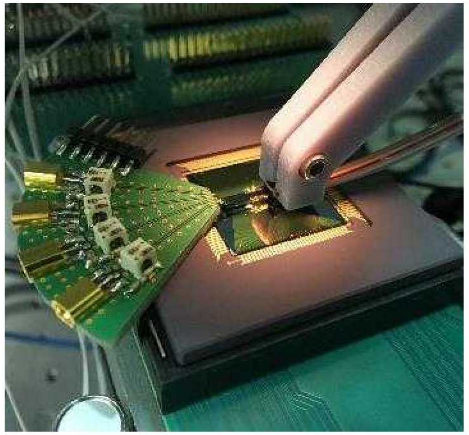


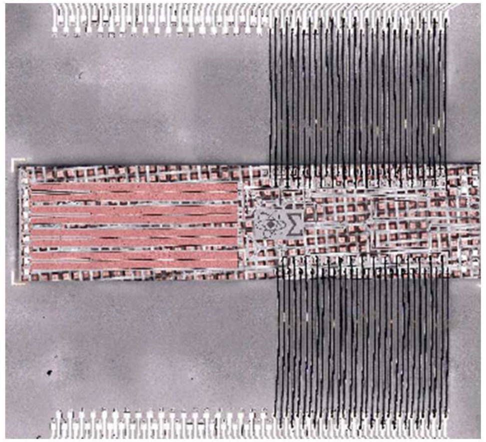
- Vacuum package: passively pumped operation > 5 month

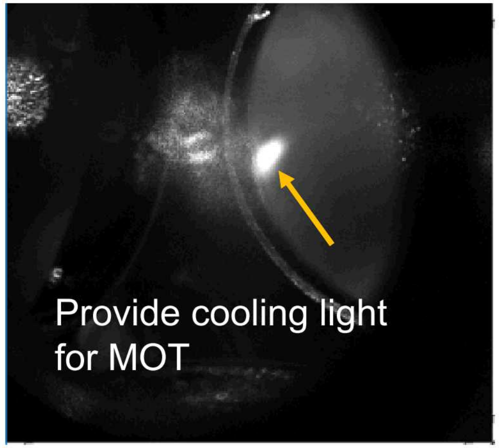


Sandia Development in SIGMA GC

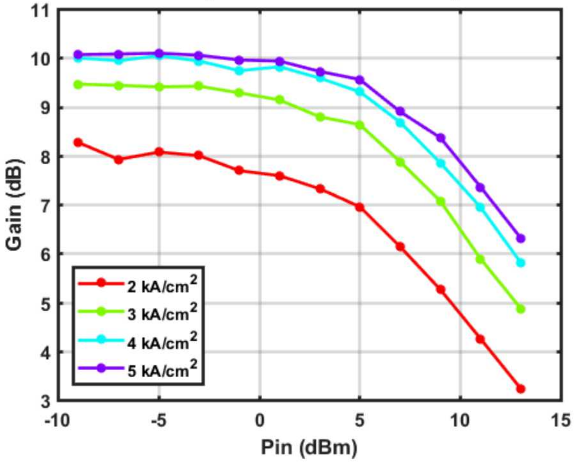
- Silicon Photonic Single Sideband Modulator

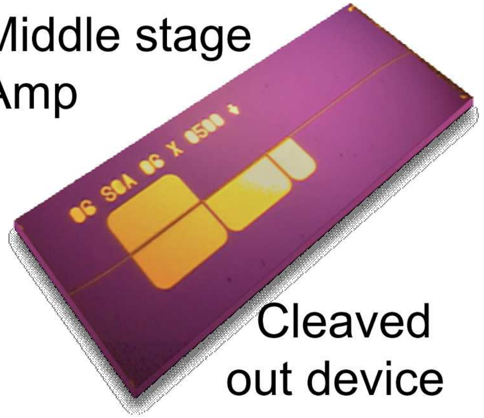






- III-V Optical Amplifier



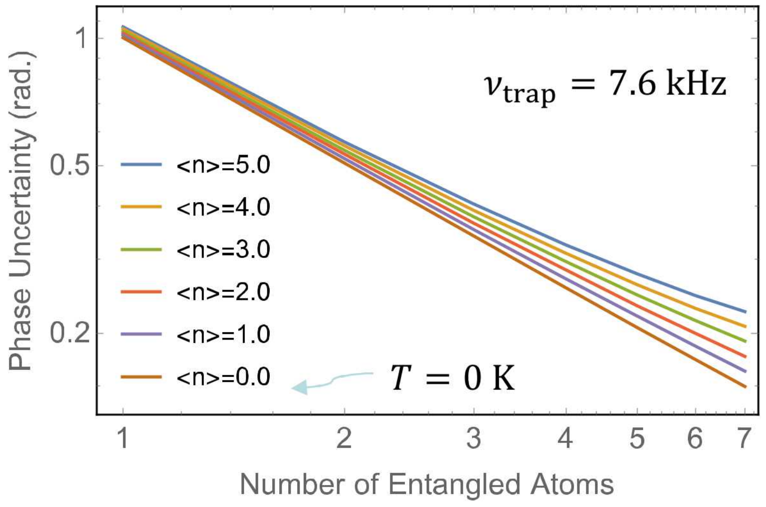


- Exploring E-FISH doubling
- Impressive results from Yale (amplifiers) and University of San Diego (LiN doublers)

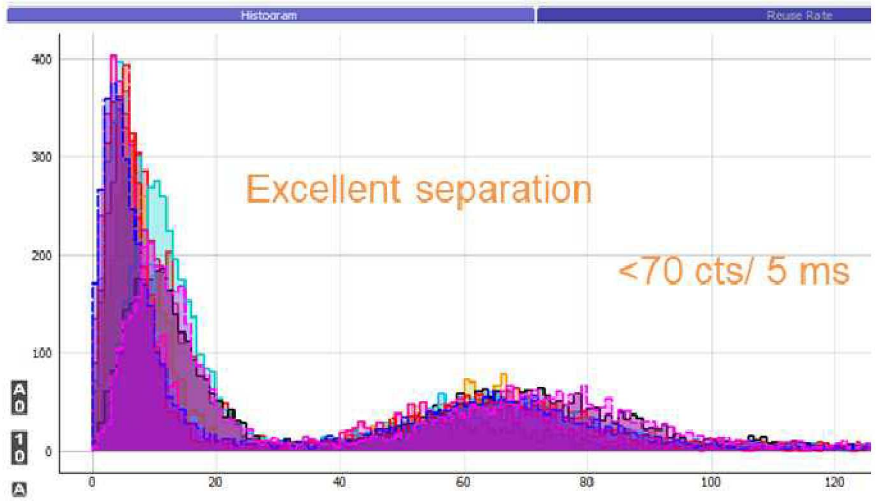
Sandia Development in SIGMA GC

- Advanced Entanglement-Based Sensing

Error characterization paper published



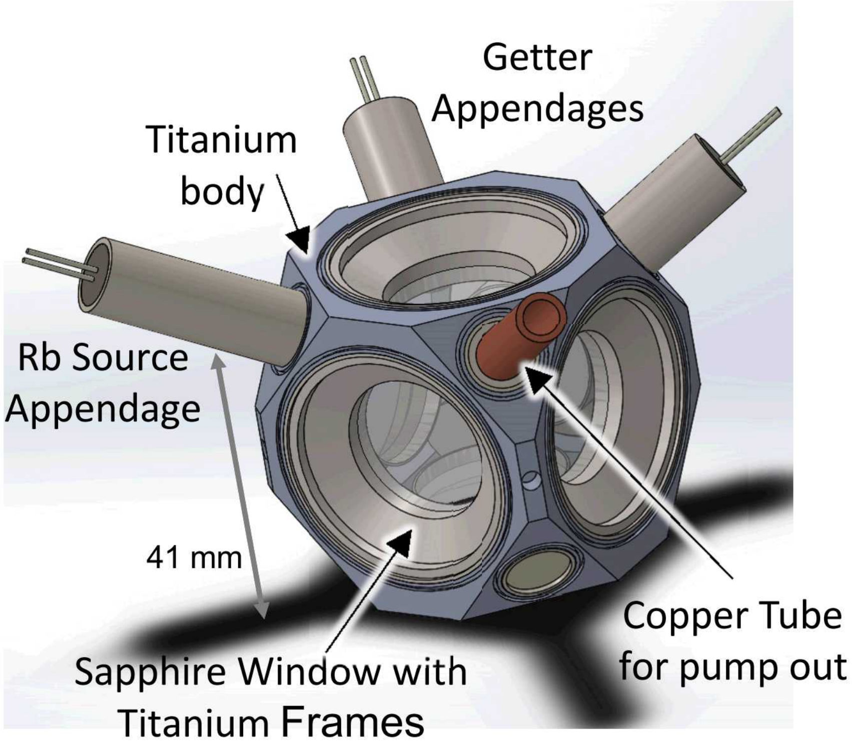
Moving toward better entanglement fidelity

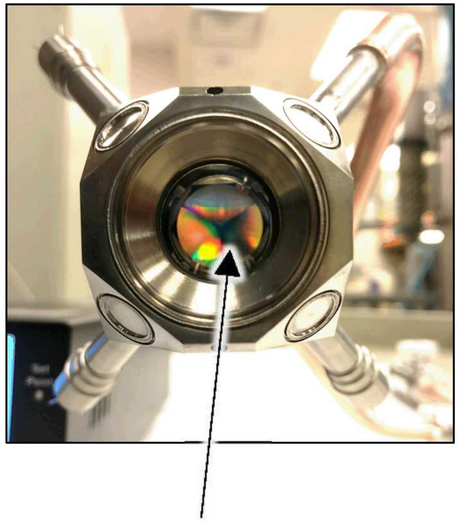


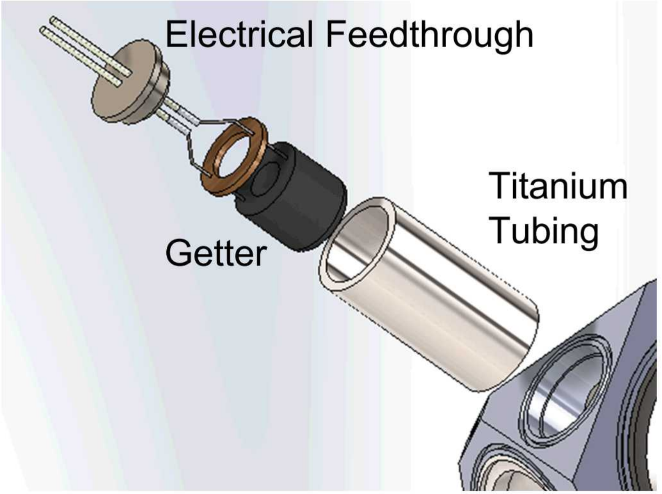
- Extending the Dynamic Range in Simulation

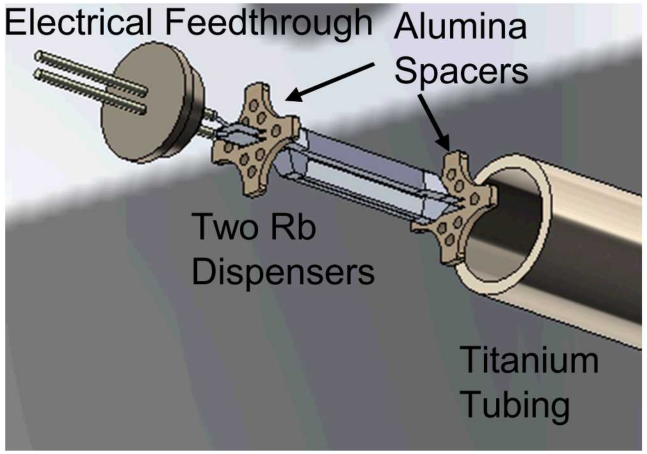
Passively pumped Vacuum Package: Titanium Package Design

- Passive pumping: SAES St172 getters
- C-cut sapphire windows, AR-coated
  - No helium permeation (or very low)
- Rb dispenser: SAES Rb-dispensers.
- Copper pump-out tube for eventual pinch-off seal.
- Sealing: laser welding and brazing
- Preparation: 400 ^{o}C bake-out in vacuum furnace

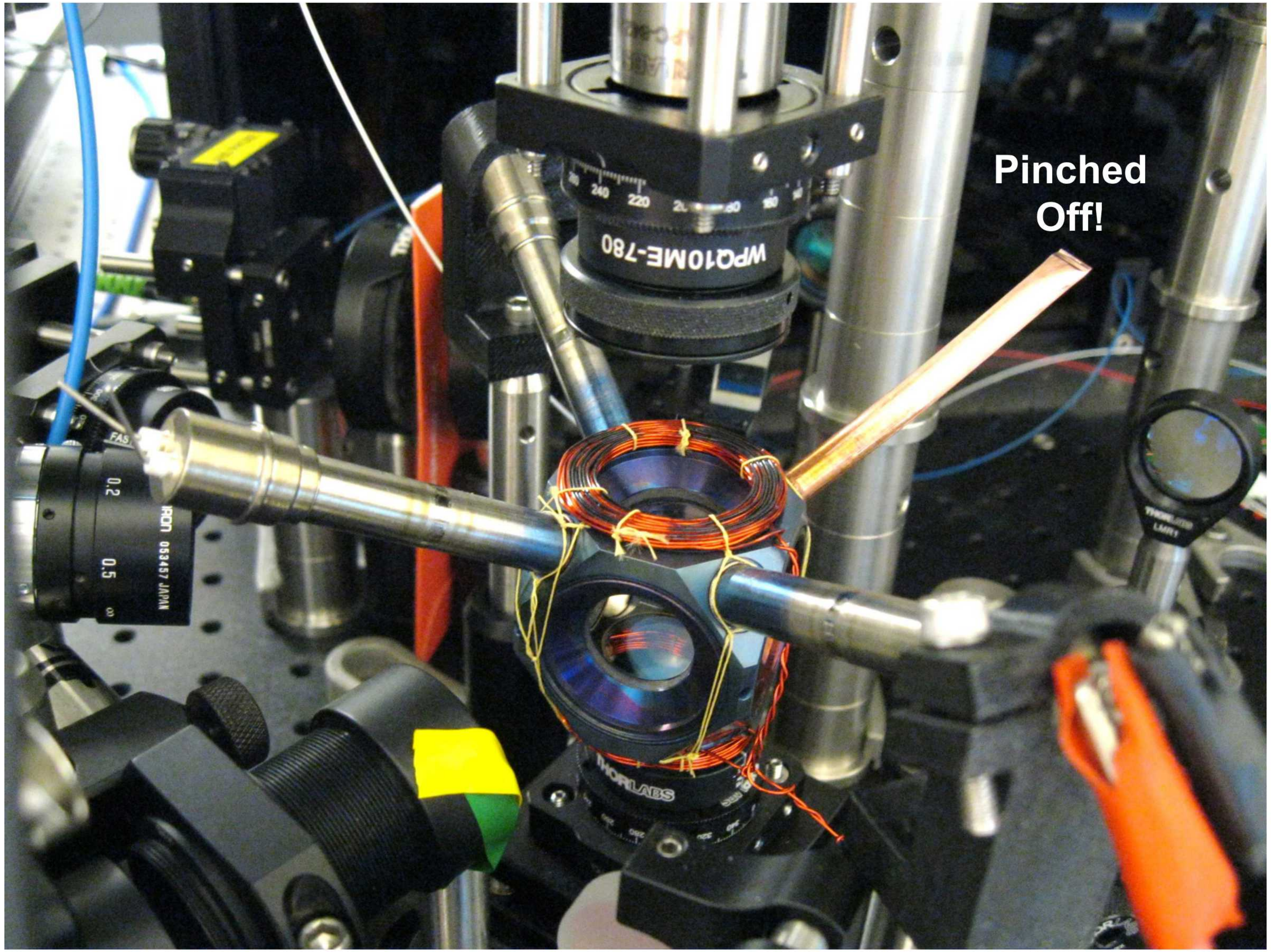






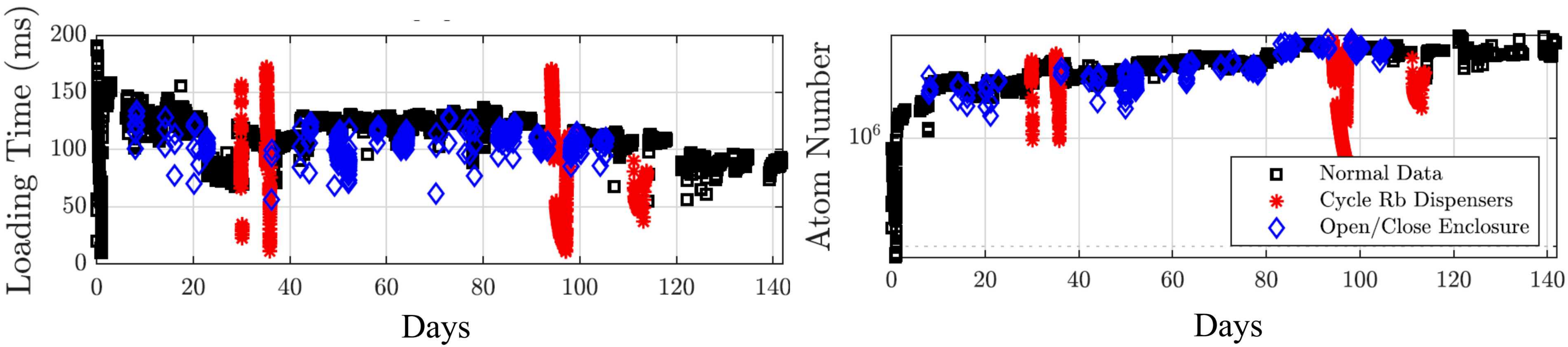


Passively pumped Vacuum Package: Titanium Package Design



MOT in the Passively Pumped Chamber

Sustaining Cold Atoms for More Than 140 Days



- MOT seems happier with “pinch-off” rather than “pump off”.
  - $(N\tau)_{\text{pinch-off}} \approx 3 \times 10^5$ atoms $\cdot$ s vs $(N\tau)_{\text{pump-off}} \approx 0.7 \times 10^5$ atoms $\cdot$ s.
- Estimate pressure to be ~2×10^{-7} Torr. P_{Rb} = ~ 0.5×10^{-7} Torr
  - Large uncertainty in pressure estimates: need a clean way to estimate/vary P_{Rb} and alignment effects.

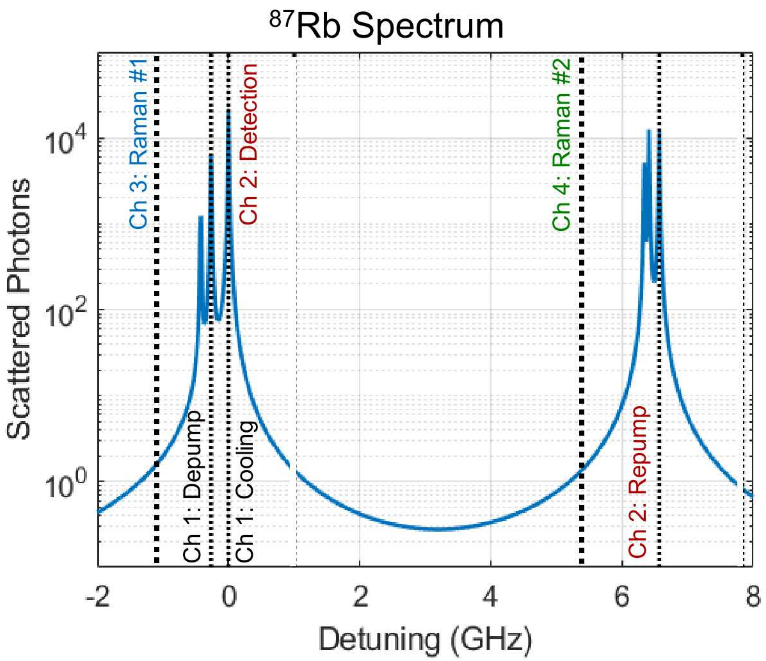
Integrated Laser Implementation

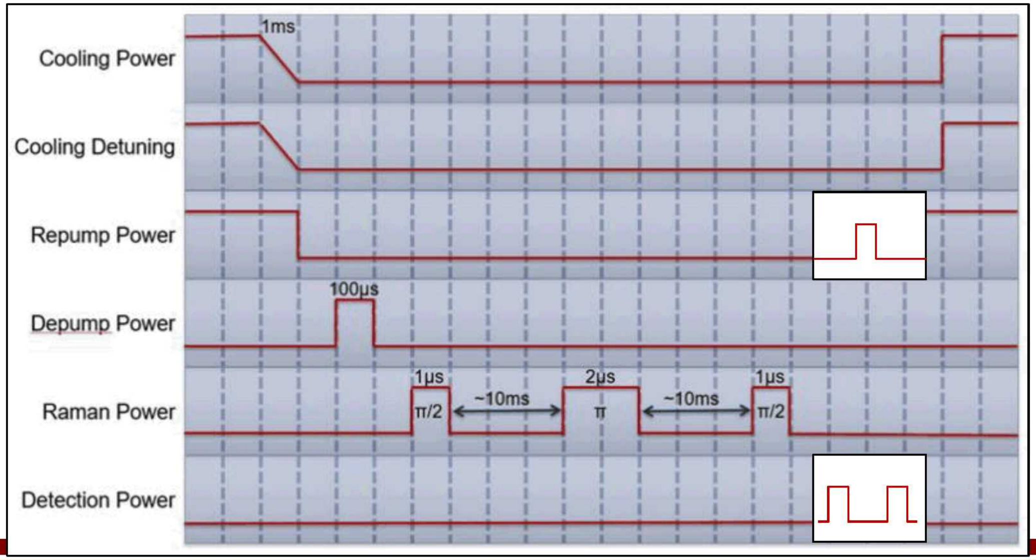
Five laser channels

- Ch 1: Cooling and depump
- Ch 2: Repump and detection
- Ch 3: Raman #1 (Seed laser frequency)
- Ch 4: Raman #2
- Ch 5: Laser Lock (Sat. spec.)

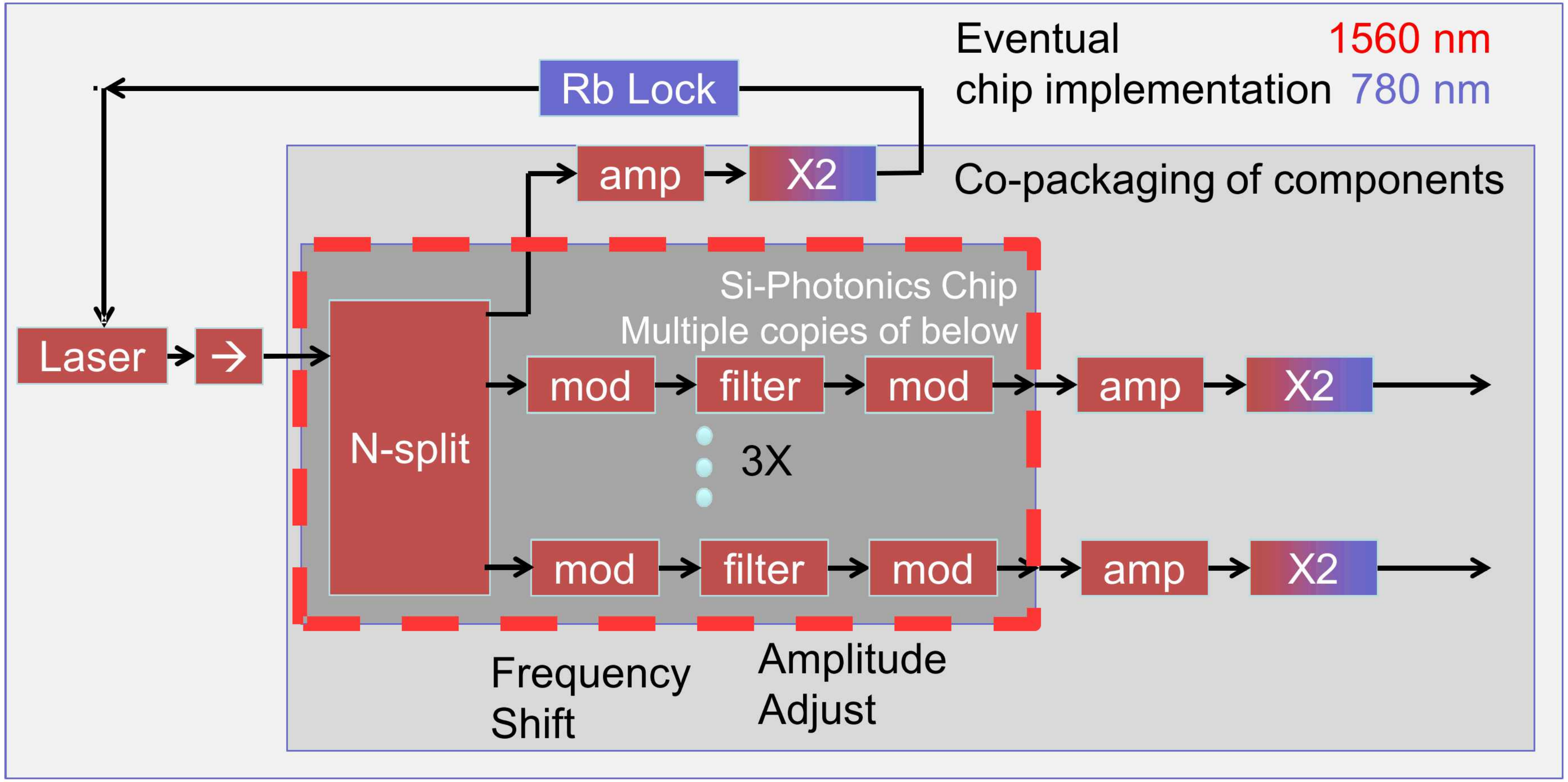
Timing

- Raman pulses: 1-10 μs
- State sensitive detection pulses: ~0.1 ms



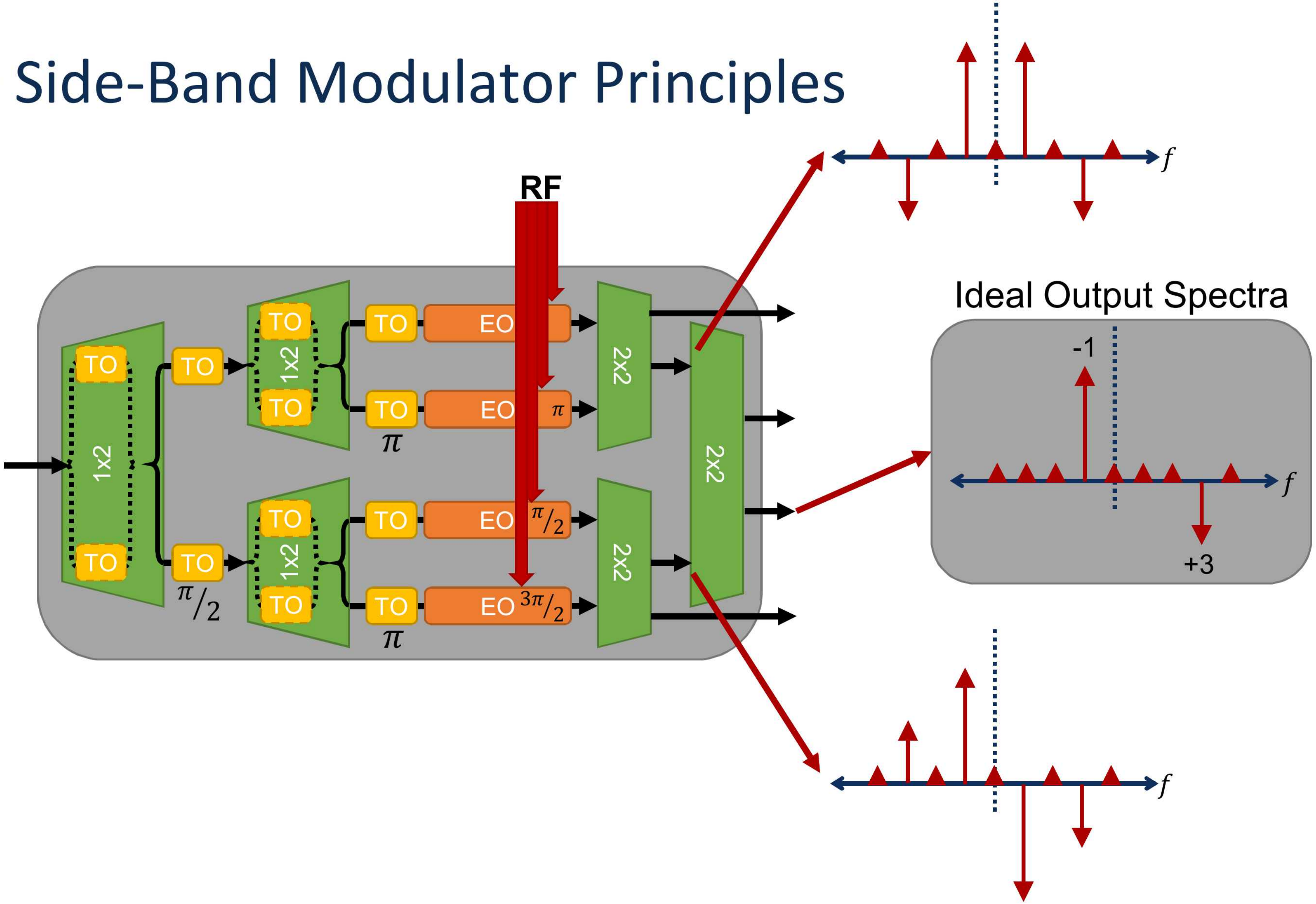


Integrated Photonics Overview

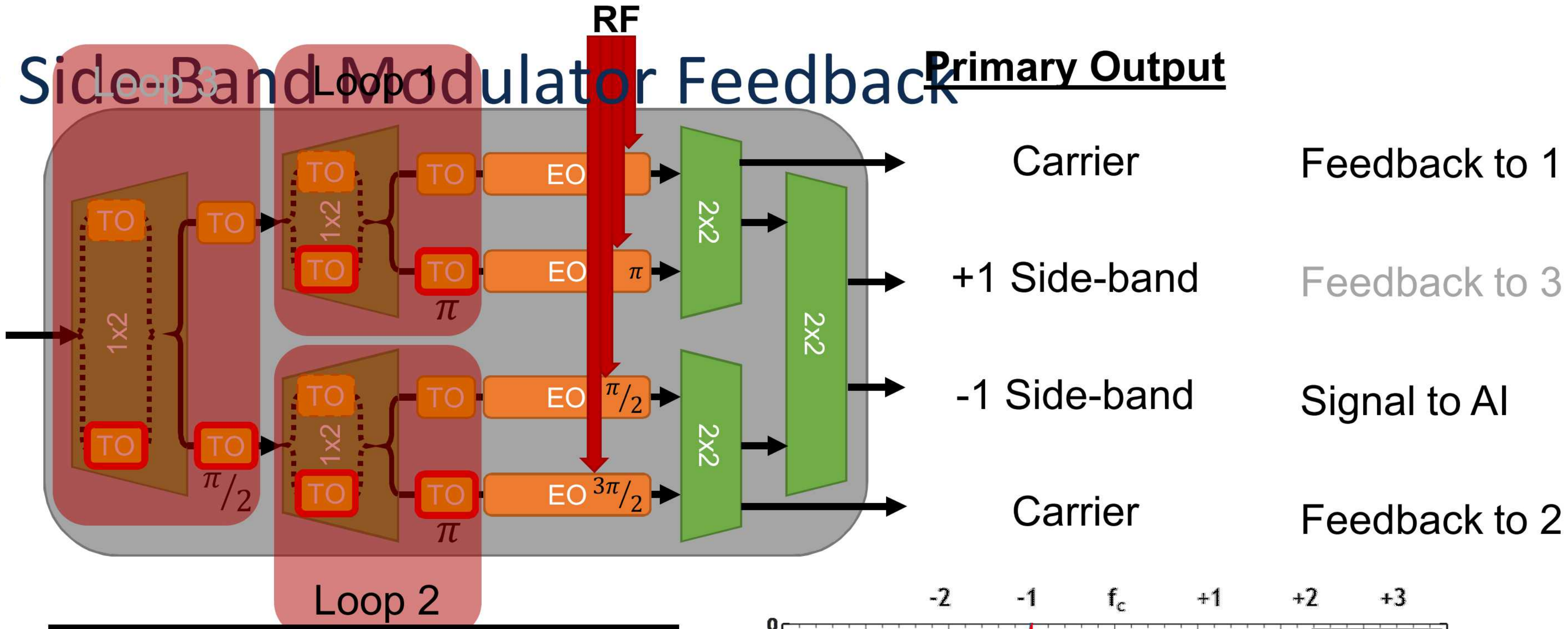


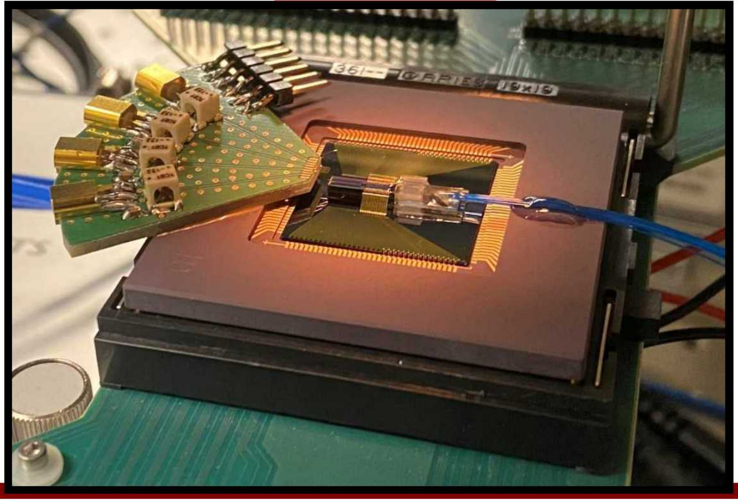
Scalable Photonic Architecture

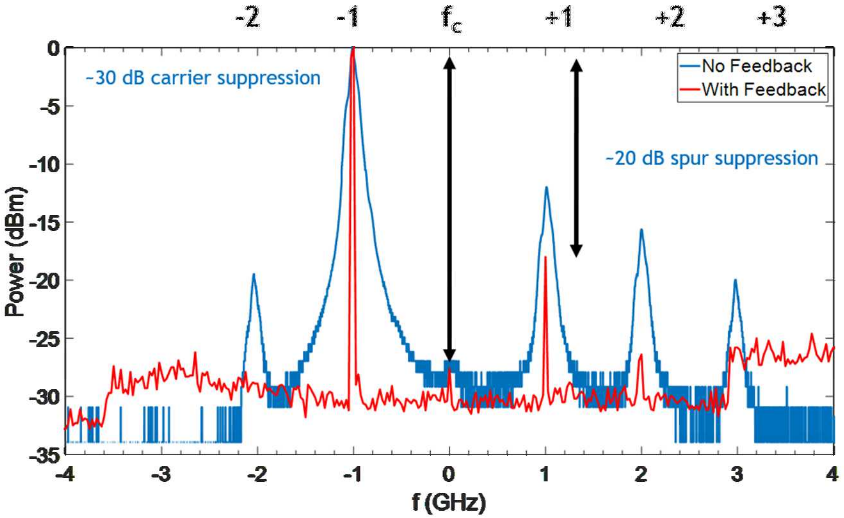
Single Side-Band Modulator Principles



Single Side Band Modulator Feedback

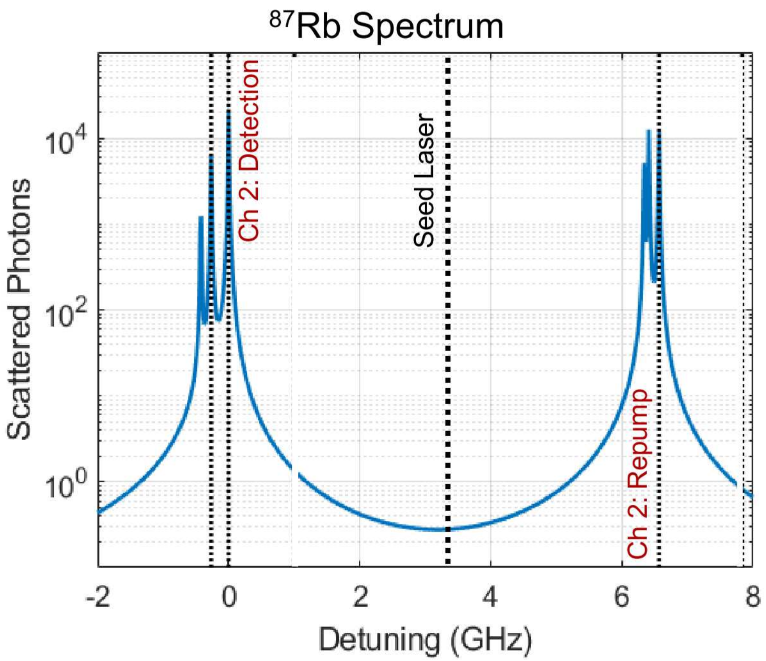


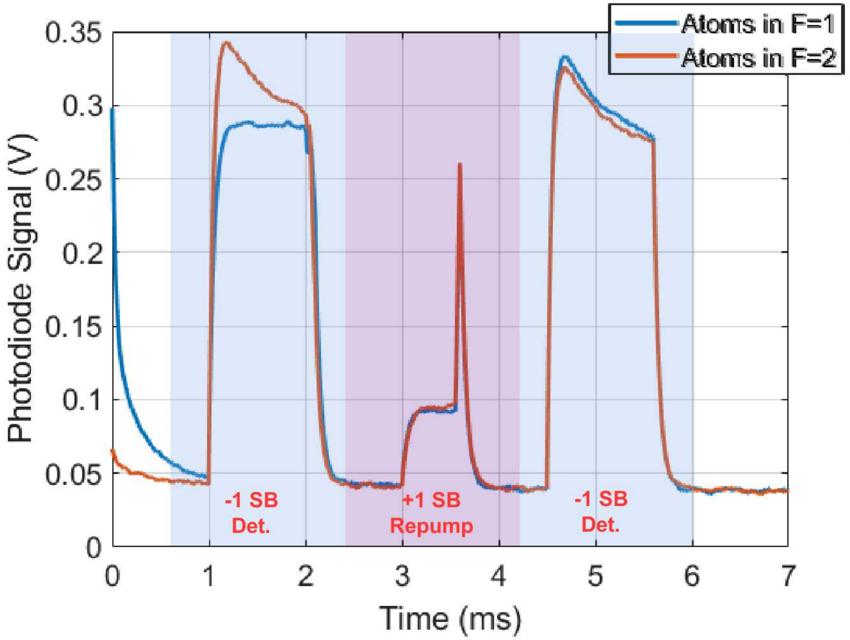


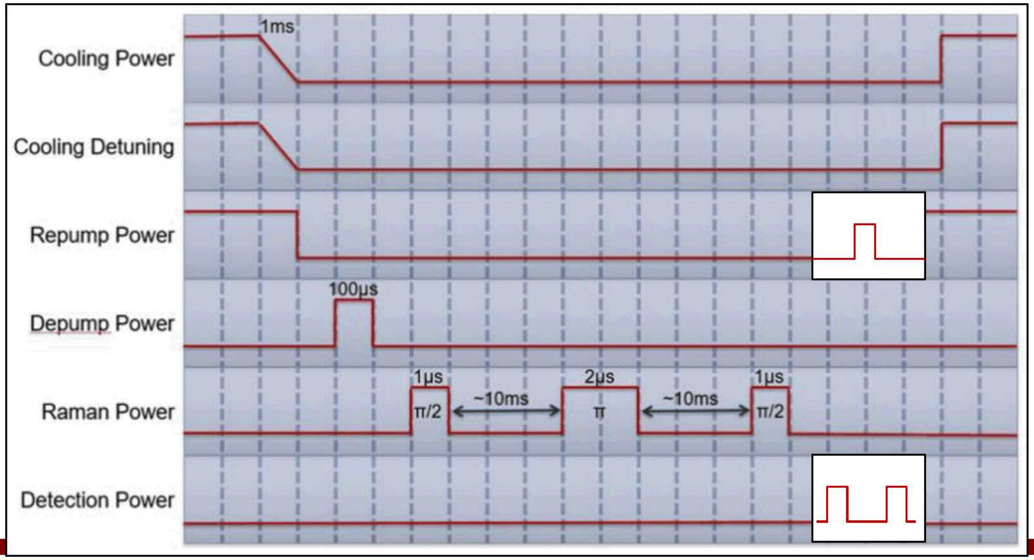


Packaged SSBM Demonstration

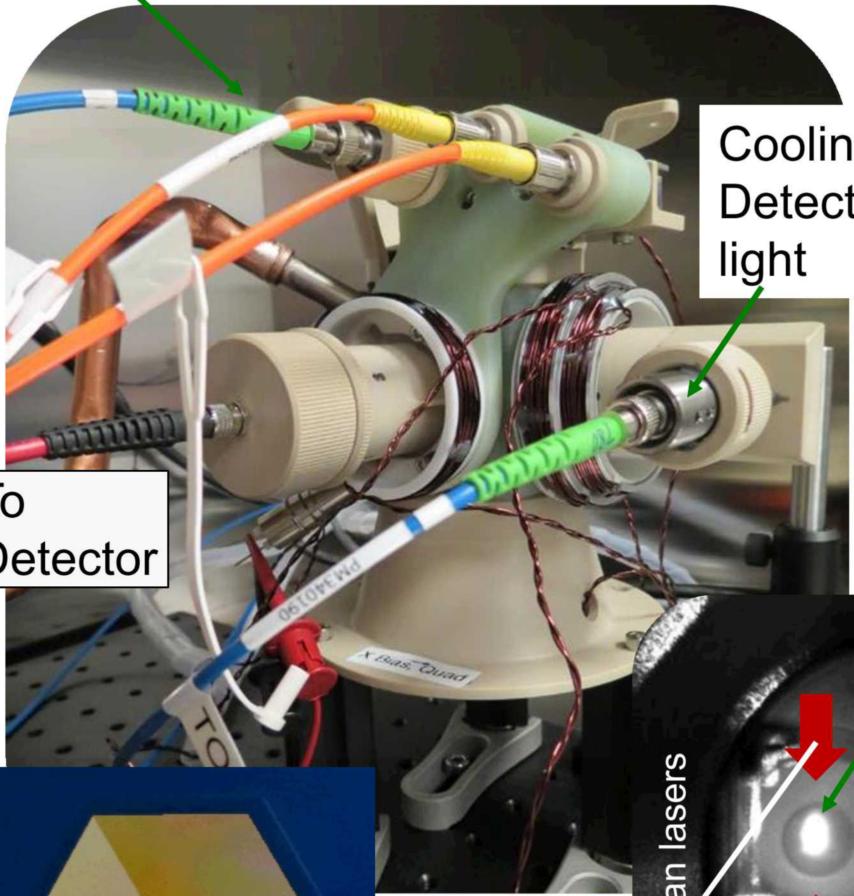
- State Selective Detection Successfully Demonstrated
  - Seed laser locked at midpoint of detection & repump frequencies
  - Modulator driven at 1.644 GHz
  - Thermo-optic phase shifters switched between +1 and -1 side-band
  - **Total frequency jump at 780nm – 6.576 GHz**



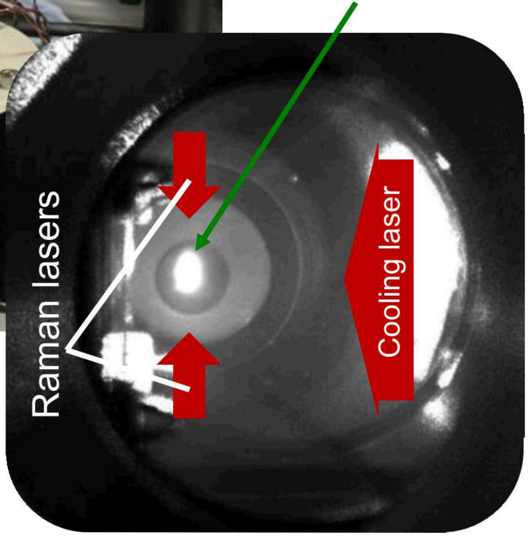




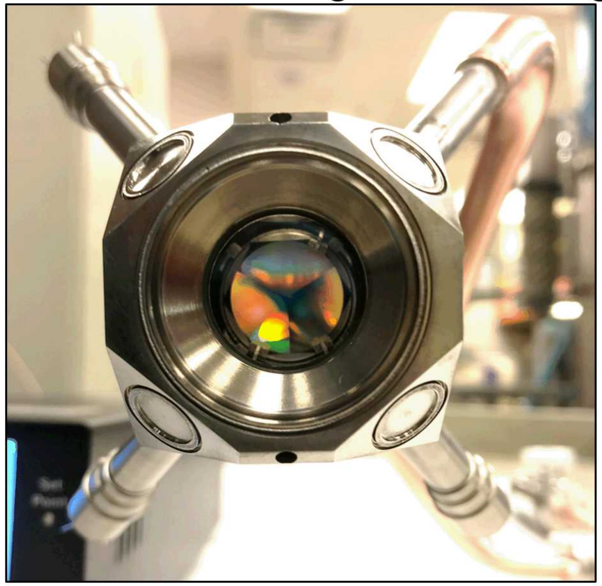
Compact Atom Interferometer Sensor Head



- Grating magneto optical trap (GMOT)
- Grating replaces one window of vacuum package
- Vacuum maintained by ion pump, fused silica windows
- Atom number: 10^6-10^7, Sub-Doppler cooling: 18 μK.



Ti Vacuum Package with Grating



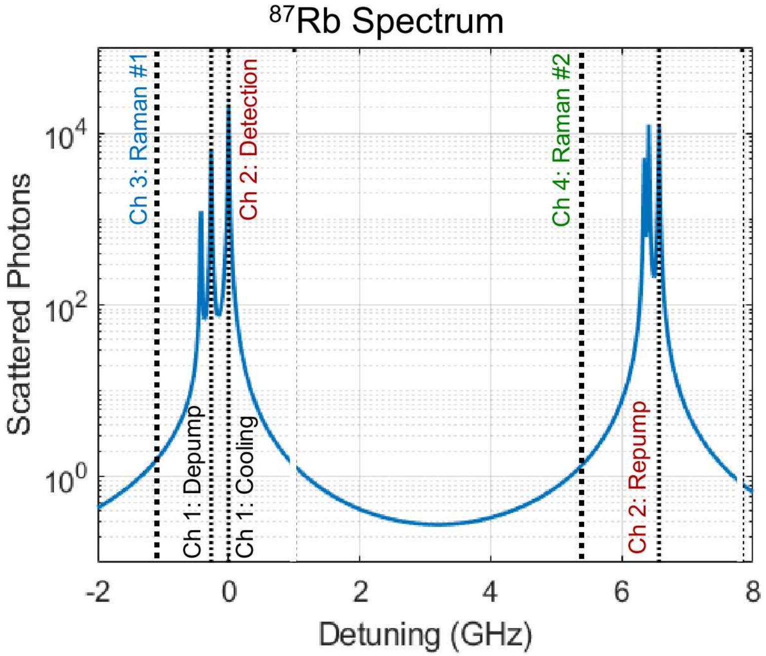
Same Raman configuration used in McGuinness, et al., APL (2012)

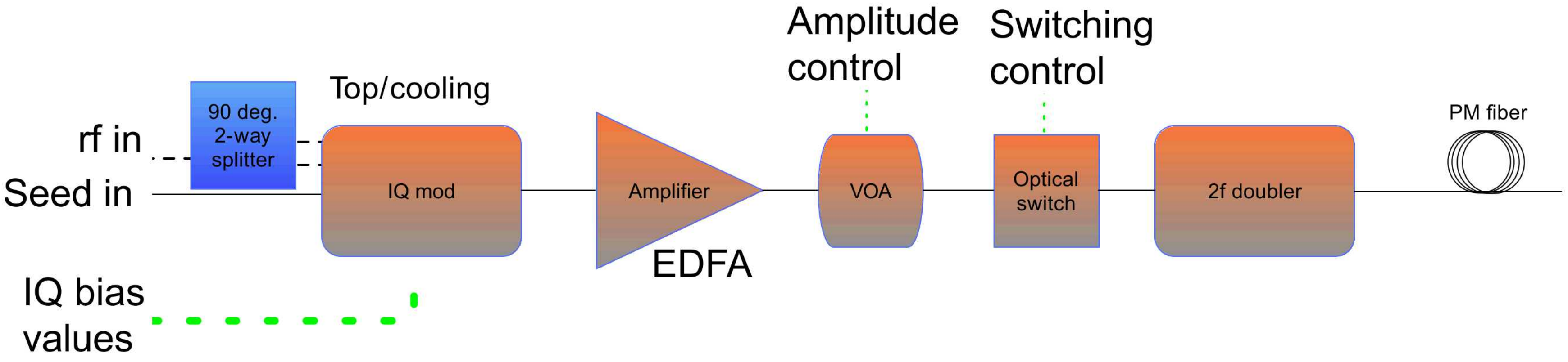
Commercial off the Shelf (COTS) Laser Architecture

Five laser channels (previously 4 channels)

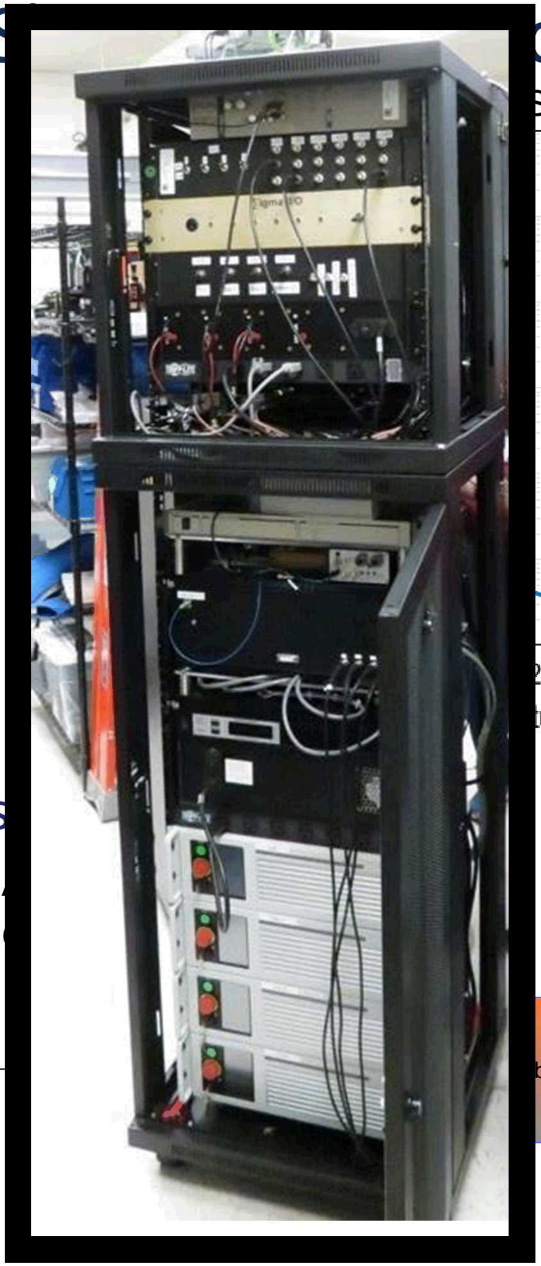
- Ch 1: Cooling and depump
- Ch 2: Repump and detection
- Ch 3: Raman #1 (Seed laser frequency)
- Ch 4: Raman #2
- Ch 5: Laser Lock (Sat. spec.)

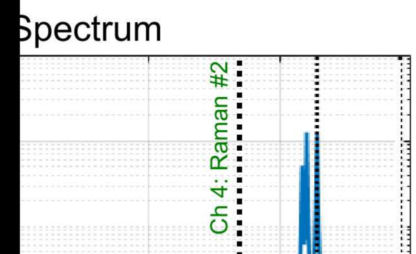
Seed : NP Photonics Rock Fiber Laser

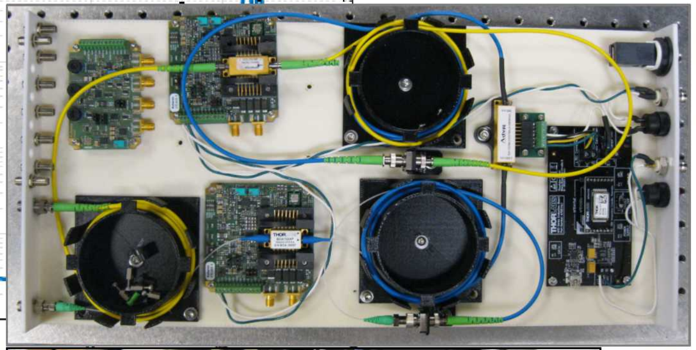




Commercial off the Shelf (COTS cture







Five laser channels (previously 4 channels)

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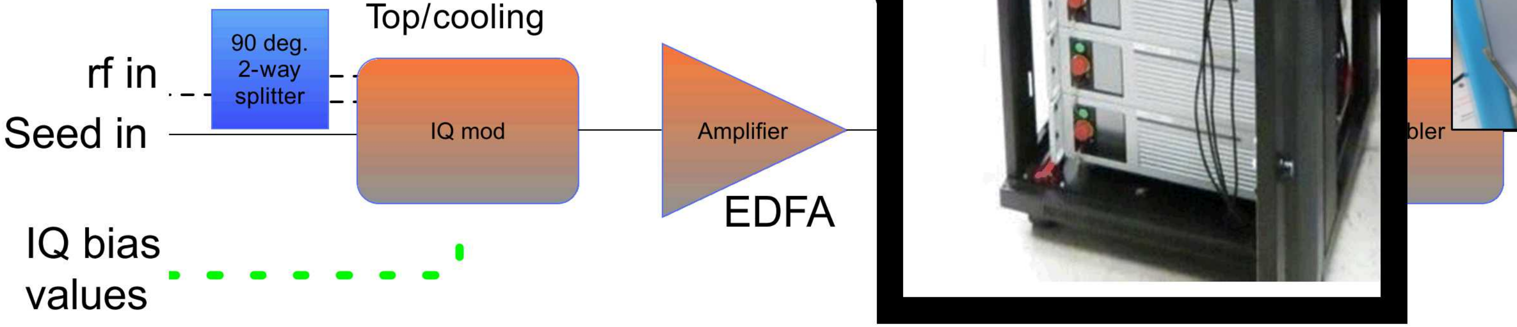
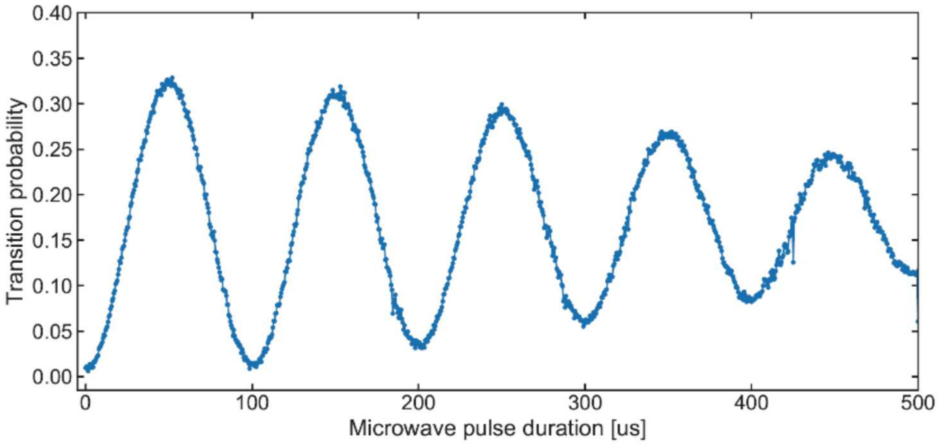


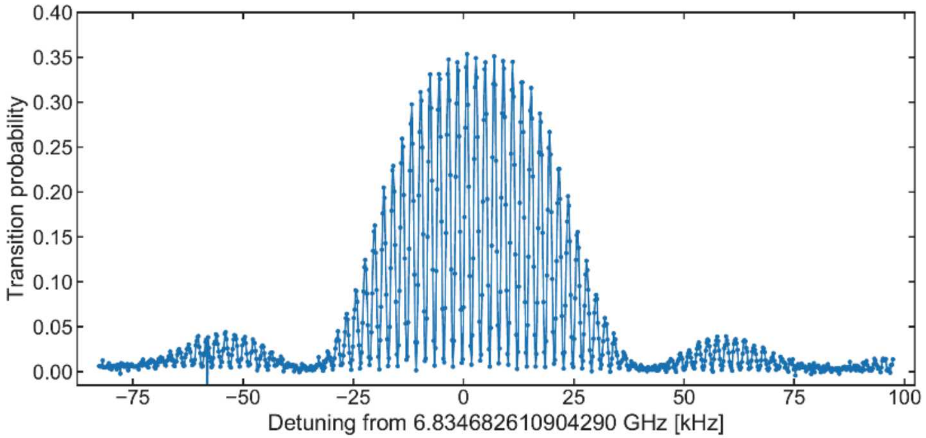
Atomic Coherence with microwaves

- Rabi oscillation with a microwave horn



Rabi oscillation:
Rabi frequency $\simeq 10\ \mathrm{kHz}$

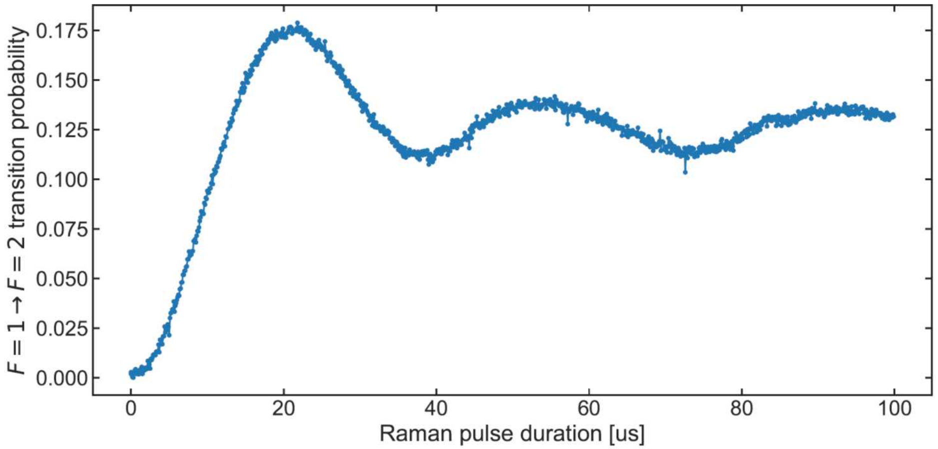
- Ramsey interferometry with a microwave horn



Ramsey sequence:
$\frac{\pi}{2} \rightarrow \mathrm{T} \rightarrow \frac{\pi}{2}$ (frequency scan)
Interrogation time $\mathrm{T} = 450\ \mu\mathrm{s}$

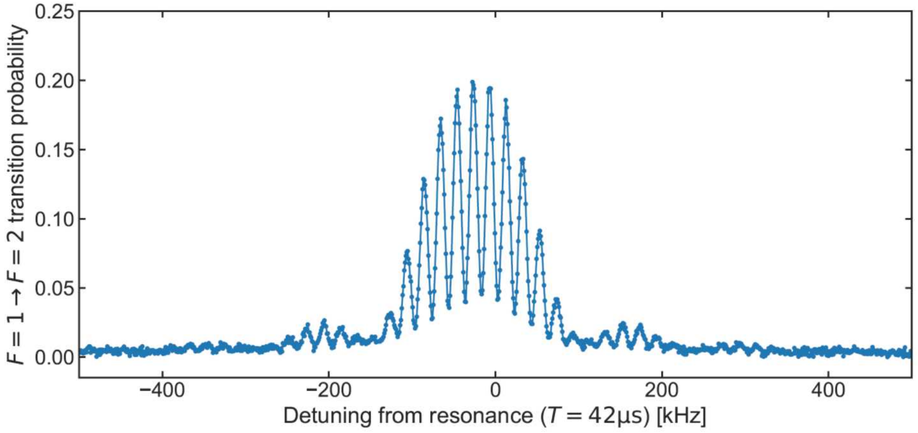
Atomic Coherence with Raman beams

- Rabi oscillation with Doppler-free Raman beams



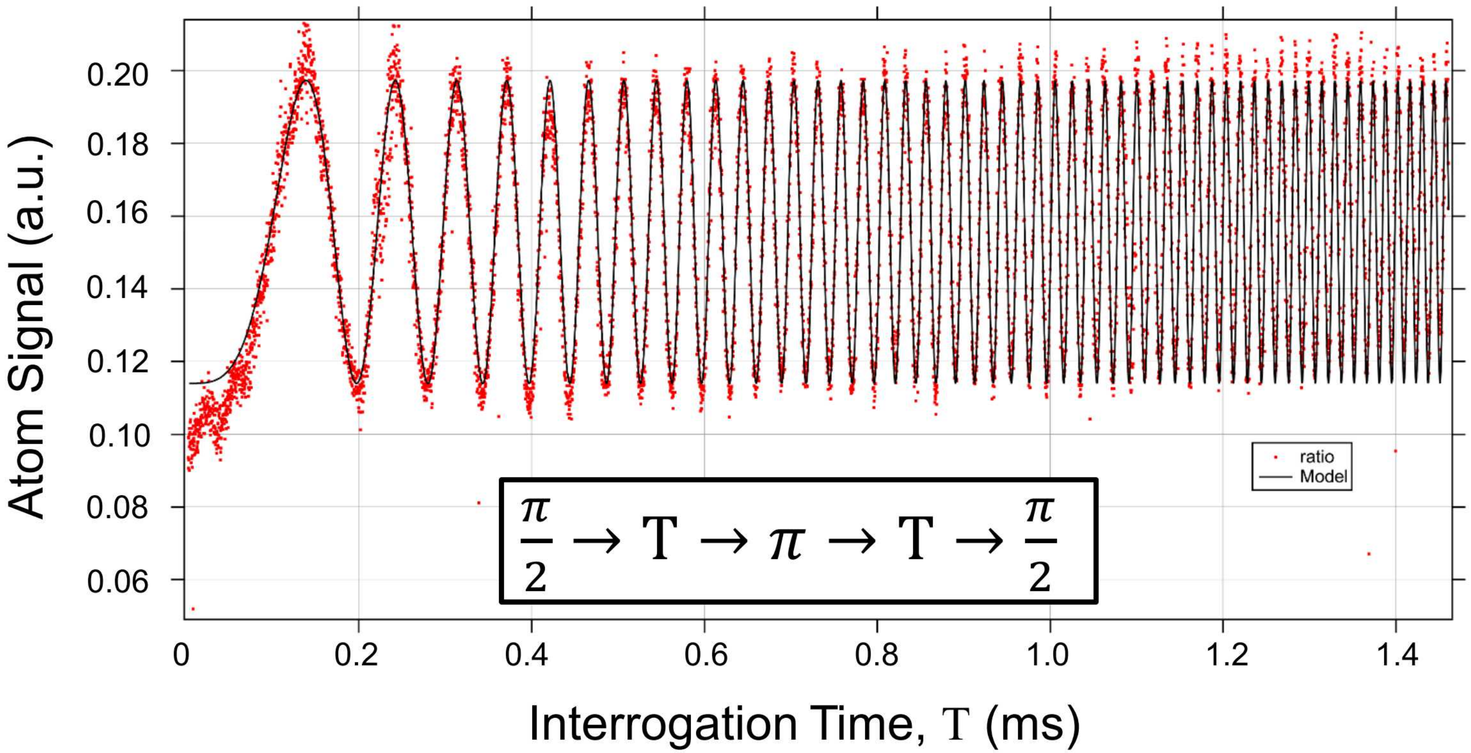
Rabi oscillation:
Rabi frequency $\simeq 27\ \mathrm{kHz}$

- Ramsey interferometry with Doppler-free Raman beams



Ramsey sequence:
$\frac{\pi}{2} \rightarrow \mathrm{T} \rightarrow \frac{\pi}{2}$ (frequency scan)
Interrogation time $\mathrm{T} = 42\ \mu\mathrm{s}$

Atom Interferometer Demonstration

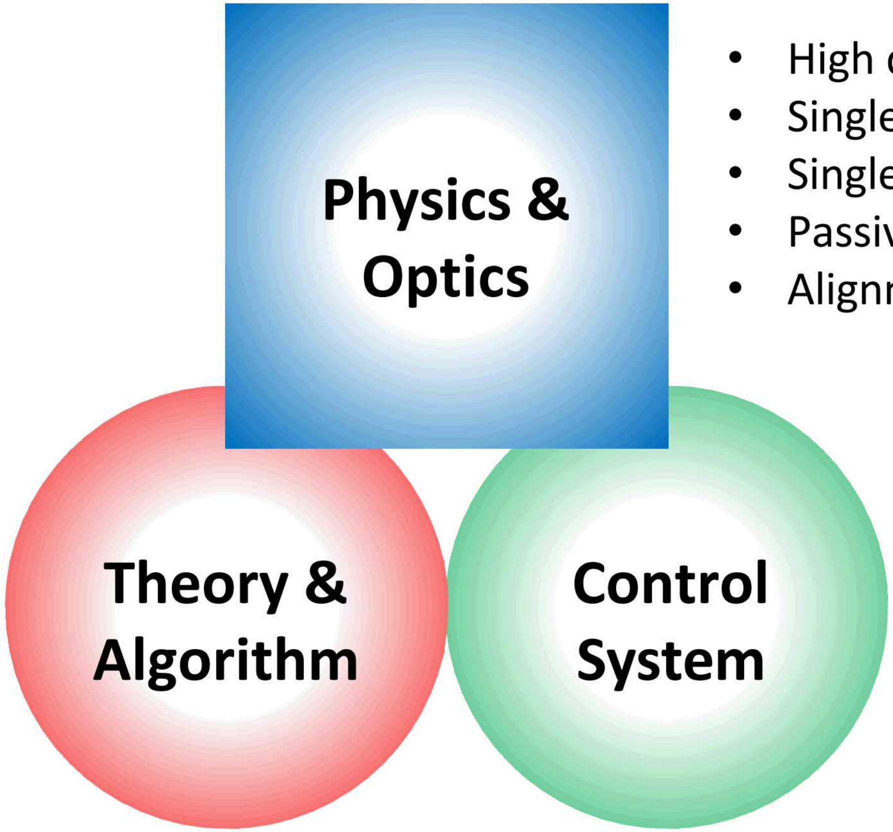


$$\frac{\pi}{2} \rightarrow \mathrm{T} \rightarrow \pi \rightarrow \mathrm{T} \rightarrow \frac{\pi}{2}$$

- Atomic accelerometer (atomic gravimeter) with a SIGMA prototype
- Sensing axis aligned to the direction of gravity.
- Atom interferometry with Doppler-sensitive Raman beams: T scan
- Data rate: 6.7 Hz
- Statistical uncertainty: < 25 μg (improving by the phase lock of two Raman beams)

SIGMA Developments toward Deployable Cold Atom Inertial Navigation Sensors

Why Sandia?



- High data-rate atom interferometry (40Hz)
- Single laser architecture (COTS & PIC)
- Single-beam grating-mirror MOT (GMOT)
- Passively pumped vacuum chamber
- Alignment-free and vibration-immune sensor head

- Navigation system expertise
- Physics modeling (Monte Carlo) + IMU cosensor + Kalman filter

- Time-critical control electronics
- Algorithm implementation for operating in dynamic environments

COTS: Commercial-off-the-shelf
PIC: Photonic Integrated circuits
MOT: magneto-optical traps

Conclusion

- SIGMA is multifaceted program
  - Vacuum package development
    - Passively pumped operation for ~ 5 month
  - Integrated photonics platform
    - Single sideband modulator with suppressed carrier
    - Demonstrated fast switching of 6.58 GHz for state-sensitive detection
  - Compact atom interferometer sensor head
    - GMOT in miniature vacuum package
    - Initial gravimeter demonstration
- Future work
  - Combine integrated photonics platform with atom interferometer prototype

SIGMA Team and Funding

Program Leadership
PI: Peter Schwindt
PM: Shanalyn Kemme
PD: Kyle McDowell

Atom Interferometer R&D, Testing & Control
Lead: **Jongmin Lee**
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Justin Christensen
Roger Ding
Gregory Hoth
Daniel Soh
Connor Brashar
Randy Rosenthal
Tony Smith
Joseph Berg
Prabodh Jhaveri
Grant Biedermann, OU

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Lead: Tony Lentine
Michael Gehl
Erik Skogen
Matt Eichenfield
Peter Rakich, Yale
Shayan Mookherjea, UCSD
Ashok Kodigala

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Brandon Ruzic
Bethany Little
Matt Chow
Paul Parazolli
Yuan-Yu Jau

Mechanical and Optical Integration & Vacuum Package
Lead: Aaron Ison
Daniel Gillund
Bradley Townsend
David Bossert
Kyle Fuerschbach
Chuck Walker
Peter Schwindt
Dennis De Smet

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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