SAND2021-5978PE

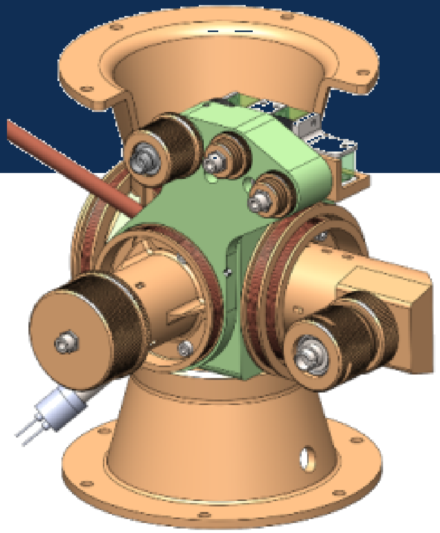
Strategic Inertial Guidance

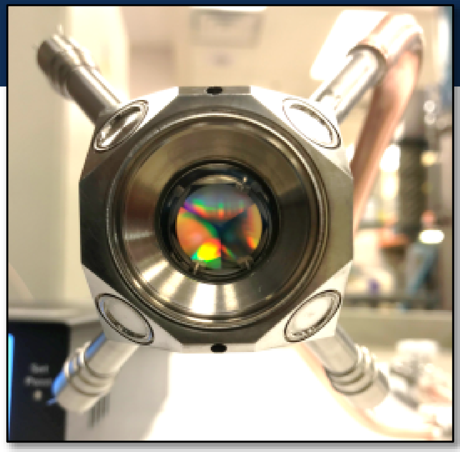
ΣΙΓΜΑ

with MAtterwaves

Exceptional service in the national interest

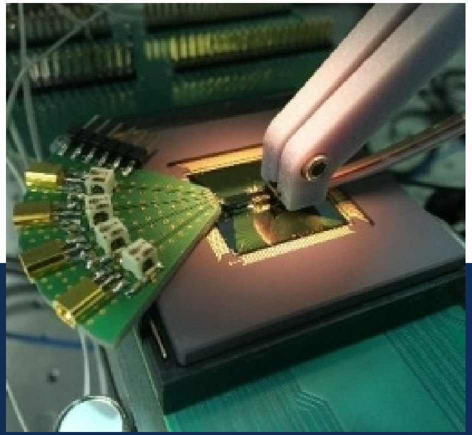
Sandia National Laboratories

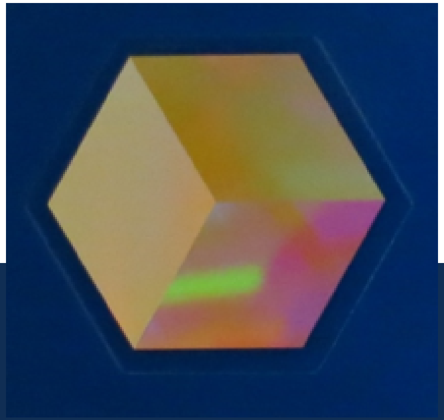




Towards a miniature cold-atom accelerometer

Peter D. D. Schwindt





U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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.

Outline

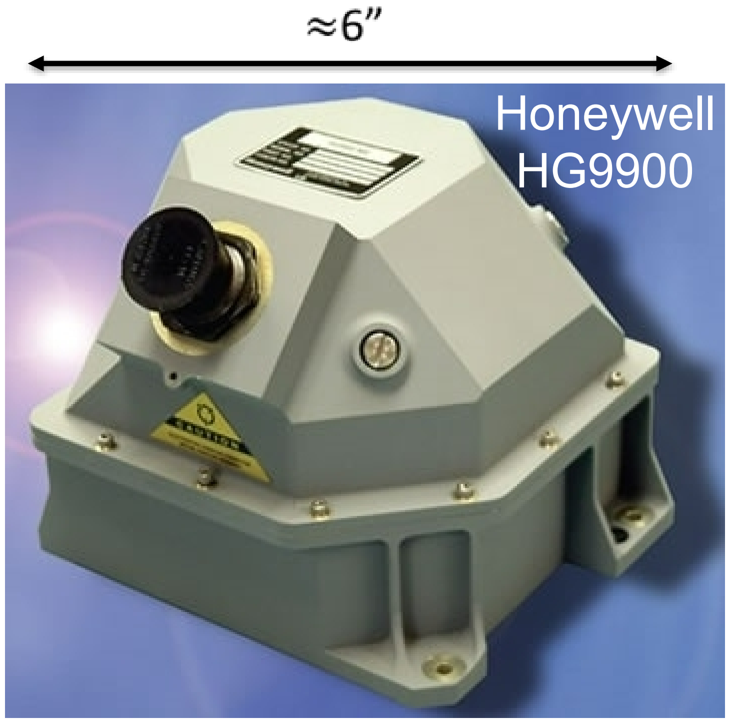
- Motivation for a compact atom interferometer (AI)
- Integrated photonics platform
- AI demonstration with compact sensor head and diffractive optics
- Passively pumped vacuum package
- Guided atom interferometry
- Conclude

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.

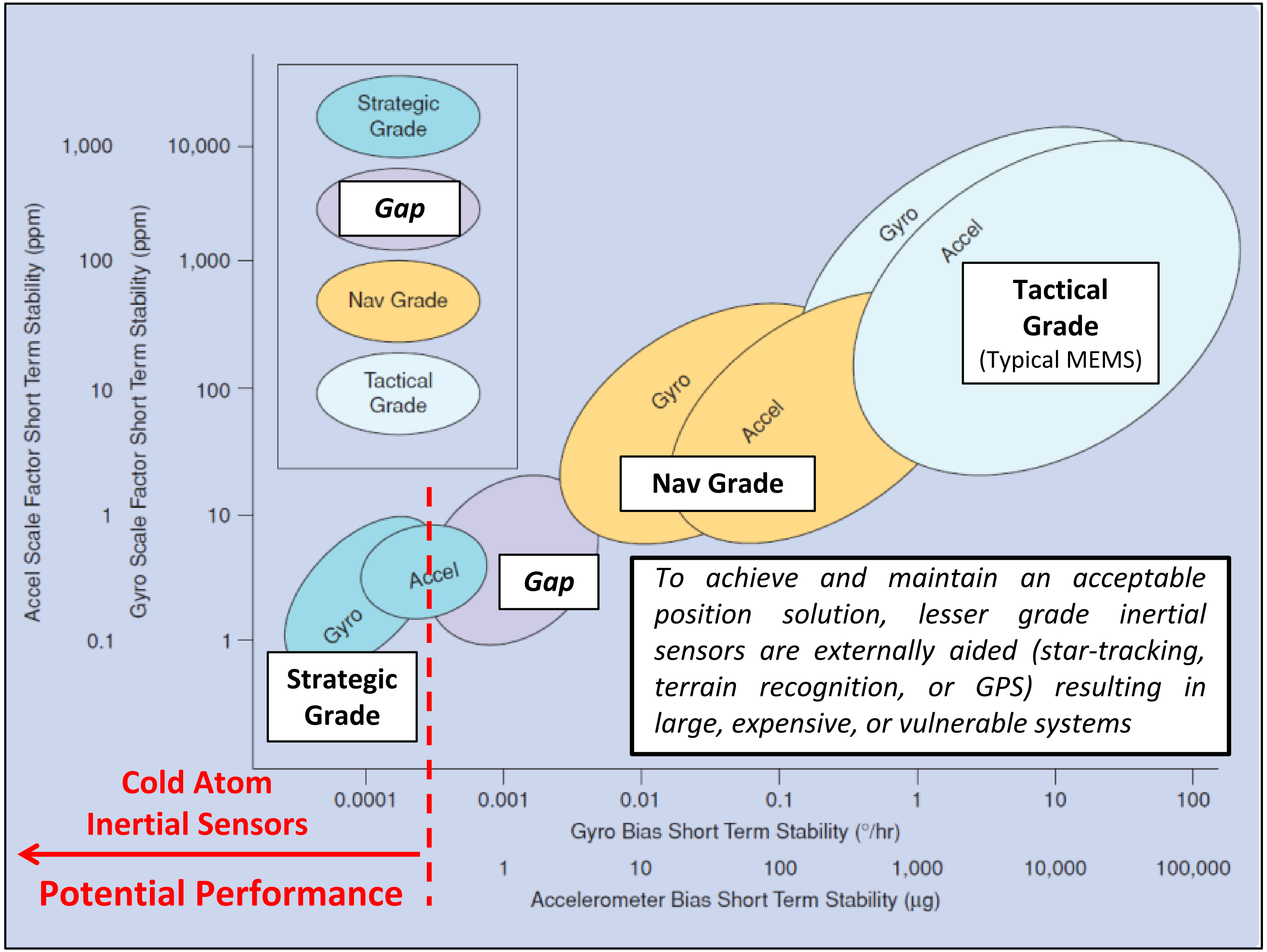
	Navigation Grade (HG9900)	Atom interferometer (Lab demos)	SIGMA Goals (1-axis accel)
Accel Bias (1σ) [μg]	< 25	< 10^{-4}	<0.25
Accel SF (1σ) [PPM]	< 100	< 10^{-4}	1
Accel Random Walk [$\mu g/\sqrt{Hz}$]	not reported QA ~ 10	10^{-5}	<1
Gyro Bias (1σ) [deg/hr]	< 0.003	< 7 x 10^{-5}	
Gyro SF [PPM]	< 5	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

QA: Quartz Accelerometer
RLG: Ring Laser Gyroscope



QA (x3) & RLG (x3)

Inertial Measurement Sensor Classifications



Sensor Grade	Drift (Per Hr)
Tactical	10 km
Navigation	1 km
Strategic	0.2 km

A selection of global AI efforts, today

Atom Interferometry Patents

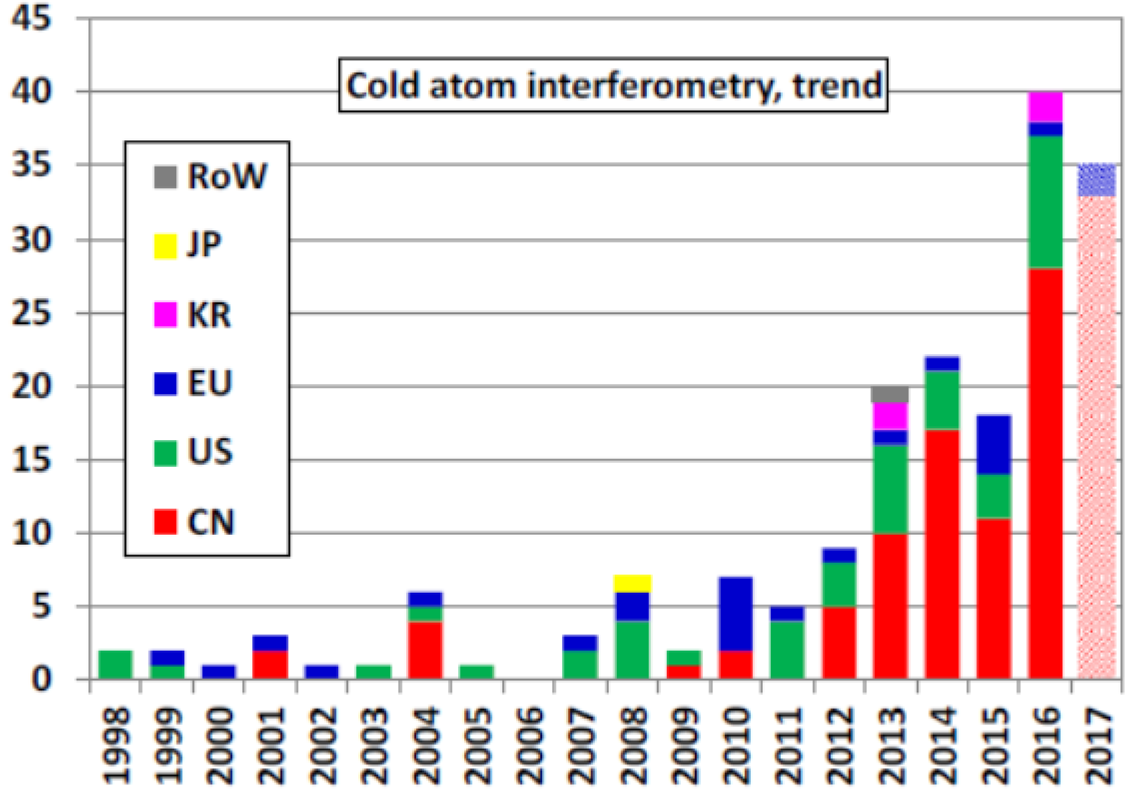
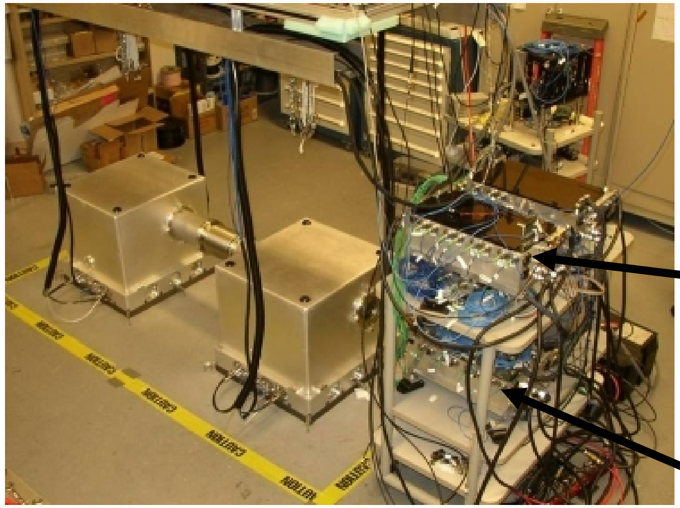


Fig. 32: time evolution of patent applications on cold atom interferometry[37].

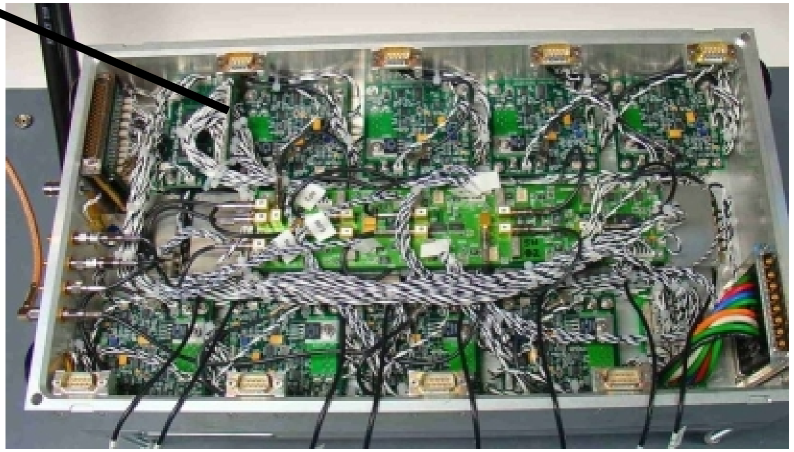
"Patent analysis of selected quantum technologies", M. Travagnin, JRC Technical Report, EUR 29614EN, 2019; https://ec.europa.eu/jrc/en/publication/patent-analysis-selected-quantum-technologies

Mobile atom interferometer

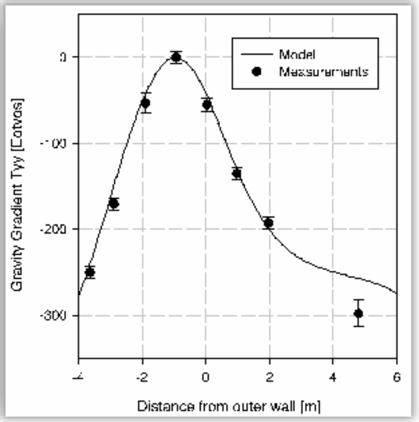


Biedermann, Ph.D. Thesis, Stanford, 2007

lasers 9”x15”

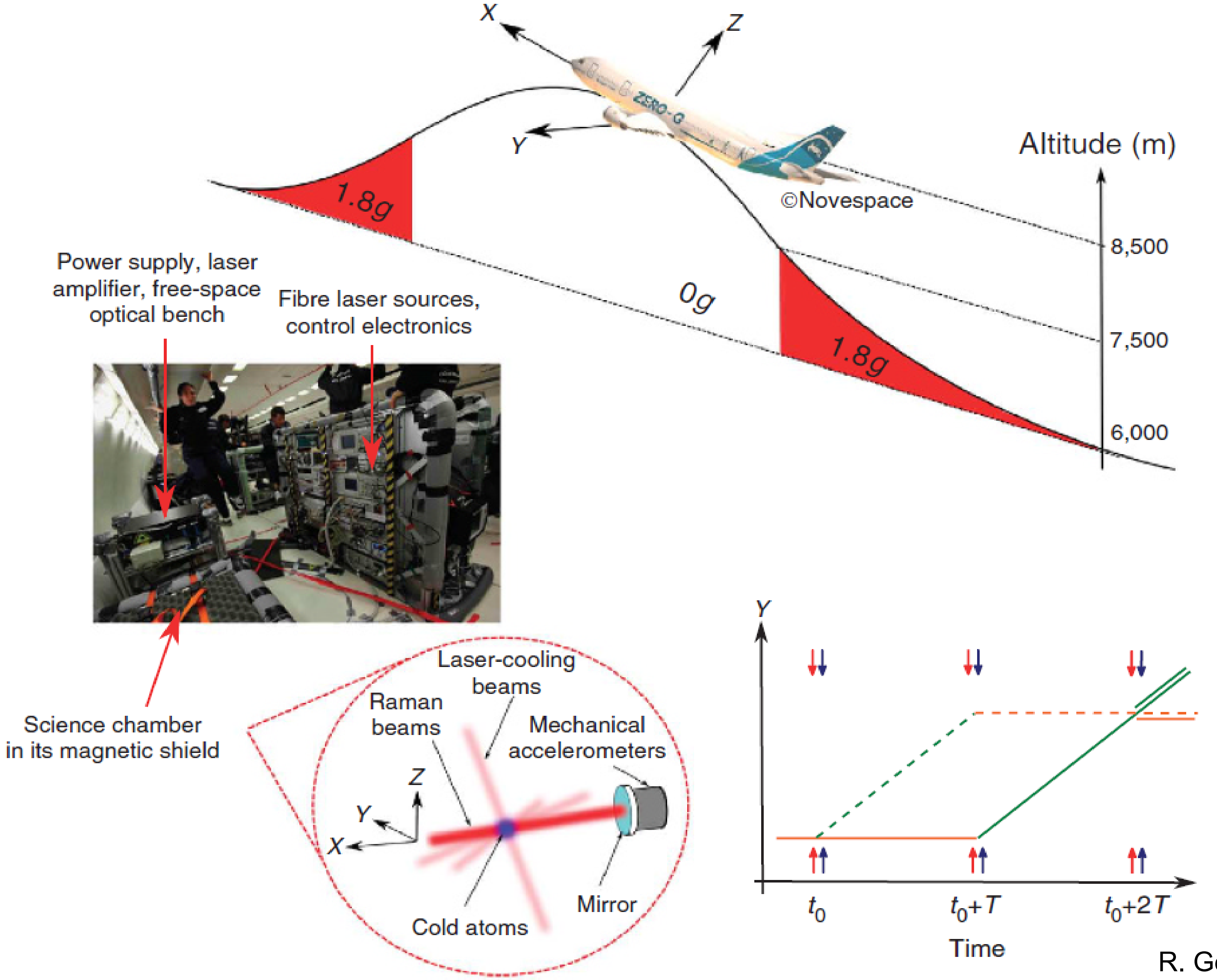


electronics 9”x15”



Wu, Ph.D. Thesis, Stanford, 2009

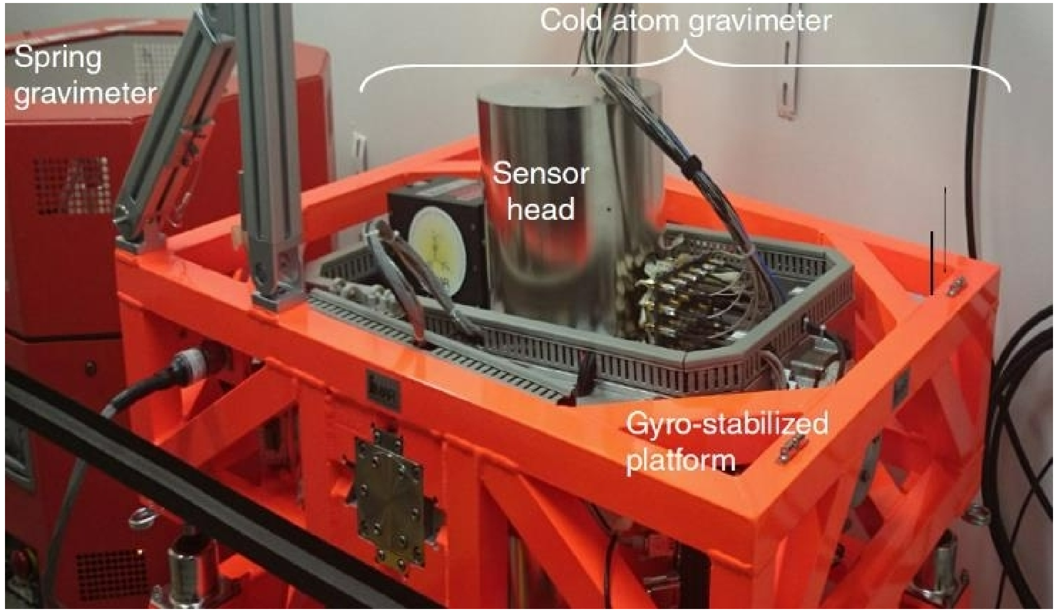
Portable Atom Interferometers for Aircraft (France)

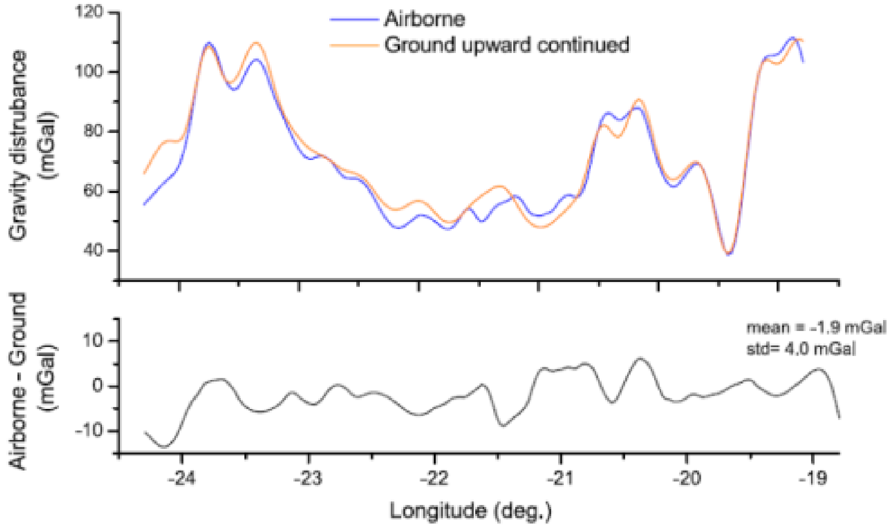


R. Geiger, nature communications, 2:474 (2011)
K. Bongs et. al, Nature Reviews, Physics 1 (2019)

Airborne Gravimetry with an Atom Interferometer

- Gravity measurements over Iceland
- Gimballed platform to maintain vertical
- Feed forward technique
  - Dynamic range = 1000 fringes or ~0.1 *g* at T = 20 ms
- Data rate = 10 Hz
- Errors: 1.7 to 3.9 μg
- ONERA – The French Aerospace Lab

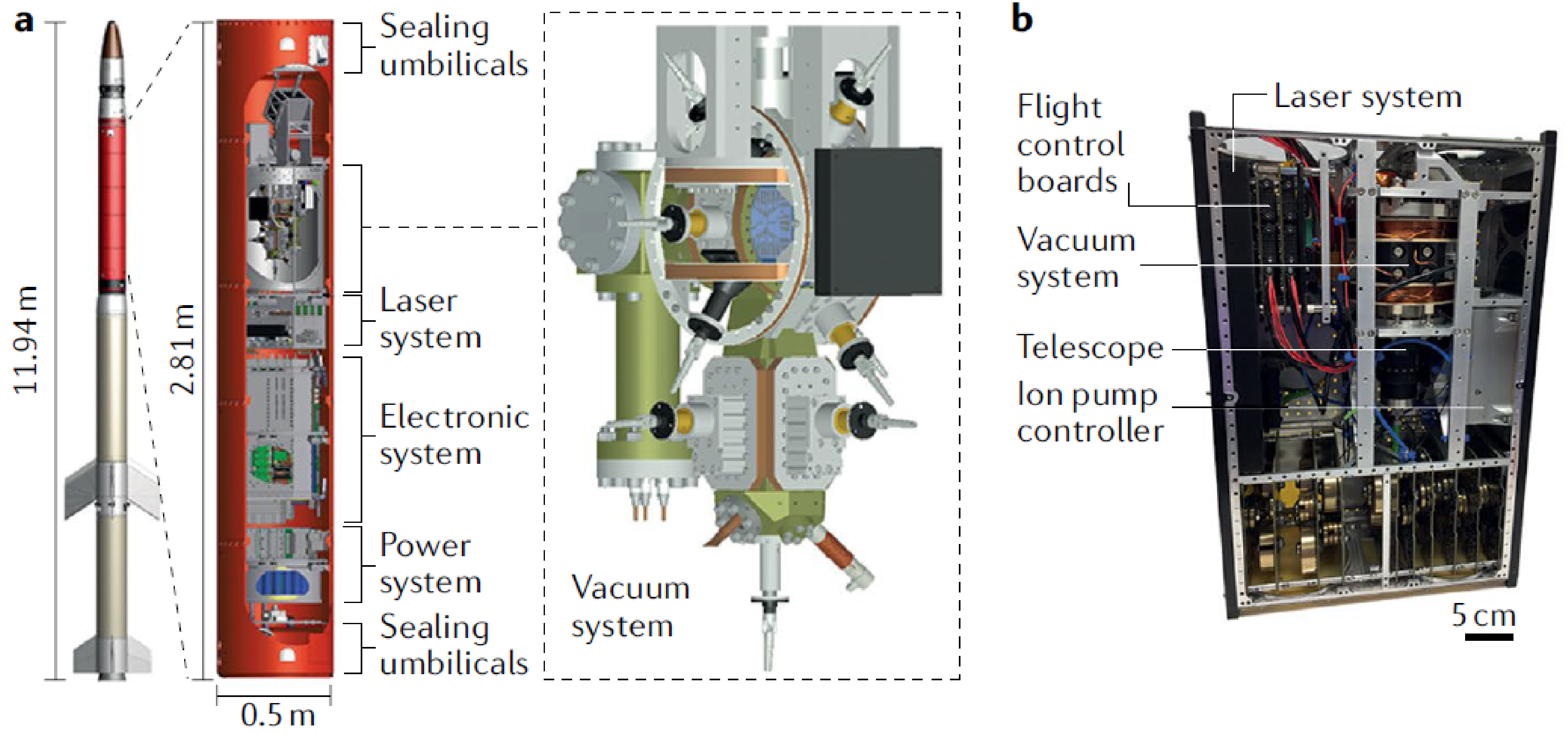




Aircraft: Bidel, Y., Zahzam, N., Bresson, A. *et al.* Absolute airborne gravimetry with a cold atom sensor. *J Geod* **94,** 20 (2020).

Ship: Bidel, Y., Zahzam, N., Blanchard, C. *et al.* Absolute marine gravimetry with matter-wave interferometry. *Nat Commun* **9,** 627 (2018).

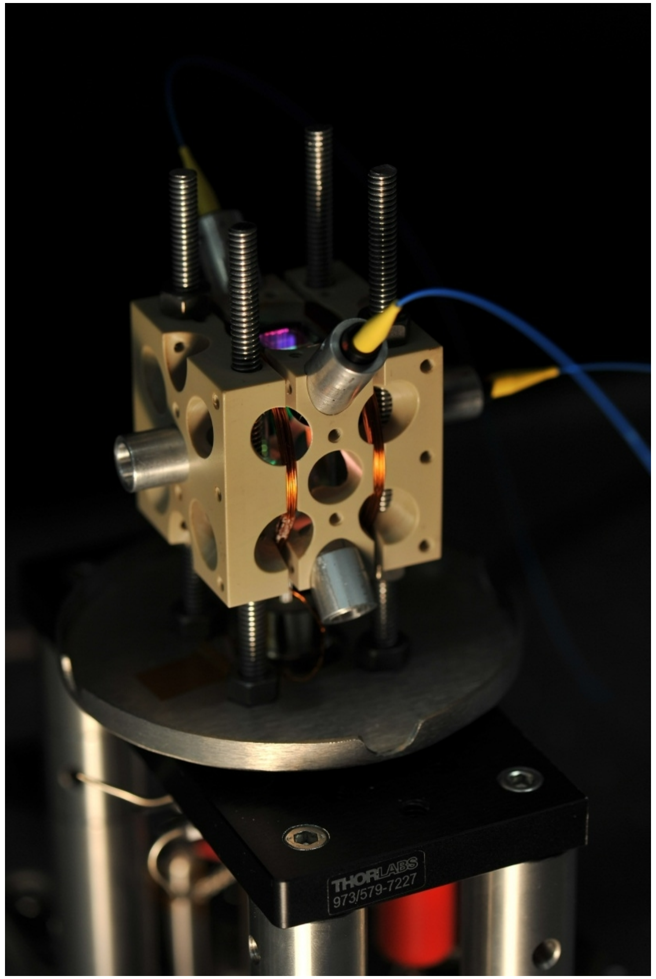
Portable Cold-Atom System for Rocket (EU) and Satellite (UK)



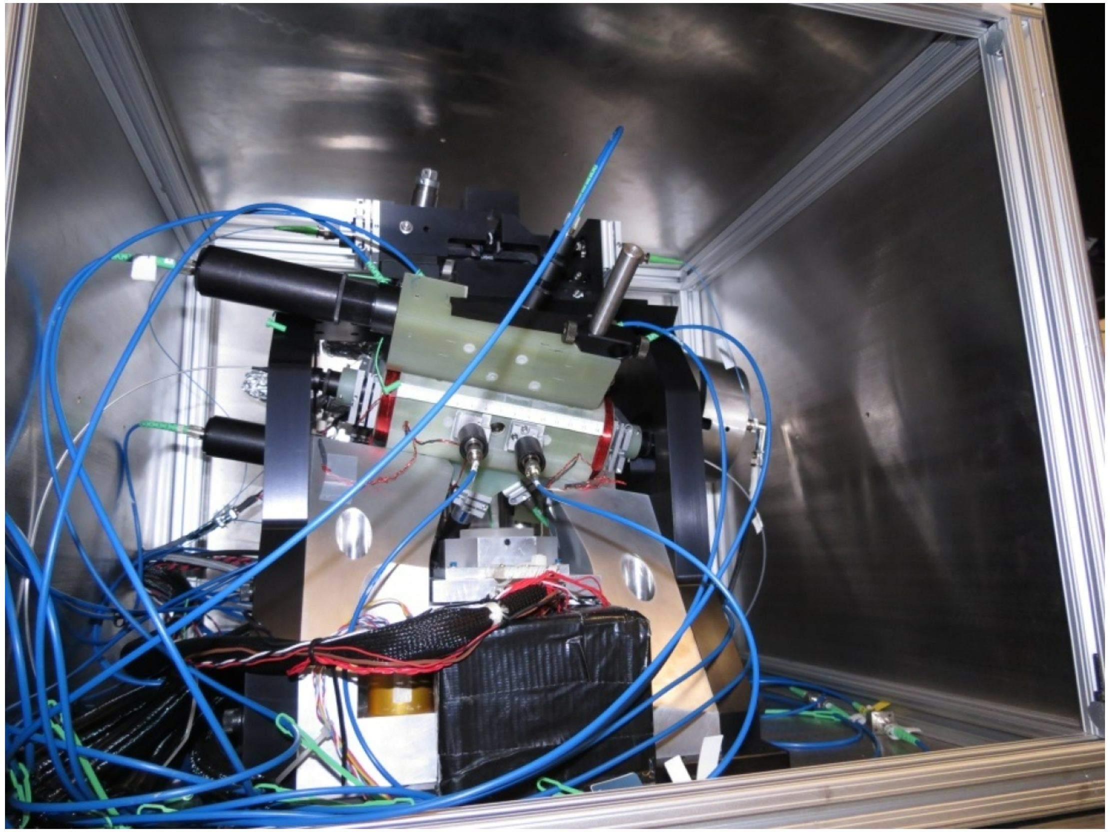
a) A ***rocket*** with a payload containing ***an atom chip*** on which the Bose–Einstein condensate was created in space: EU

b) A cold-atom payload designed to fit onto ***a cube satellite***: UK

Compact atom interferometers



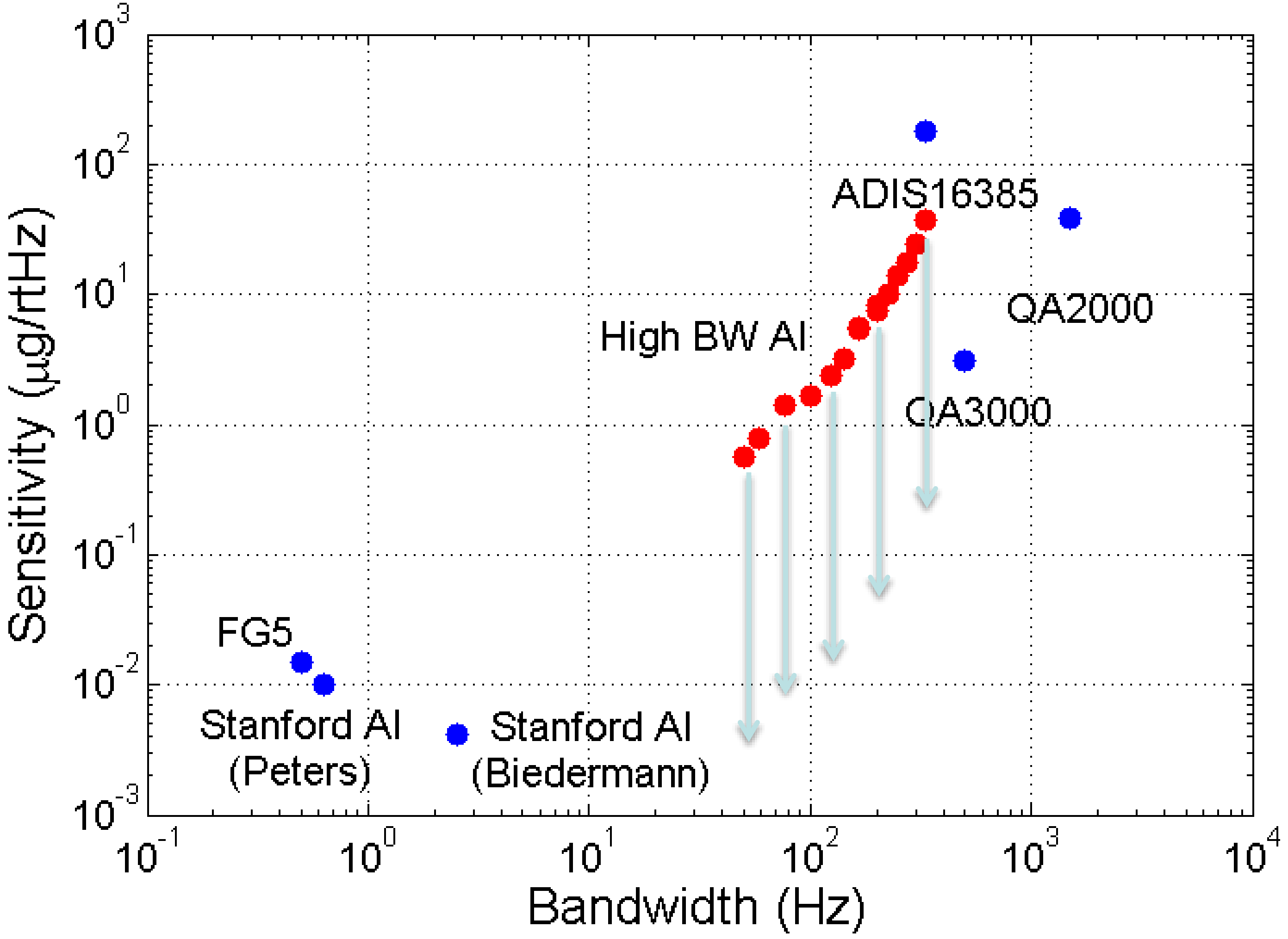
NIST accel/gyro



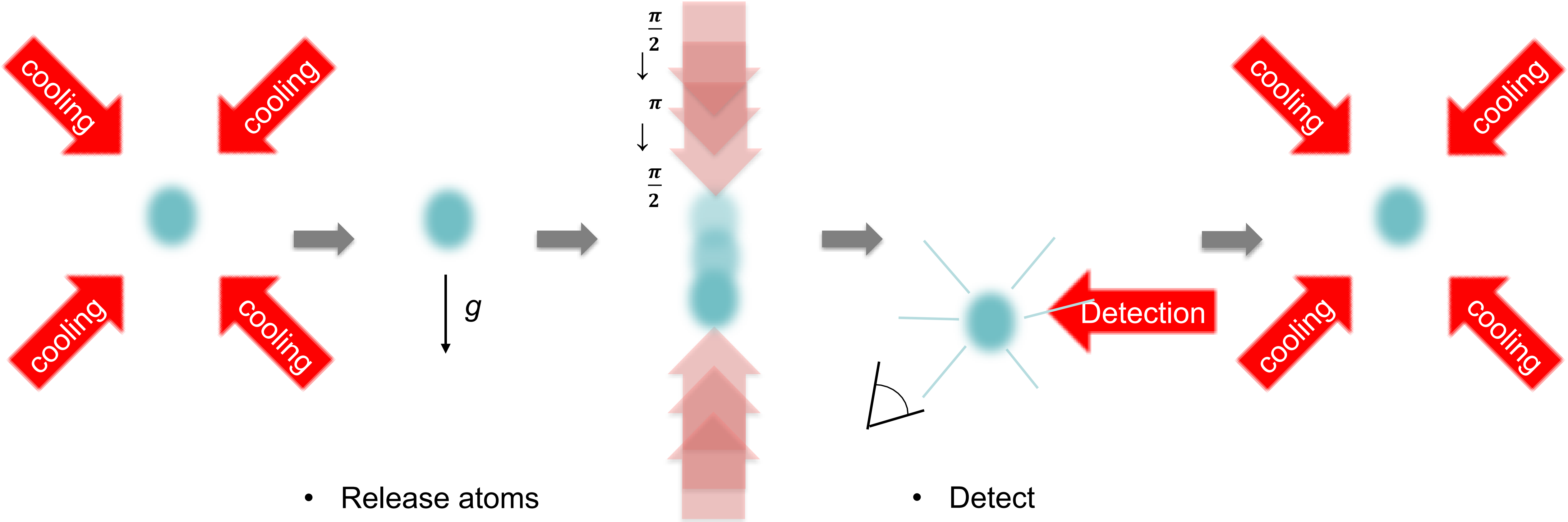
Sandia accel/gyro

Bandwidth considerations

- Bandwidth required for inertial sensor applications
- AI sensitivity reduces with bandwidth
- Compact size lends itself to high bandwidth



High Data-Rate Atom Interferometry



- Release atoms
- Detect

- Laser cooled atoms (4.3 ms, $T \approx 15\ \mu$K, $N \approx 10^6$)
- Raman pulse sequence (14 ms, T = 7 ms)

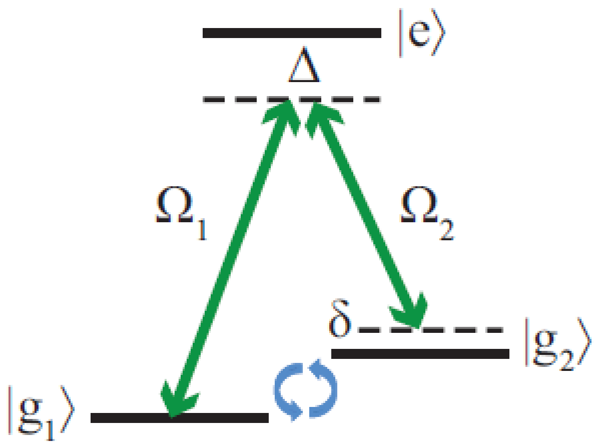
$$\frac{\pi}{2} \rightarrow T \rightarrow \pi \rightarrow T \rightarrow \frac{\pi}{2}$$

- Recapture (1.7 ms)

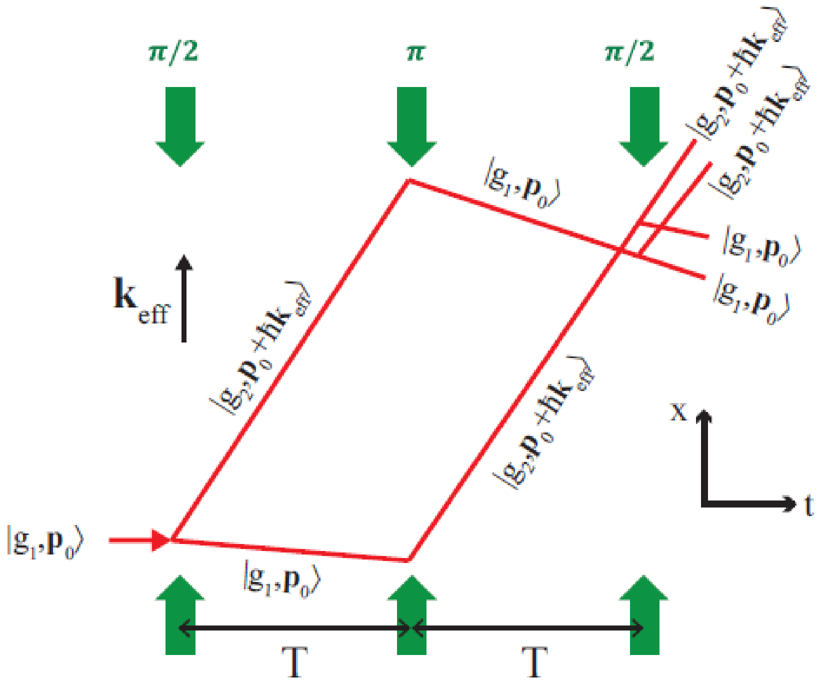
Example, (40 Hz)$^{-1}$ cycle

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

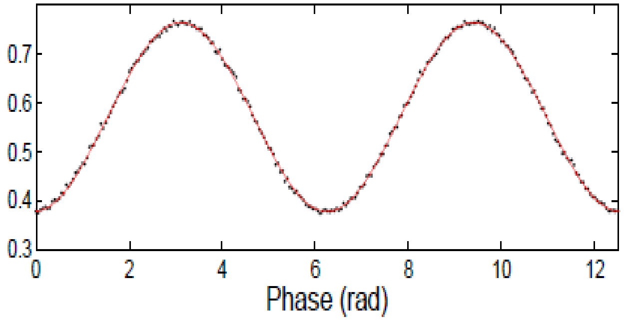
Light Pulse Atom Interferometer



$$\Omega_{Raman} = \frac{\Omega_1 \Omega_2}{2\Delta}$$



Acceleration →

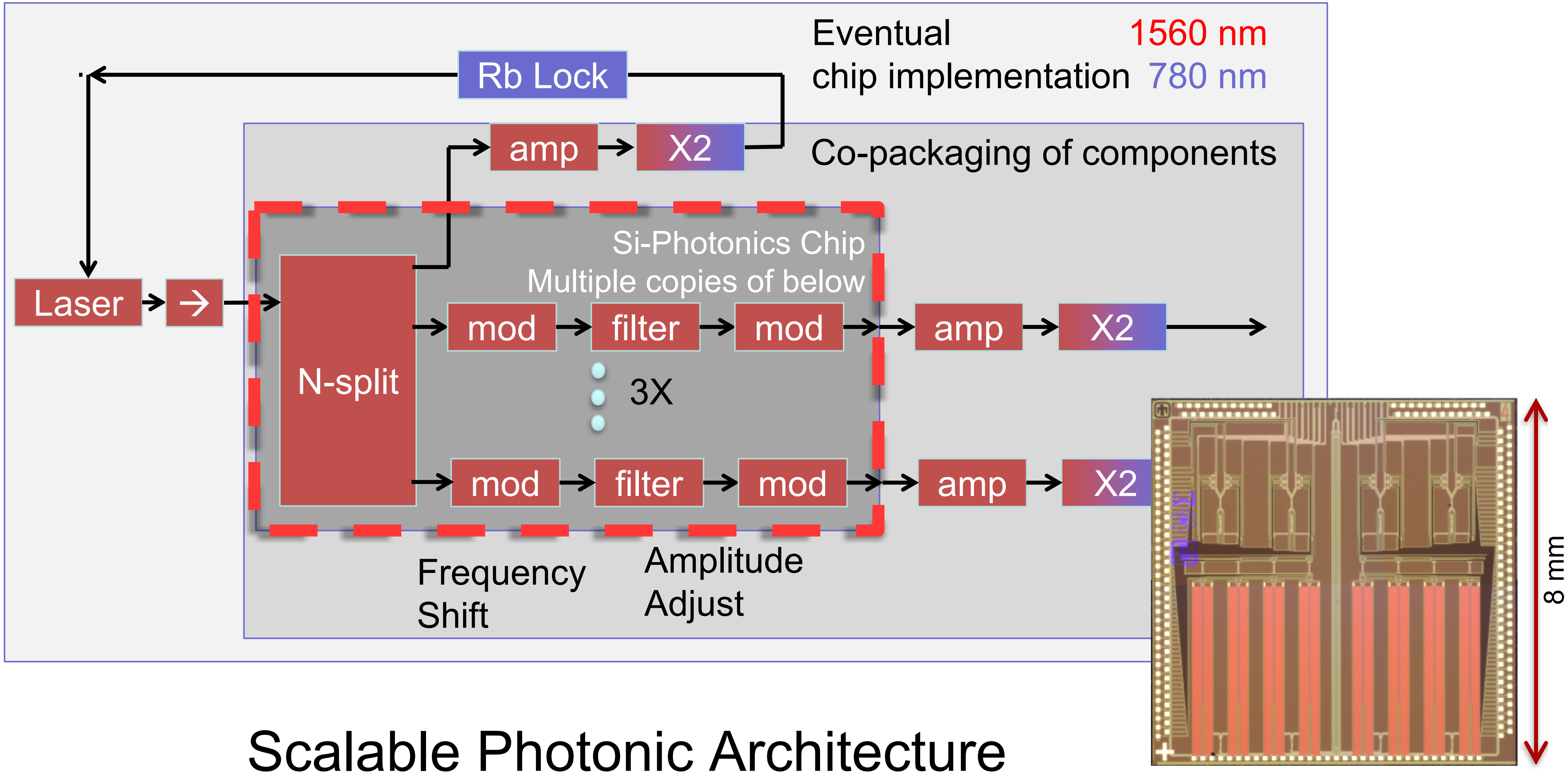


- Three Doppler-sensitive Raman pulses: $\frac{\pi}{2} \rightarrow \pi \rightarrow \frac{\pi}{2}$
- Stimulated Raman transitions: the state-dependent momentum kicks on atoms
- Split → Redirect → Recombine for AI demonstration
- Atom interferometer accelerometers and gyroscopes

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

INTEGRATED PHOTONICS

Integrated Photonics Overview

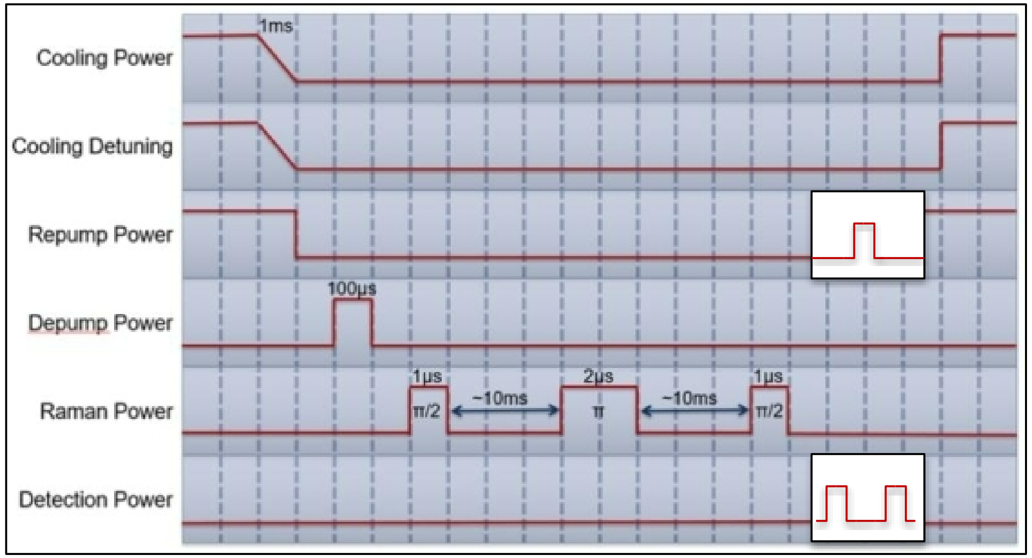


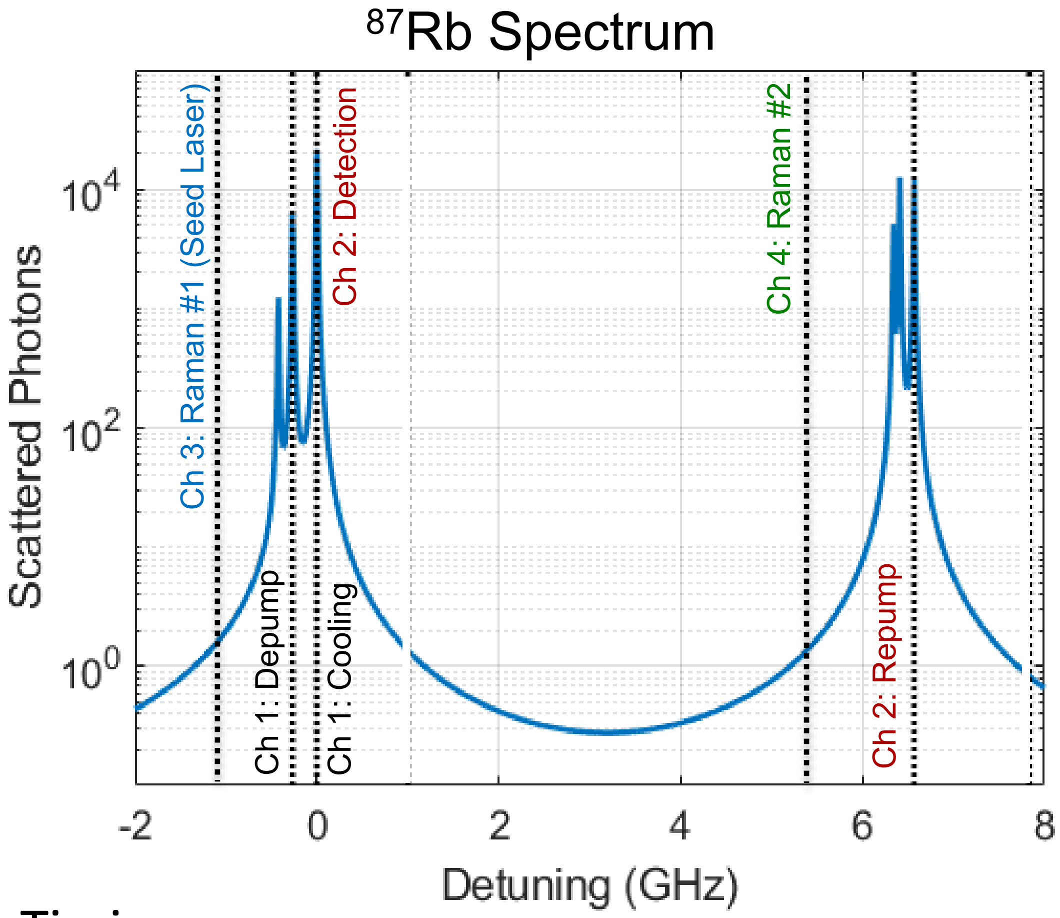
Scalable Photonic Architecture

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.)

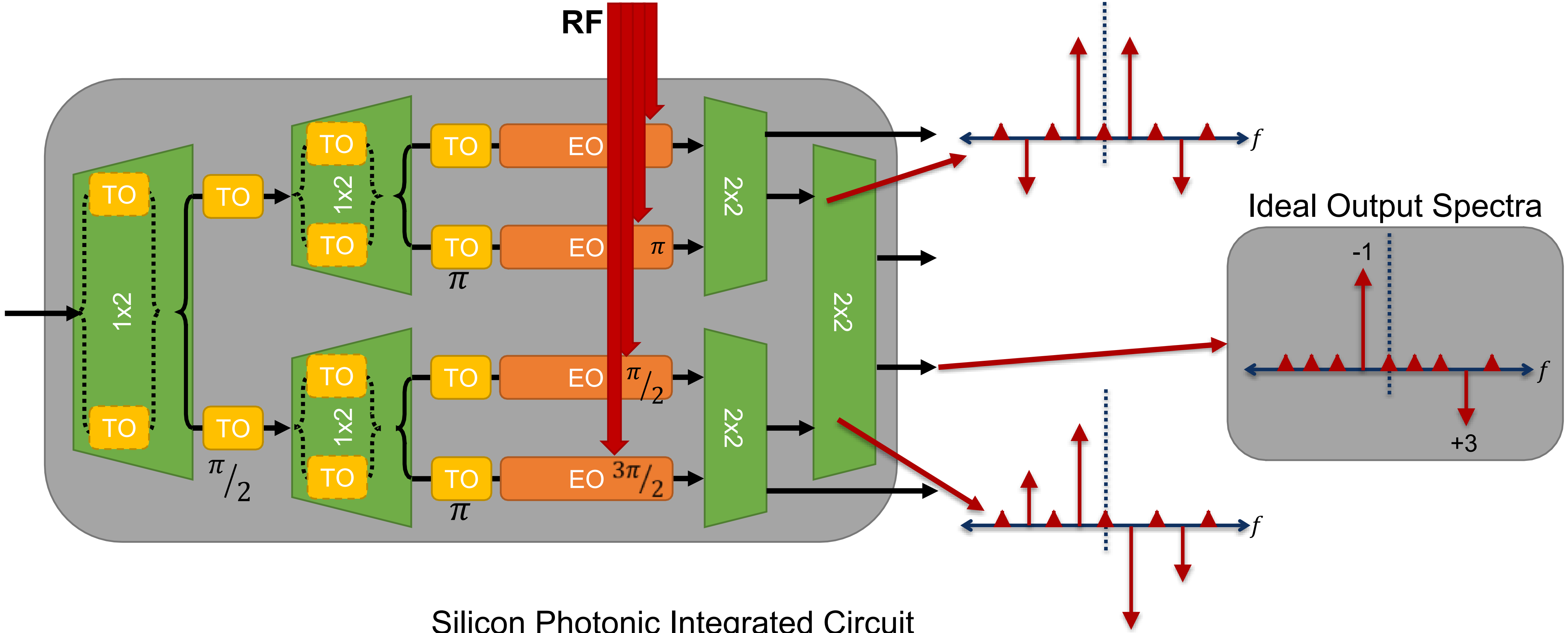




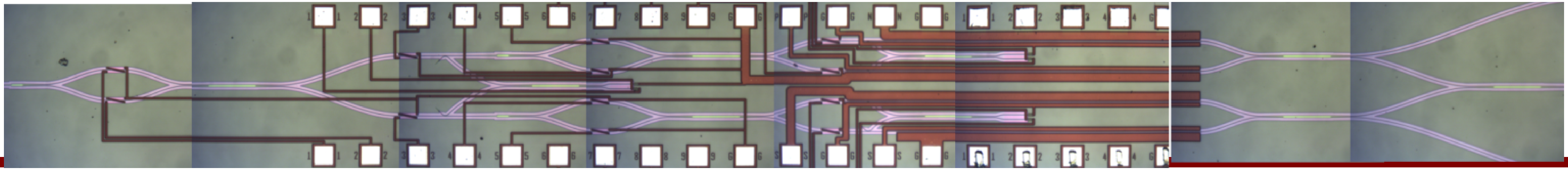
Timing

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

Suppressed-Carrier Single Side-Band Modulator

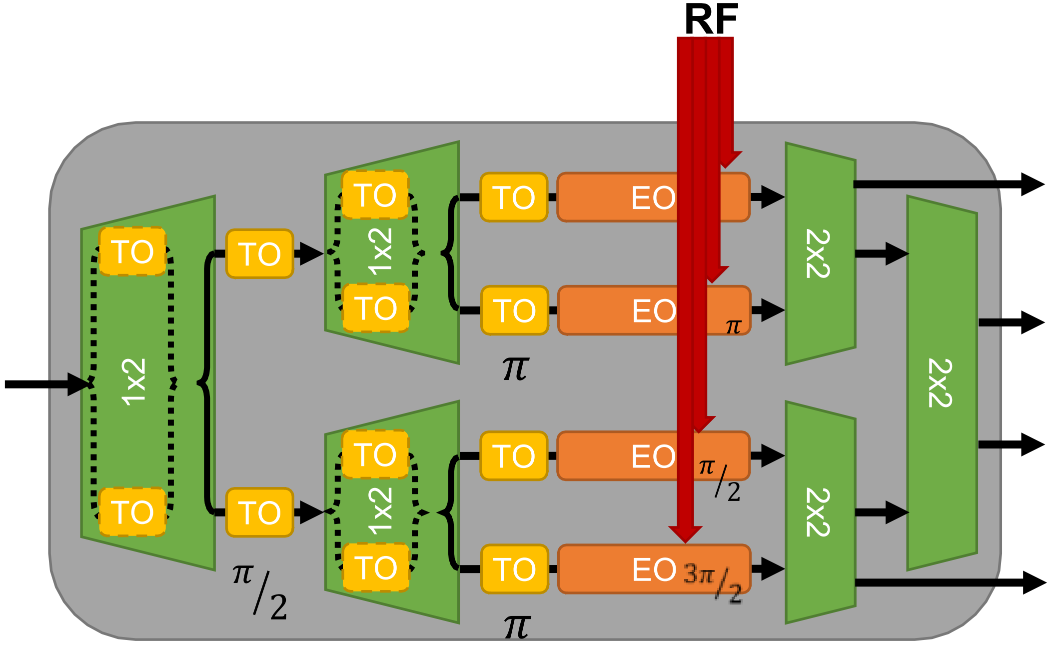


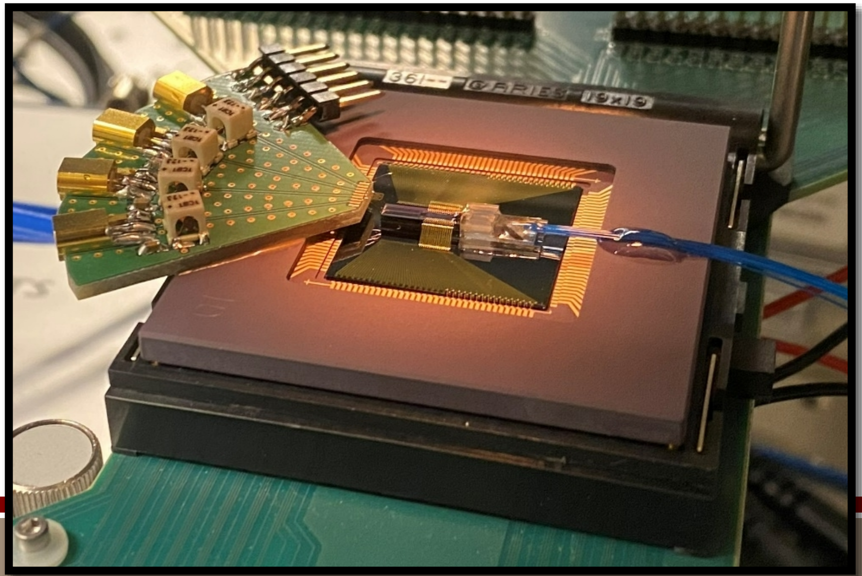
Silicon Photonic Integrated Circuit

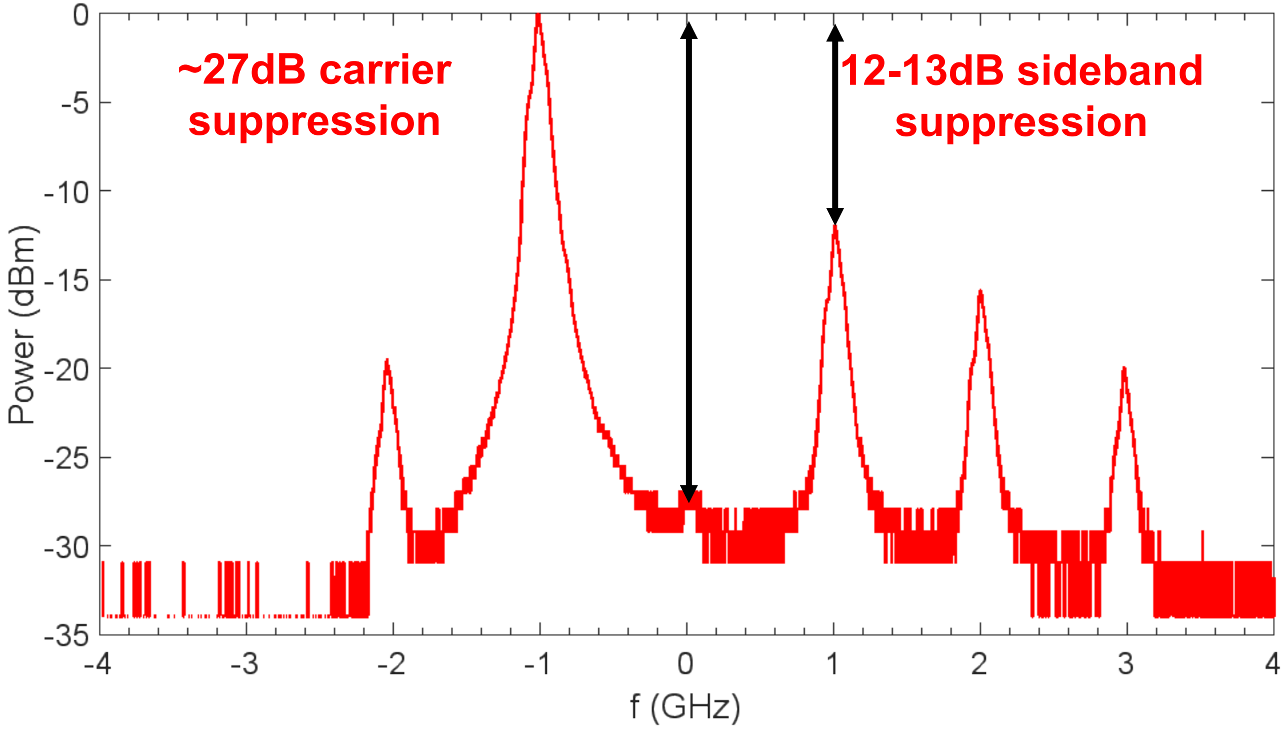


M. Izutsu, et. al. *IEEE J. Quant. Elect.* **QE-17** 2225 (1981)

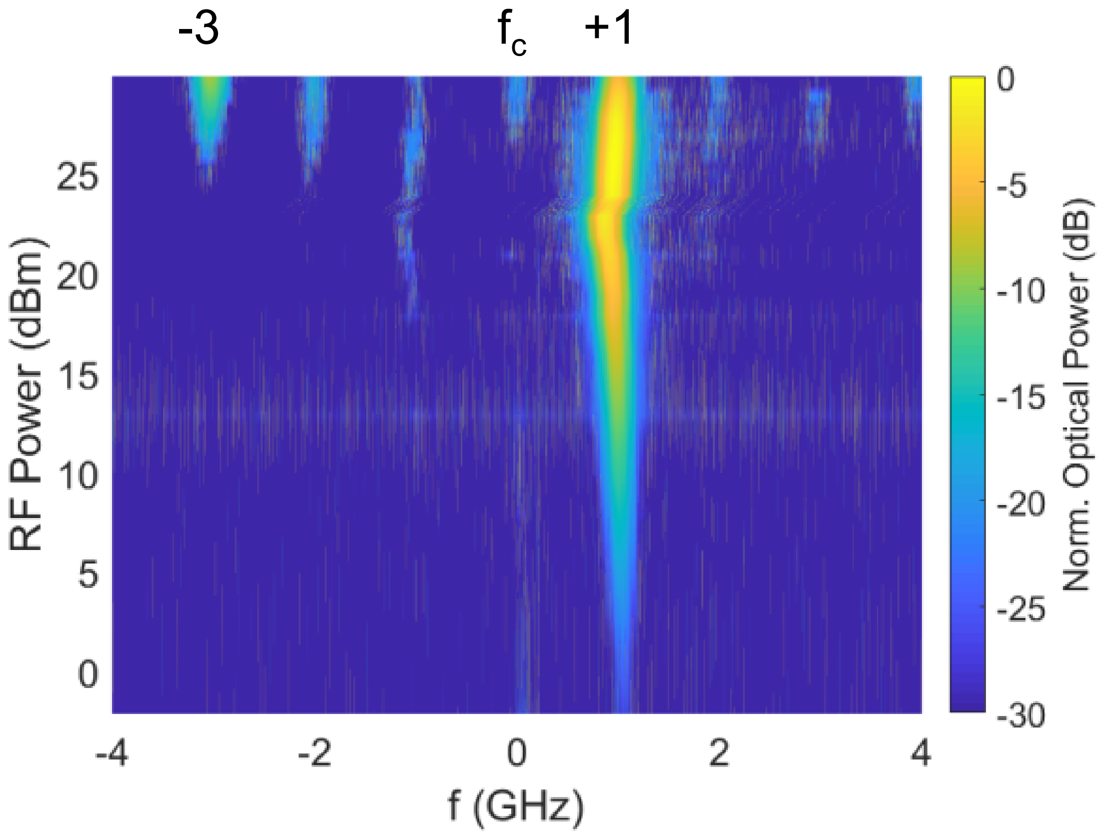
Single Side-Band Modulator Spectrum

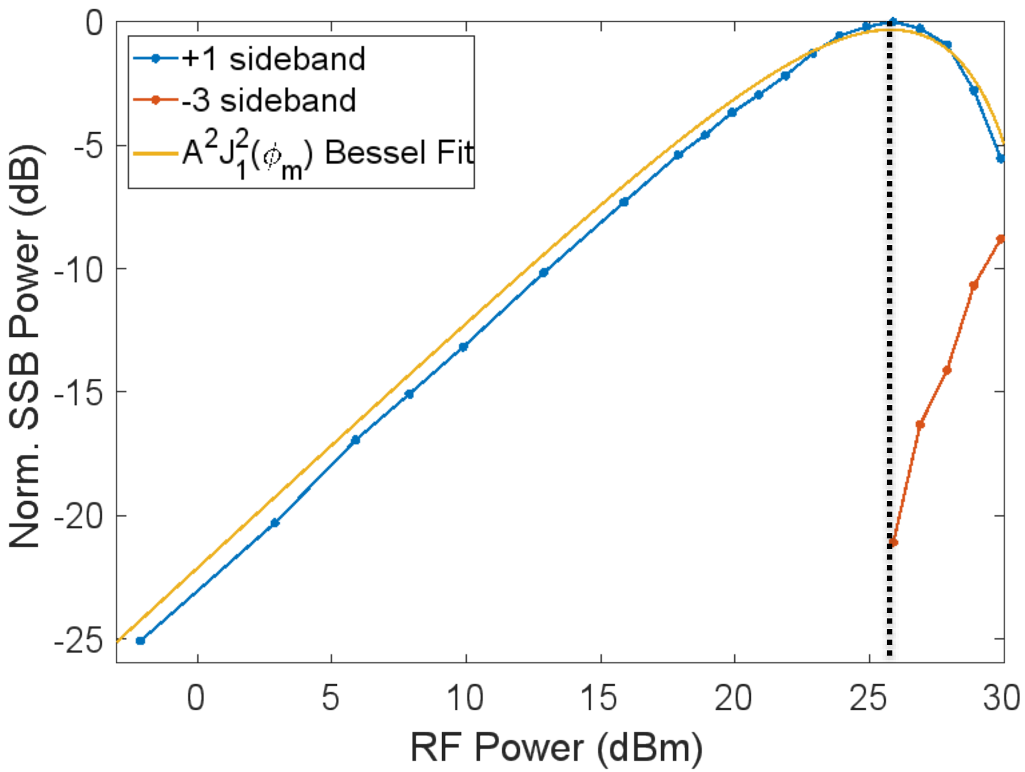






Single Side-Band Modulator Gen II Results

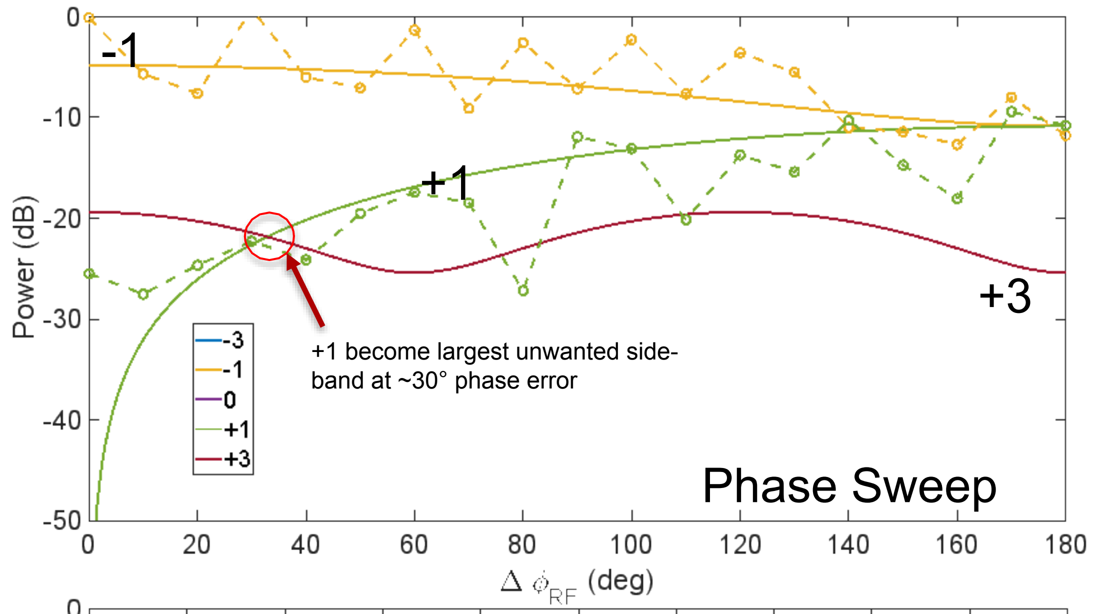


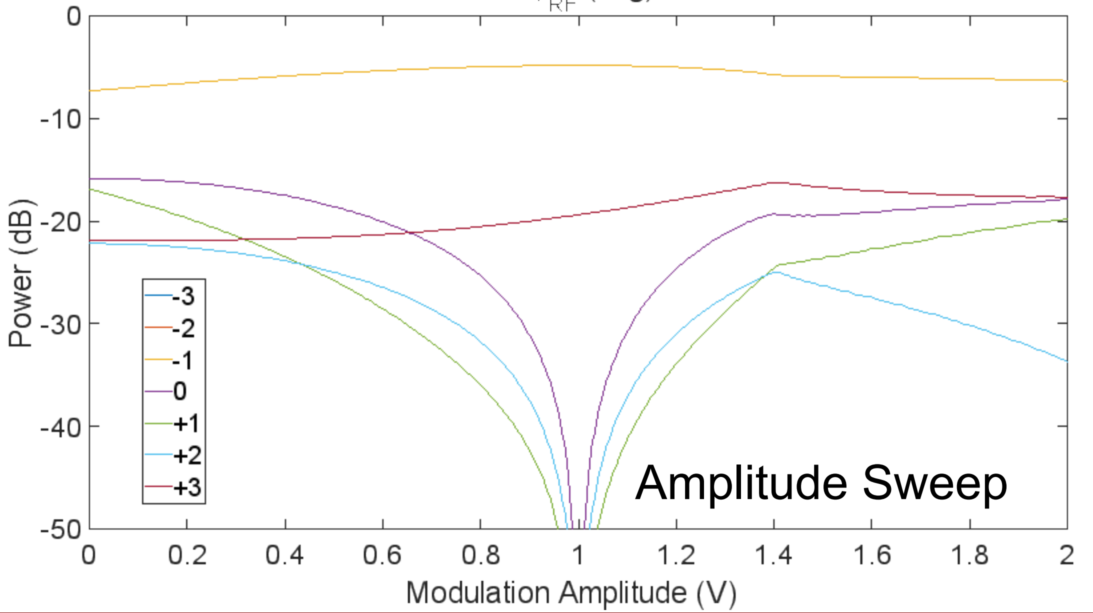


Optimum at RF powers close to ~400mW
Bessel Fit Provides - VπL = 0.557 V×cm

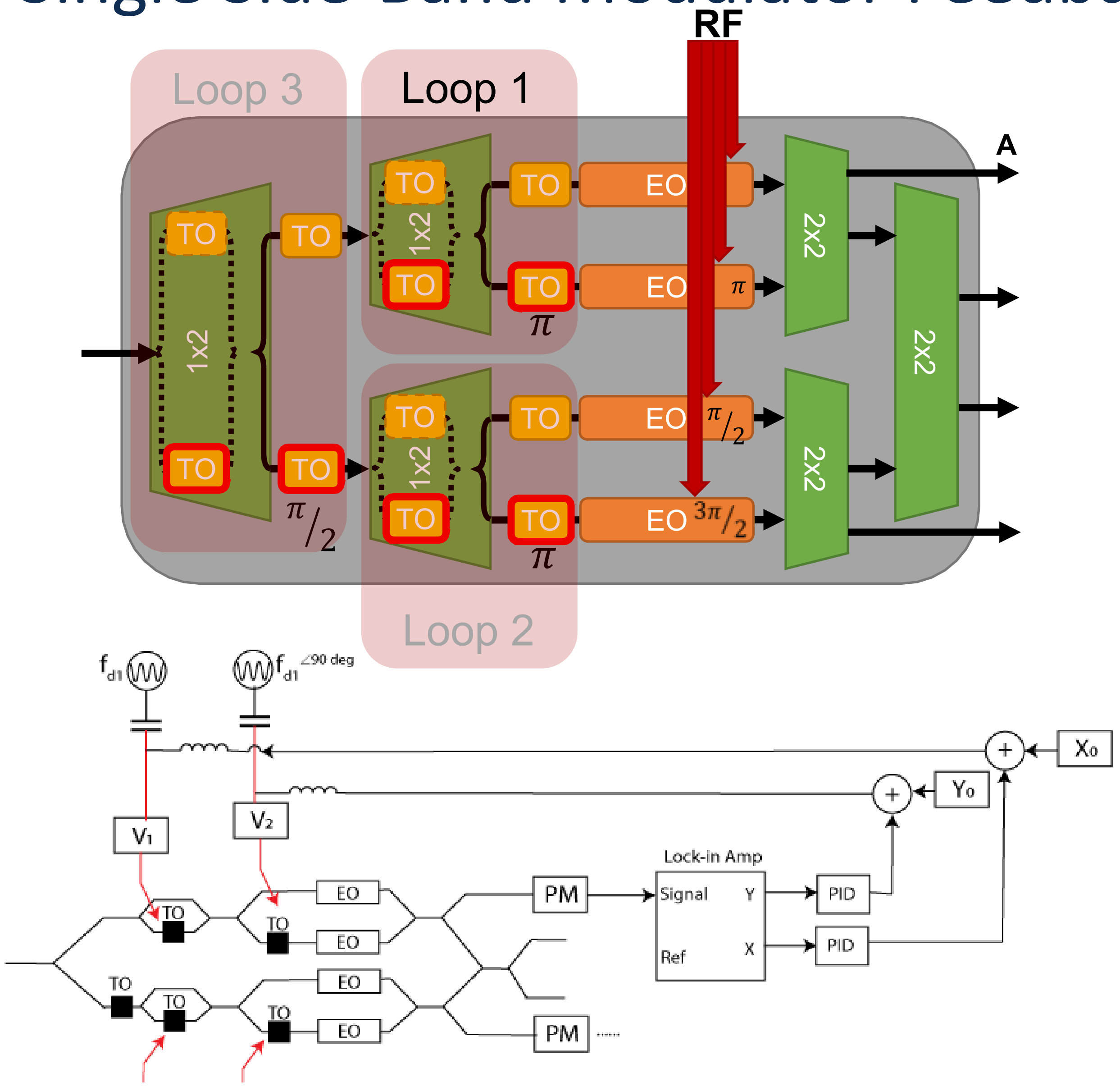
Single Side-Band Modulator Modeling

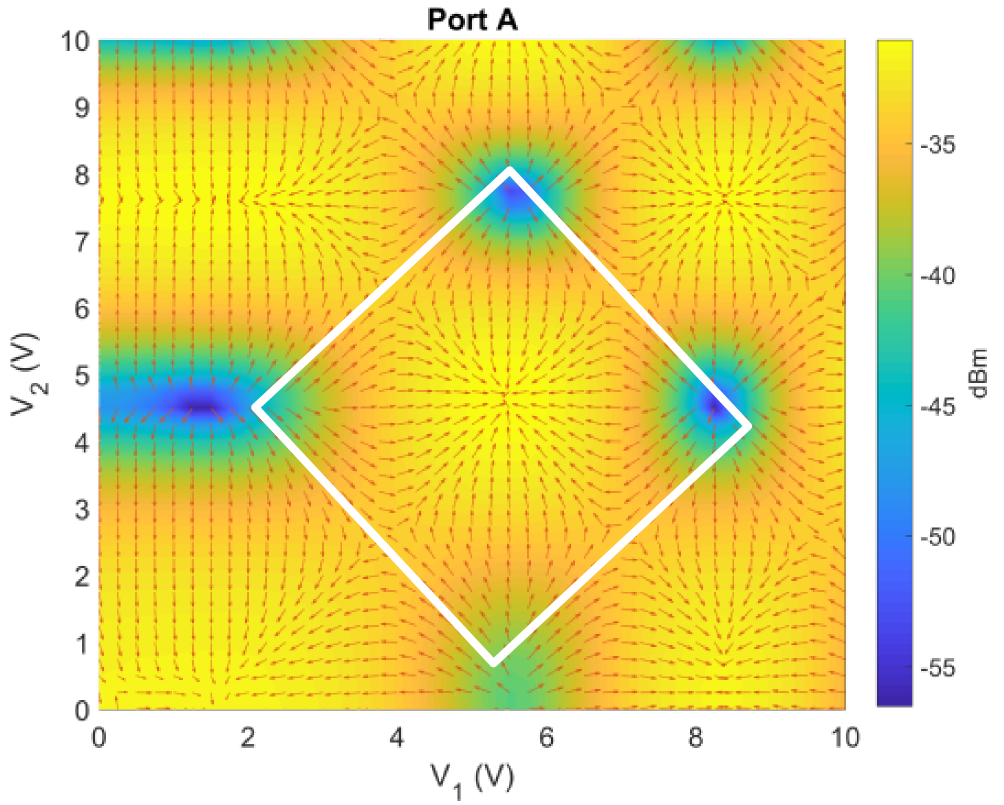
- Implemented 4 channel RF source for independent phase and amplitude control of modulator
- Comparison to previous modeling work in progress
  - Relatively insensitive to RF phase
    - ±30°before extra spurs become dominate
  - Very sensitive to RF amplitude
    - ±0.3 dB required to maintain >35 dB carrier suppression



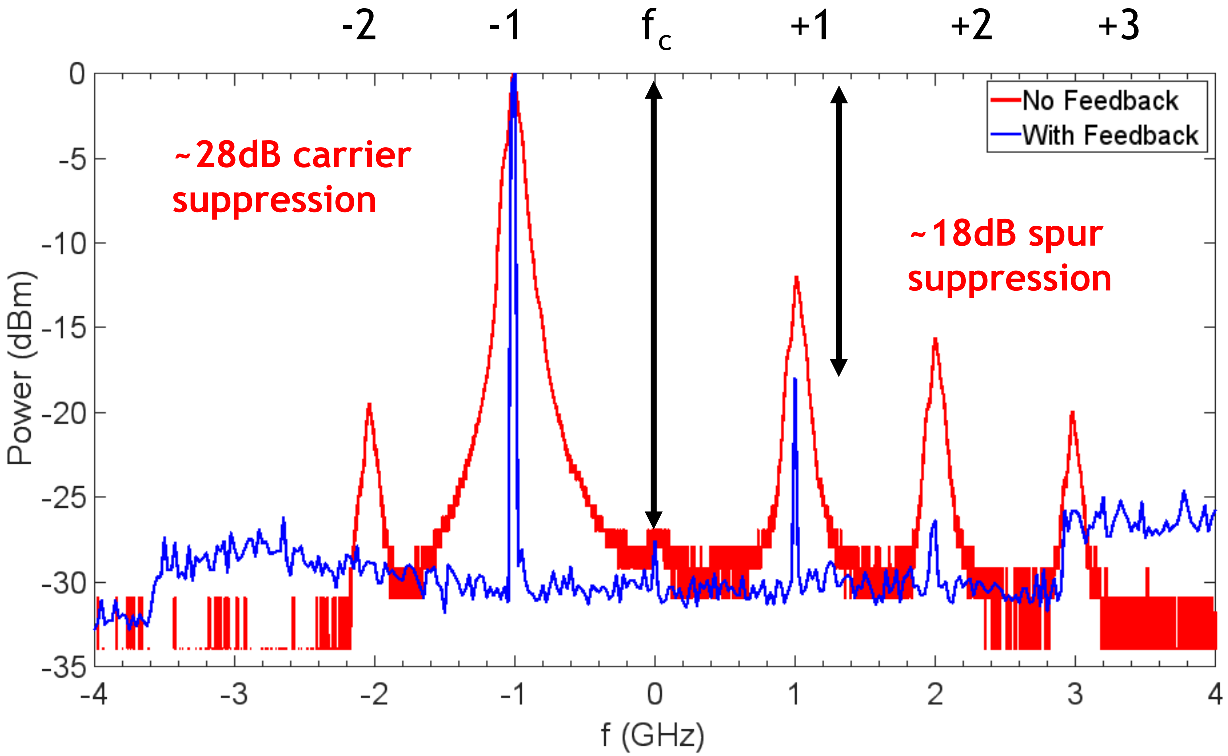


Single Side-Band Modulator Feedback

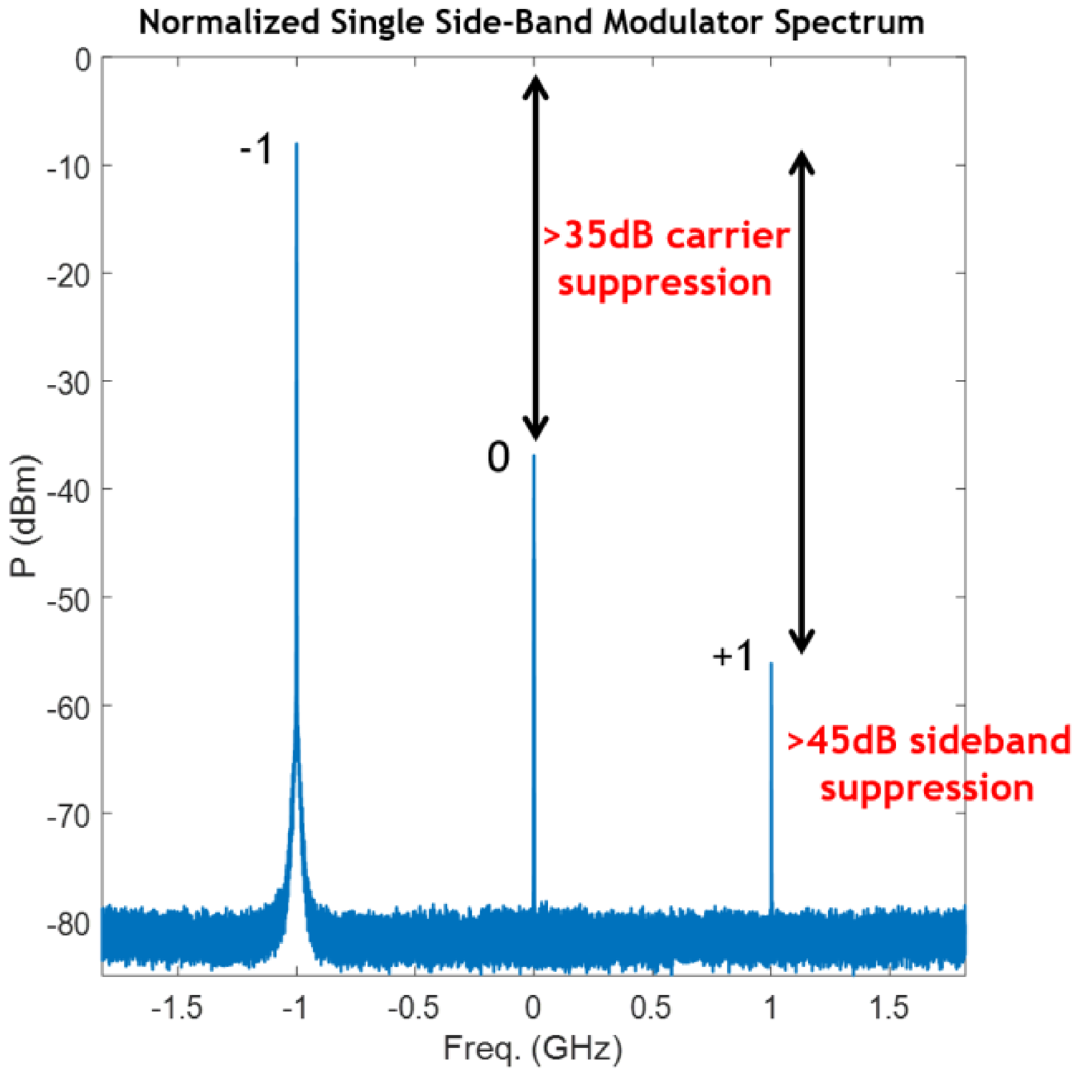




Single Side-Band Modulator Active Control



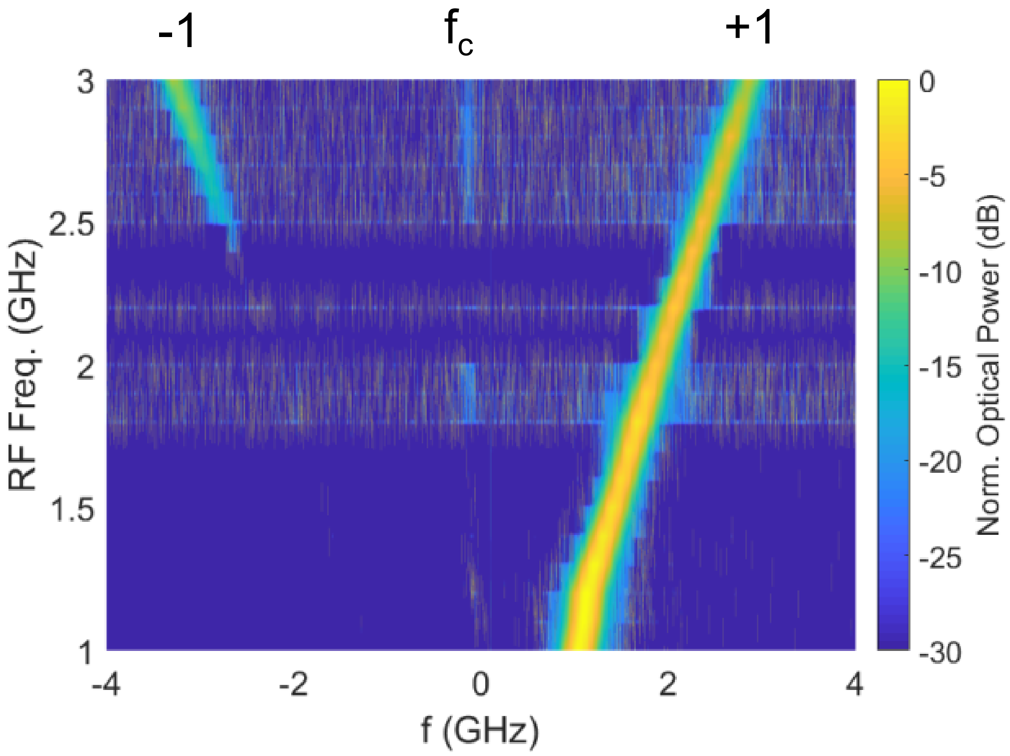
*implemented higher resolution heterodyne spectral measurement



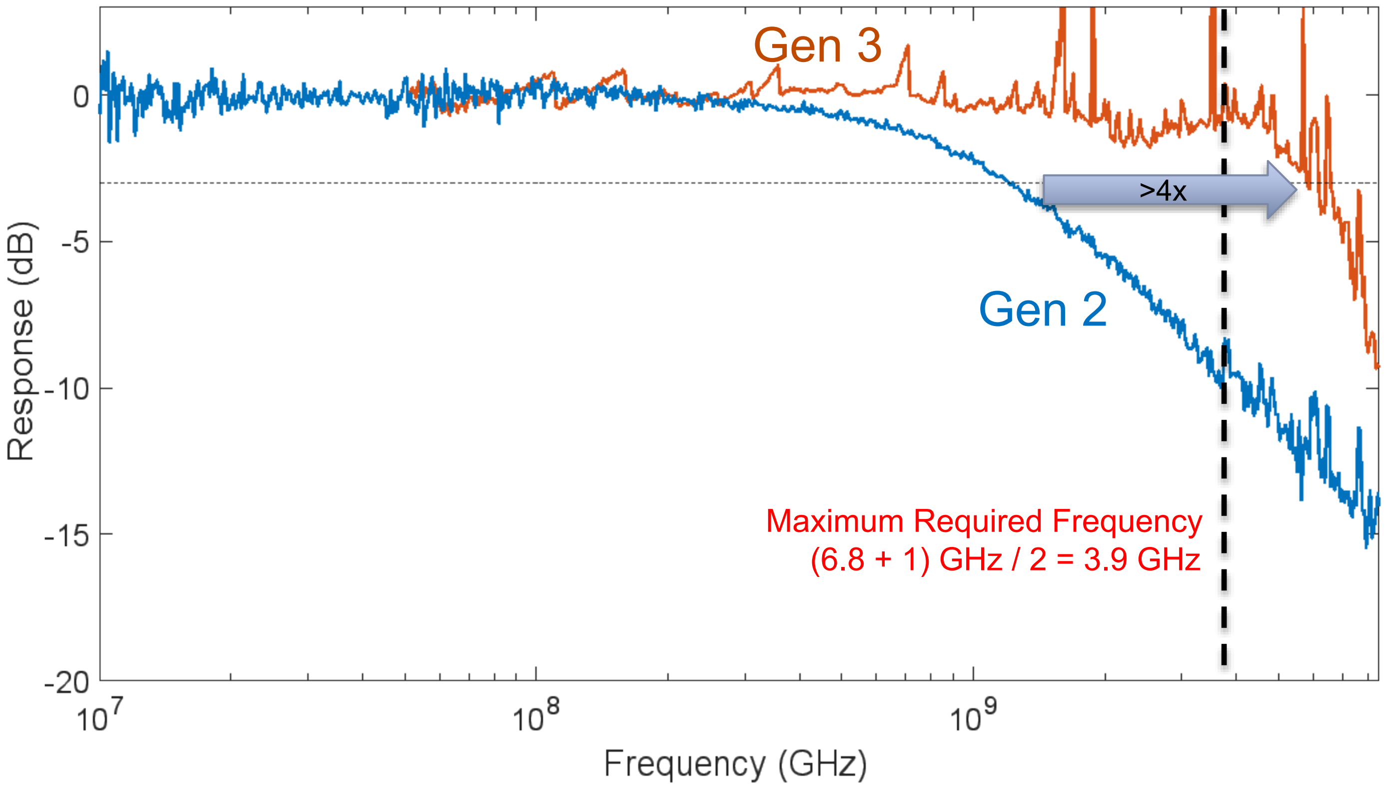
Frequency Response

Sandia National Laboratories

- **Generation 2**
  - Lumped element modulators

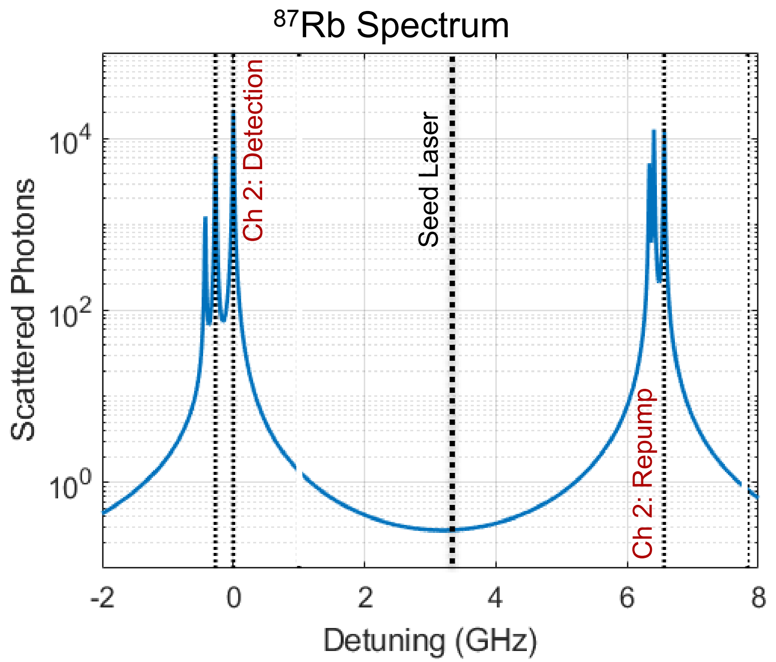


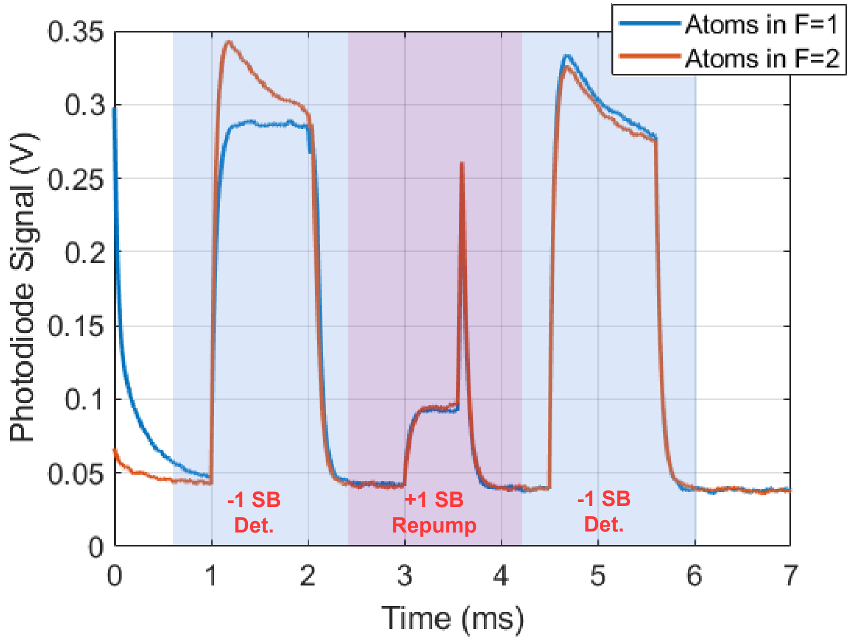
- **Generation 3**
  - Traveling wave modulators

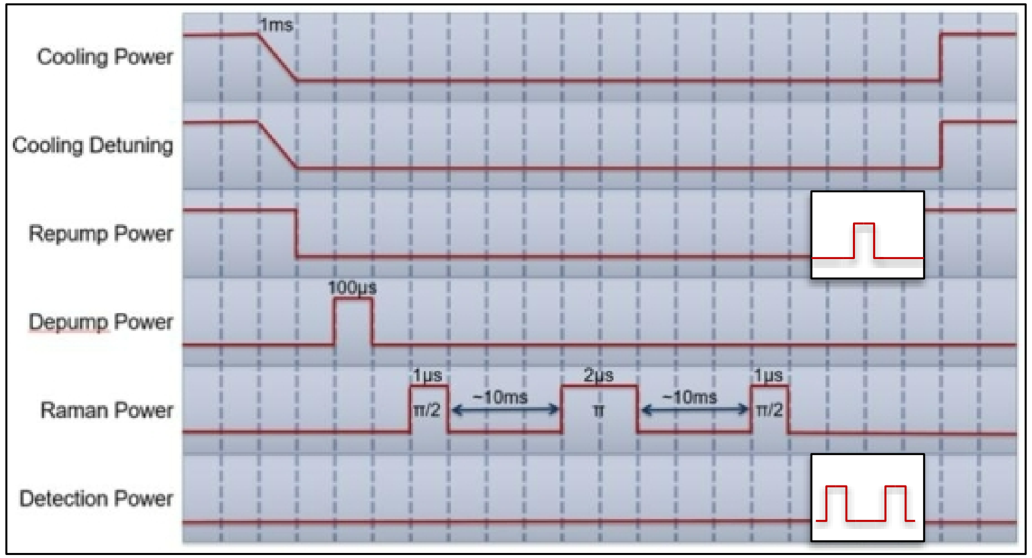


Packaged SSBM Demonstration

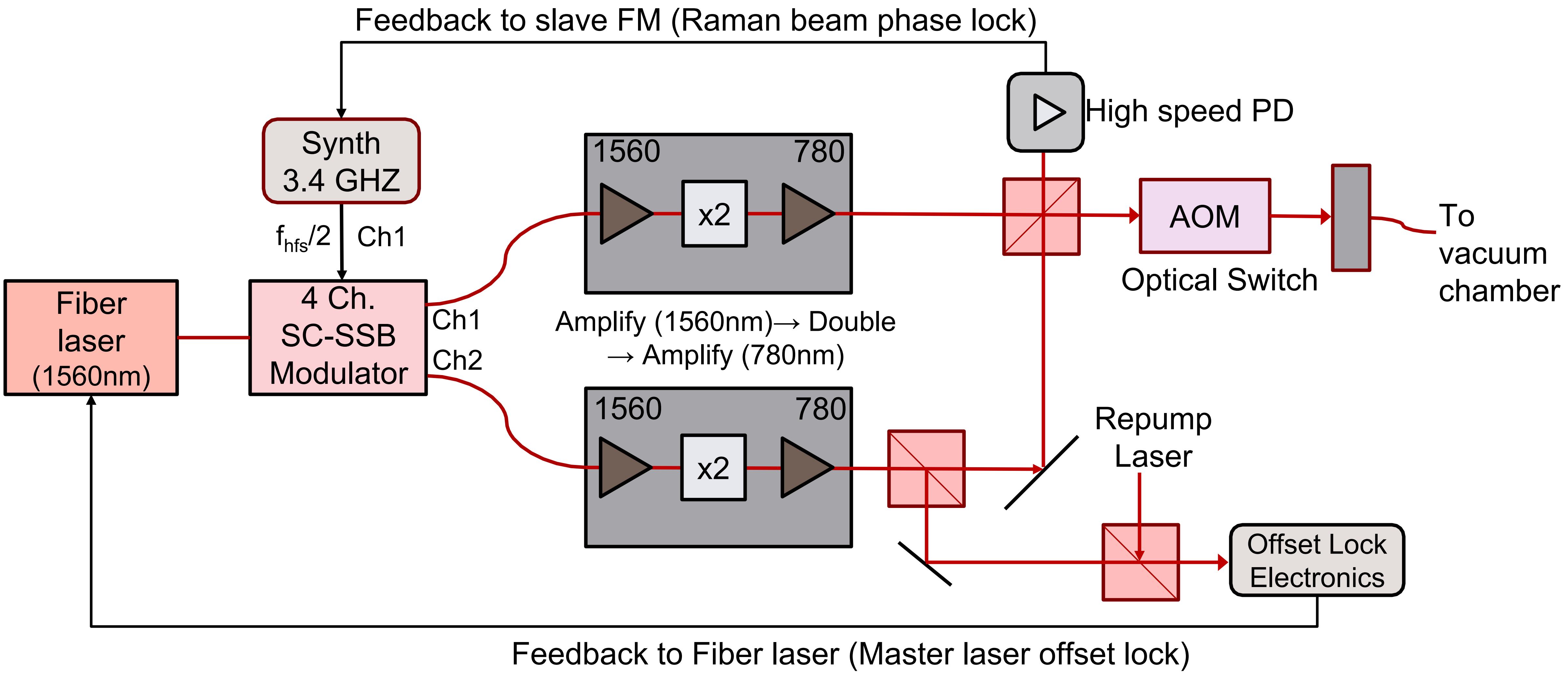
- State Selective Detection Successfully Demonstrated
  - Seed laser locked at midpoint of detection & repump frequencies
  - Modulator driven at 1.644 GHz
  - Thermo-optic phase shifters switched between +1 and -1 side-band
  - **Total frequency jump at 780nm – 6.576 GHz**





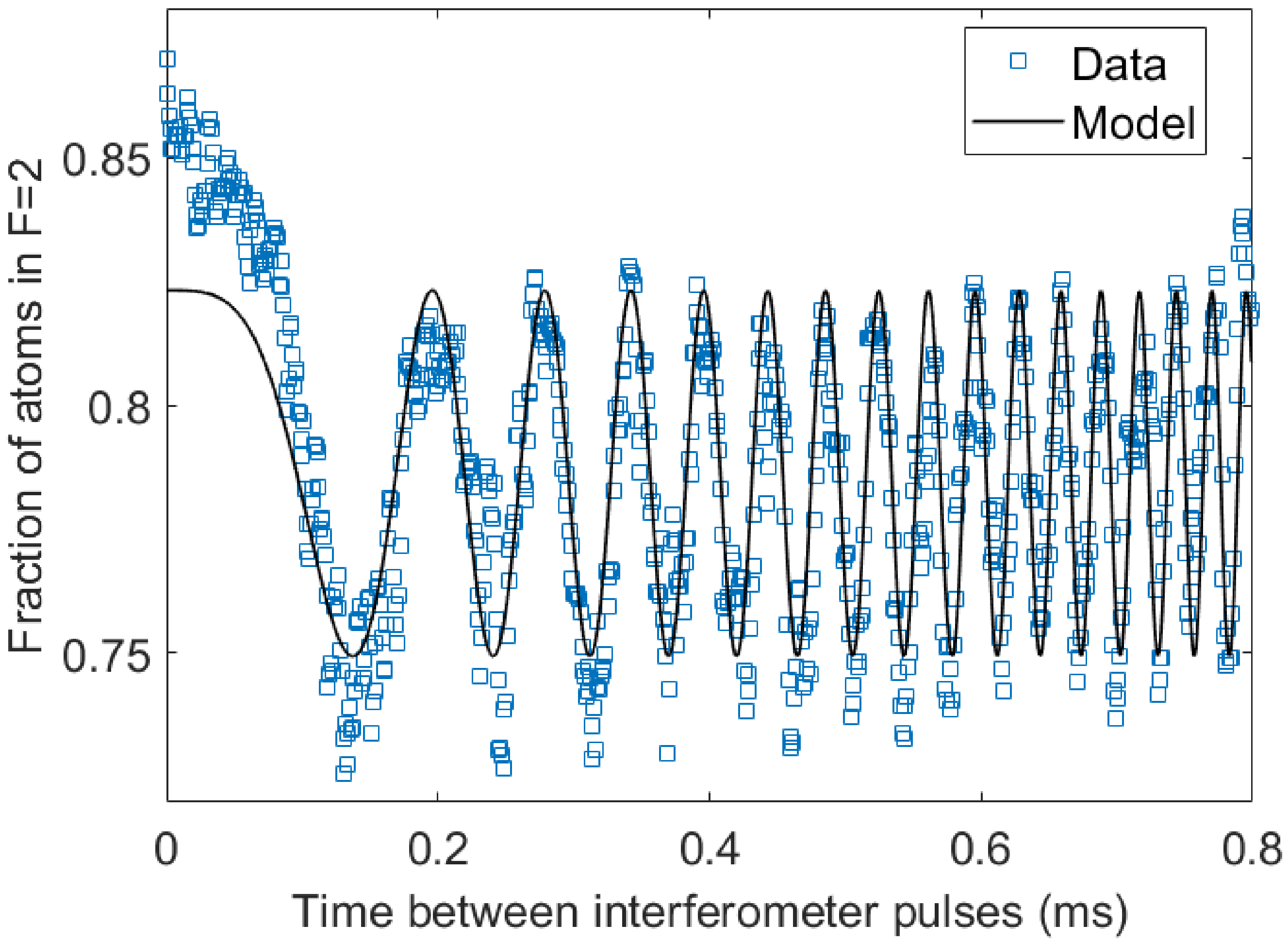


Integrated Photonics Raman Laser Setup



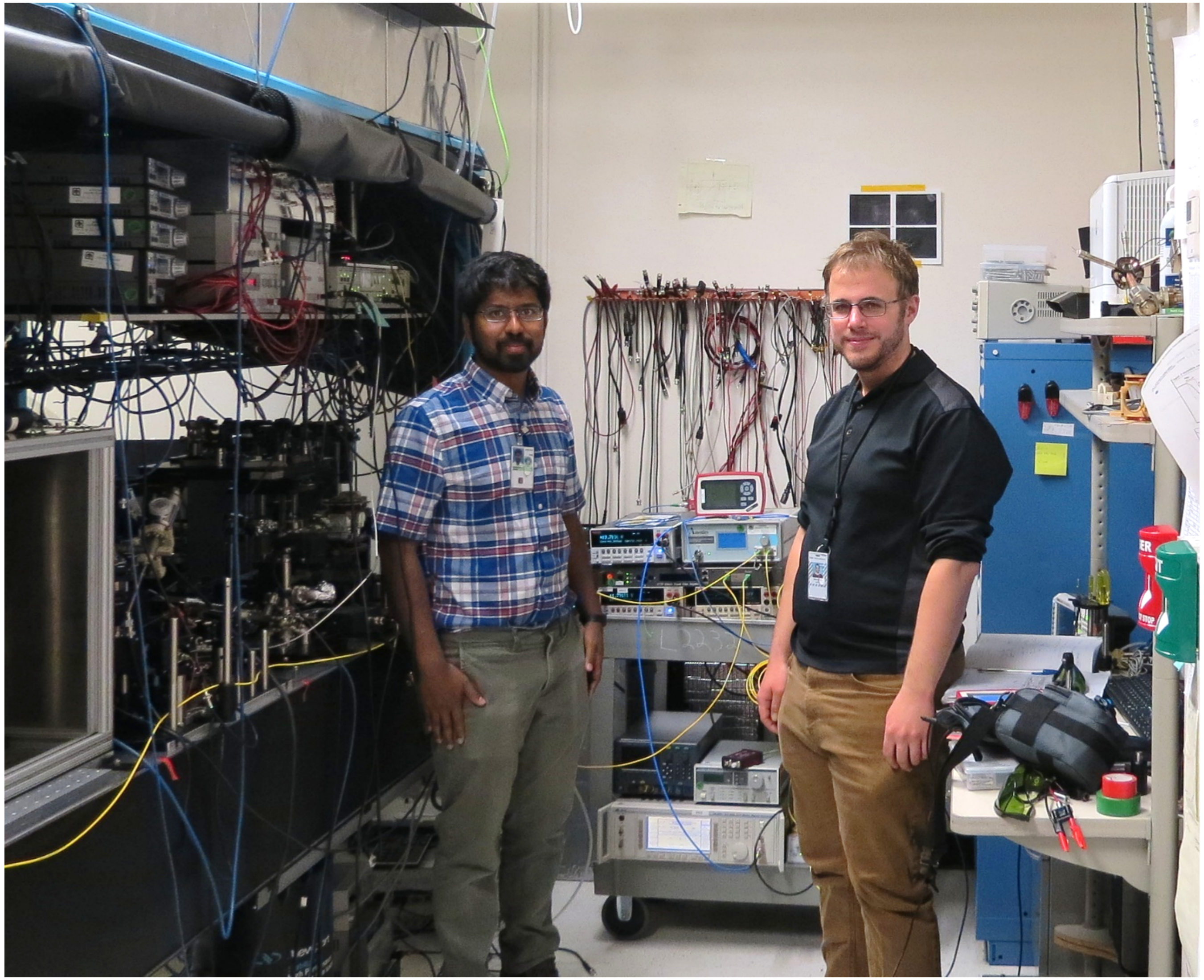
SC-SSB: Suppressed Carrier Single Sideband

AI Demonstration with Integrated Raman Laser Setup



- Demonstrate an AI accelerometer, an atomic gravimeter with SIP Raman laser setup
- $\pi/2 \rightarrow \pi \rightarrow \pi/2$, where $\tau_\pi = 5\ \mu s$
- Measure the chirped fringe from the Doppler-shifted atomic resonance due to gravitational acceleration
- Estimate the gravity with a model: $g \approx 9.77 \pm 0.01\ m/s^2$

Packaged SSBM Demonstration

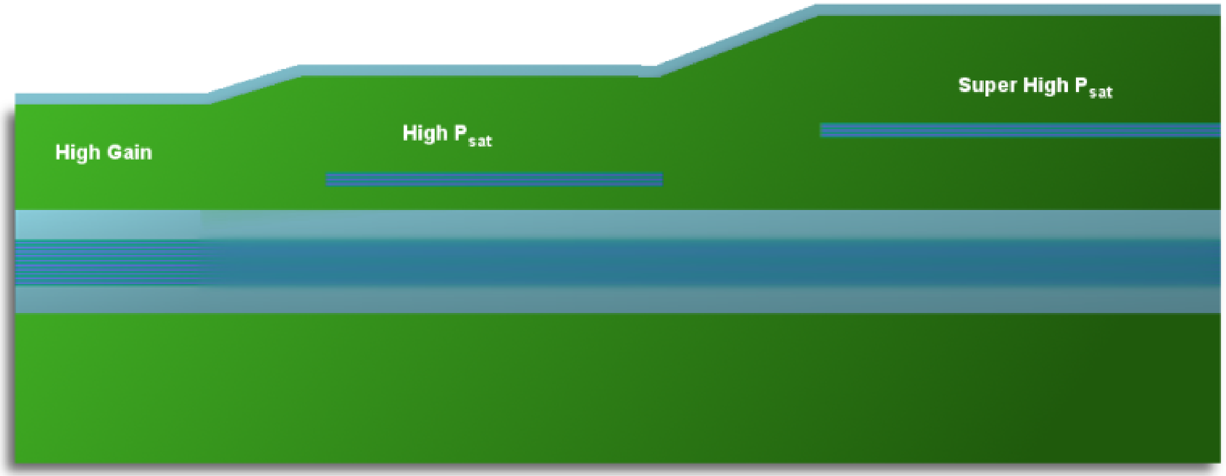


Ashok Kodigala and Greg Hoth demonstrating a rubidium MOT with a cooling beam generated by silicon photonics

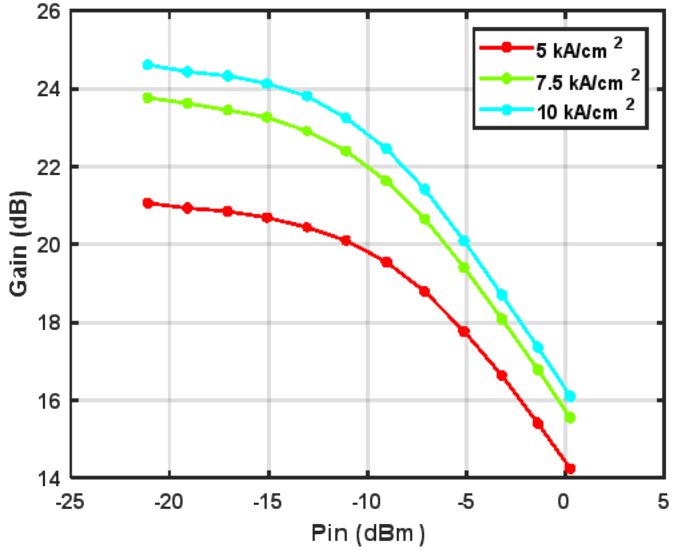
AMPLIFIER AND FREQUENCY DOUBLER

Three-stage optical amplifier

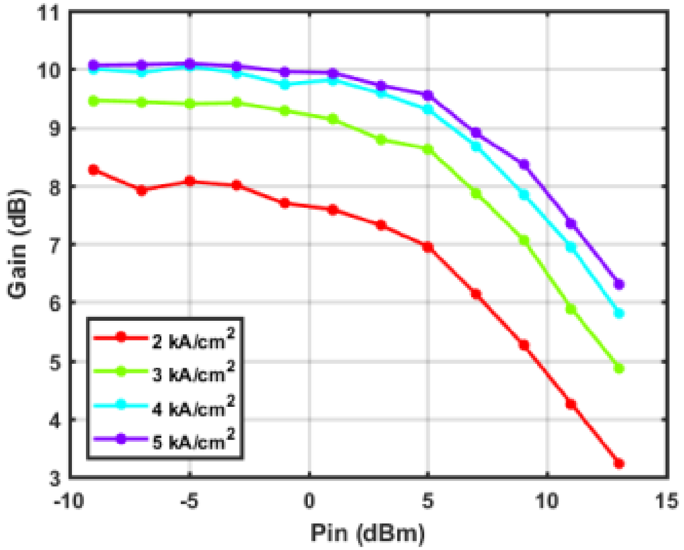
- Need nearly 1 W of 1560 nm power
- Large optical power challenging
  - Saturate gain materials
- First two stages successful
- Last stage needs more fabrication development

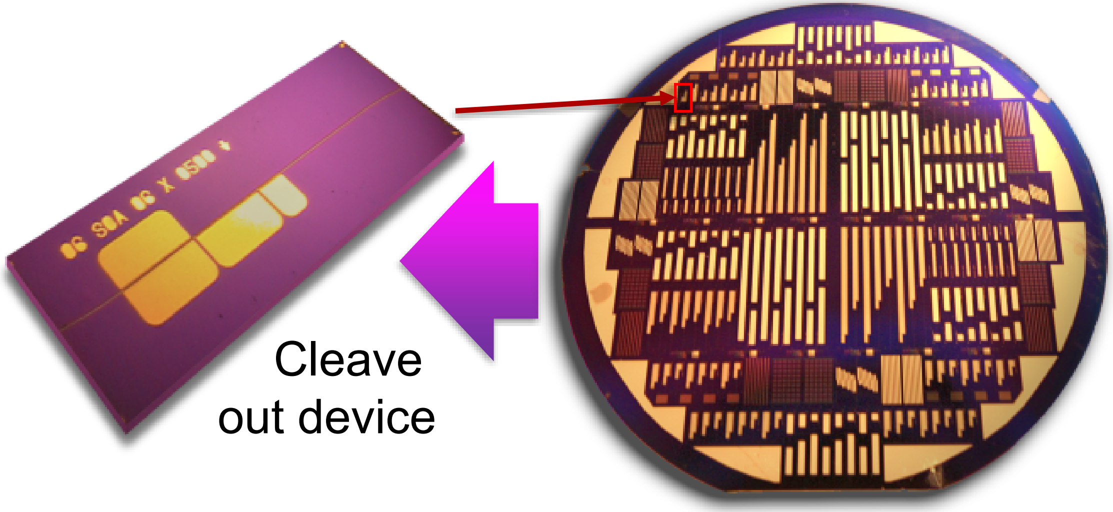


First stage amplifier



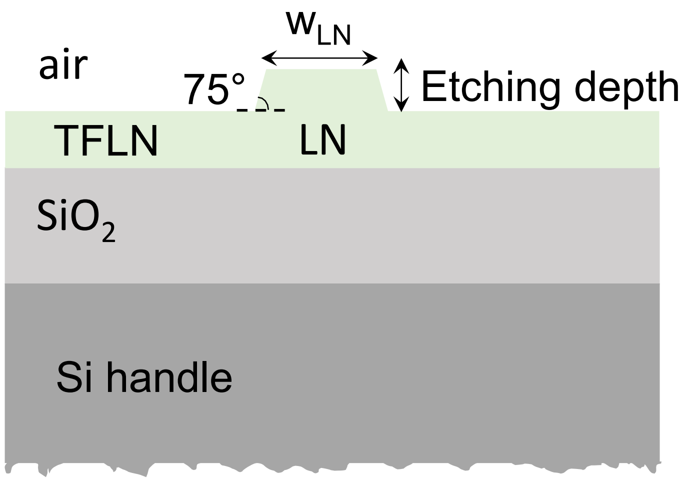
Middle stage amplifier





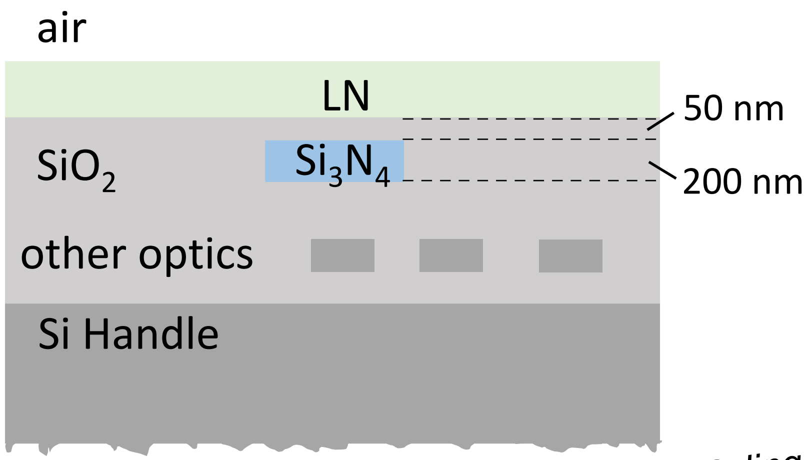
Frequency Doubler with Lithium Niobate: Two approaches to Waveguides

Rib-etched LNOI

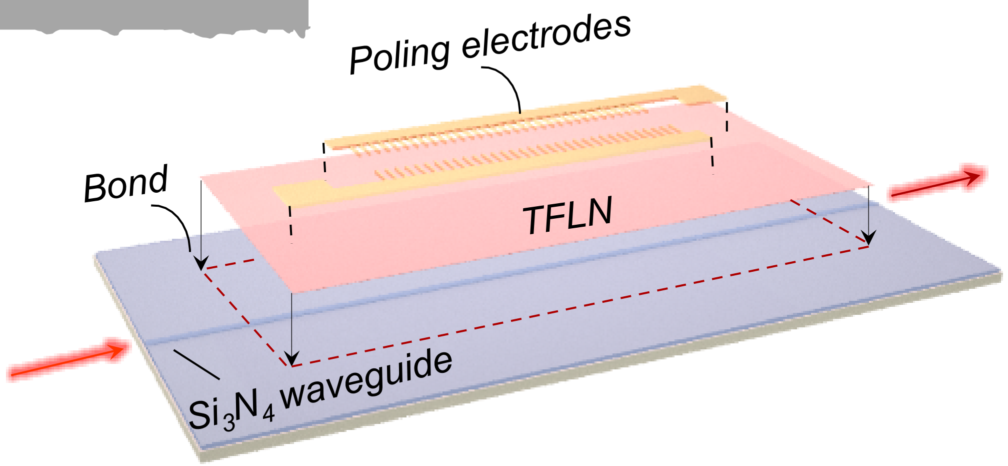


- Disorder-tolerant waveguide design.
- First pole, then verify poling quality, and finally, shallow etch.
- Etched at Univ. Rochester, collaboration w/ Qiang Lin's group. Other options now exist.

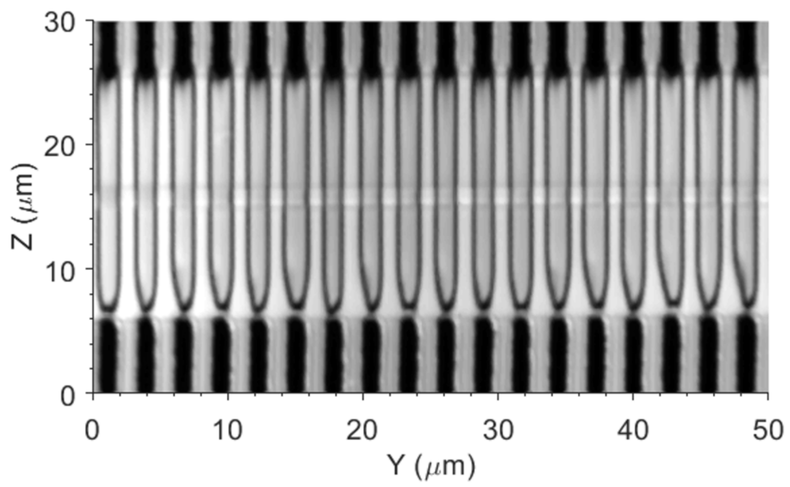
Strip-loaded, bonded LNOI

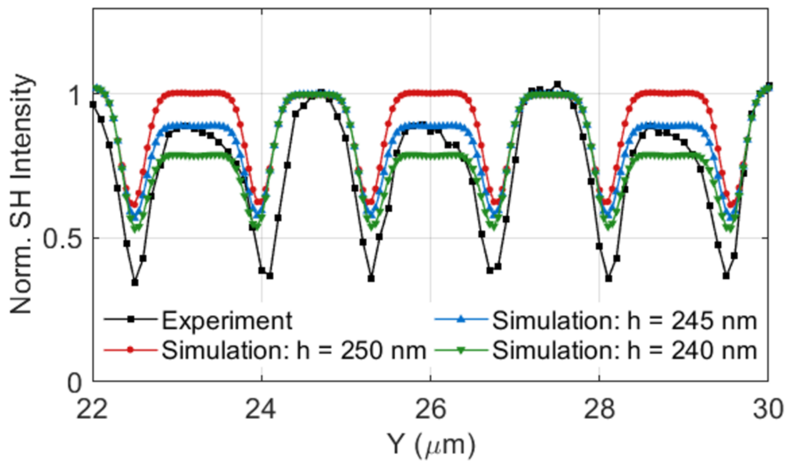


- Relies on bonding. No etching of LN.
- Integrate LN with other photonic structures through vertical (inter-layer) transitions.
- Has been used by Sandia for EOM Sandia e.g., N. Boynton et al. Opt. Express 28, 1864 (2020).

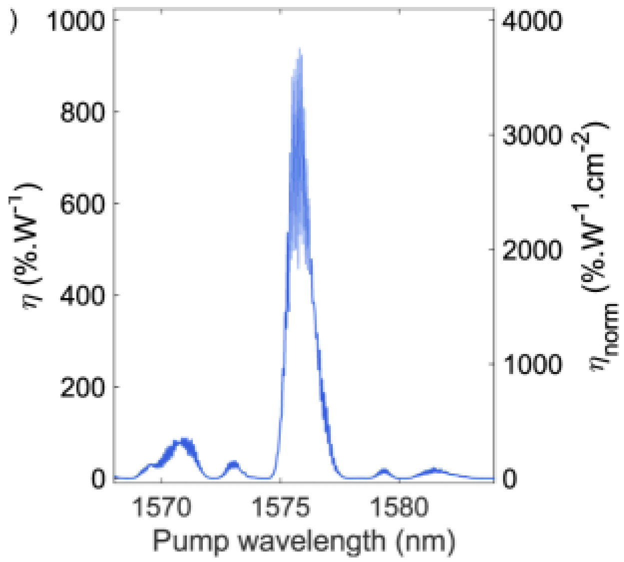


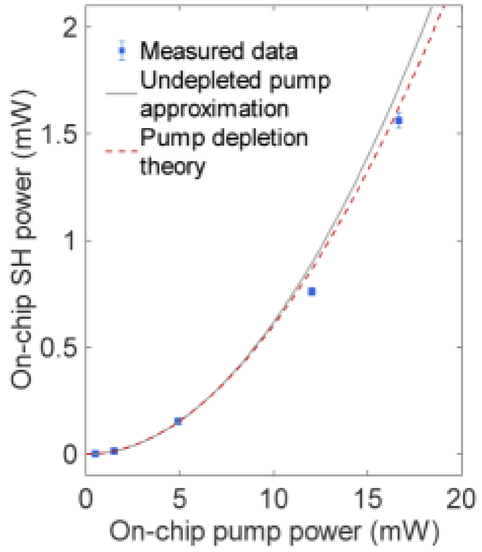
Imaging of domain walls and record doubling efficiency





- Second harmonic (fs) microscopy
  - Suppression second harmonic generation at domain walls
- High-resolution line scans show the domain walls between oppositely-oriented poled domains.
- Highest waveguide conversion efficiency (939 %/W)
- Next steps: bond poled LiN to silicon for hybrid integration

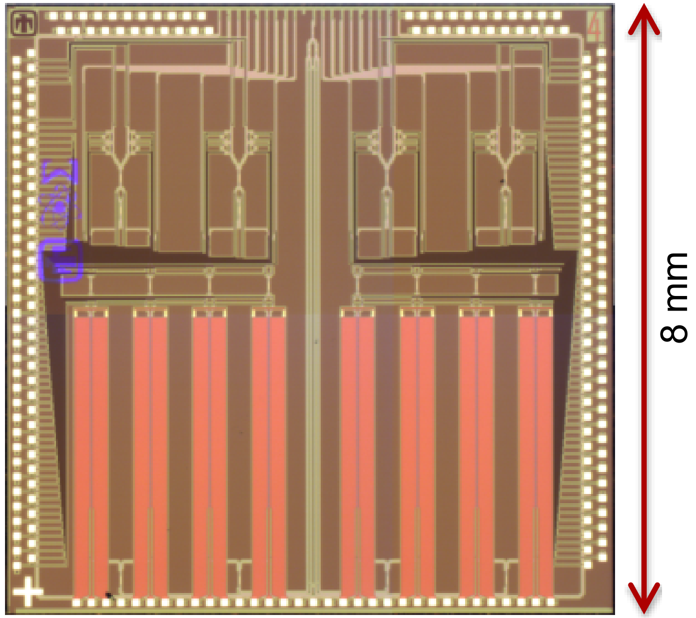




- Jie Zhao, et al. Phys. Rev. Lett. 124, (2020)
- M. Ruesing, et al. J. of App. Phys., Vol. 126, 114105 (2019)

Development of key components: hybrid integration in single Si chip

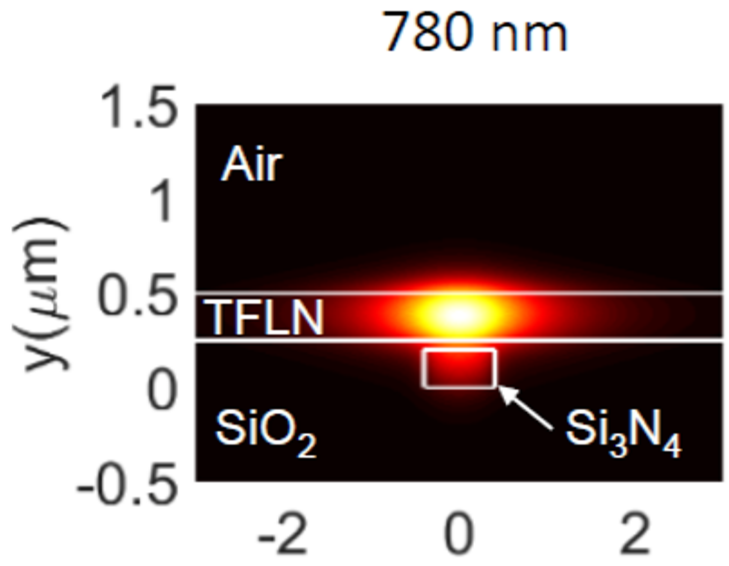
Single Sideband Modulator



Amplifier

- Move toward hybrid integrated III-V material on silicon
- Continued work in DARPA LUMOS

Thin film LN doubler on silicon



Vision: Several cubic centimeter laser system

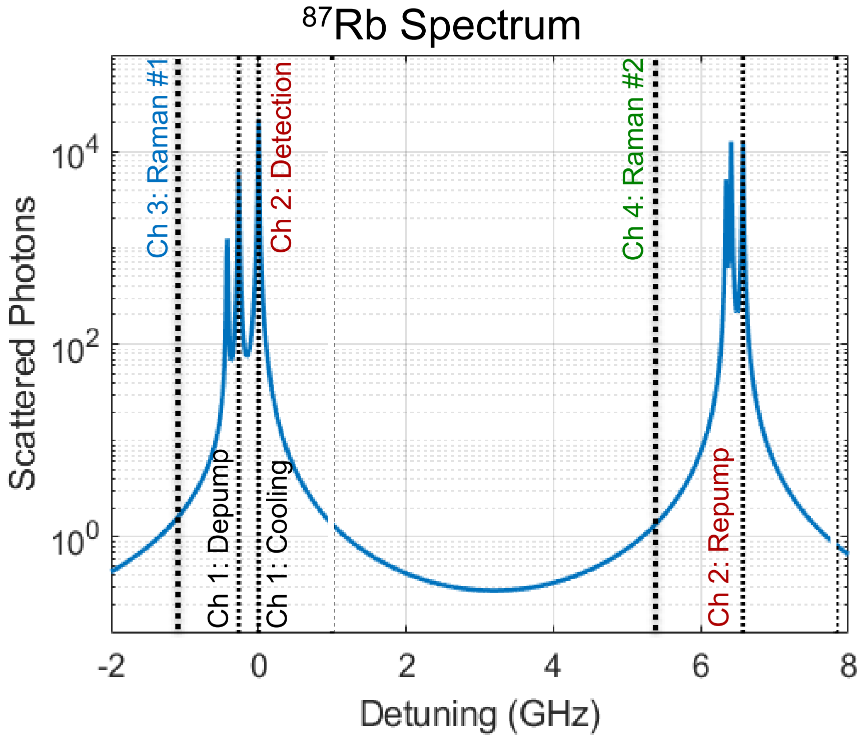
COMPACT ATOM INTERFEROMETER SENSOR HEAD

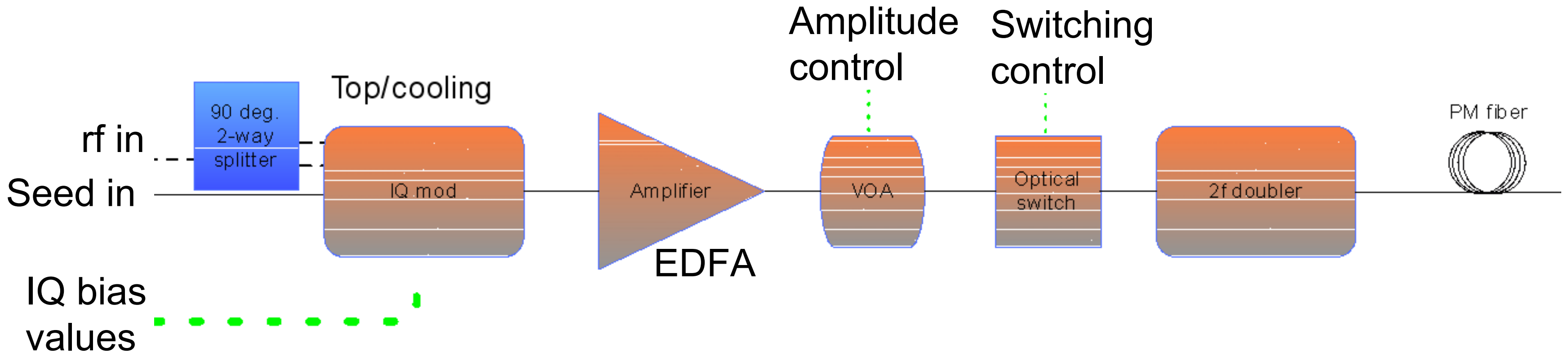
Commercial off the Shelf (COTS) Laser Architecture

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



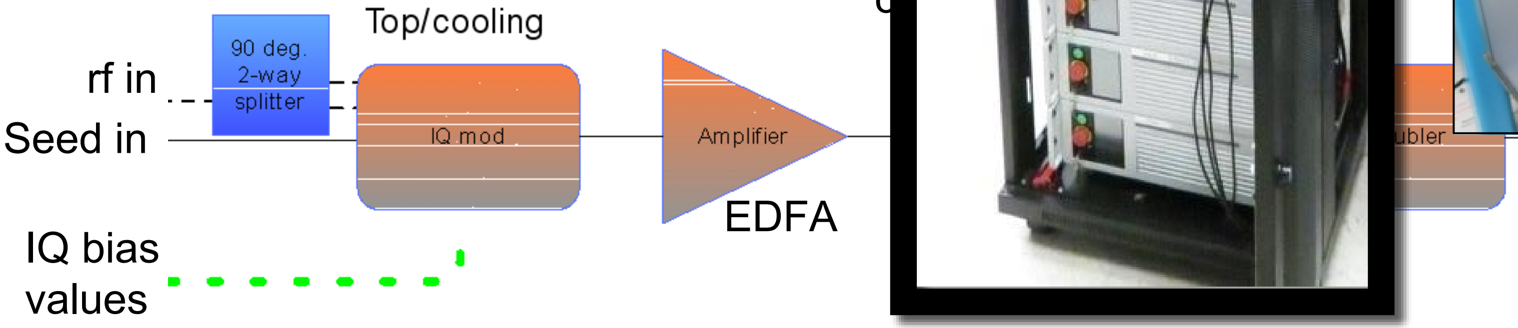


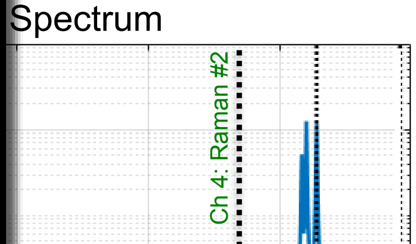
Commercial off the Shelf (COTS) Laser Architecture

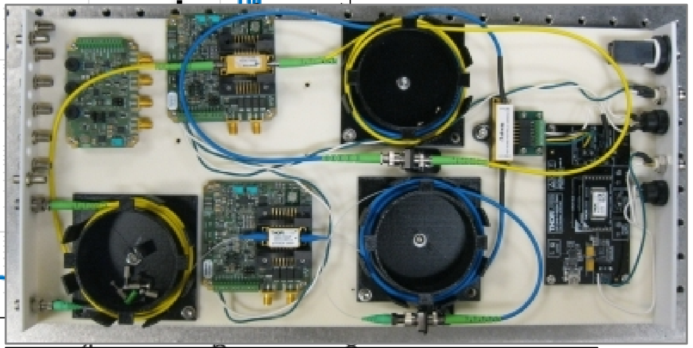
Five laser channels (previously 4 channels)

- 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.)

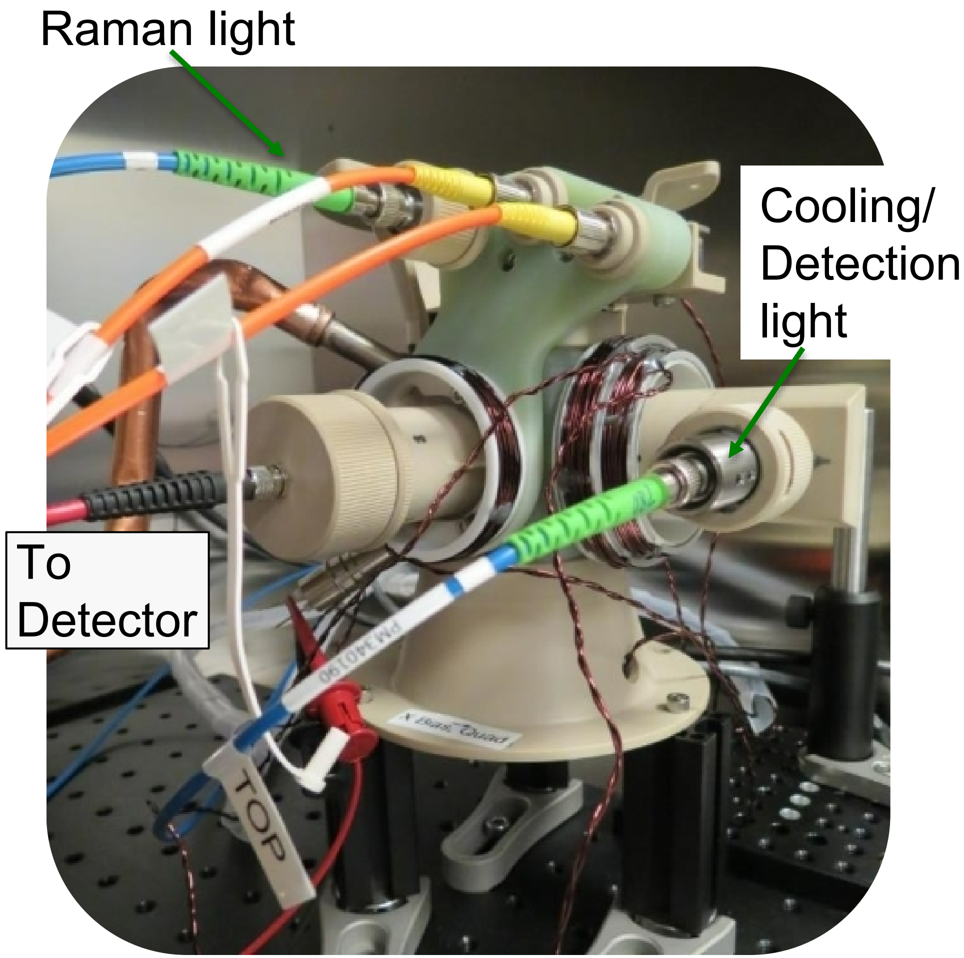
Seed : NP Photonics Rock Fiber Lase



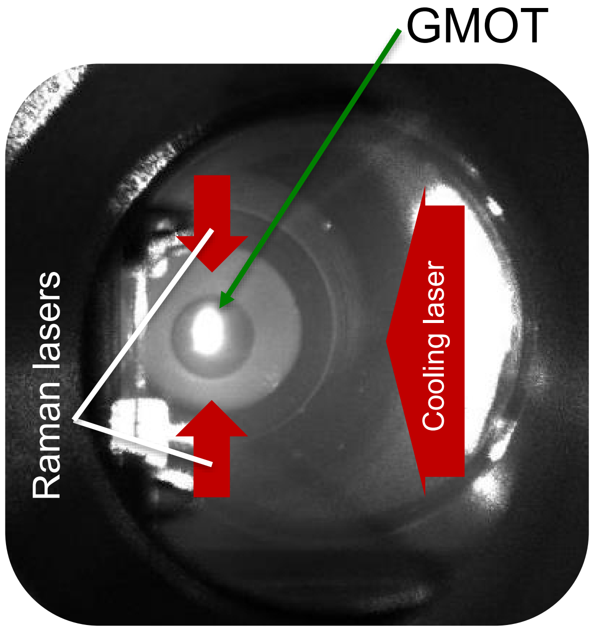




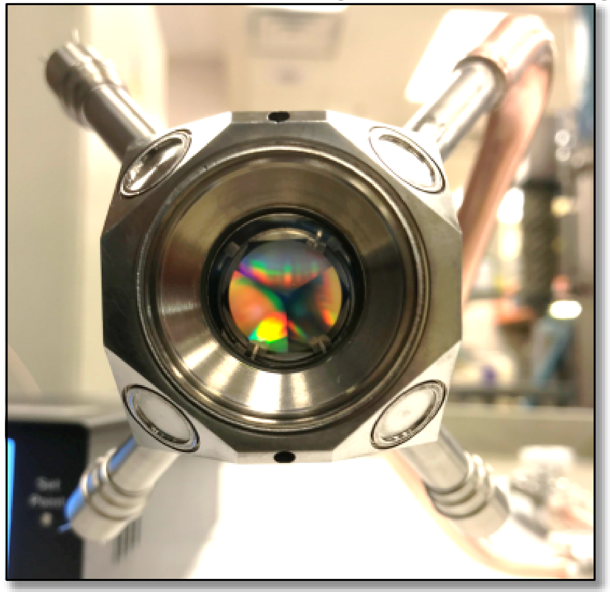
Compact Atom Interferometer Sensor Head

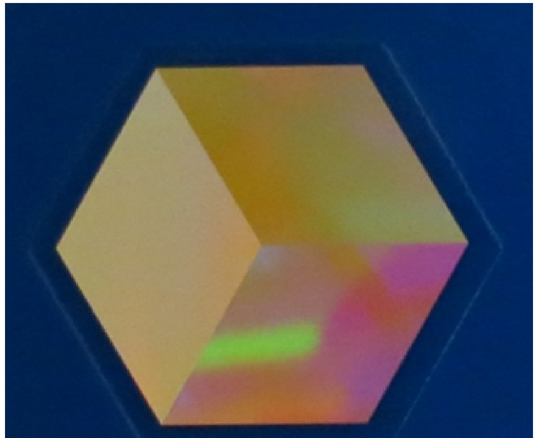


- Grating magneto optical trap (GMOT)
- Grating replaces one window of vacuum package
- Vacuum maintained by ion pump, fused silica windows
- Atom number: 10^6-10^7, Sub-Doppler cooling: 18 μK.



Ti Vacuum Package with Grating



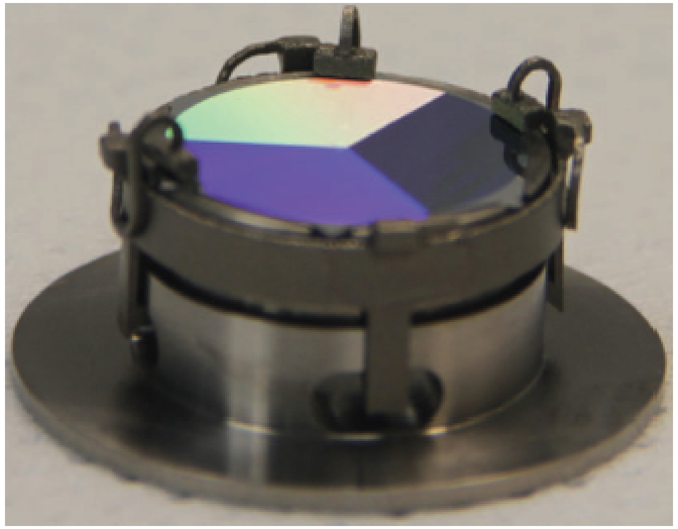


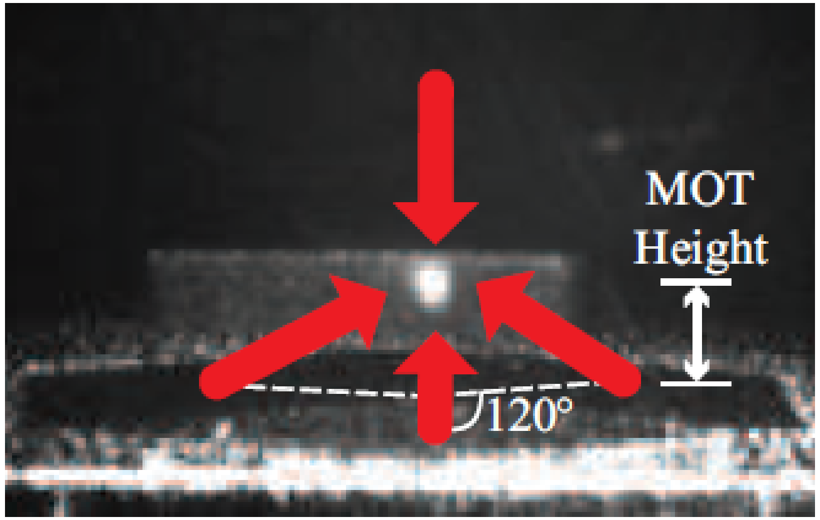
GMOT Grating

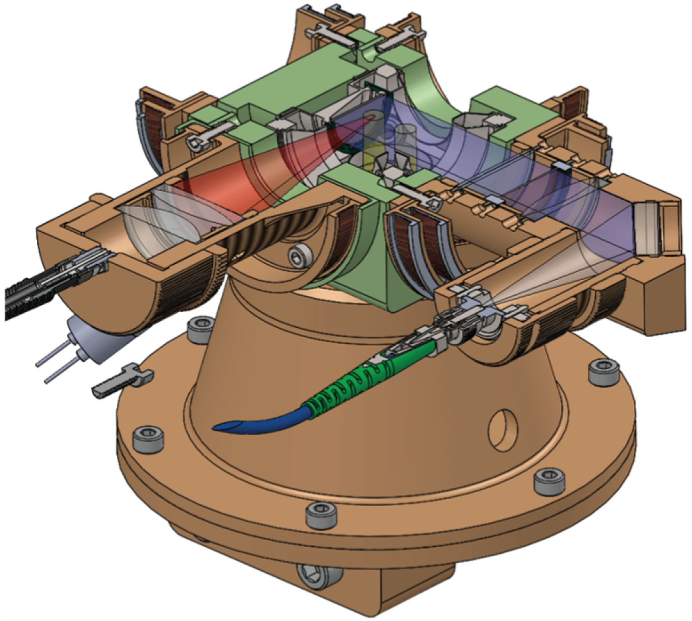
Same Raman configuration used in McGuinness, et al., APL (2012)

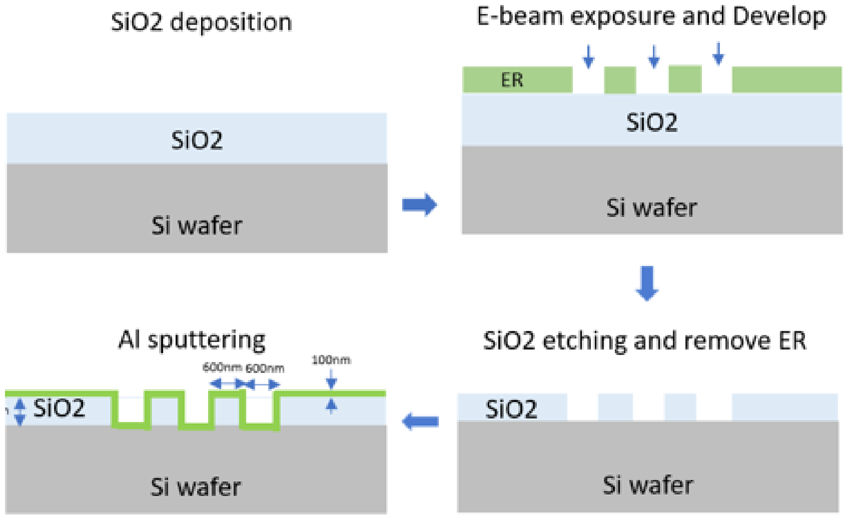
Grating-mirror Magneto-Optical Trap (GMOT)

Sandia National Laboratories



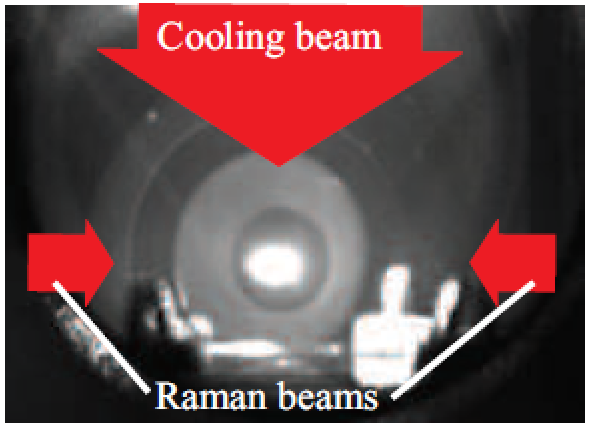




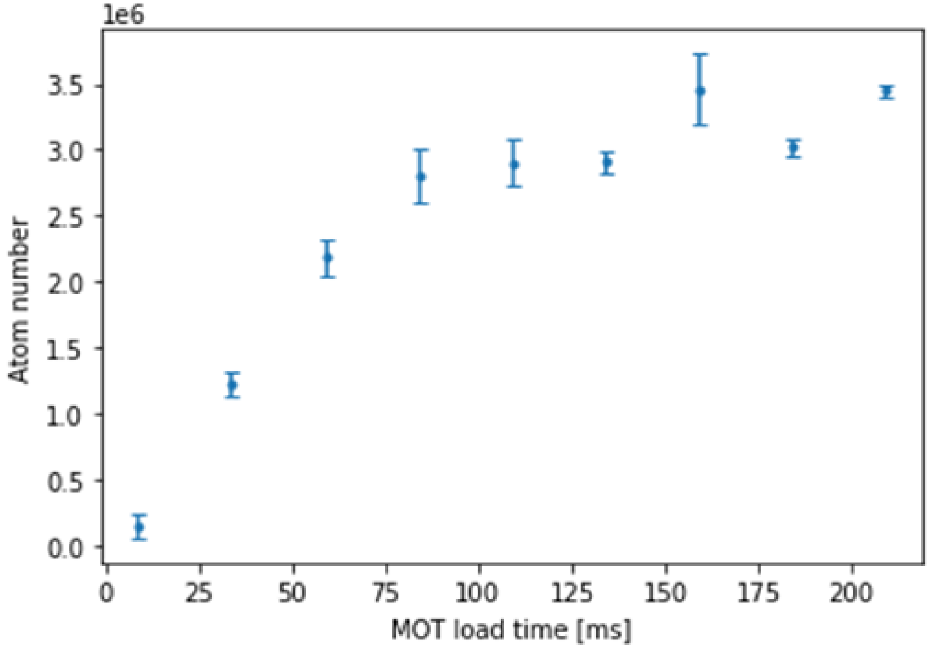


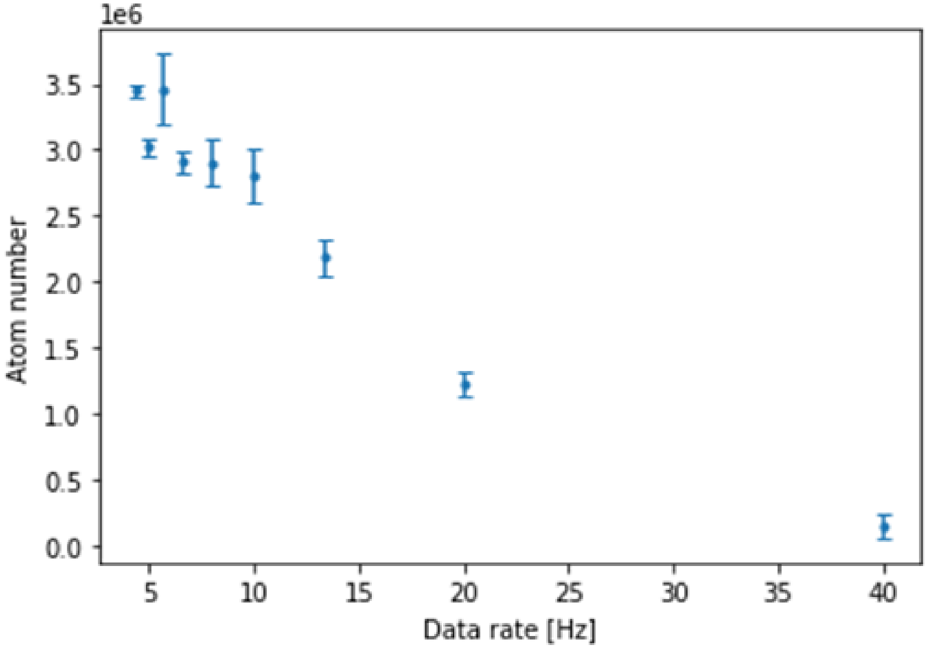
- Sandia-fabricated hexagonal reflective grating chip
  - 1.2 μm pitch, ~50% duty-cycle, and 195nm depth
  - Aluminum coating
- 3D-printed retainer ring to hold the grating chip for high dynamics
- Single-beam tetrahedral MOT configuration
- Compact sensor head with fixed alignment optical package to minimize vibration for deployable cold atom inertial sensors

Grating-mirror Magneto-Optical Trap (GMOT)



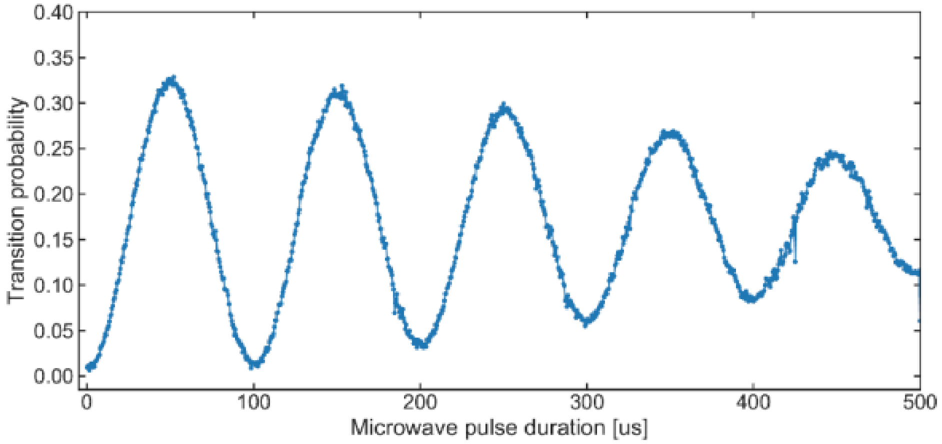
- Sub-Doppler cooled GMOT atoms (T = 15μK)
- High data-rate GMOT operation
- Atom interferometry with Doppler-sensitive Raman beams





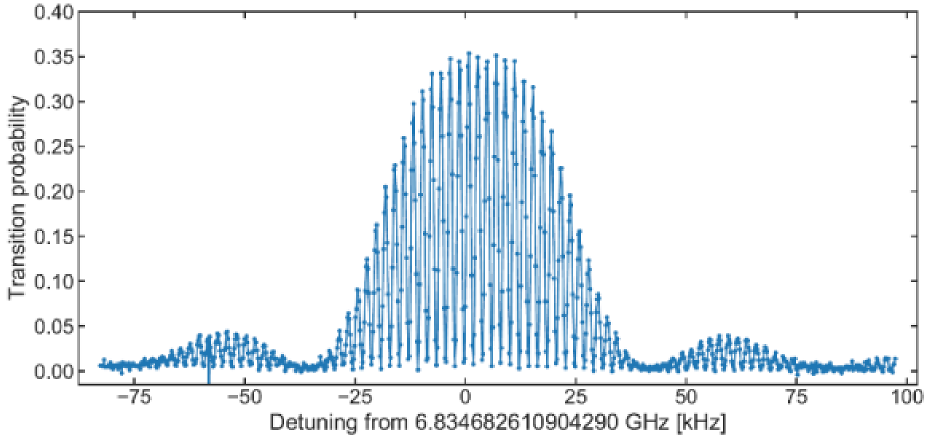
Atomic Coherence with GMOT

- Rabi oscillation with a microwave horn



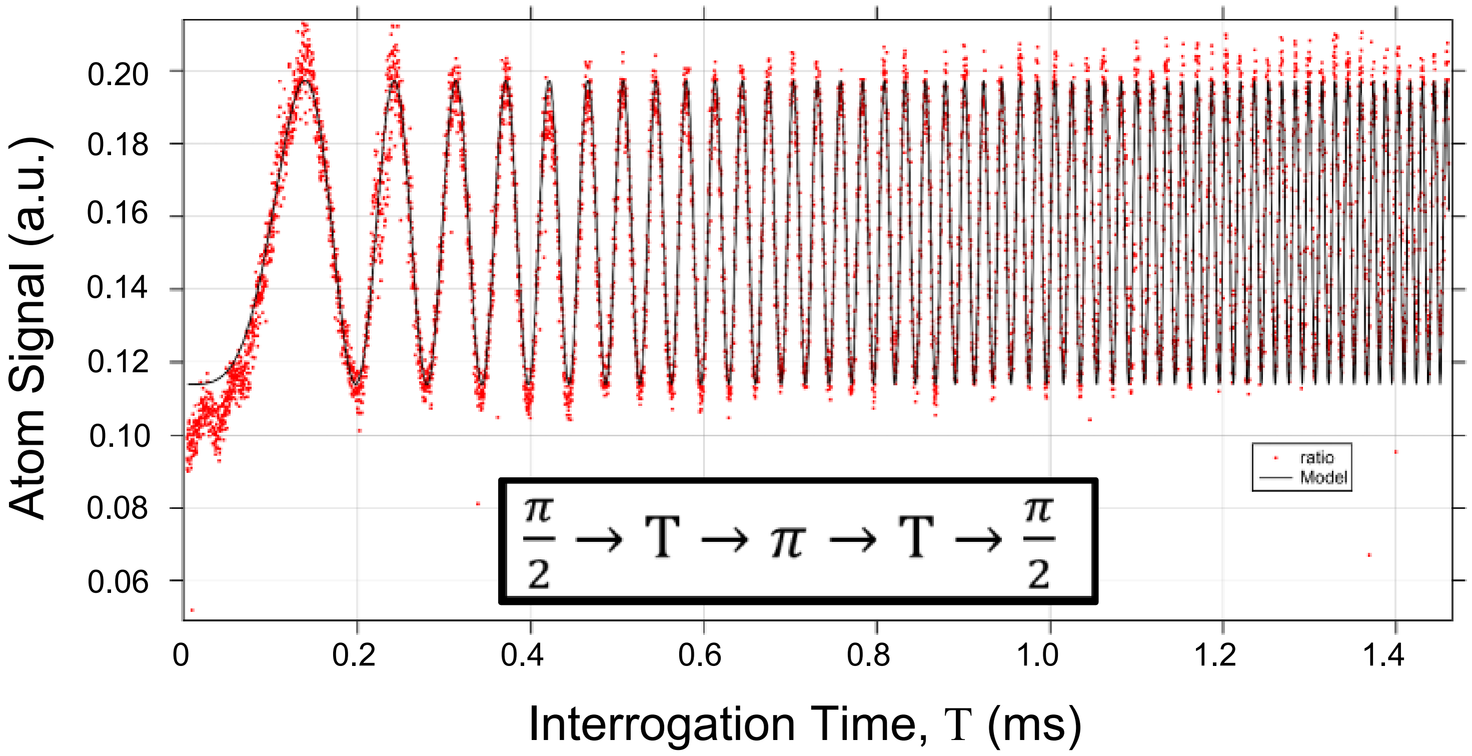
Rabi oscillation:
Rabi frequency $\simeq 10$ kHz

- Ramsey interferometry with a microwave horn



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

Atom Interferometer Demonstration with GMOT

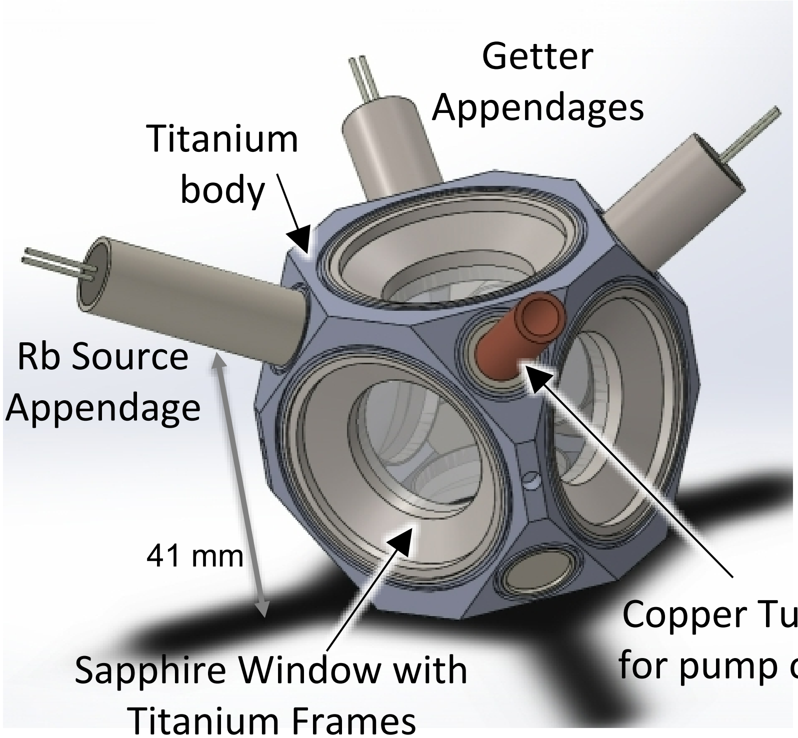


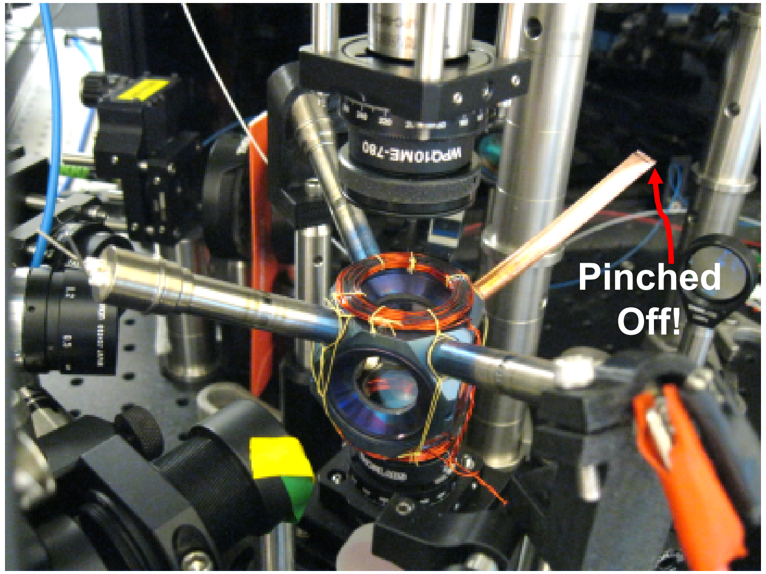
- Atomic accelerometer (atomic gravimeter) with a SIGMA prototype
- Sensing axis aligned to the direction of gravity.
- Atom interferometry with Doppler-sensitive Raman beams: T scan
- Data rate: 6.7 Hz
- Statistical uncertainty: < 25 μg (improving by the phase lock of two Raman beams)

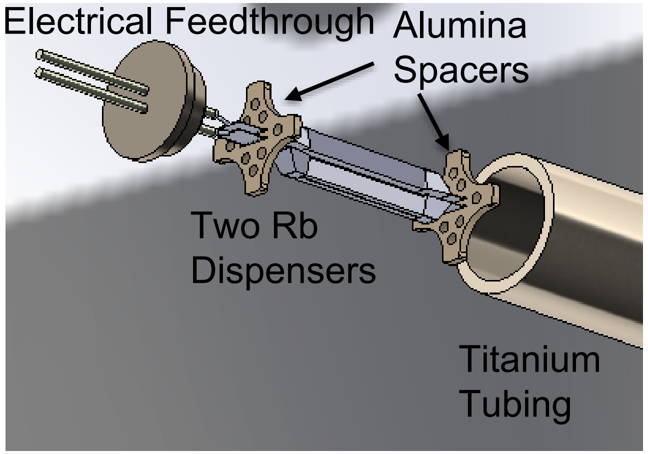
PASSIVELY PUMPED VACUUM PACKAGE

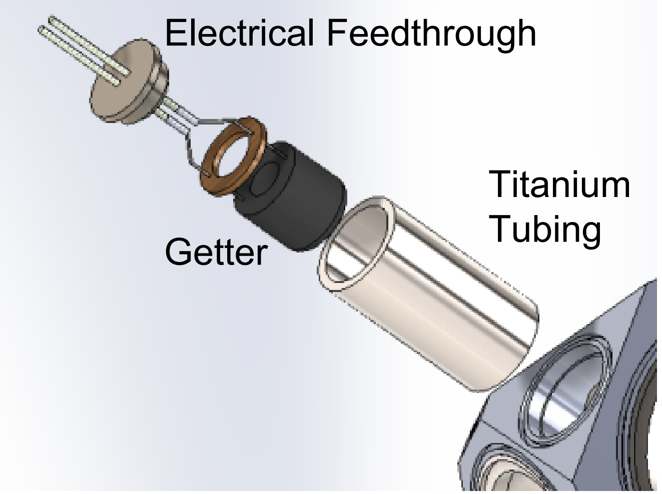
Passively pumped Vacuum Package: Titanium Package Design

- 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 °C bake-out in vacuum furnace

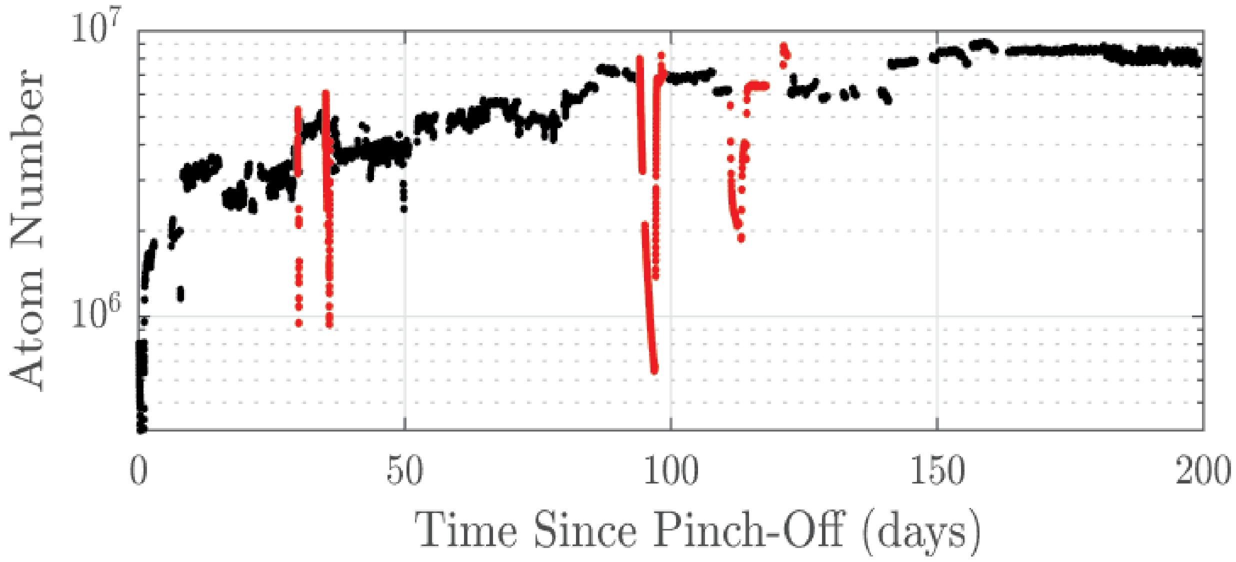


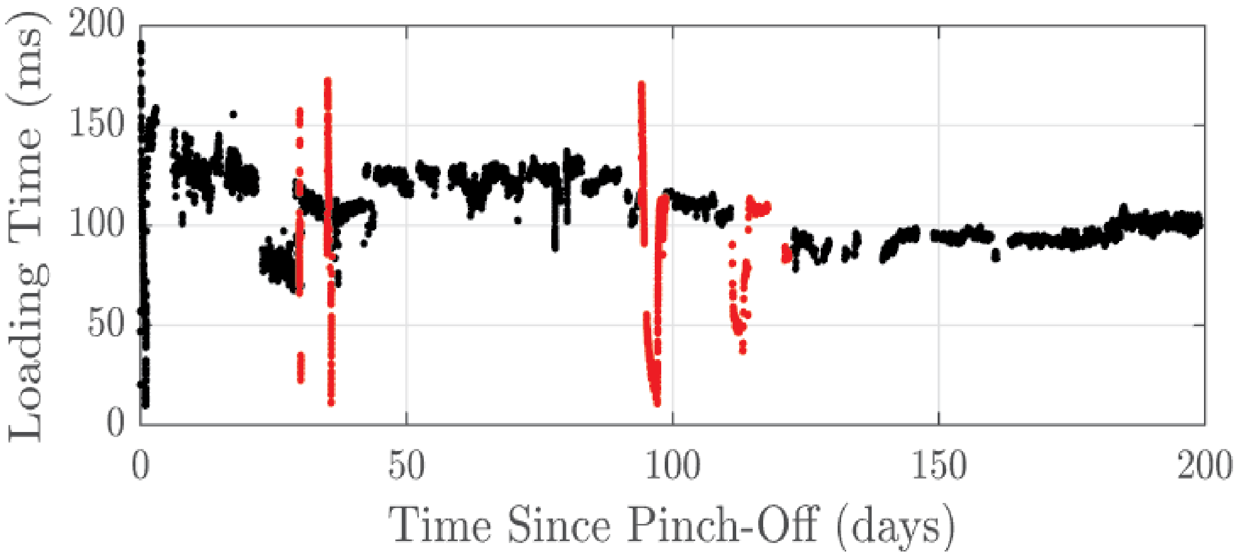




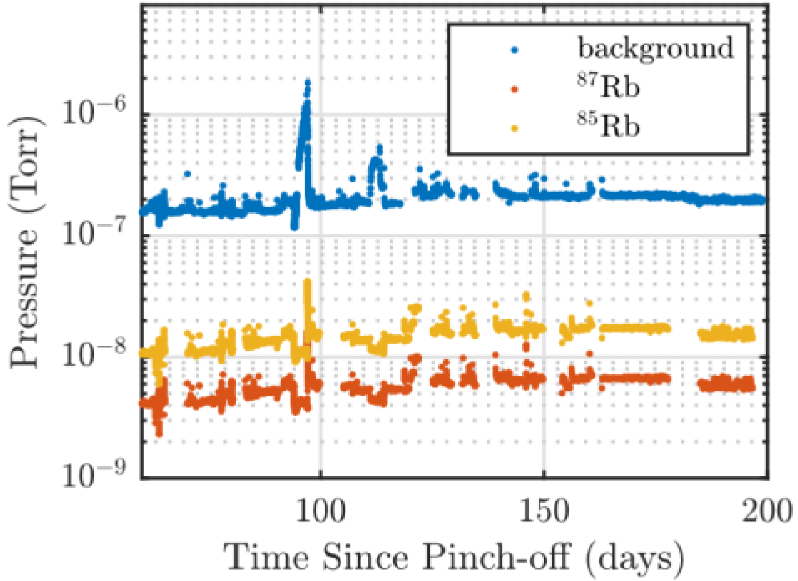


MOT in the Passively Pumped Chamber

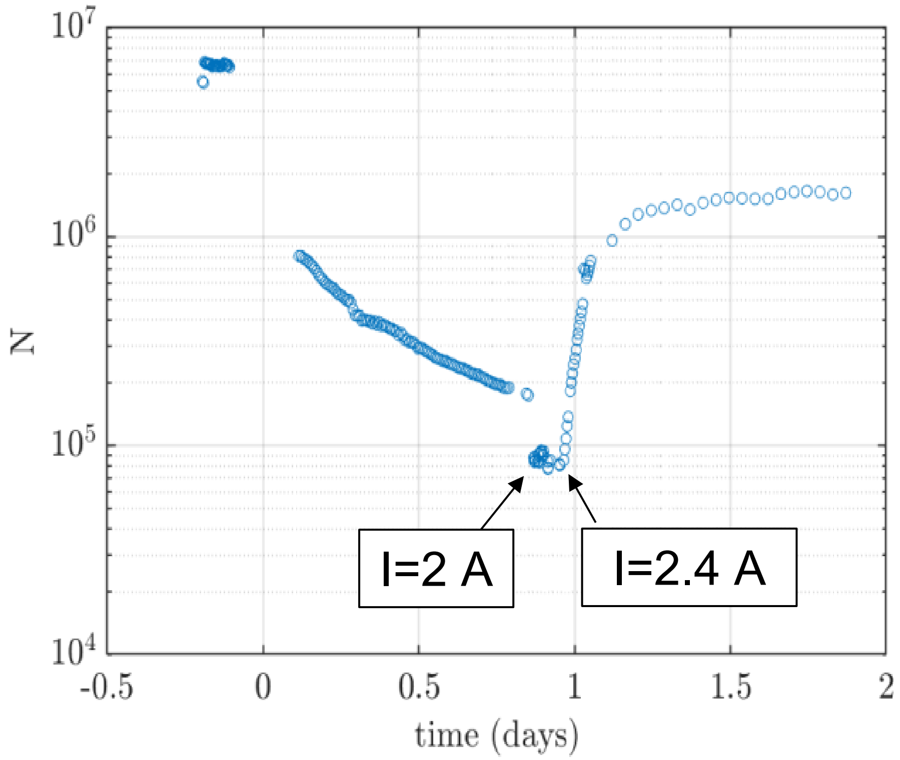


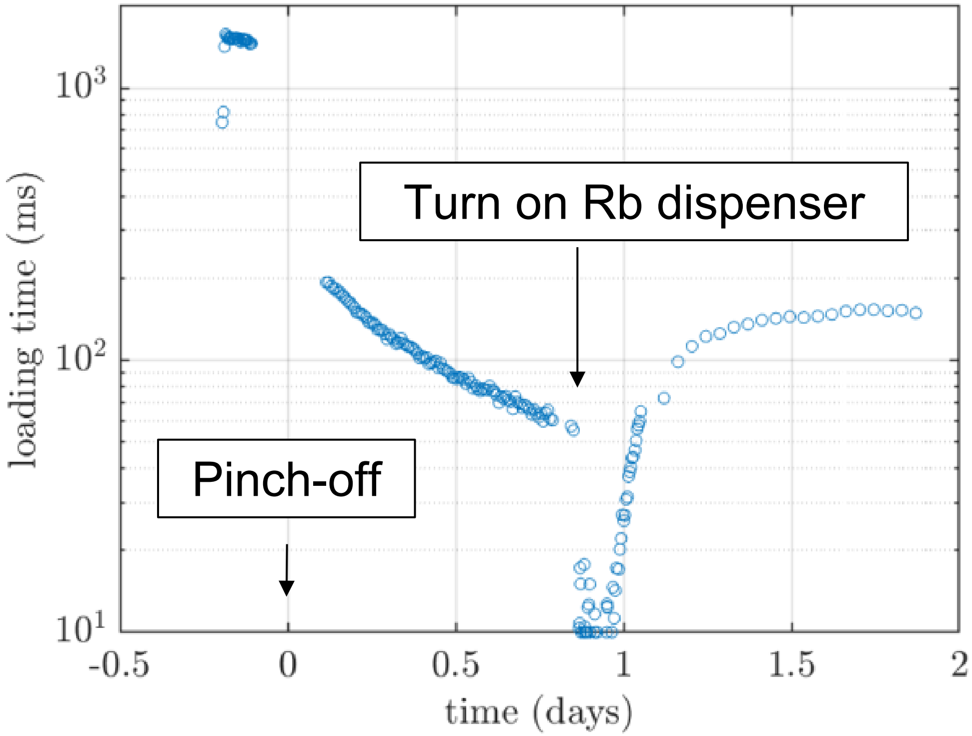


- Sustaining Cold Atoms for More Than 200 Days
- MOT seems happier with “pinch-off” rather than “pump off”.
  - $(N\tau)_{\text{pinch-off}} \approx 3 \times 10^5$ atoms $\cdot$ s vs $(N\tau)_{\text{pump-off}} \approx 0.7 \times 10^5$ atoms $\cdot$ s.
- Estimate pressure to be ~2×10^{-7} Torr. P_{Rb} = ~ 2×10^{-8} Torr
  - Large uncertainty in pressure estimates: need a clean way to estimate/vary P_{Rb} and alignment effects.

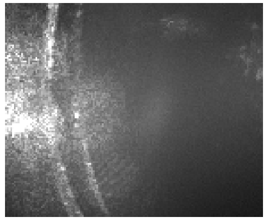


N-τ Evolution After Pinch-off



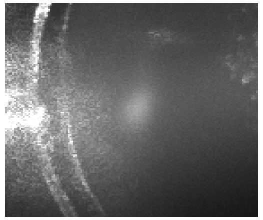


I= 2 A



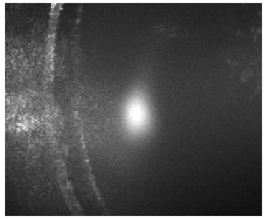
t_{exp}= 4 ms

I=2.4 A + 20 min



t_{exp}= 4 ms

I=2.4 A + 90 mins

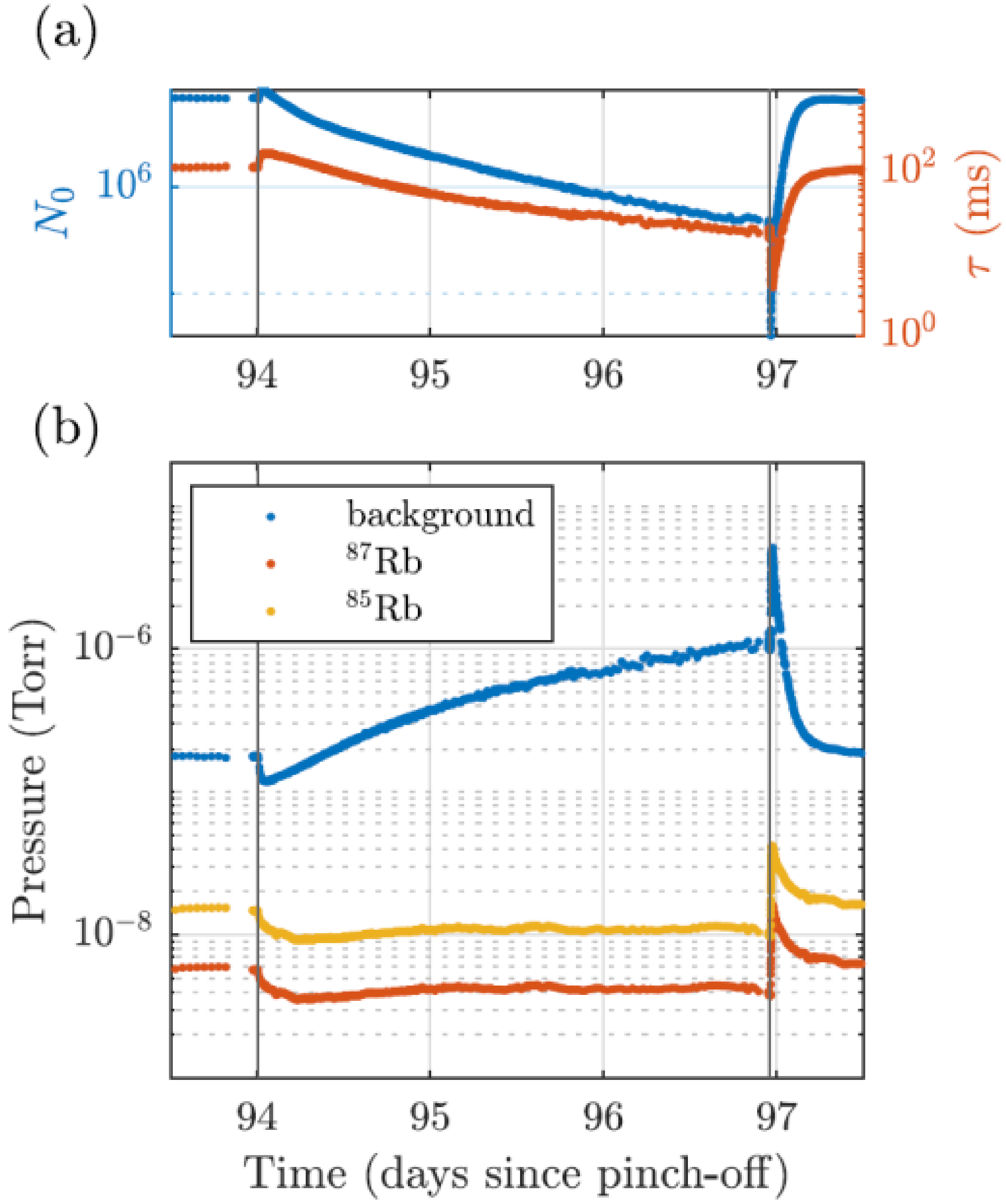


t_{exp}= 2 ms

- After pinch-off, $N-\tau$ decay slower than with "pump off".
- Driving the dispenser hard enough still improves vacuum.

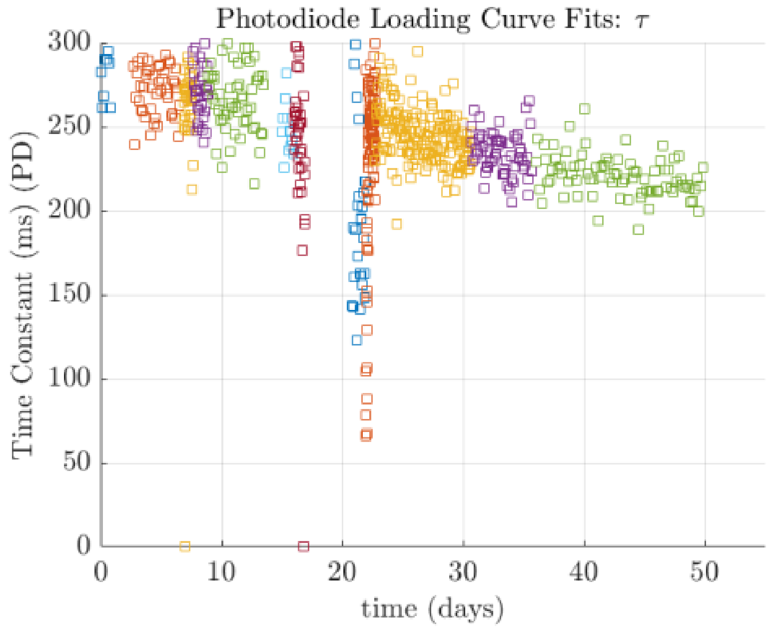
Effect of Rb dispenser

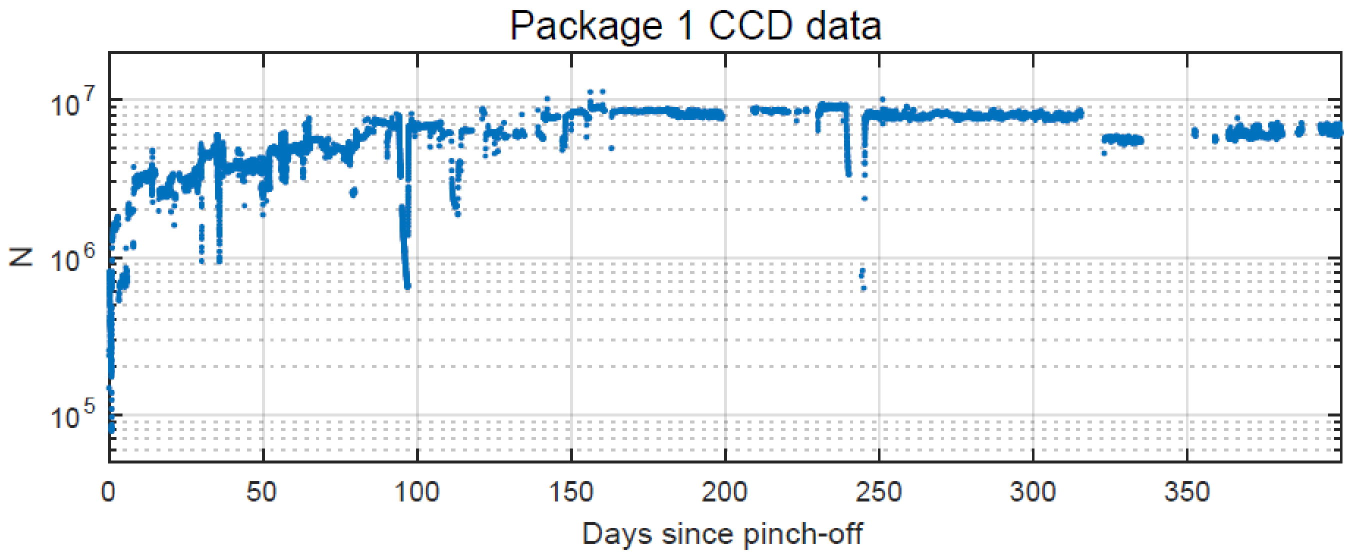
- Switch dispenser off
- Atom number decreases (expected)
- Load time decreases (not expected)
- Substantial pumping effect from the dispenser.
  - P. della Porta, C. Emili, and J. Hellier, in IEEE Conference on Tube Techniques (IEEE, 1968)

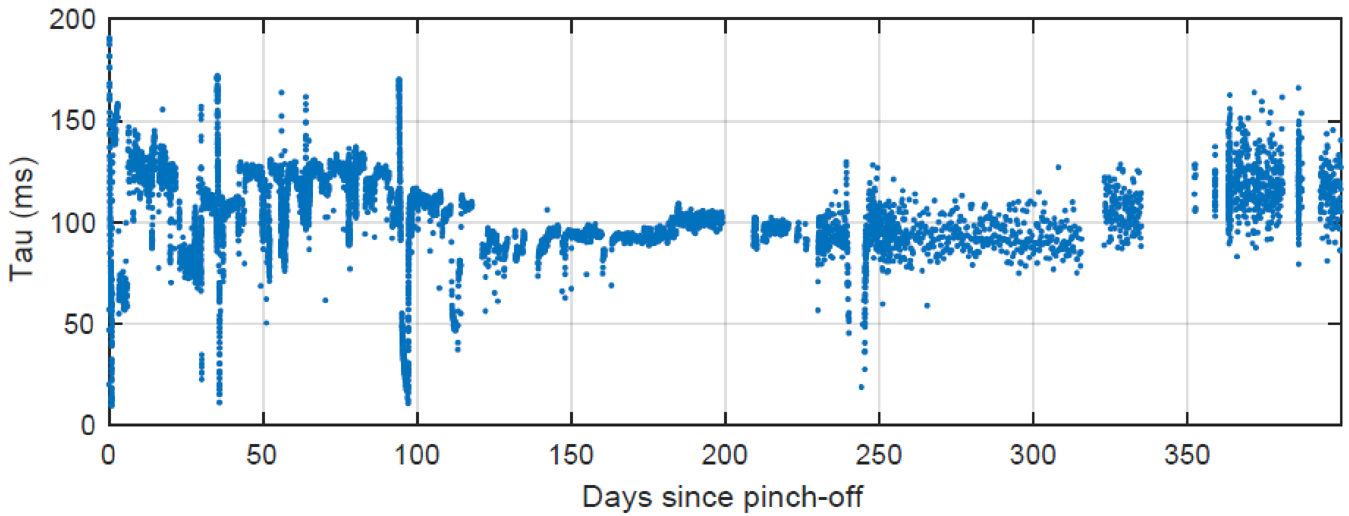


Package operating for more than one year!

- On day 231 changed to a Rb-85 MOT
  - Detection noisier
  - New data acquisition system on day 322
- Package 2
  - Valved off (not pinched)
  - Somewhat better vacuum conditions





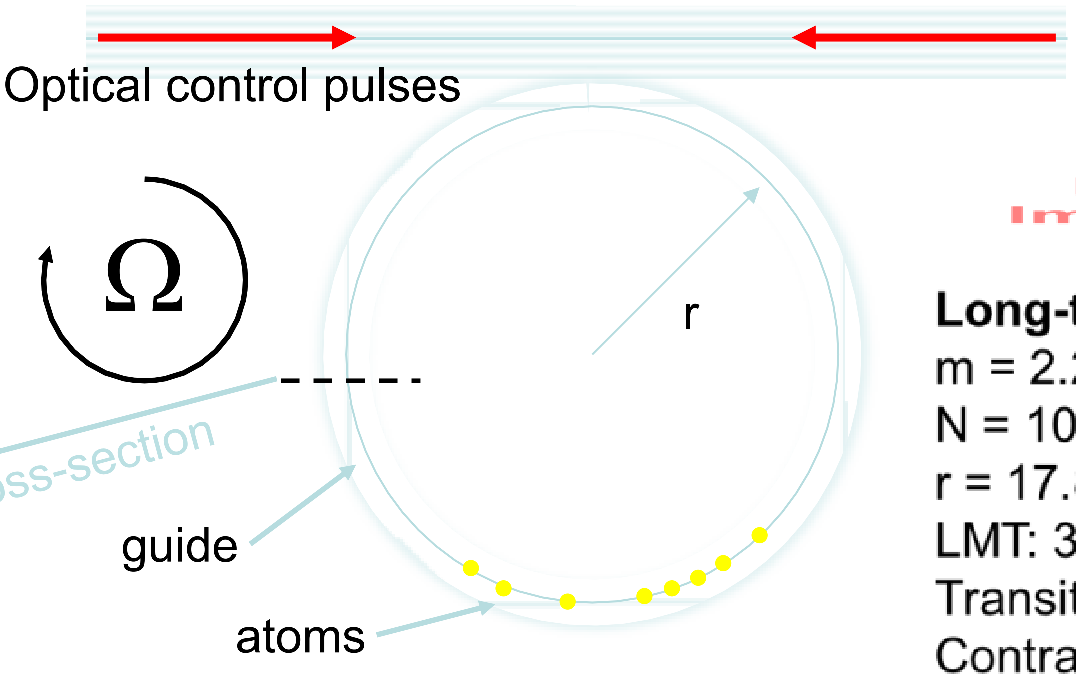


TOWARD GUIDED ATOM INTERFEROMETRY

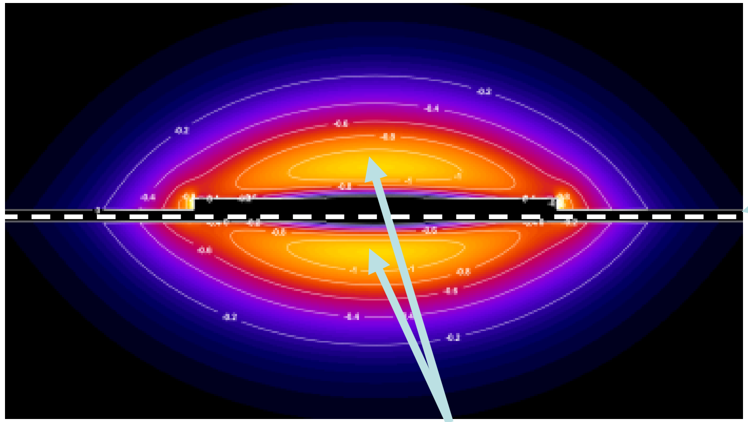
Sagnac matterwave interferometer using optical waveguides

Concept

1. Guide atoms along the evanescent-field optical trap (EFOT)
2. Separate atomic wavepacket with resonant light pulses: $\frac{\pi}{2} \rightarrow \frac{\pi}{2}$
3. Measure interferometric phase with the state-dependent optical probe



Waveguide Atom Trap Potential

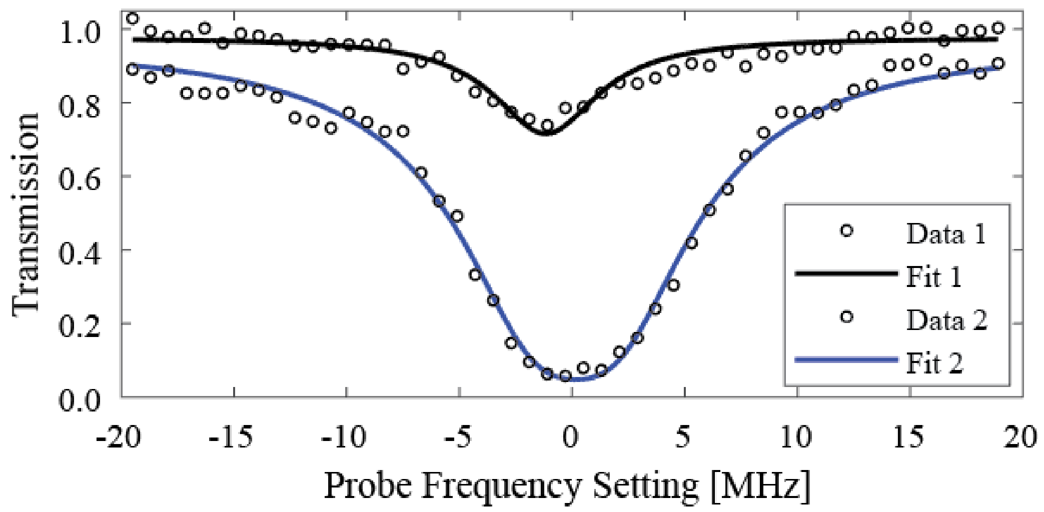


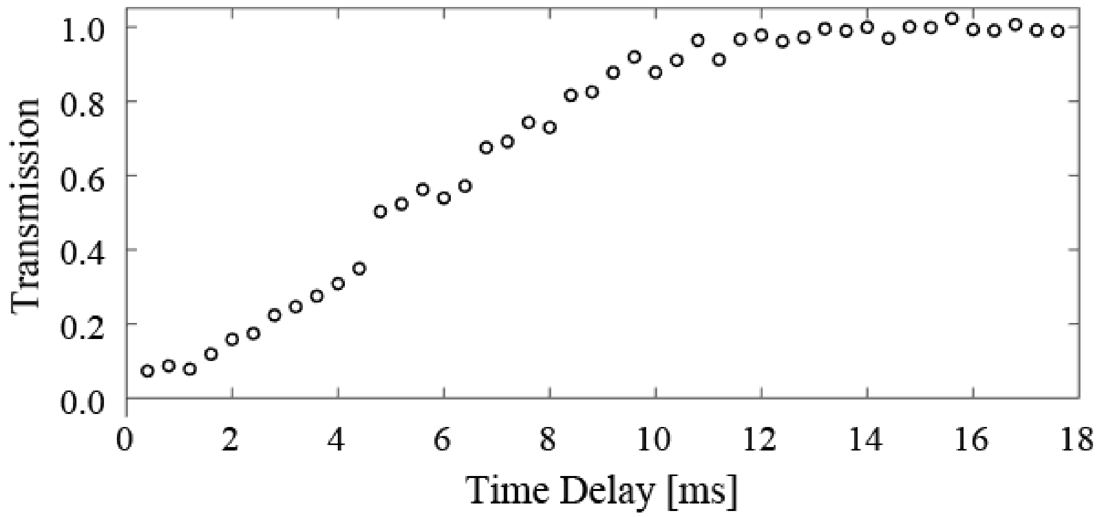
Guide atoms here with the membrane rib waveguide:
Two quasi-TE modes for blue- / red-detuned trap beams

Long-term goals
m = 2.21 E-25 kg
N = 1000 atoms
r = 17.8 mm
LMT: 300 $\hbar k$
Transits = 10
Contrast: 80%

[1] R. Stevenson, et al., *Sagnac interferometry with a single atomic clock*, PRL 115, 163001 (2015)

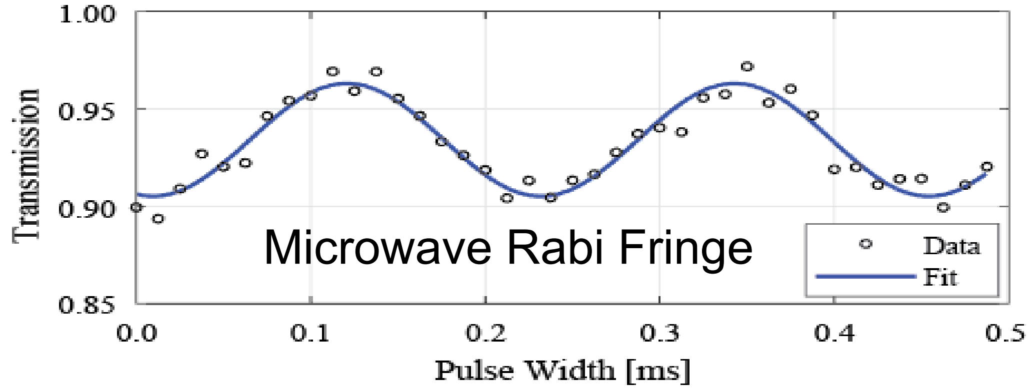
Tapered fiber: 1-D Guided Atoms with Evanescent-Field Optical Dipole Trap



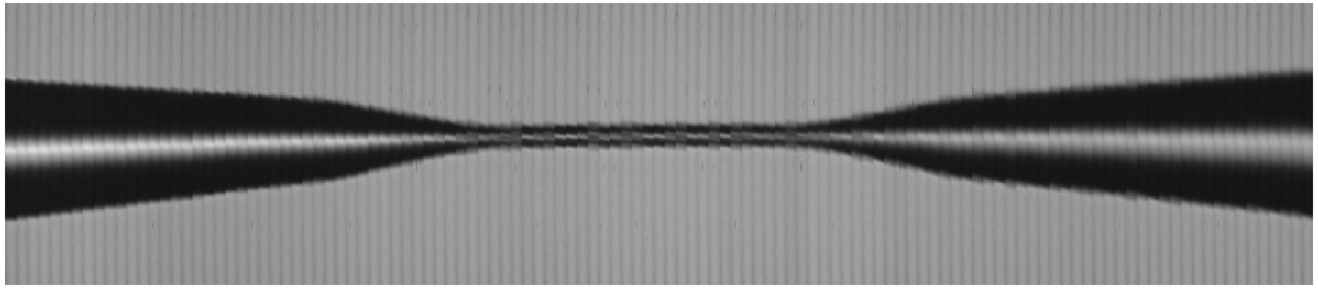


- 685nm and 937nm trapping beams coupled to nanofiber
- Atom number measurement with an absorption probe
  N = 47.2 ± 3.2 for 1-D guided atoms

- Lifetime measurement of 1-D guided atoms
  τ = 8.1 ± 0.8 ms

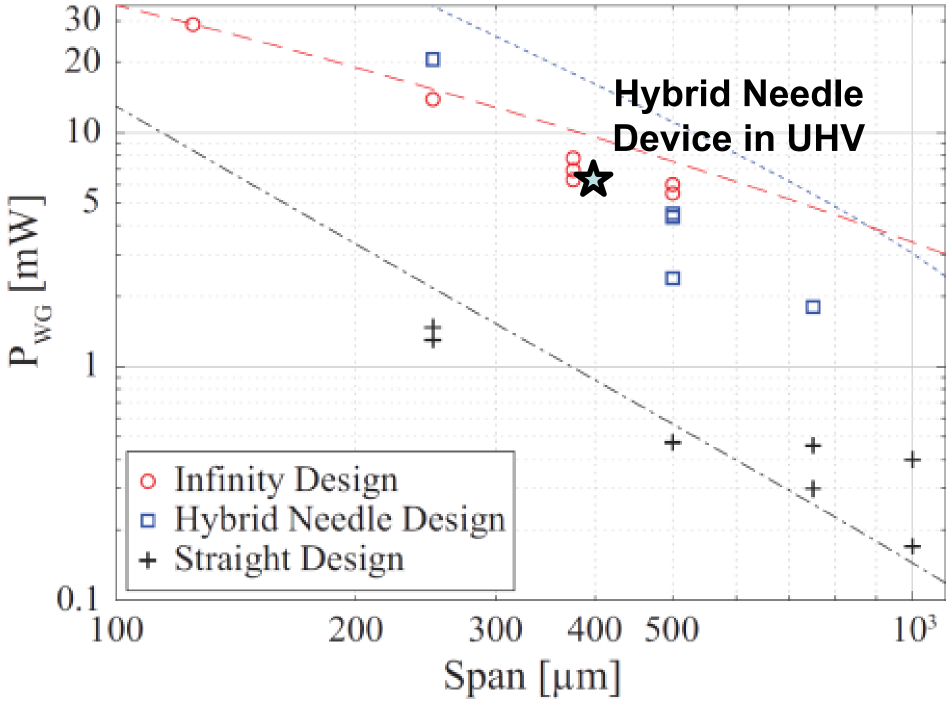


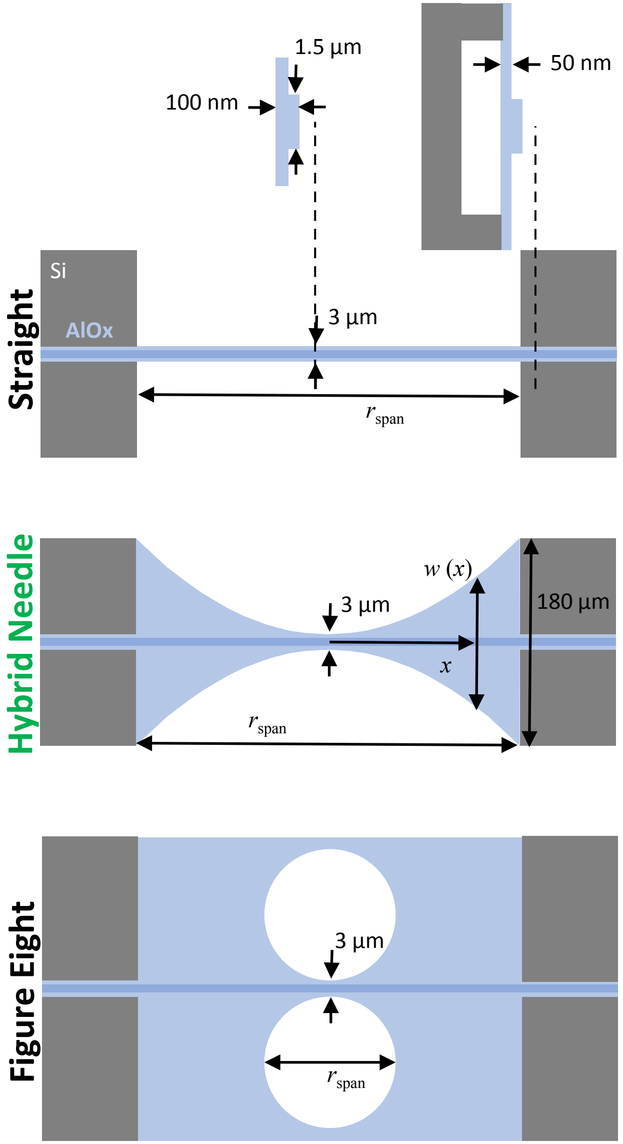
Tapered Fiber

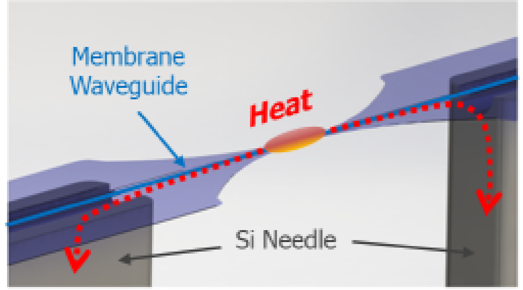


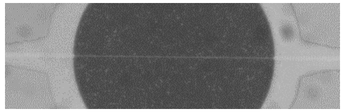
Aluminum Oxide Waveguides: High Optical Power Handling

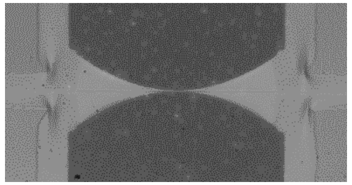
- Big challenge: heat dissipation
- Samples were redesigned based on experimental measurements and calibrated thermal simulations
- New designs handle ~30mW at shortest lengths and **>6mW in target design**
- Publication accepted to *Optics Express* 2/22/21

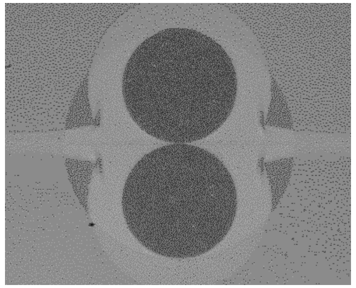




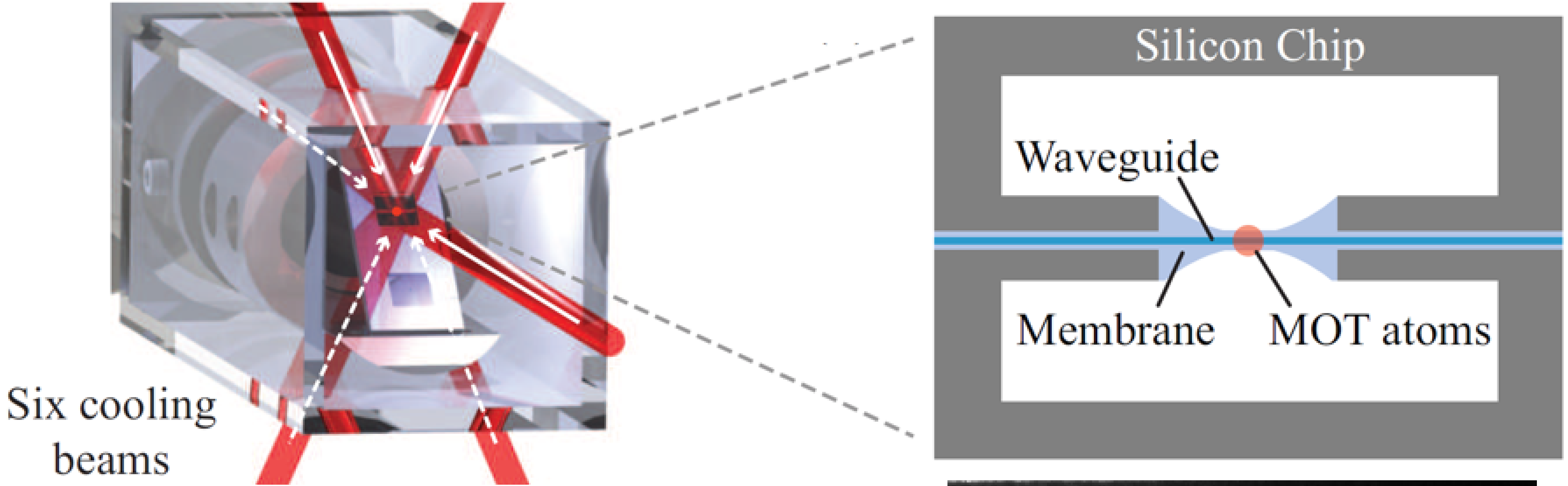


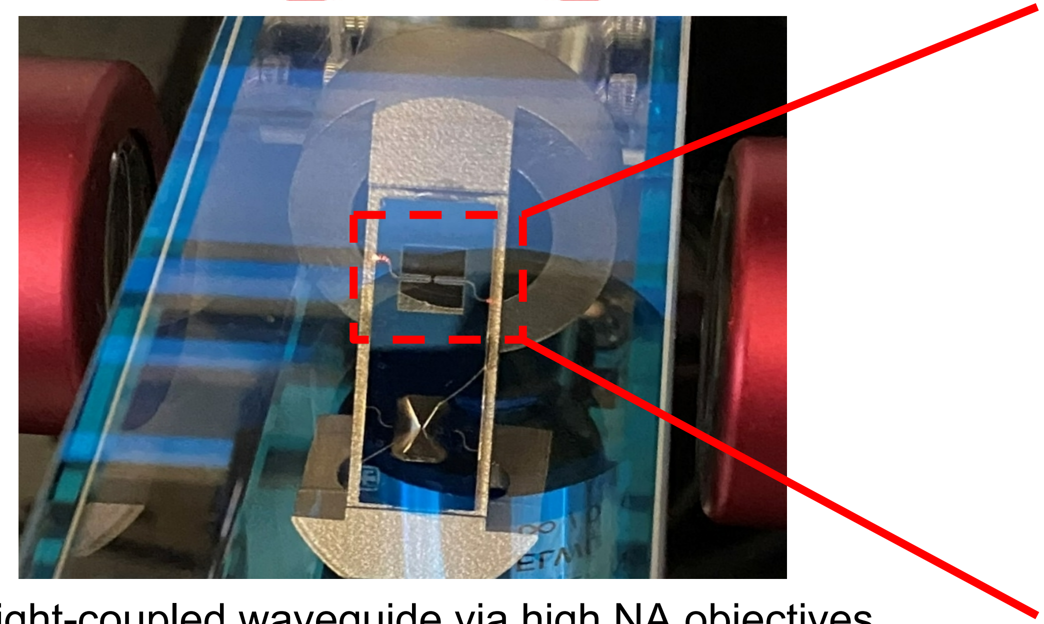




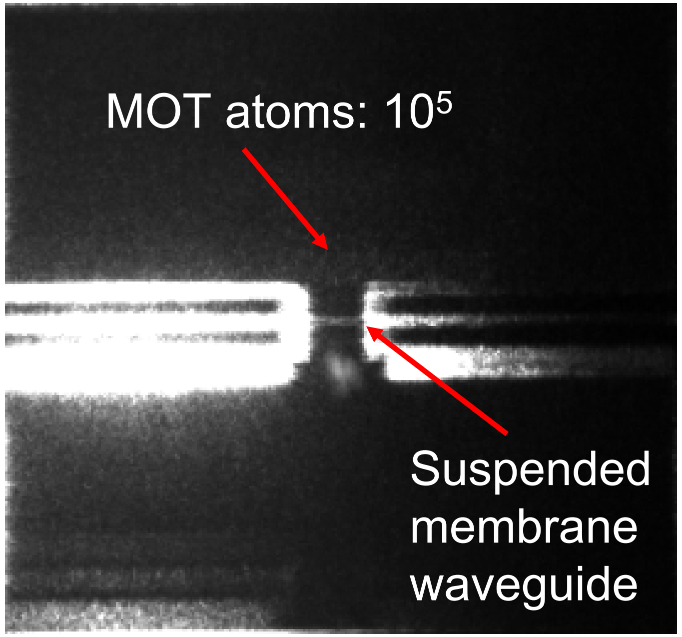


Atom Trap Integrated Platforms with Membrane Integrated Photonics

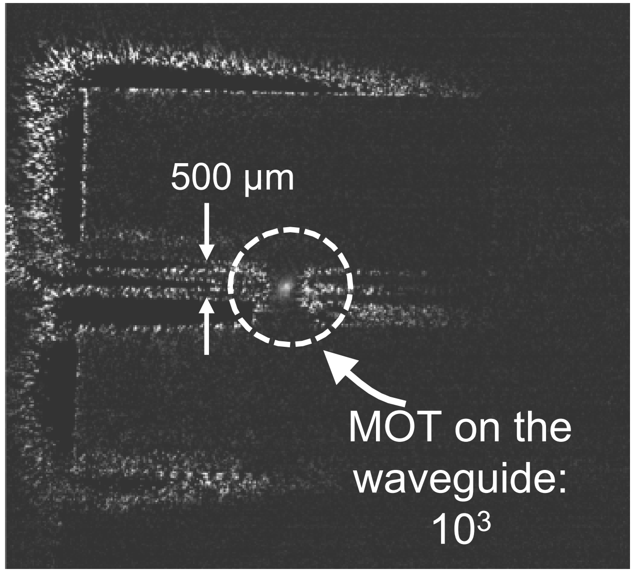


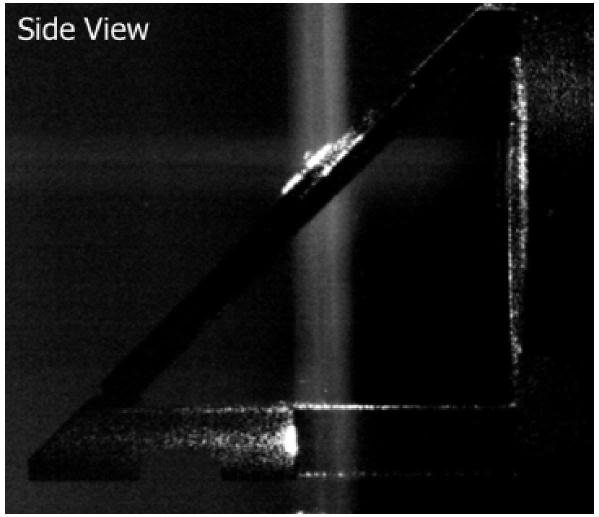


Light-coupled waveguide via high NA objectives



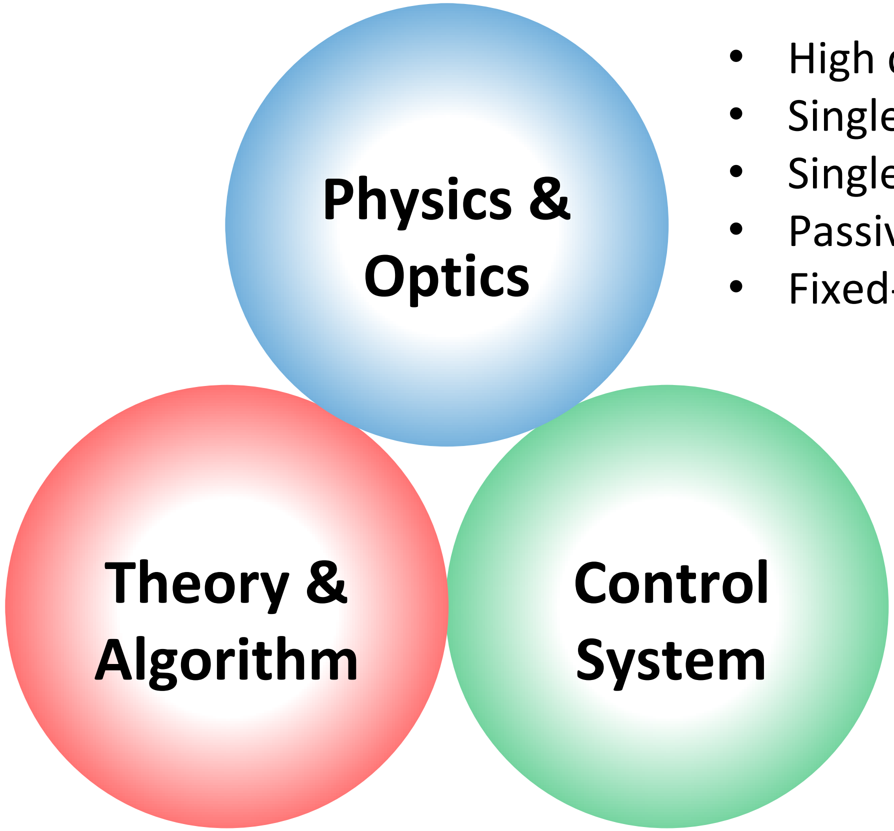
Background subtracted image





CONCLUSION

SIGMA Developments toward Deployable Cold Atom Inertial Navigation Sensors



- High data-rate atom interferometry (40Hz)
- Single laser architecture (COTS & PIC)
- Single-beam grating-mirror MOT (GMOT)
- Passively pumped vacuum chamber
- Fixed-optics, vibration-resistant sensor head

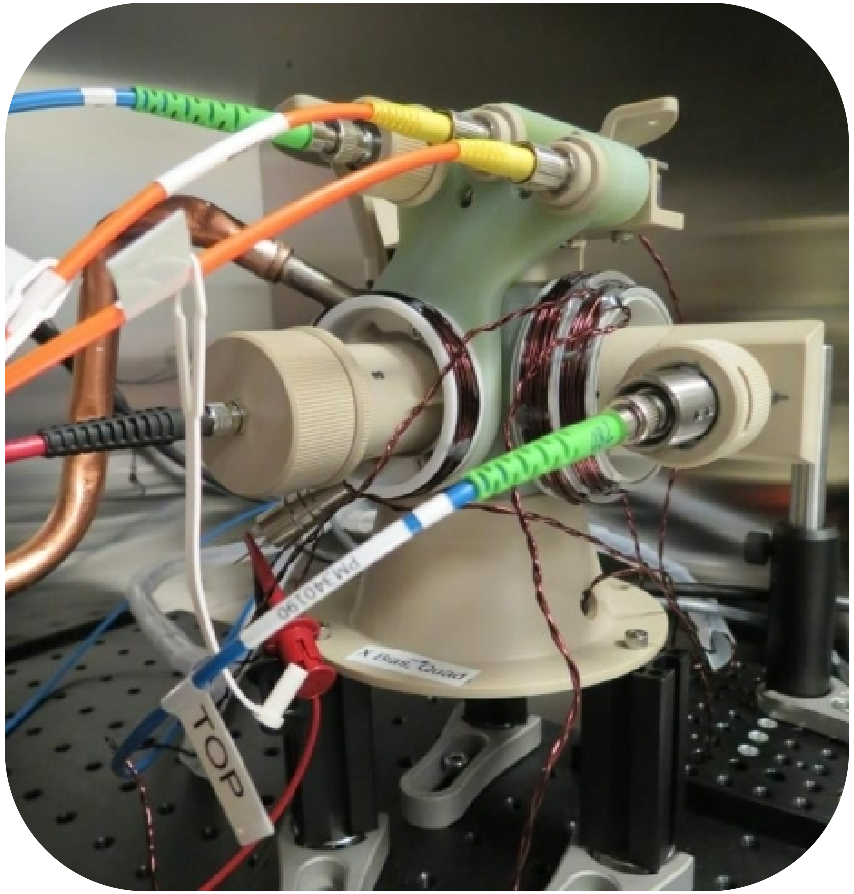
- Navigation system expertise
- Physics modeling (Monte Carlo) + IMU cosensor + Kalman filter

- 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 a multifaceted program
  - Integrated photonics platform
    - Single sideband modulator with suppressed carrier
    - Demonstrated state-sensitive detection and atom interferometry
  - Compact atom interferometer sensor head
    - GMOT in miniature vacuum package
    - Initial atomic gravimeter demonstration
  - Vacuum package development
    - Passively pumped operation for ~ 10 months
- Future work
  - Combine integrated photonics platform with atom interferometer prototype



SIGMA Team and Funding

Sandia National Laboratories

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

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

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

Advanced Sensing: Entanglement
Lead: Constantin Brif
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

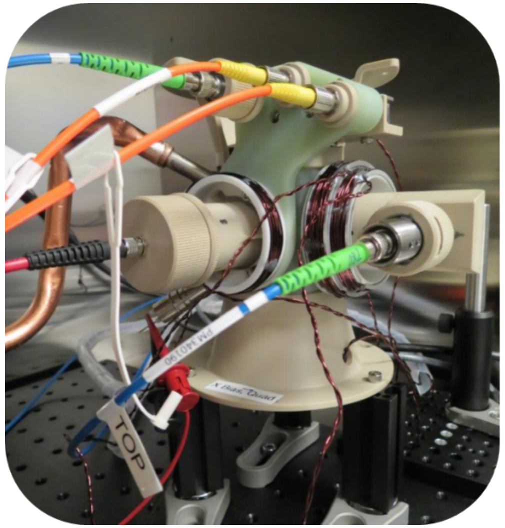
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

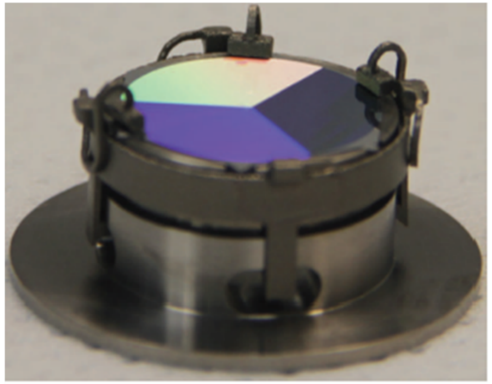
Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's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

Abstract: Towards a miniature cold-atom accelerometer

Atom interferometers hold substantial promise as high-performance inertial sensors for moving platforms, but miniaturization of atom interferometer systems continues to be a substantial challenge. In this talk, I will describe our efforts in the development of a compact, deployable cold-atom interferometry sensor platform. Our effort targets the miniaturization of key components of the sensor platform and includes significant engineering efforts in the development of a chip-scale solution for the lasers system including silicon-photonic-chip multi-channel single sideband modulators, a grating-mirror magneto-optical trap (G-MOT), a vibration-resistant structural design, a custom titanium vacuum package with passive pumping, and techniques to extend the dynamic range of the atom interferometer inertial sensors. I will highlight three main aspects of our effort with the first being the development of a compact cold-atom sensor head for measuring acceleration. Laser light is brought to the sensor head via optical fiber to perform the functions of laser cooling and trapping, the atom interferometer three pulse laser sequence, and atomic state sensitive detection. The atoms are contained in a custom Ti vacuum chamber (volume of ~90 cm^3) and trapped using a G-MOT. Second, I will discuss our custom vacuum chamber that it is only passively pumped; no active pumping is required to maintain the vacuum for a cold-atom trapping, eliminating the need for an ion pump. We have demonstrated a MOT in the passively pumped chamber for more than one year with no apparent degradation in the vacuum quality. Third, we have a significant effort in the development of heterogeneously integrated photonic integrated circuits (PICs) for the cold-atom sensor using silicon photonics, amplification with III-V gain materials, and second harmonic generation. Such a PIC-based system could shrink the size of the typical laser system for an atom interferometer from the size of an optical table to tens of cm^3.

This work is supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, 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. This paper describes technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the view of the U.S. Department of Energy or the United States Government.





(Left) Our compact interferometer sensor head. (Right) The mounted diffraction grating for the GMOT.