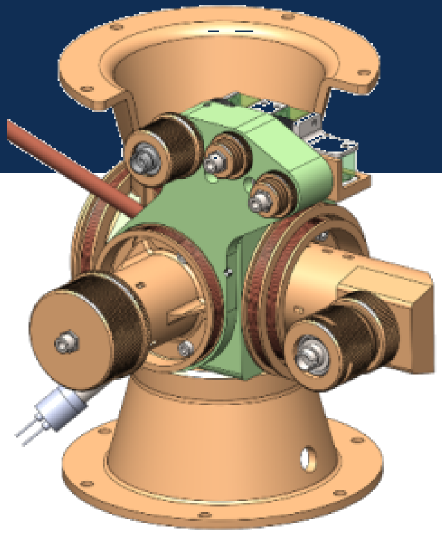
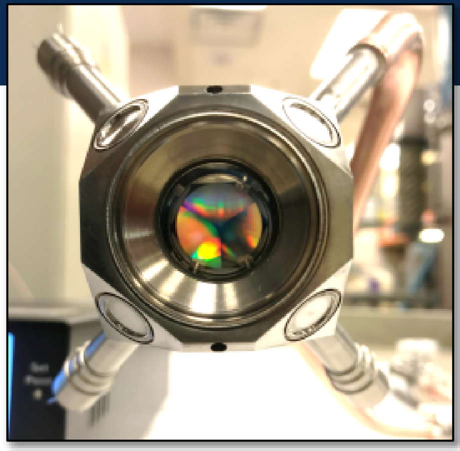
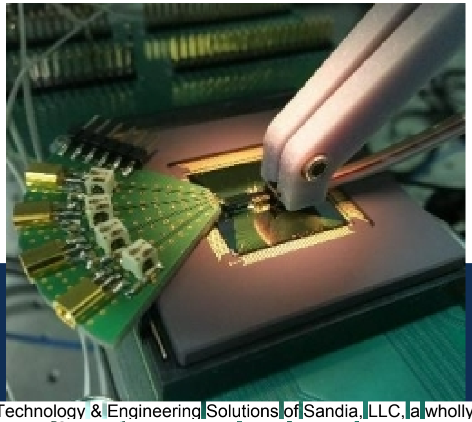
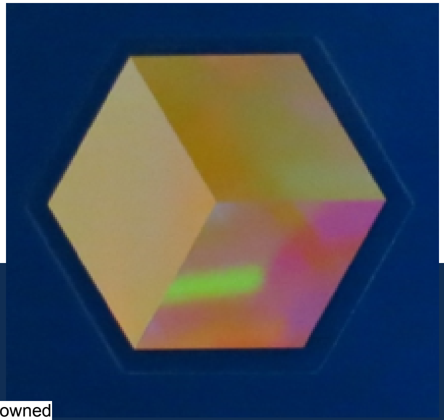
SAND2022-5273C

Strategic Inertial Guidance
ΣΙΓΜΑ
with MAtterwaves

Exceptional service in the national interest

Sandia National Laboratories

Integrated Photonics and Vacuum Package Development for a Cold-Atom Interferometer

Peter D. D. Schwindt
pschwin@sandia.gov

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.

Outline

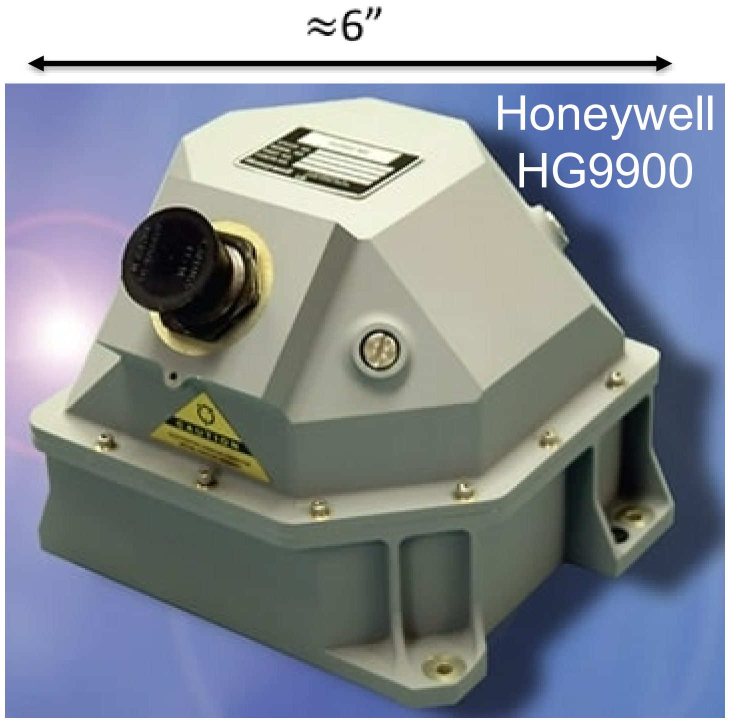
- Motivation for a compact atom interferometer (AI)
- Integrated photonics platform
- AI demonstration with compact sensor head and diffractive optics
- Phase noise measurements in a van
- Passively pumped vacuum package
- Conclude

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.

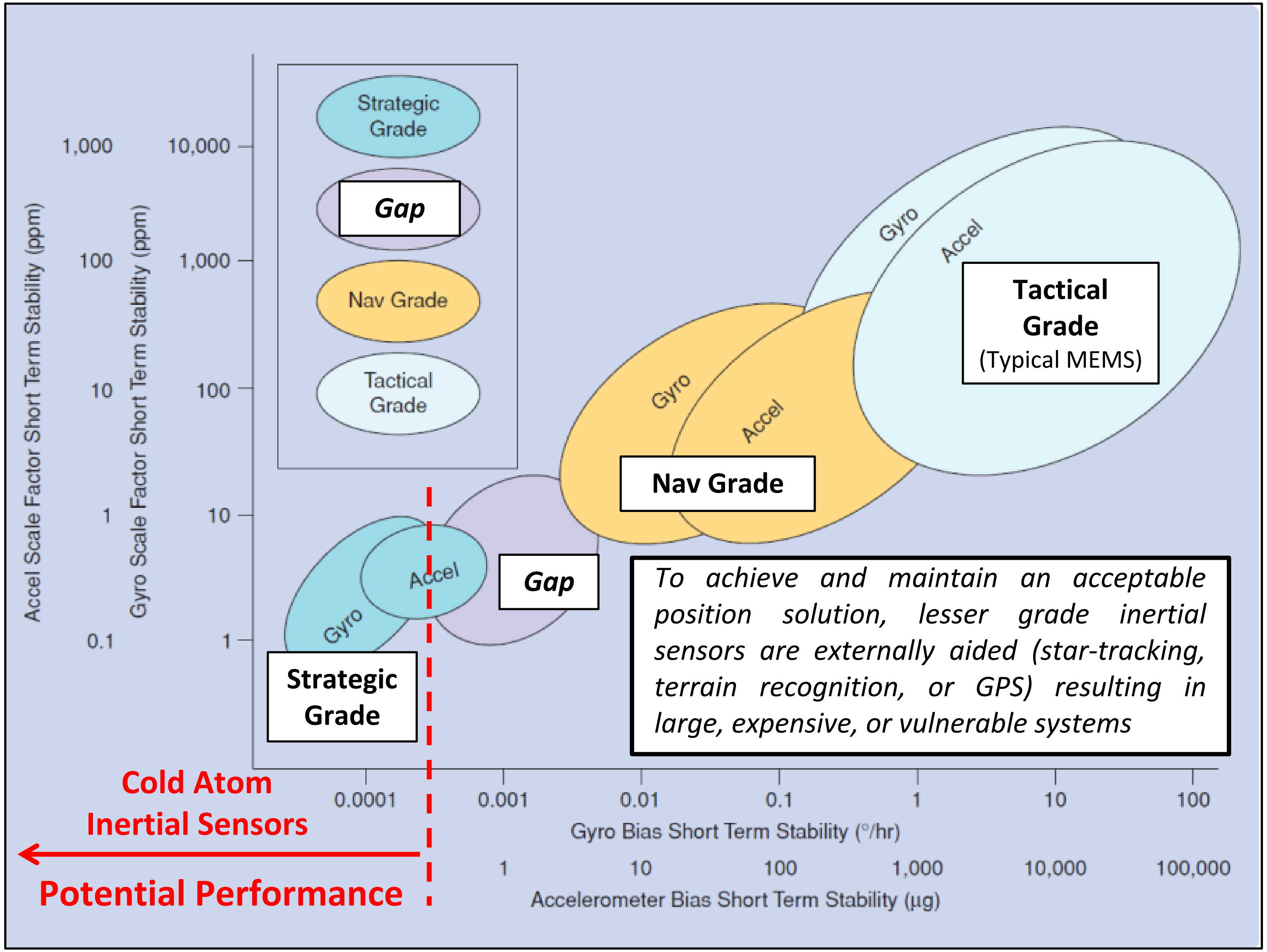
	Navigation Grade (HG9900)	Atom interferometer (Lab demos)	SIGMA Goals (1-axis accel)
Accel Bias (1σ) [μg]	< 25	< 10^{-4}	<0.25
Accel SF (1σ) [PPM]	< 100	< 10^{-4}	1
Accel Random Walk [$\mu g/\sqrt{Hz}$]	not reported QA ~ 10	10^{-5}	<1
Gyro Bias (1σ) [deg/hr]	< 0.003	< 7 x 10^{-5}	
Gyro SF [PPM]	< 5	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

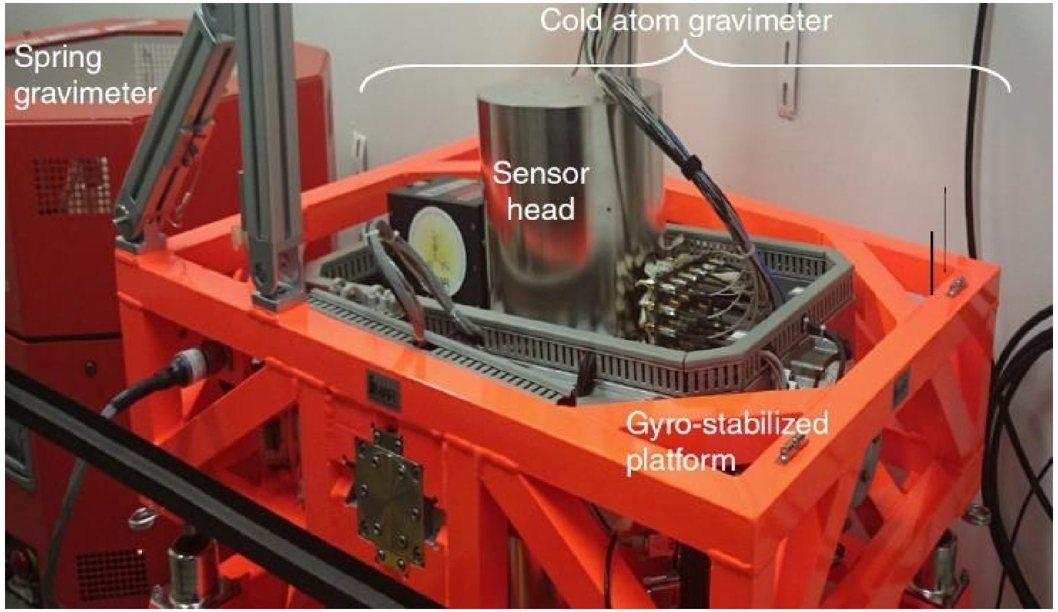


Sensor Grade	Drift (Per Hr)
Tactical	10 km
Navigation	1 km
Strategic	0.2 km

A selection of global AI efforts, today

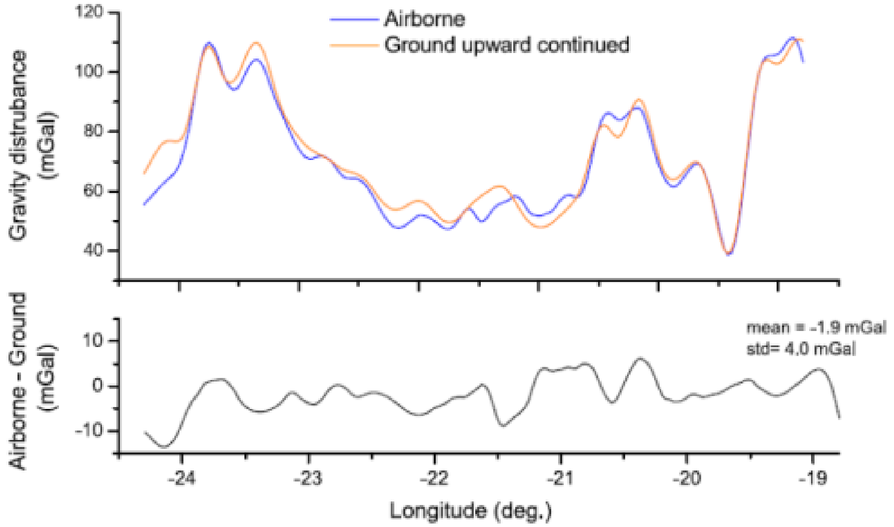
Airborne Gravimetry with an Atom Interferometer

- 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



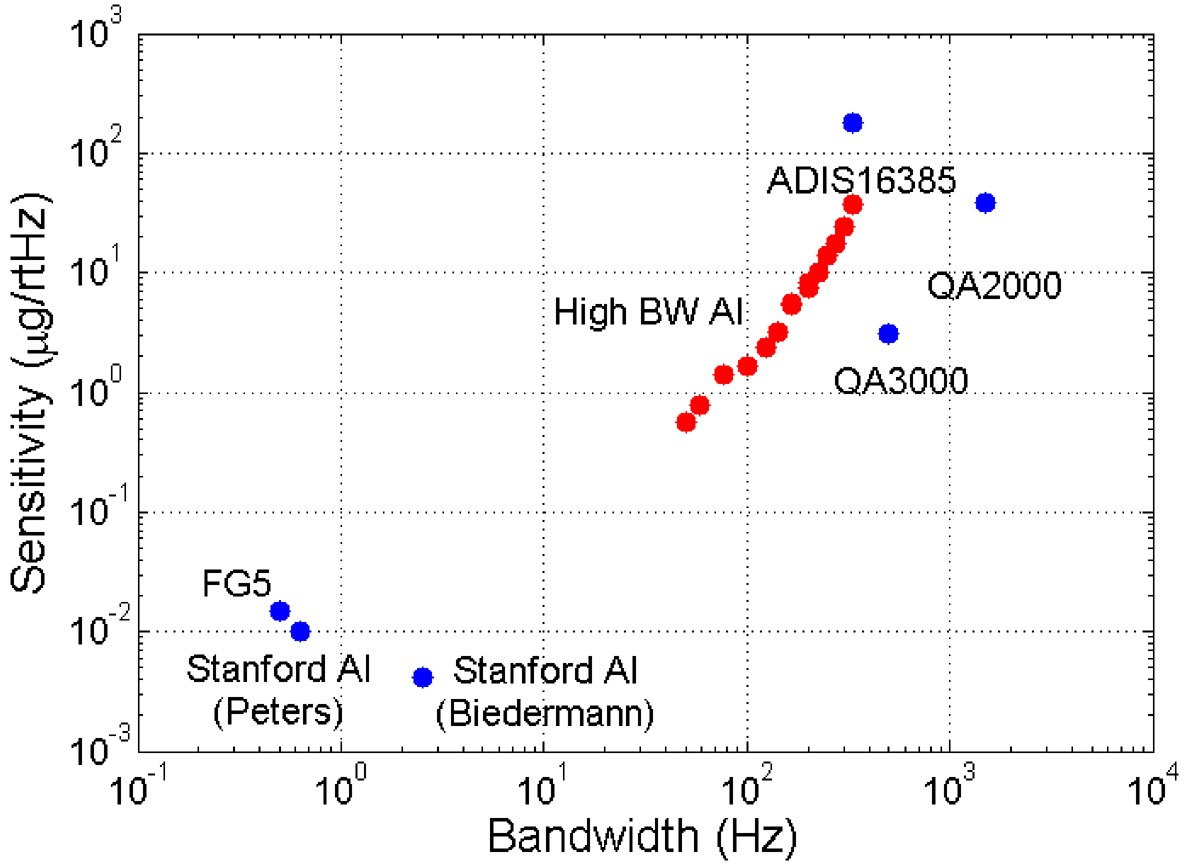
Aircraft: Bidel, Y., Zahzam, N., Bresson, A. *et al.* Absolute airborne gravimetry with a cold atom sensor. *J Geod* **94,** 20 (2020).

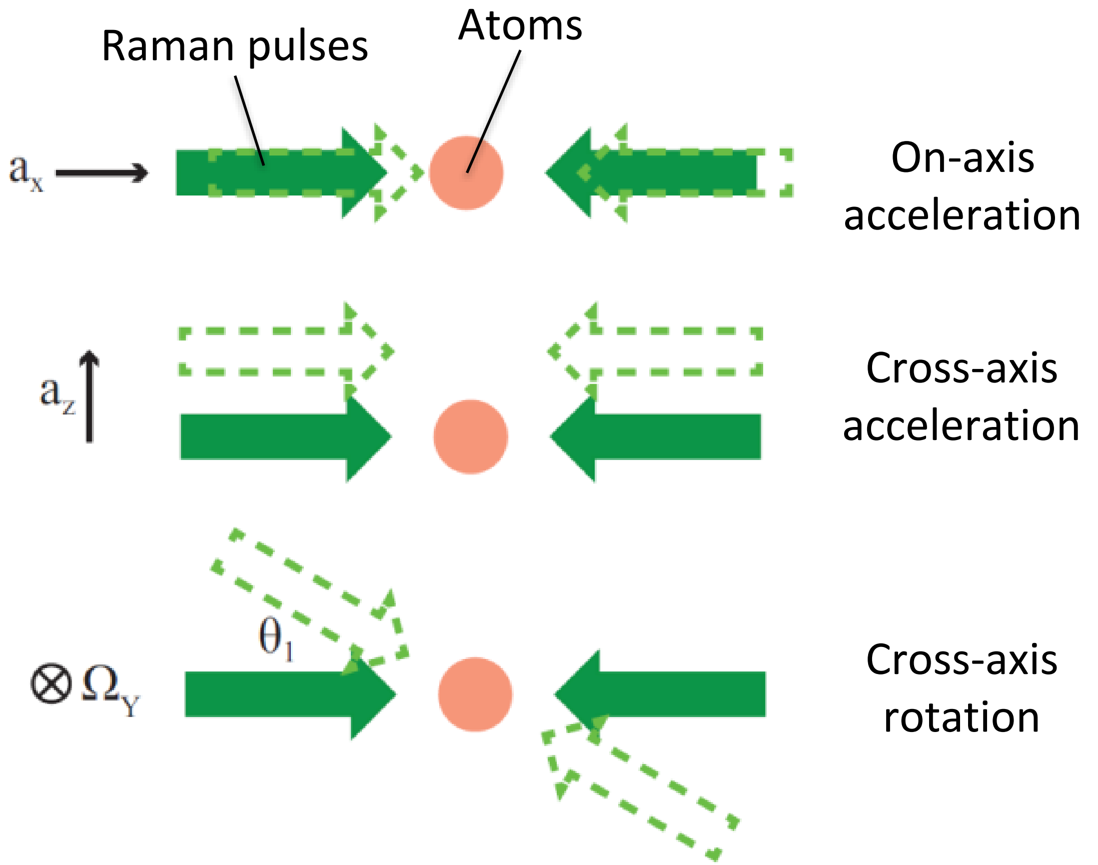
Ship: Bidel, Y., Zahzam, N., Blanchard, C. *et al.* Absolute marine gravimetry with matter-wave interferometry. *Nat Commun* **9,** 627 (2018).



Bandwidth Considerations for Dynamic Environments

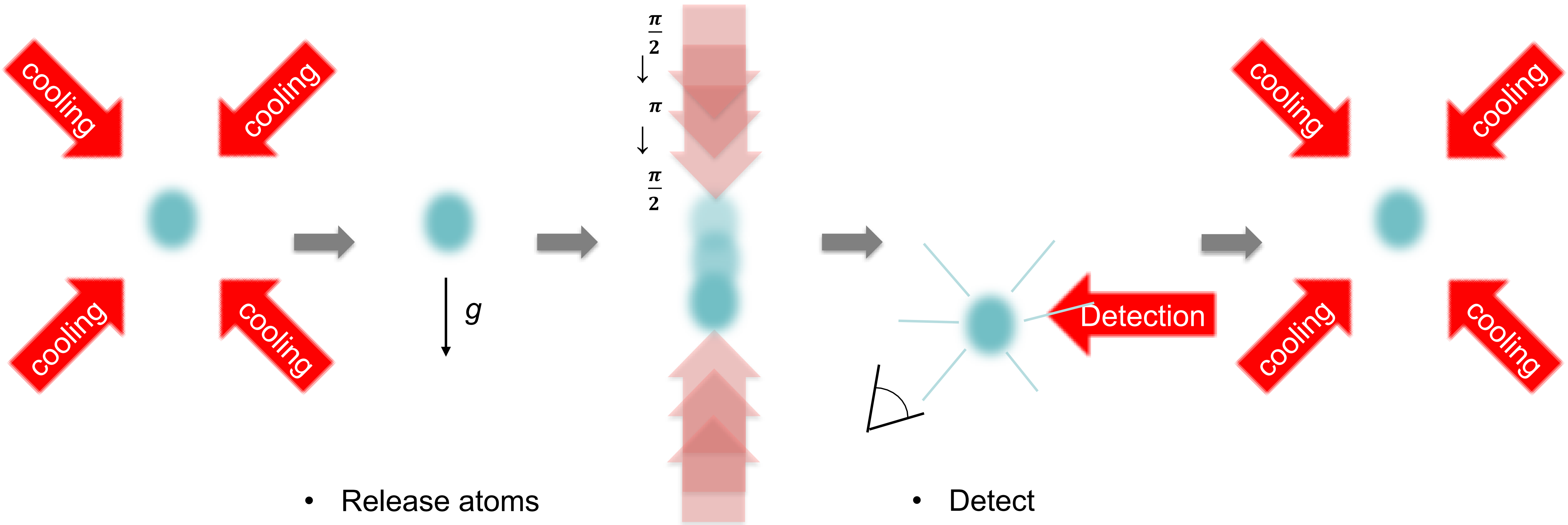
Sandia National Laboratories





- Bandwidth required for inertial sensor applications
- AI sensitivity reduces with bandwidth & Compact size lends itself to high bandwidth
- Hybrid Inertial Navigation: LPAIs + an inertial measurement unit (IMU) cosensor + feedforward processor

High Data-Rate Atom Interferometry



- Release atoms
- Detect

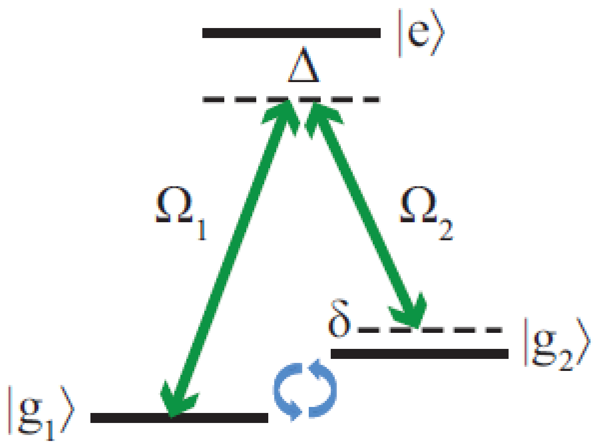
- Laser cooled atoms (4.3 ms, $T \approx 15\ \mu$K, $N \approx 10^6$)
- Raman pulse sequence (14 ms, T = 7 ms)

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

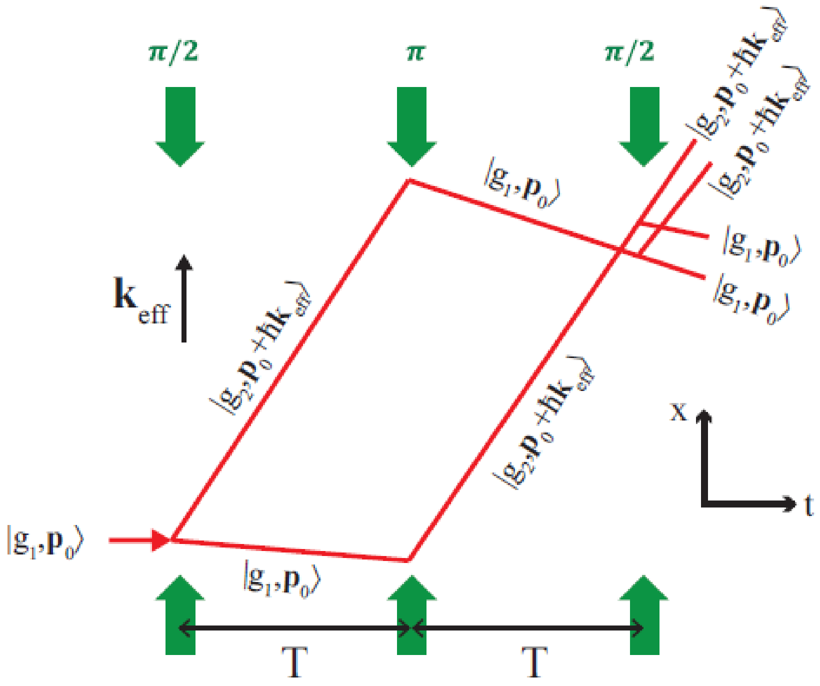
- Recapture (1.7 ms)

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

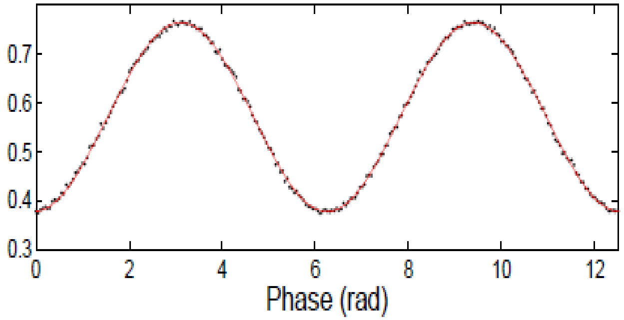
Light Pulse Atom Interferometer



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



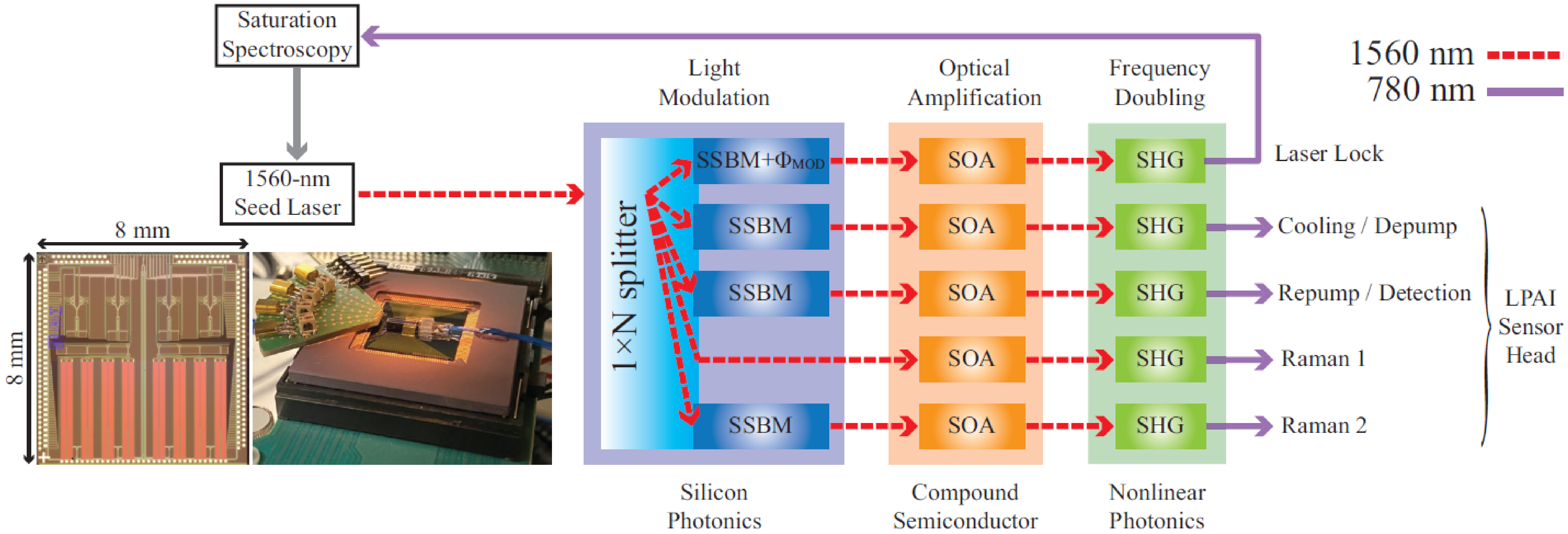
Acceleration →



- 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

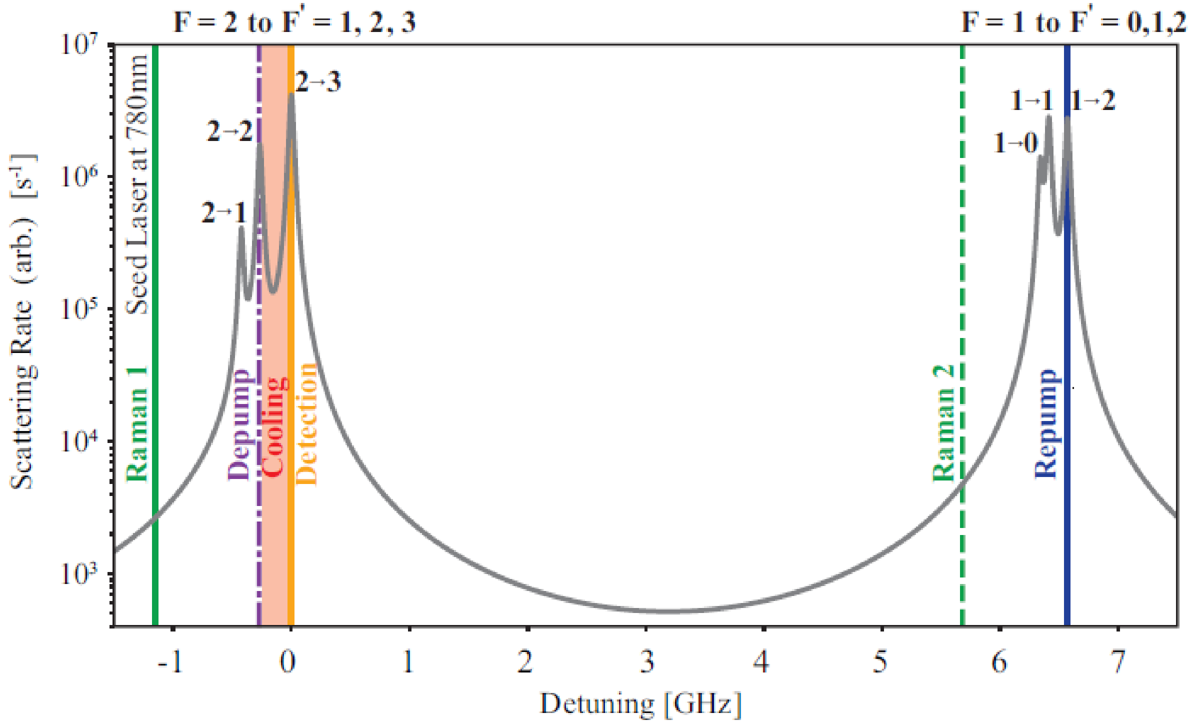
H. J. McGuinness, et al., Appl Phys Lett **100**, 011106 (2012).

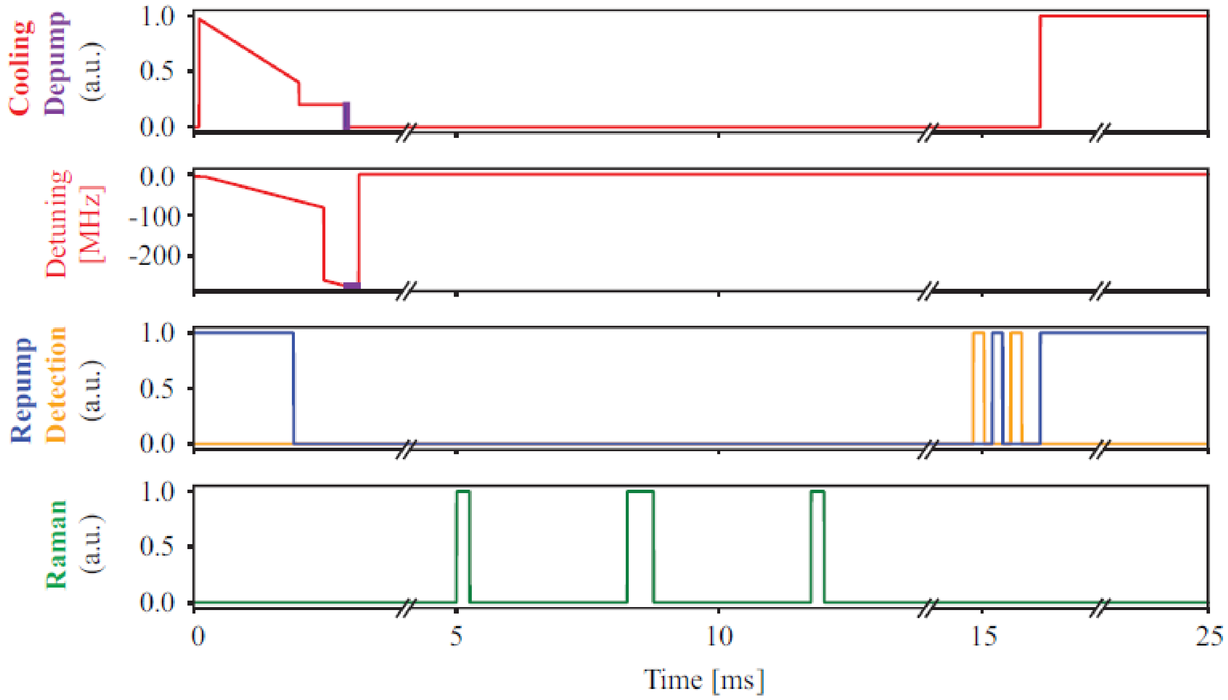
Photonic Integrated Circuit (PIC)-Based Laser System



- Chip-scale PIC-based laser system: 1560-to-780 nm approach
  - Mass-producibility, miniaturization, and ruggedization
- Single sideband (SSBM)/phase (Φ_{MOD}) modulators,
- Multi-stage high power semiconductor optical amplifiers (SOAs)
- Second harmonic generation (SHG) for frequency doubling

Integrated Laser Implementation



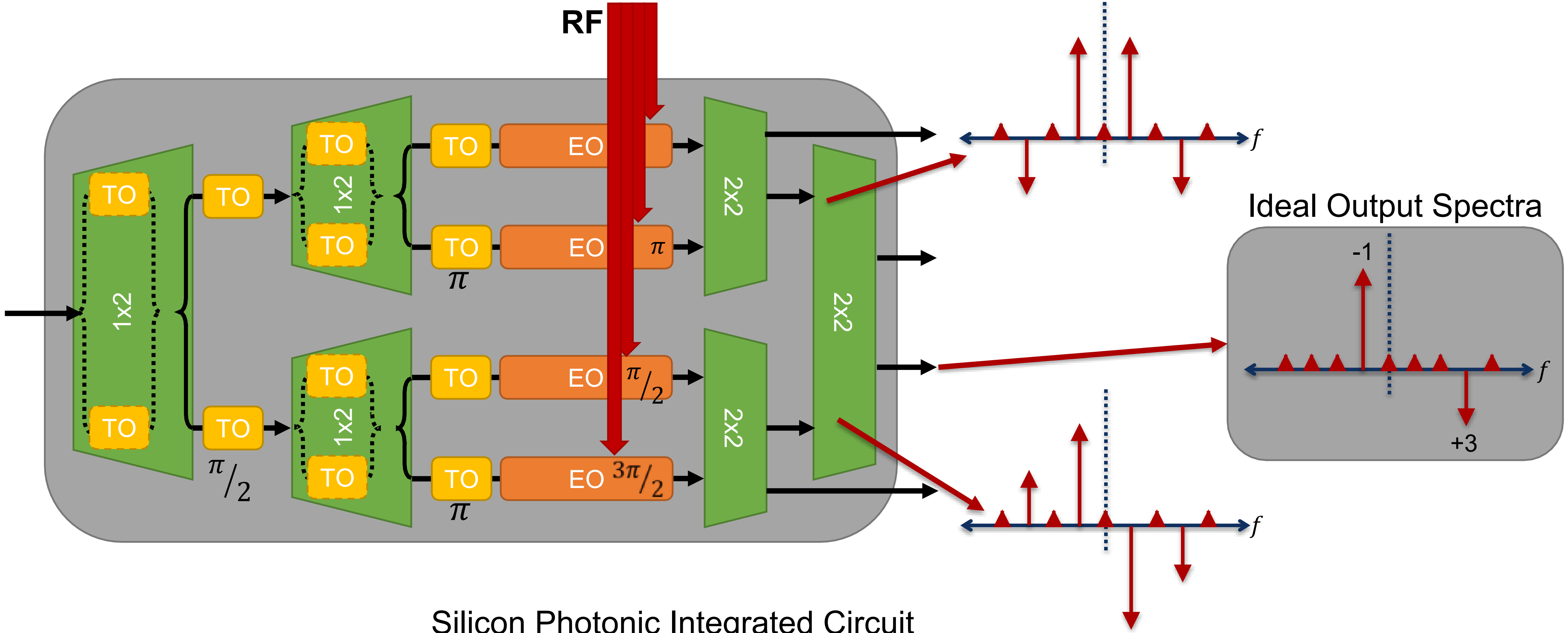


Five laser channels for ^{87}Rb atoms (D2)

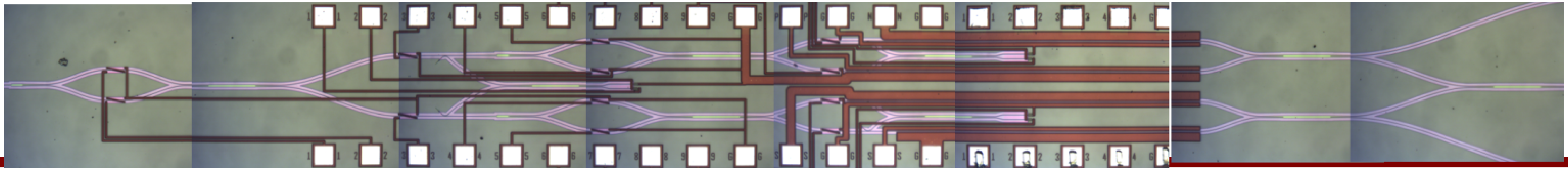
- Ch 1: Laser Lock (saturation spectroscopy)
- Ch 2: Cooling or Depump
- Ch 3: Repump or Detection
- Ch 4: Raman #1 (Seed laser frequency)
- Ch 5: Raman #2

- Time-multiplexed frequency shifting with SSBMs
- Raman pulses: 1-10 μs
- State sensitive detection pulses: ~0.1 μs

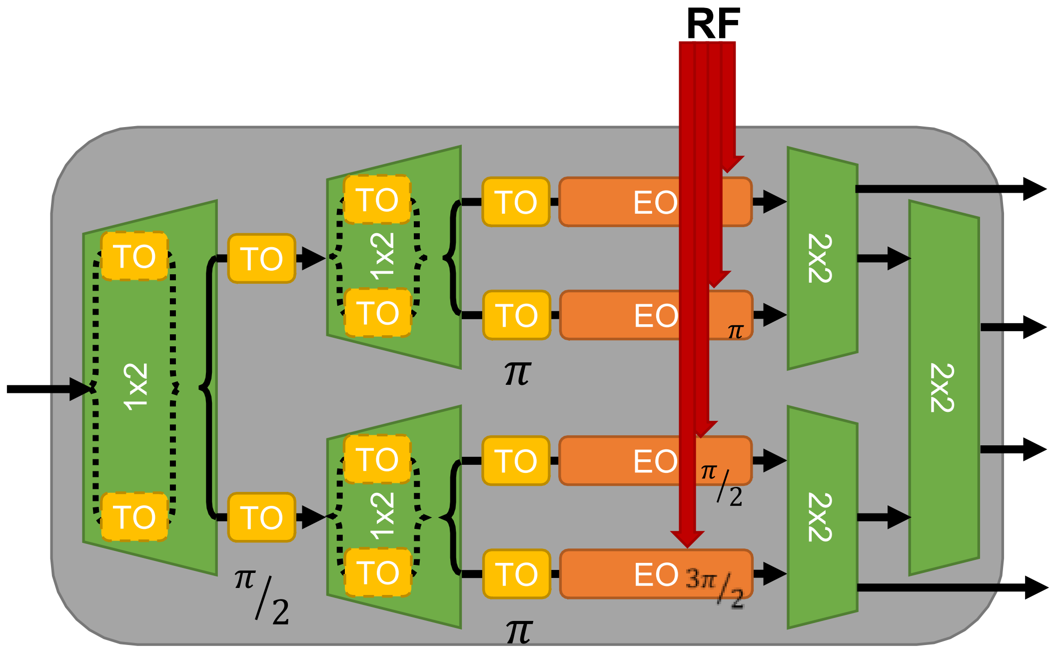
Suppressed-Carrier Single Side-Band Modulator

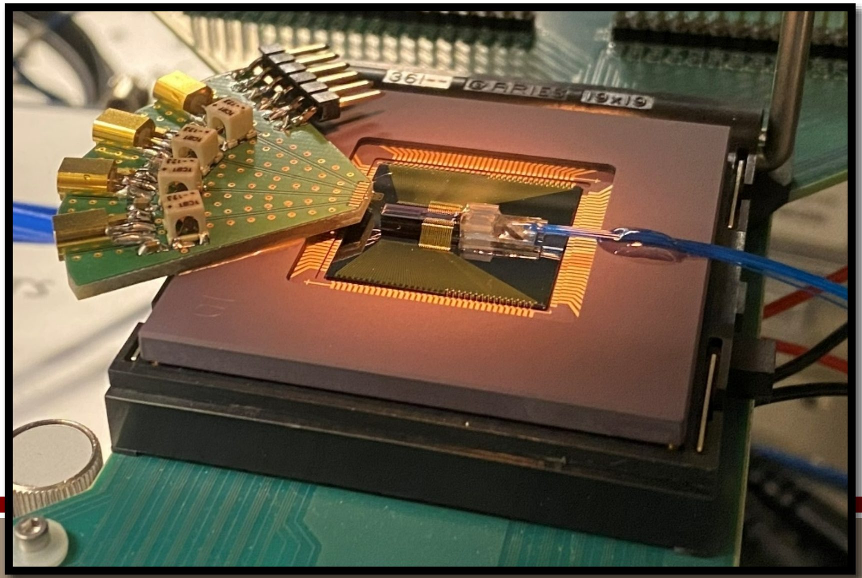


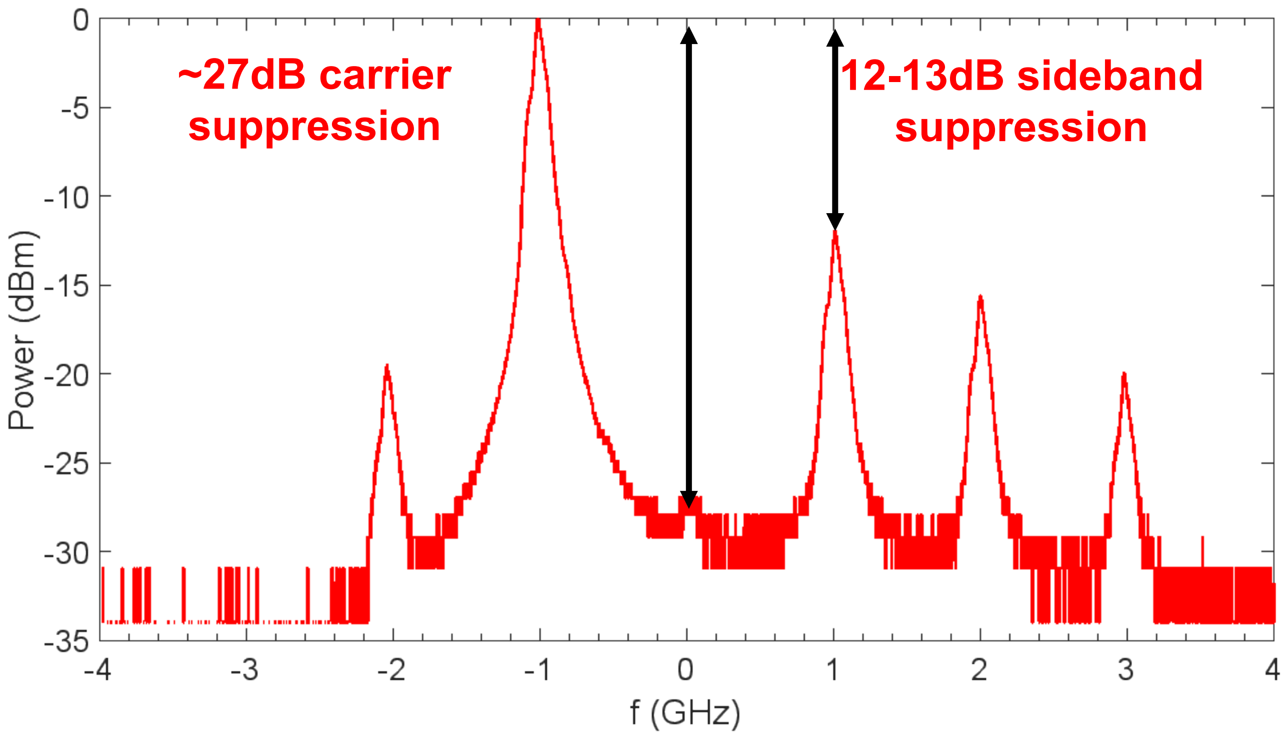
Silicon Photonic Integrated Circuit



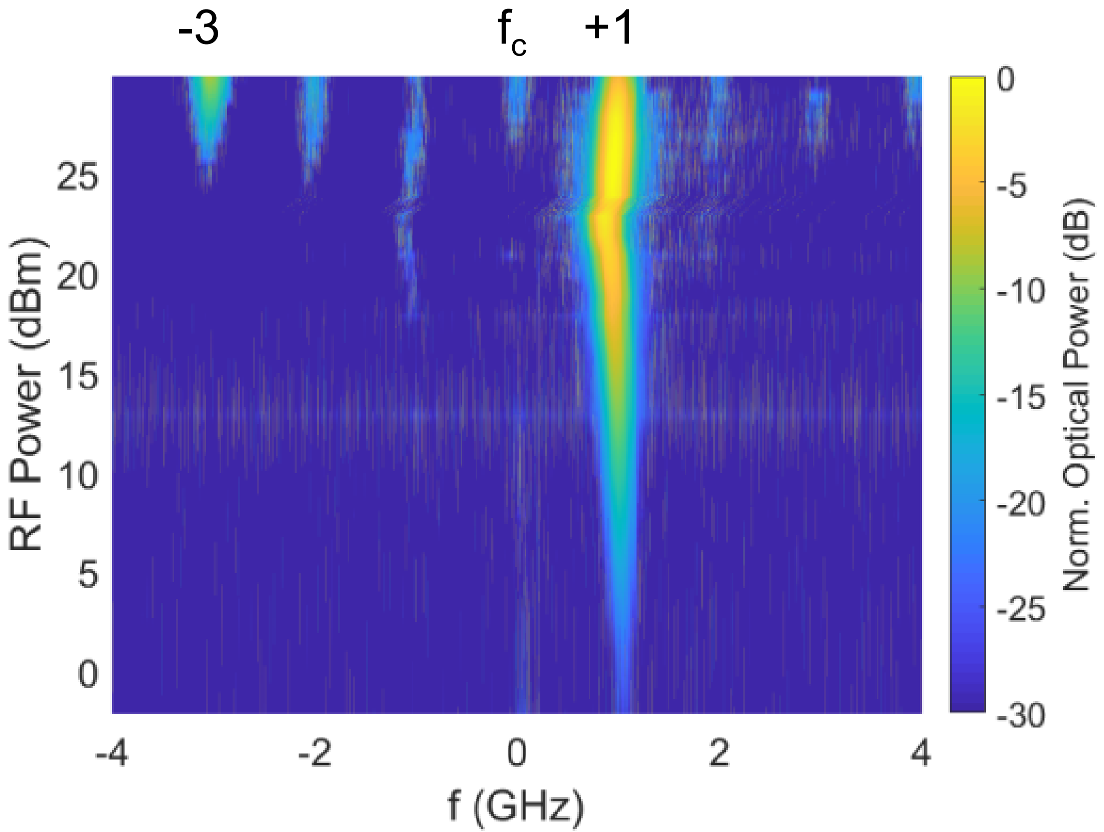
Single Side-Band Modulator Spectrum

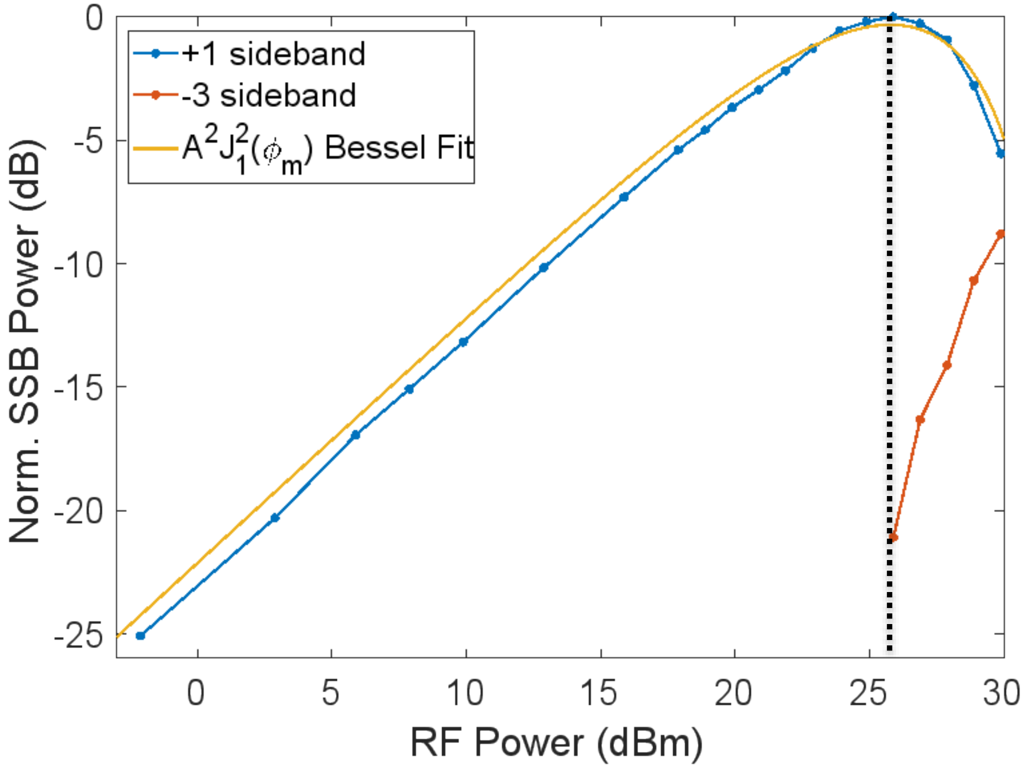






Single Side-Band Modulator Gen II Results

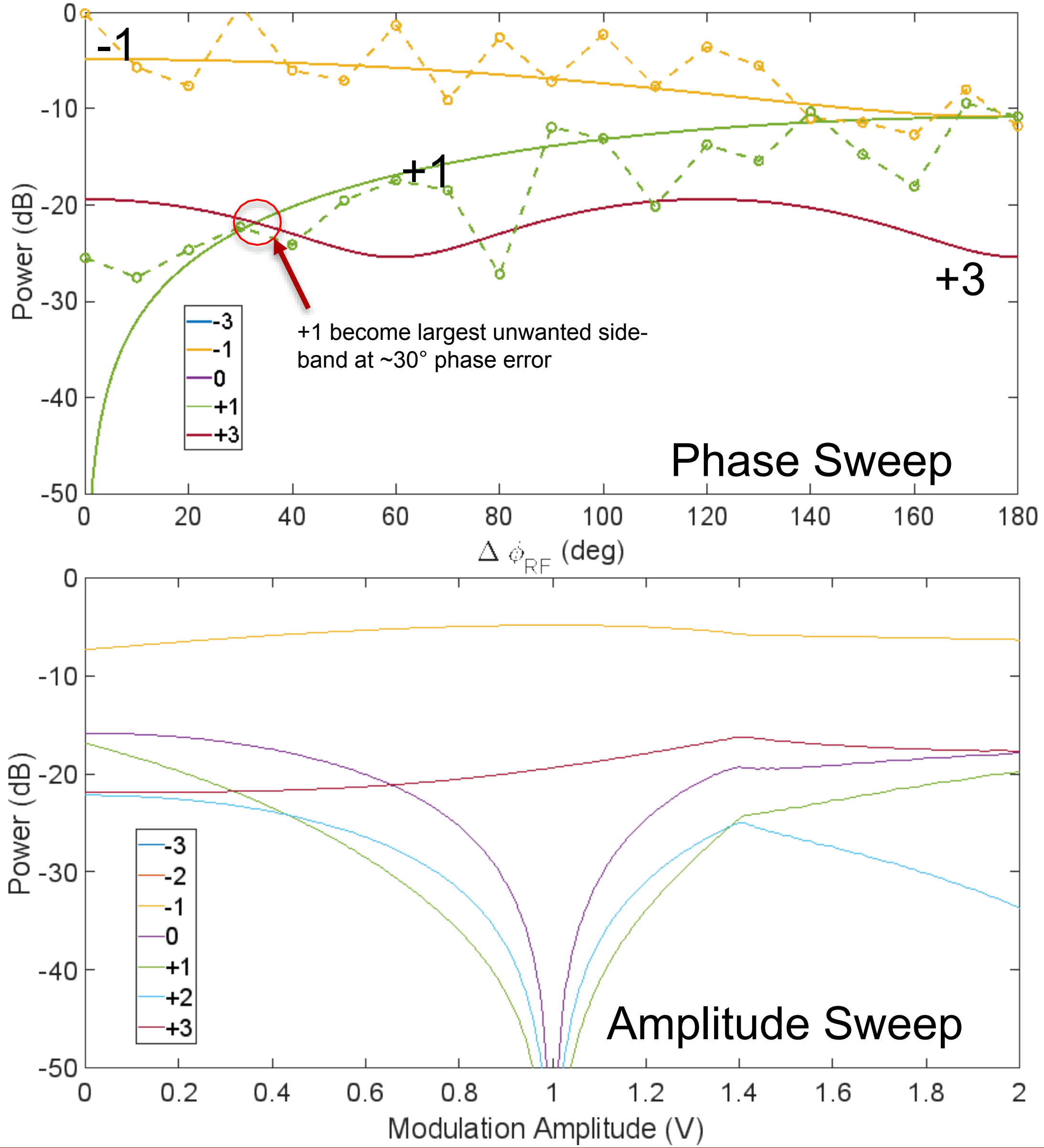




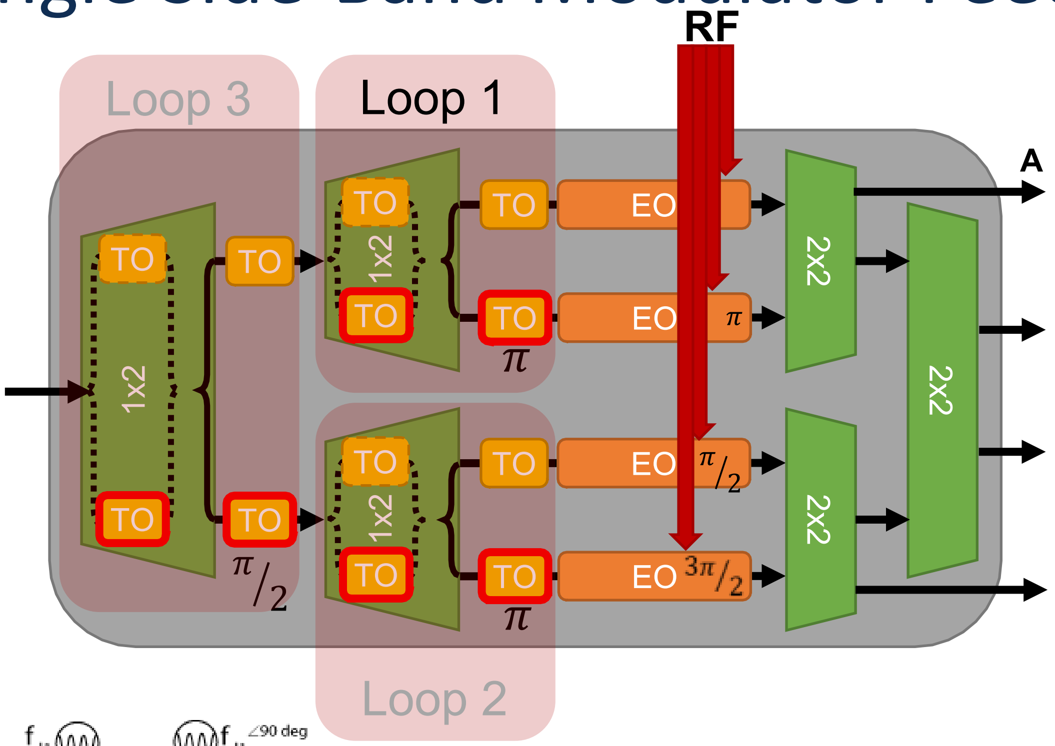
Optimum at RF powers close to ~400mW
Bessel Fit Provides - VπL = 0.557 V×cm

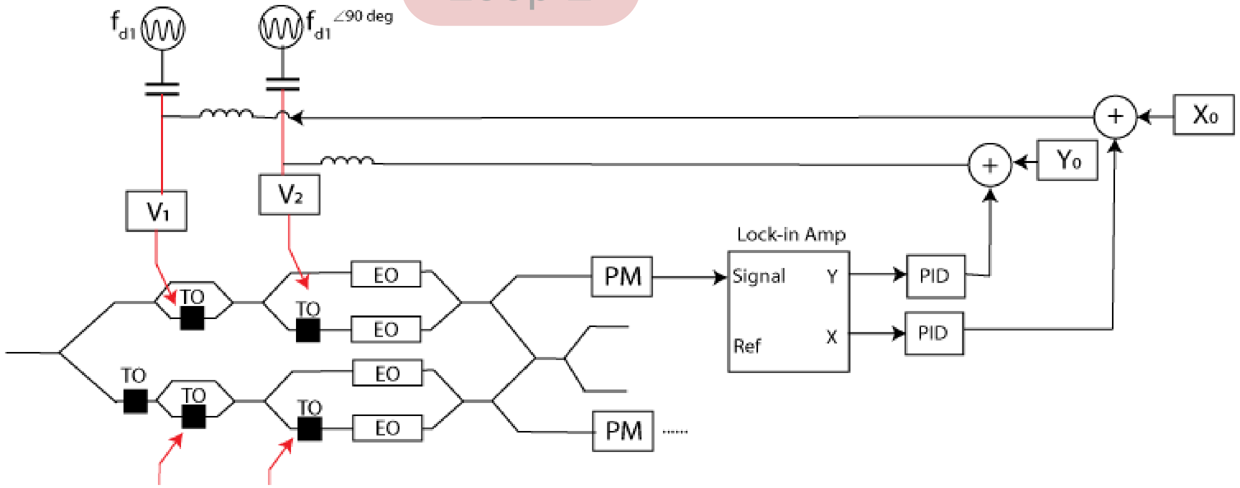
Single Side-Band Modulator Modeling

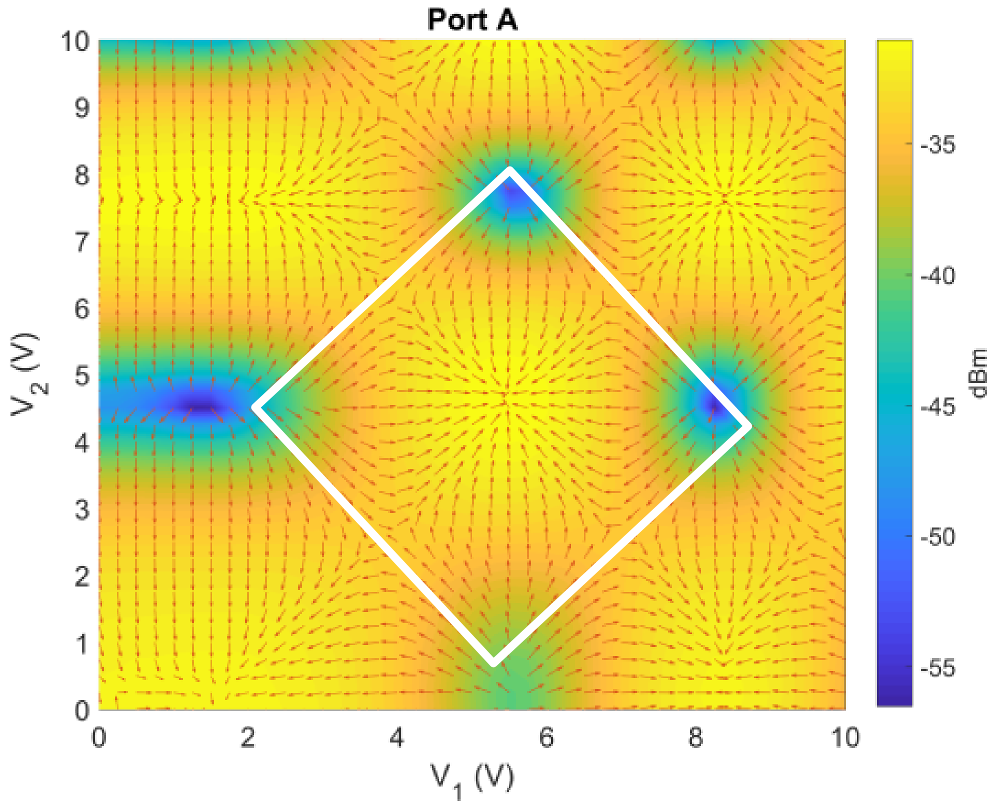
- Implemented 4 channel RF source for independent phase and amplitude control of modulator
- Comparison to previous modeling work in progress
  - Relatively insensitive to RF phase
    - ±30°before extra spurs become dominate
  - Very sensitive to RF amplitude
    - ±0.3 dB required to maintain >35 dB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



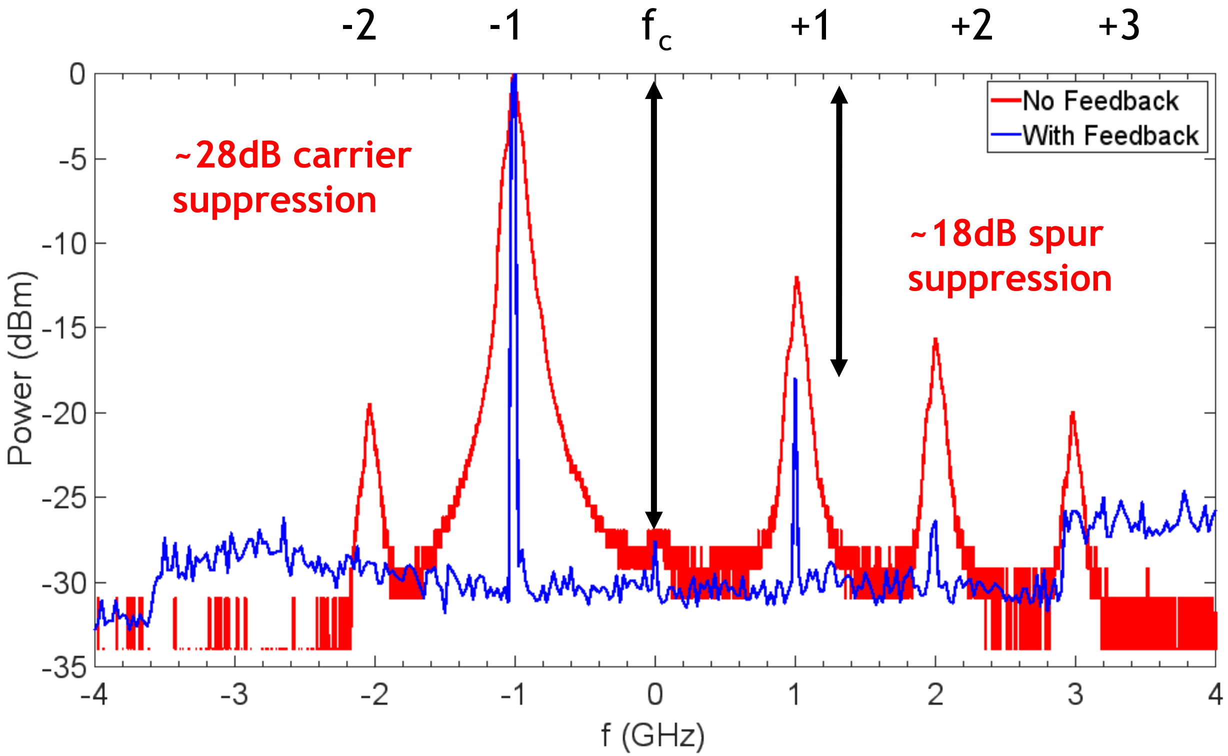
Single Side-Band Modulator Feedback



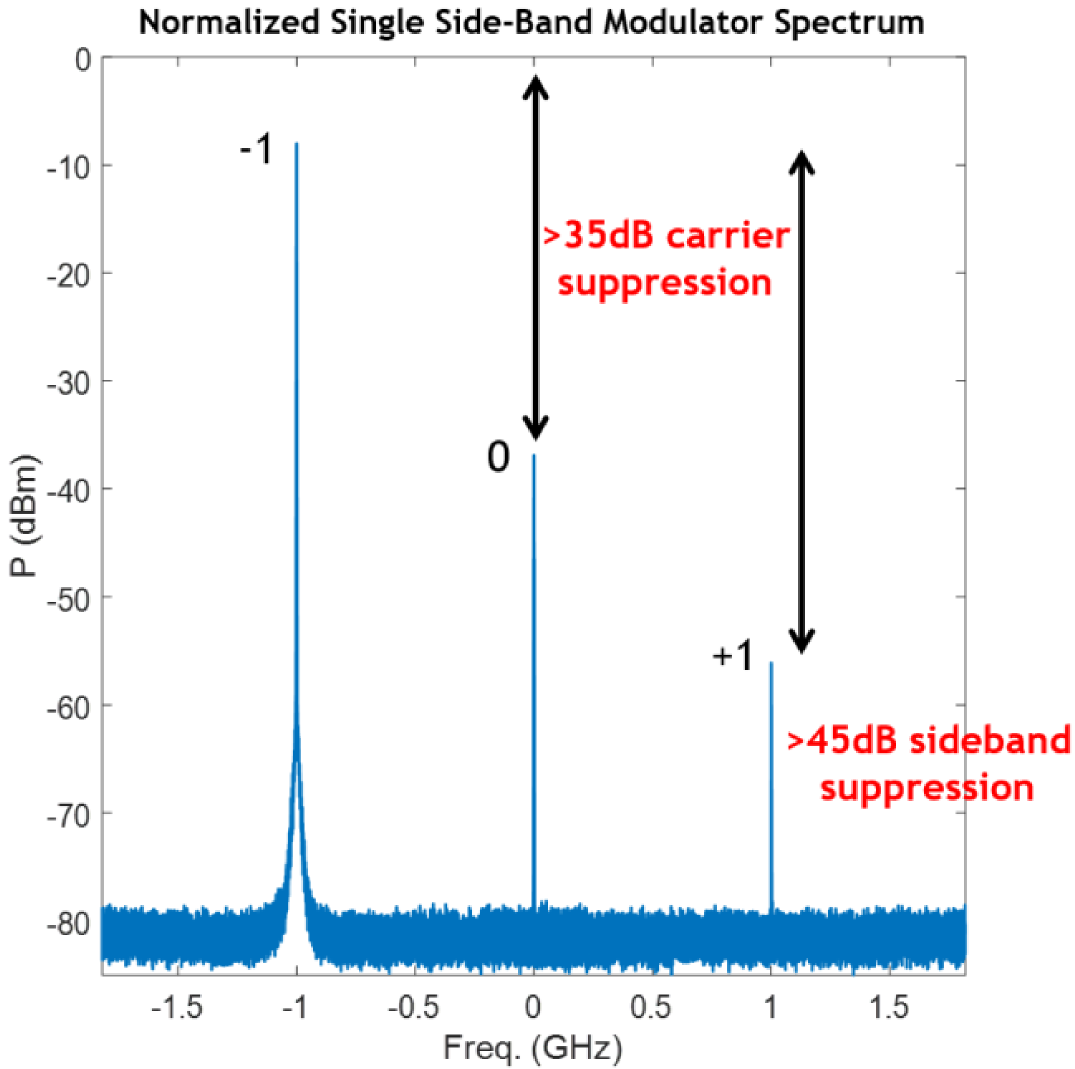




Single Side-Band Modulator Active Control

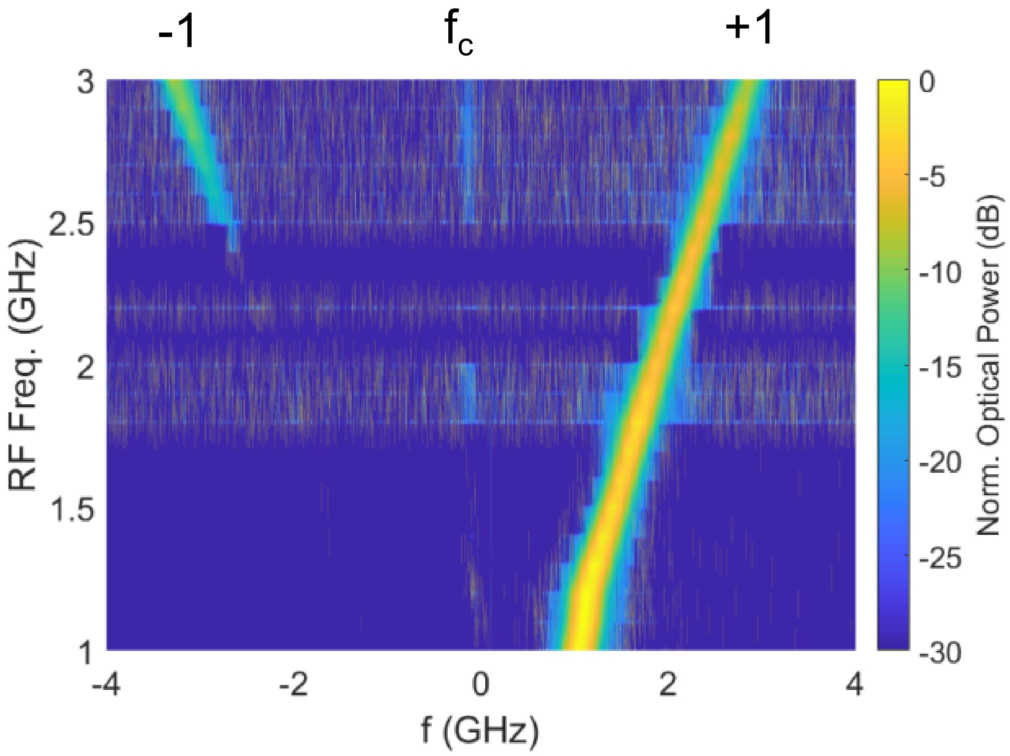


*implemented higher resolution heterodyne spectral measurement

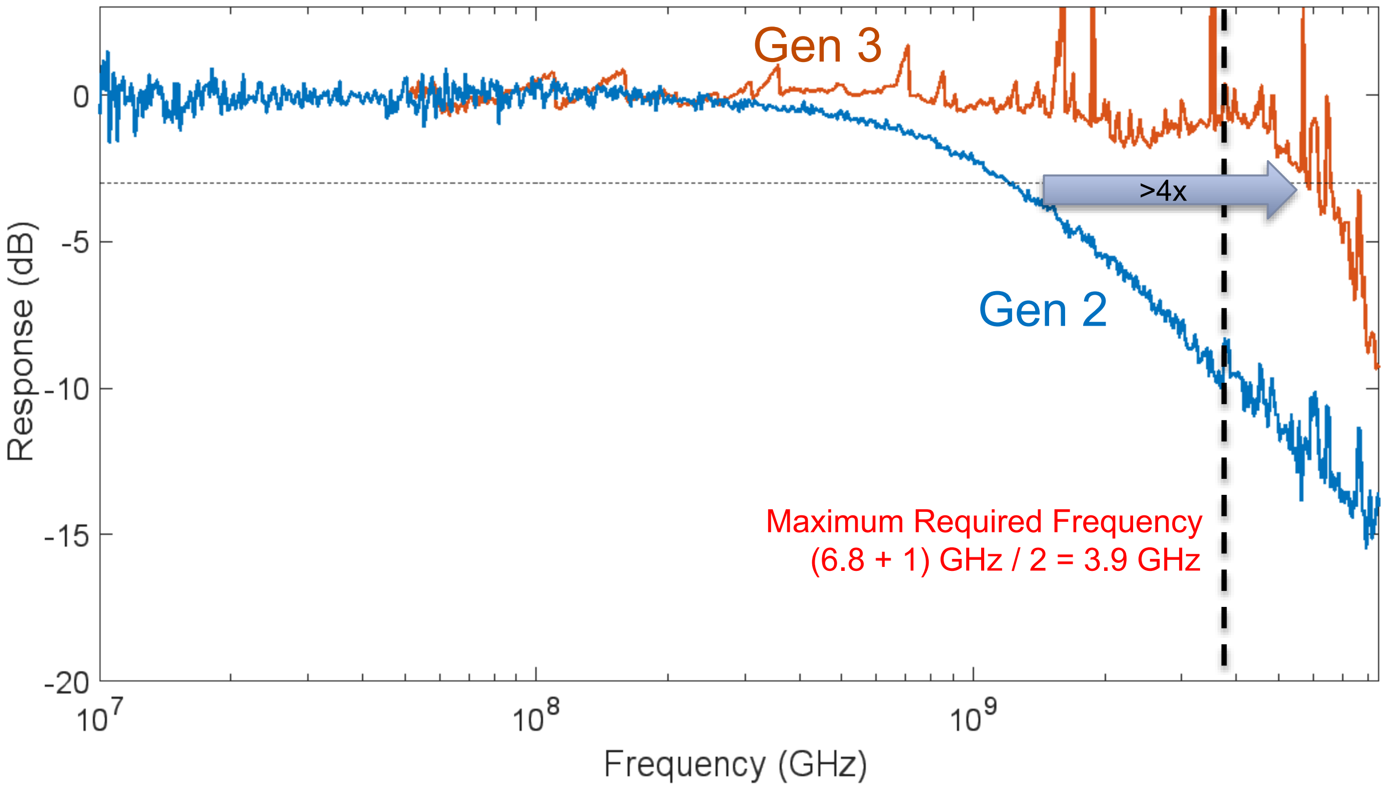


Frequency Response

- **<u>Generation 2</u>**
  - Lumped element modulators

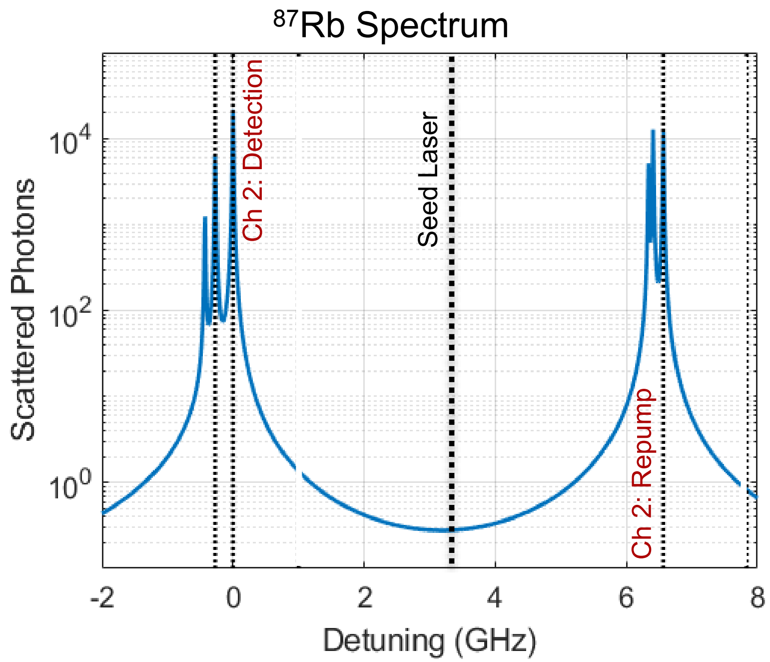


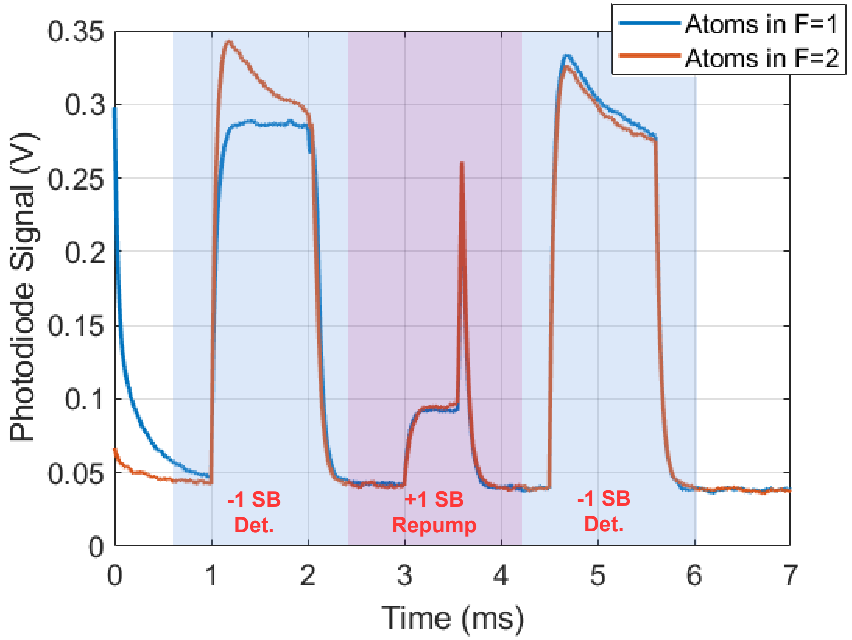
- **<u>Generation 3</u>**
  - Traveling wave modulators

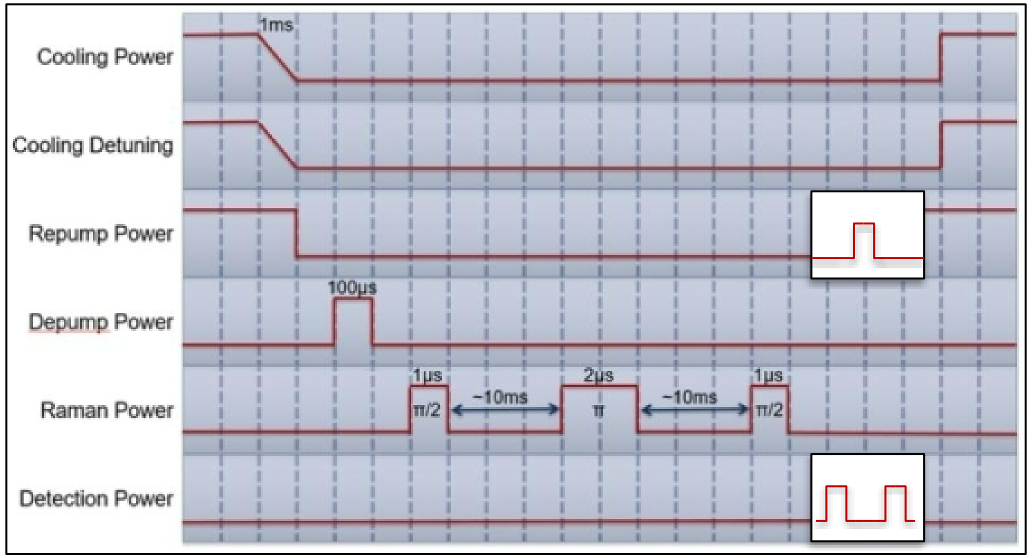


Packaged SSBM Demonstration

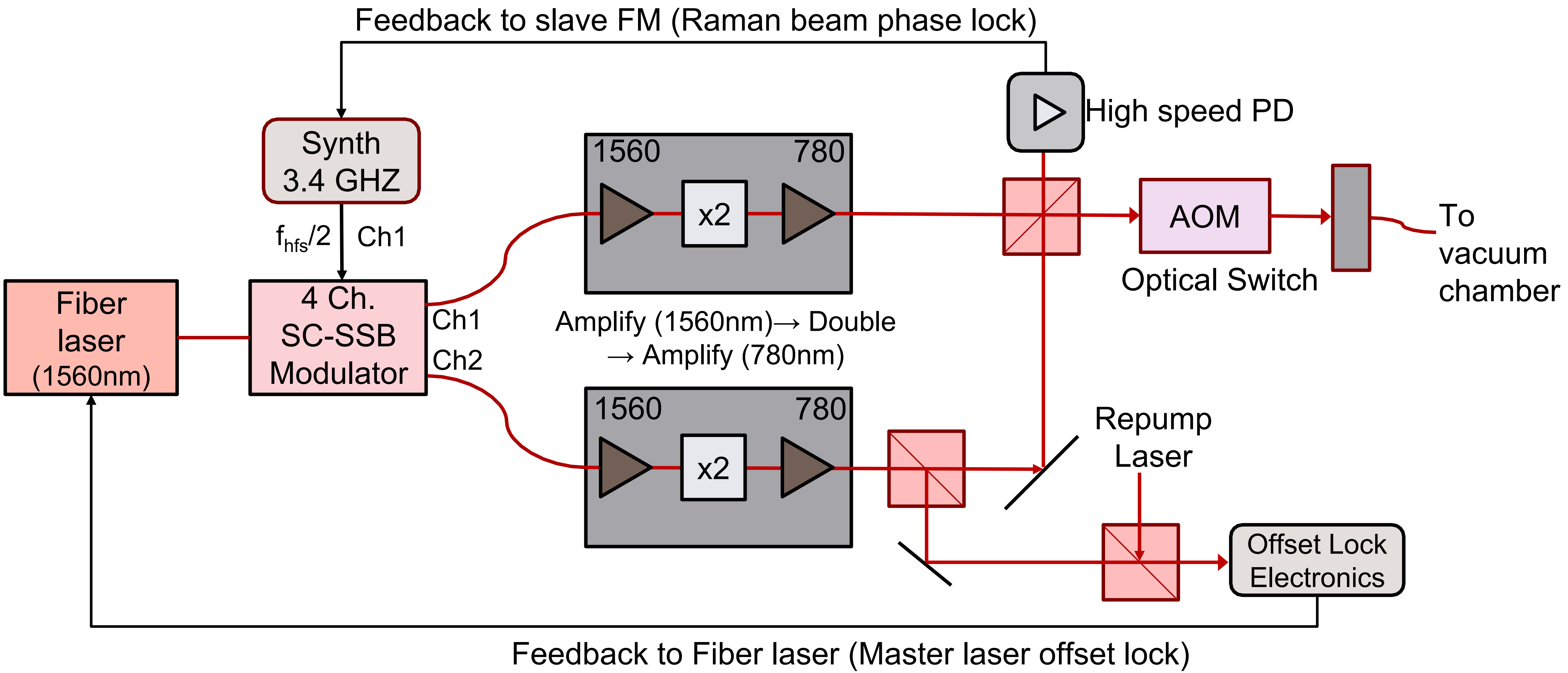
- State Selective Detection Successfully Demonstrated
  - Seed laser locked at midpoint of detection & repump frequencies
  - Modulator driven at 1.644 GHz
  - Thermo-optic phase shifters switched between +1 and -1 side-band
  - **Total frequency jump at 780nm – 6.576 GHz**





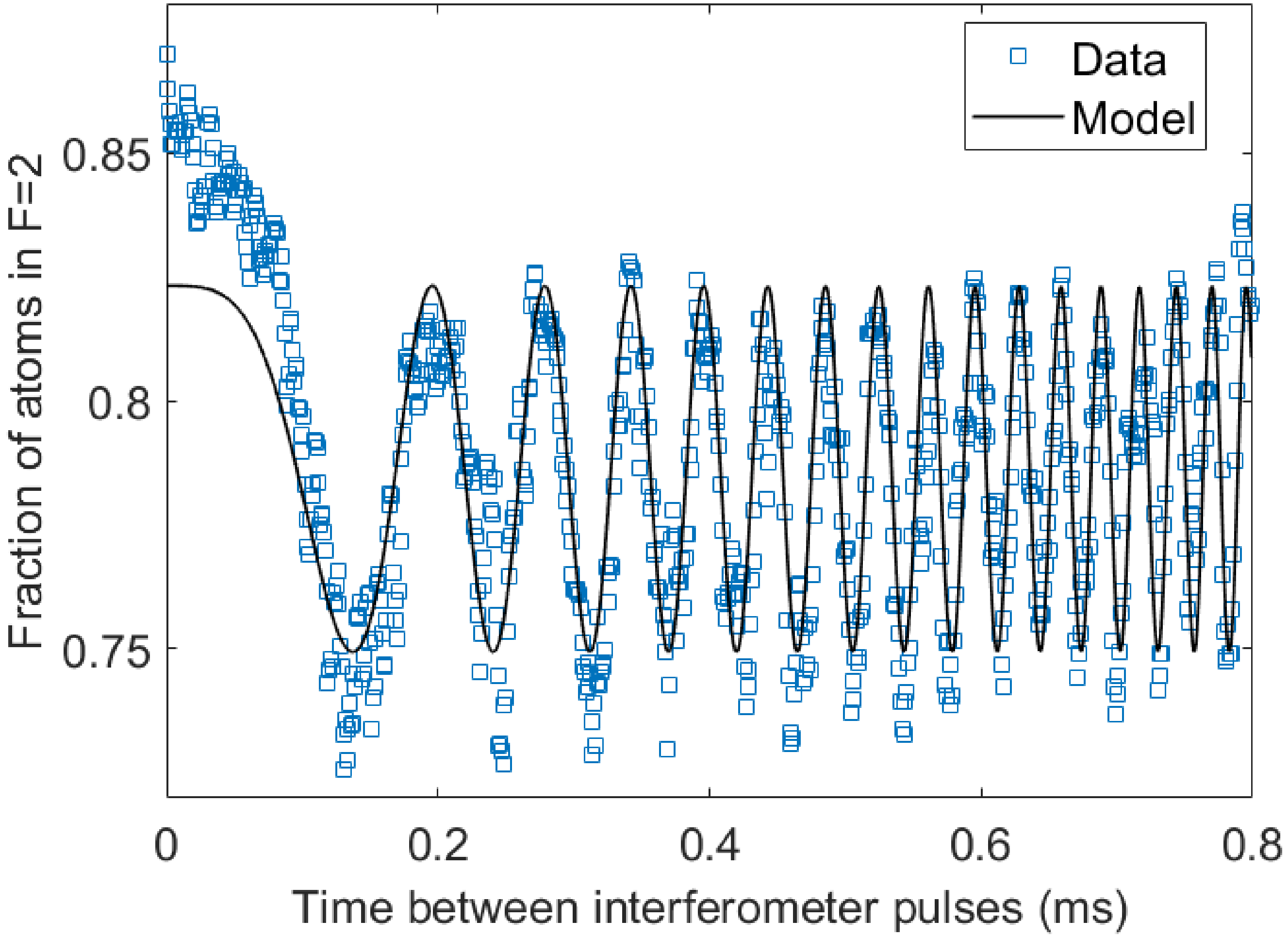


Integrated Photonics Raman Laser Setup

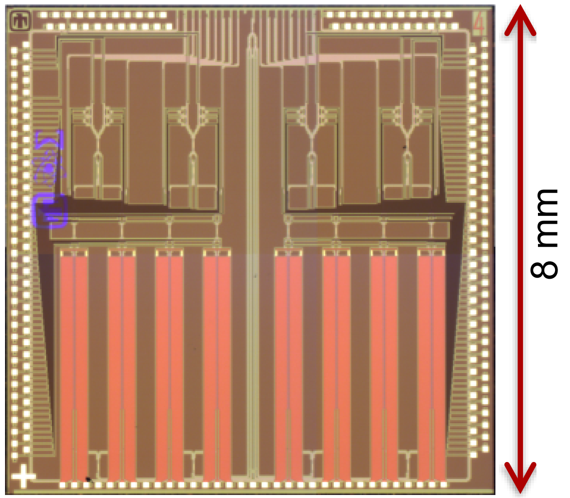


SC-SSB: Suppressed Carrier Single Sideband

AI Demonstration with Integrated Raman Laser Setup



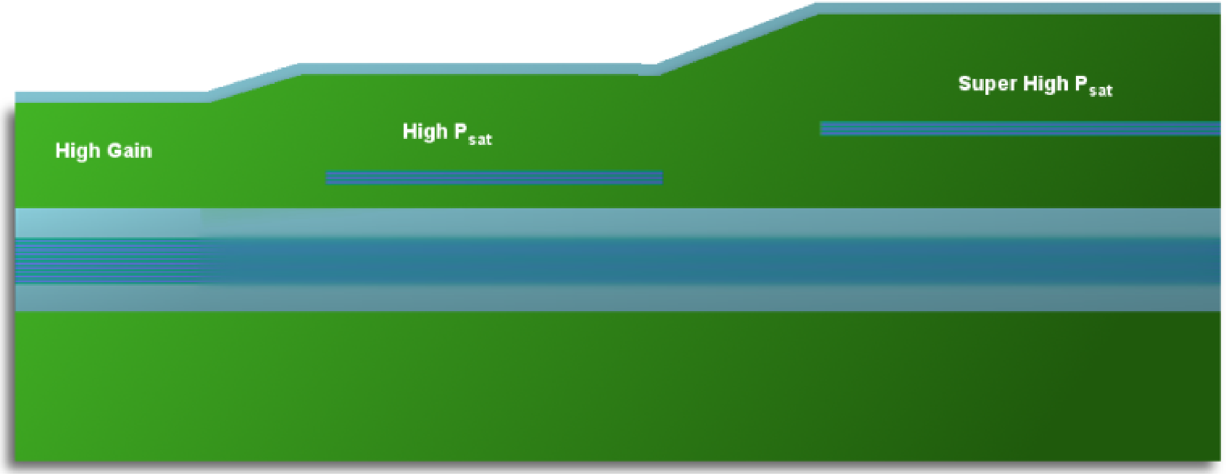
- Demonstrate an AI accelerometer, an atomic gravimeter with SIP Raman laser setup
- $\pi/2 \rightarrow \pi \rightarrow \pi/2$, where $\tau_\pi = 5\ \mu s$
- Measure the chirped fringe from the Doppler-shifted atomic resonance due to gravitational acceleration
- Estimate the gravity with a model: $g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



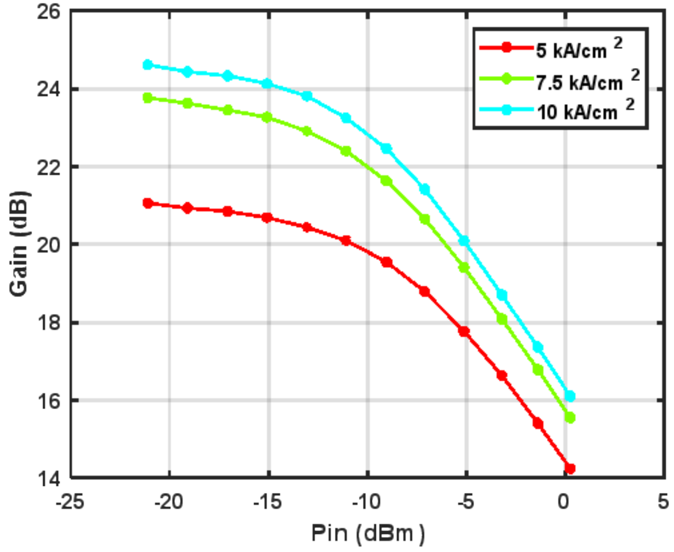
Three-Stage Optical Amplifier in III-V Materials

Sandia National Laboratories

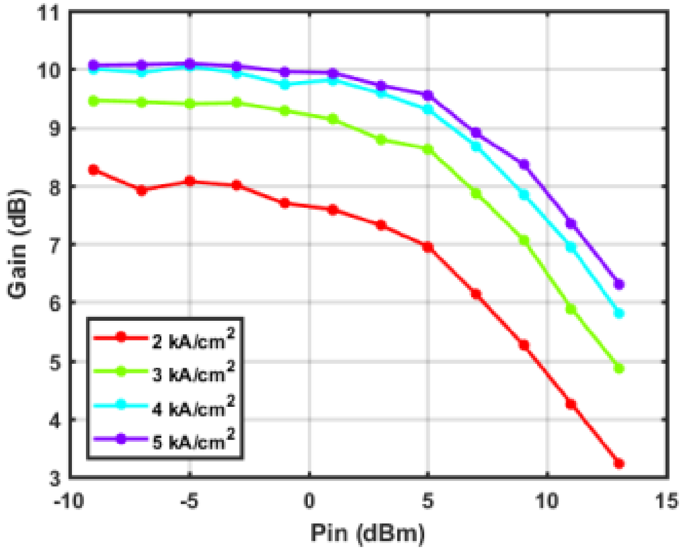
- Demonstrate > 200mW of 1560 nm power
- Large optical power challenging
  - Saturate gain materials
- First two stages successful
- Last stage needs more fabrication development

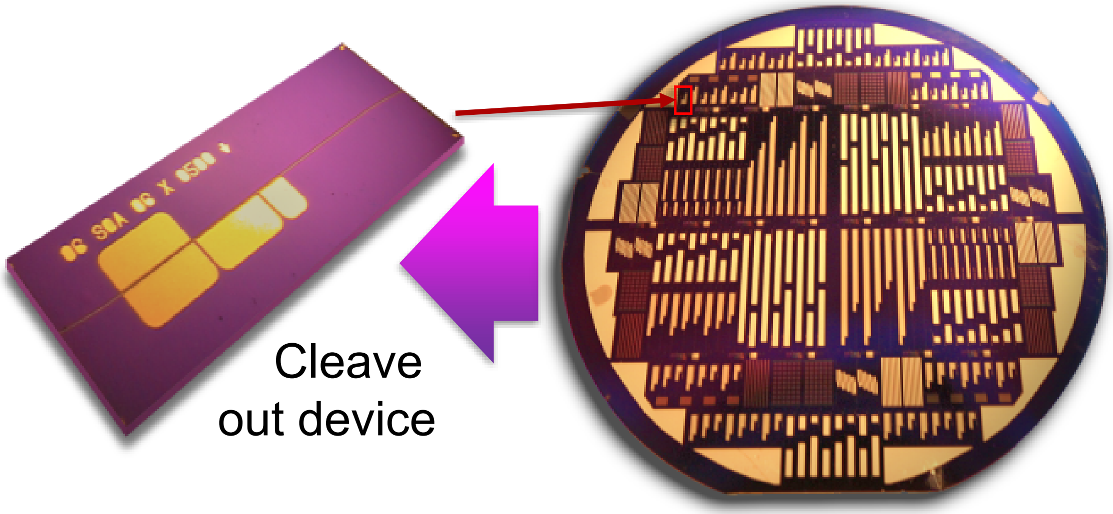


First stage amplifier



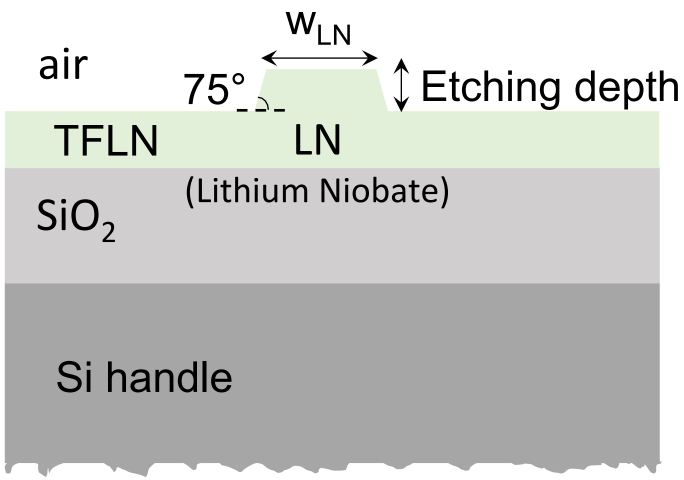
Middle stage amplifier



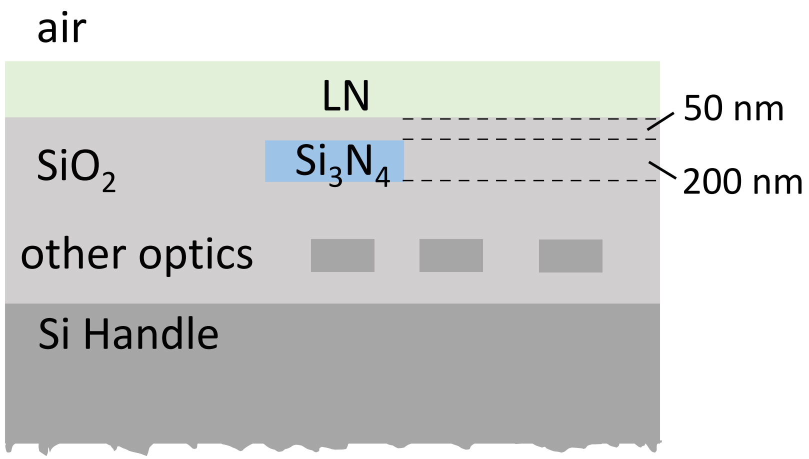


Frequency Doubling with Lithium Niobate

Rib-etched LNOI



Strip-loaded, bonded LNOI

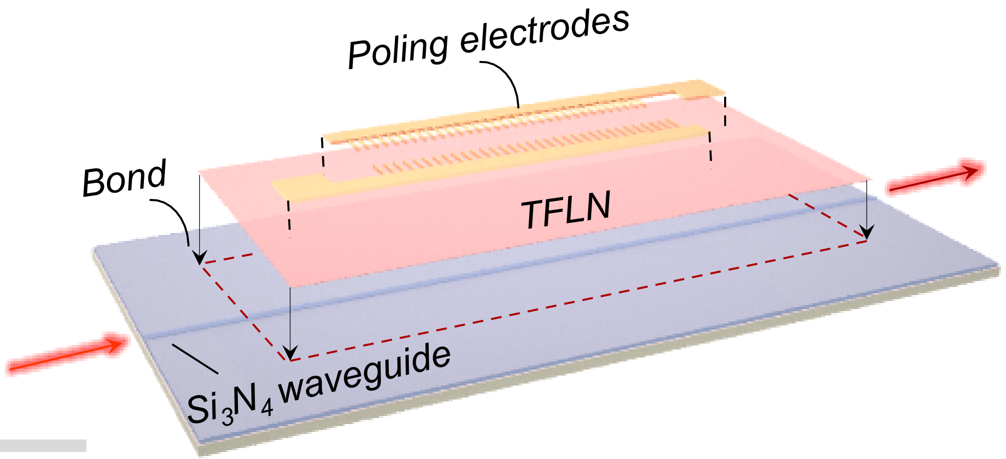


- Relies on bonding. No etching of LN
- Integrate LN with other photonic structures through vertical (inter-layer) transitions.
- Has been used by Sandia for EOM (electro-optic modulator)

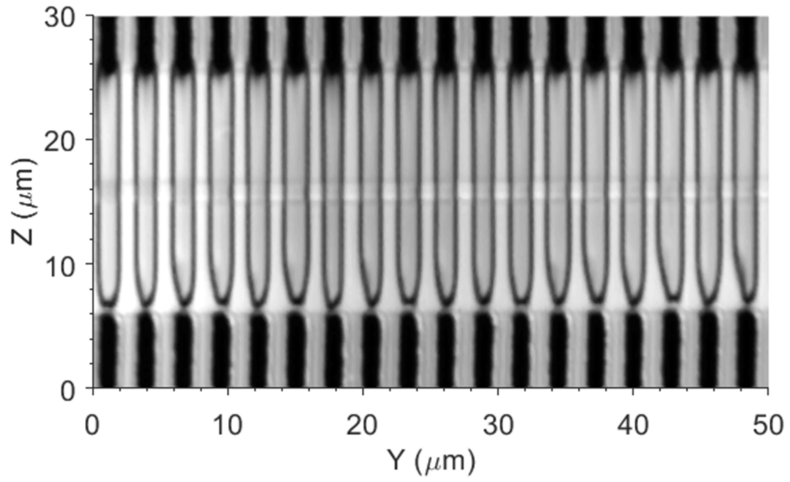
N. Boynton et al., *Opt. Express* 28, 1864 (2020)

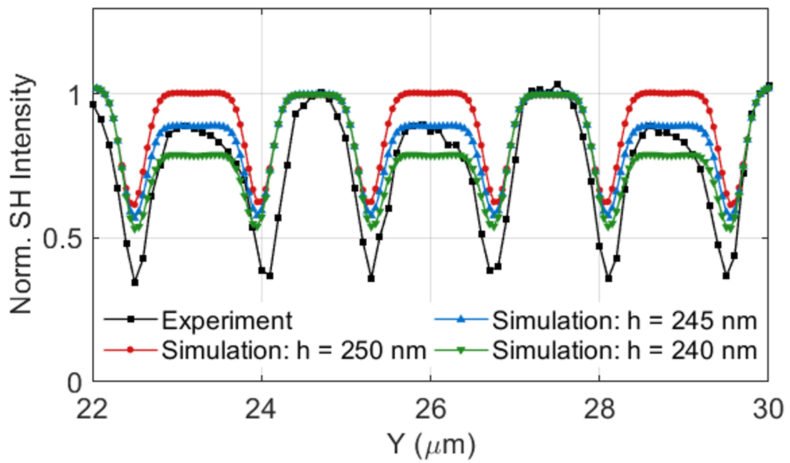
- Disorder-tolerant waveguide design.
- First pole, verify poling quality, and finally, shallow etch.
- Highest waveguide conversion efficiency (939 %/W)

J. Zhao et. al., *Opt. Express* 28, 19669-19682 (2020)

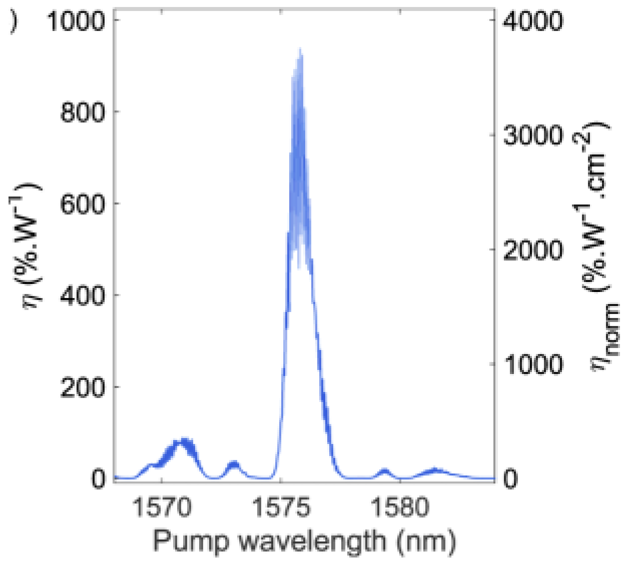


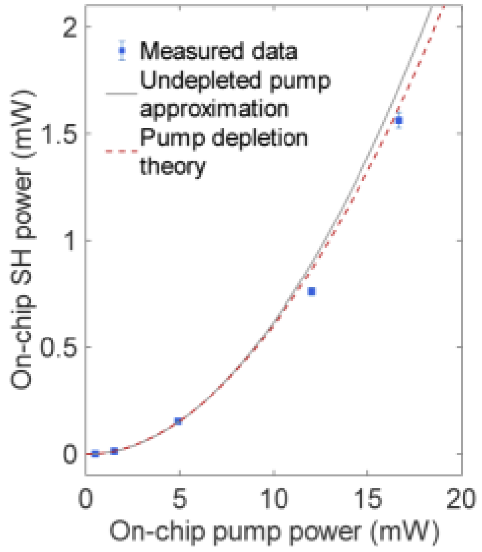
Imaging of domain walls and record doubling efficiency





- 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





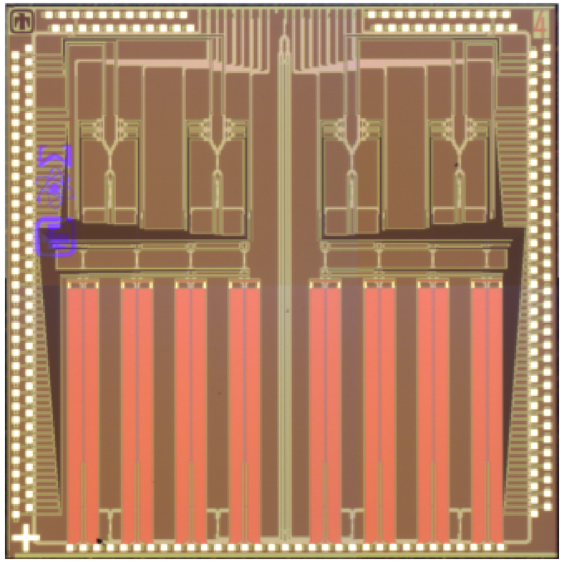
- Jie Zhao, et al. Phys. Rev. Lett. 124, (2020)
- M. Ruesing, et al. J. of App. Phys., Vol. 126, 114105 (2019)

Laser System Architecture using PICs

Silicon Photonics

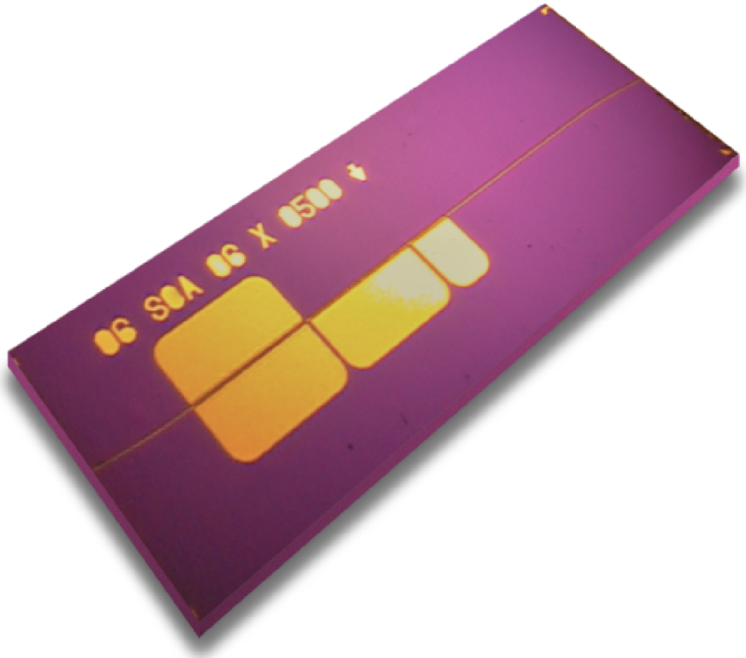
- Modulators & phase shifters
- VOAs & optical filters
- Photo-detectors (Ge)
- HI: III-V or LN on silicon
  (laser & SOA)

HI: Heterogeneous Integration



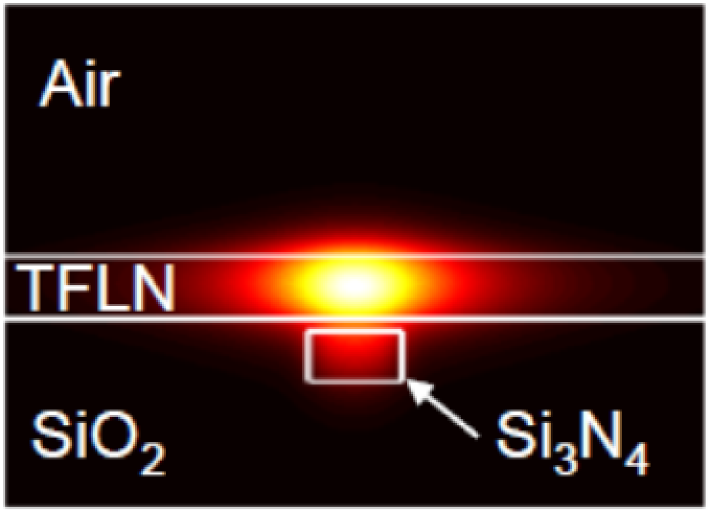
Compound Semiconductor (III-V Photonics)

- Narrow-linewidth lasers
- Electro-absorption modulators
- SOAs
- HI: III-V on silicon (laser & SOA)



Nonlinear Photonics

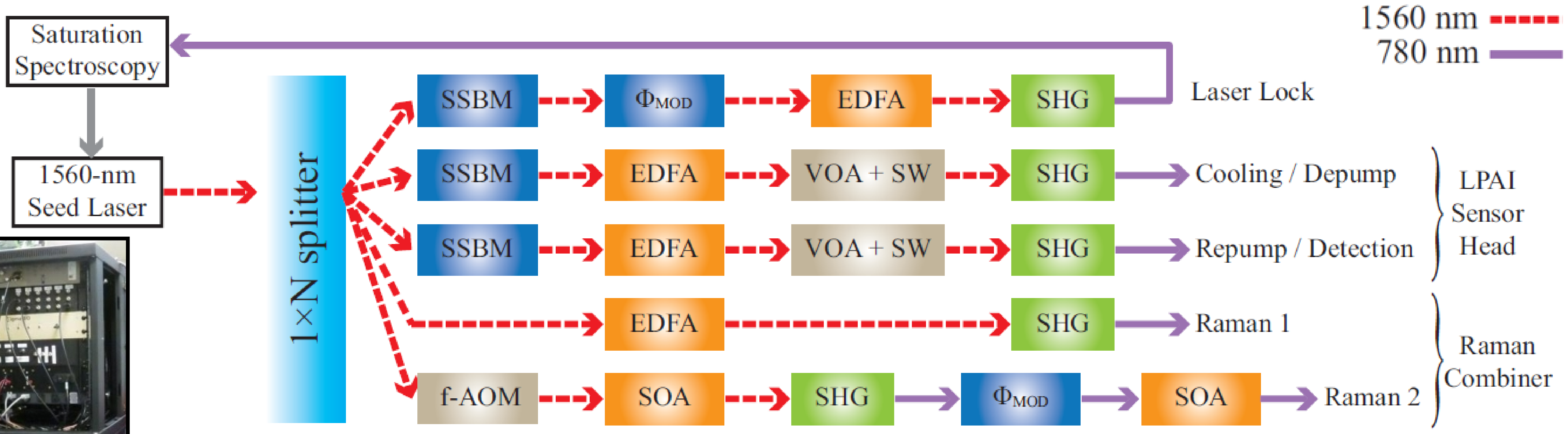
- HI: LN on silicon
  (frequency doubler & EOM)

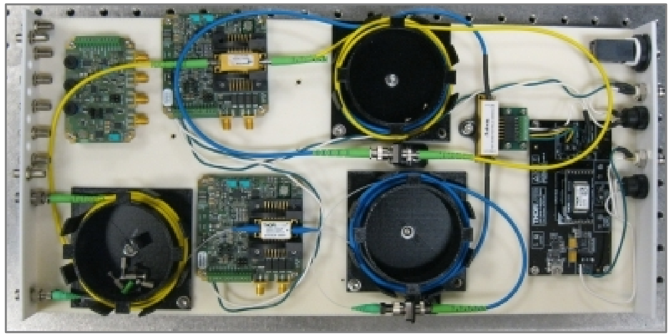


Vision: Several cubic centimeter laser system

PIC-Compatible Laser System

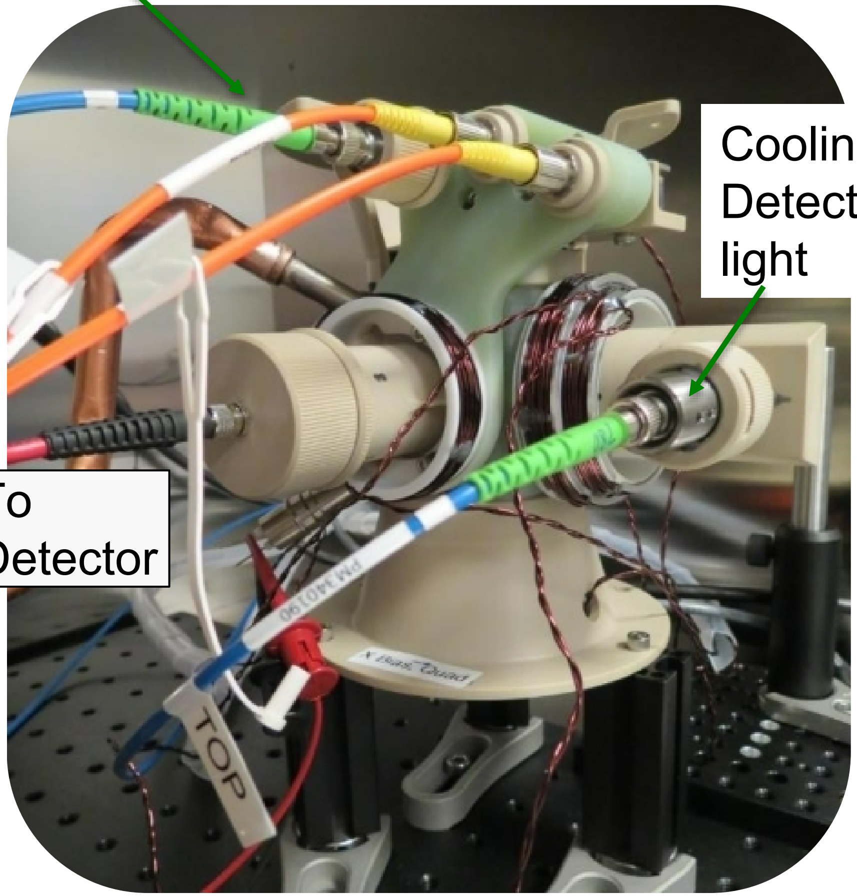
Sandia National Laboratories



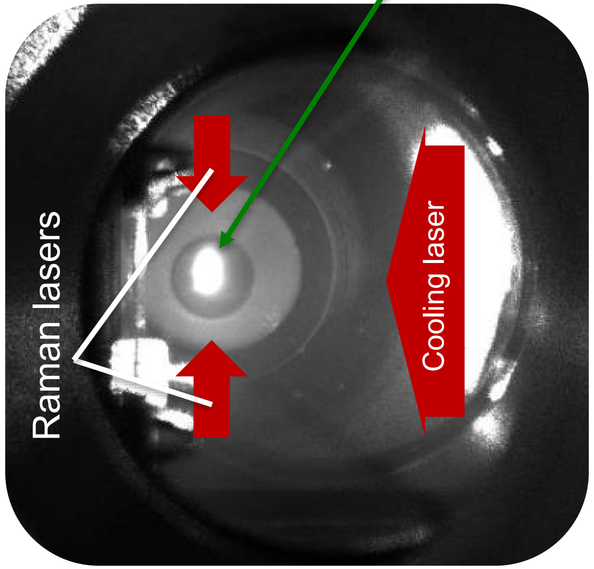


SSBM: single sideband modulator; Φ_{MOD} : phase modulator; f-AOM: fiber acousto-optic modulator; EDFA: erbium doped fiber amplifier; SOA: semiconductor optical amplifier; VOA: variable optical attenuator; SW: optical switch; SHG: Second harmonic generation

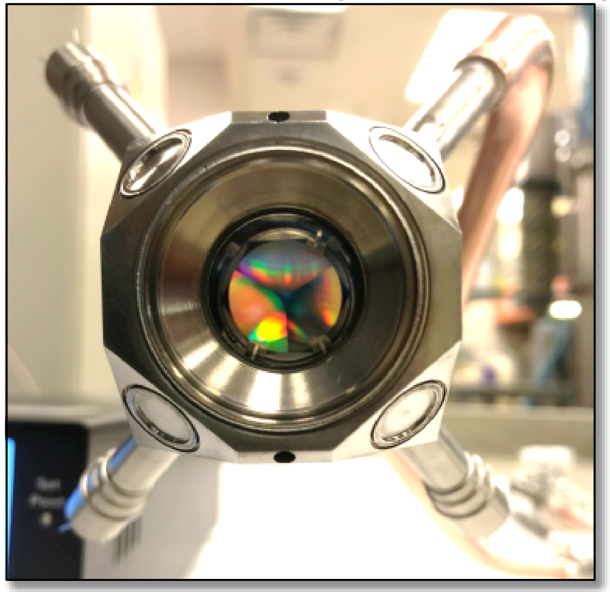
Compact Atom Interferometer Sensor Head

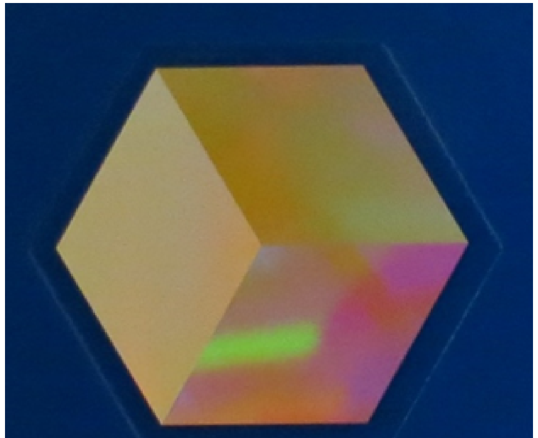


- Grating magneto optical trap (GMOT)
- Grating replaces one window of vacuum package
- Vacuum maintained by ion pump, fused silica windows
- Atom number: 10^6-10^7, Sub-Doppler cooling: 18 μK.

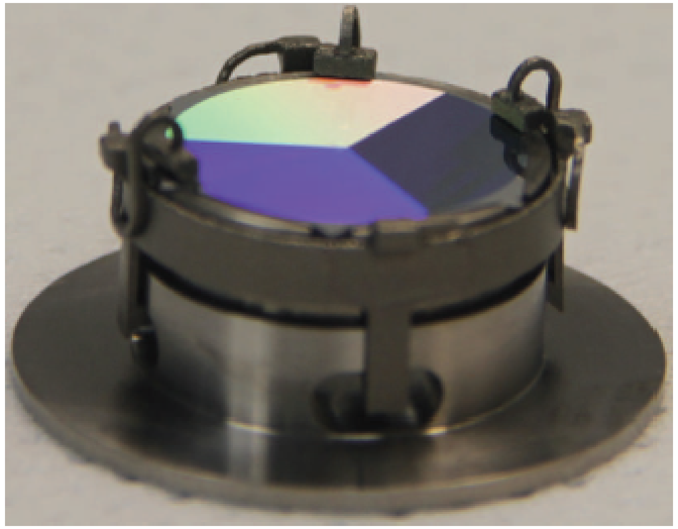


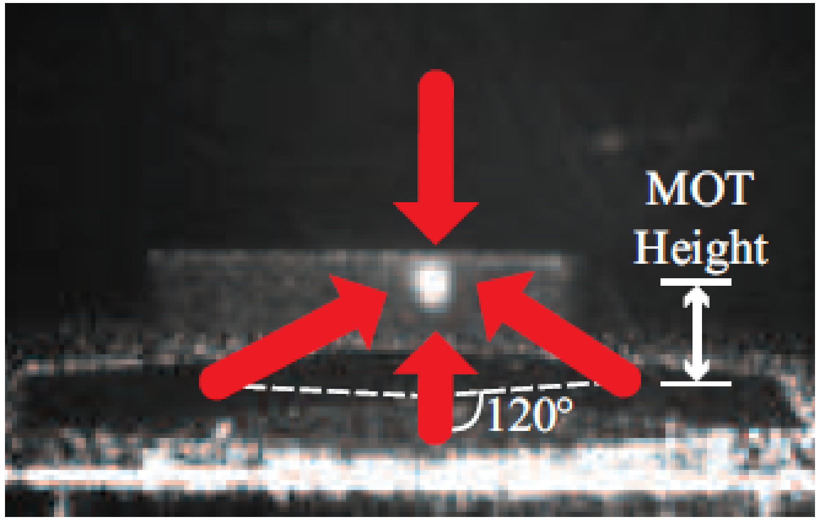
Ti Vacuum Package with Grating

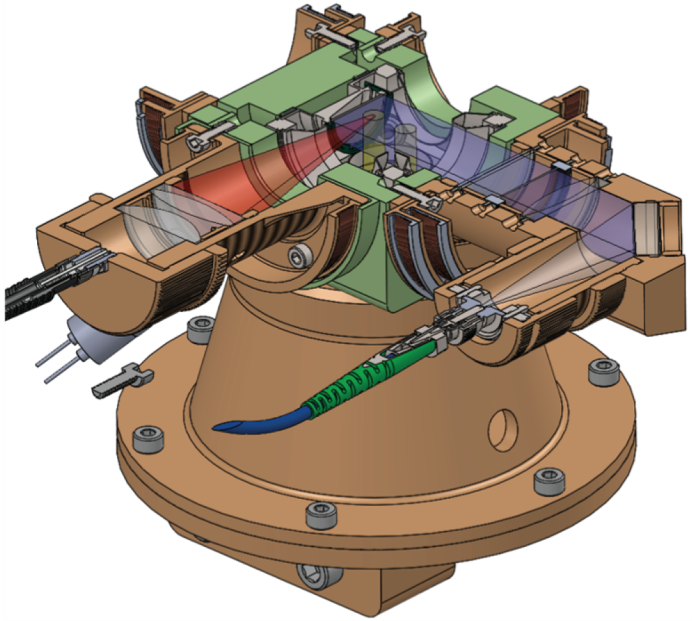


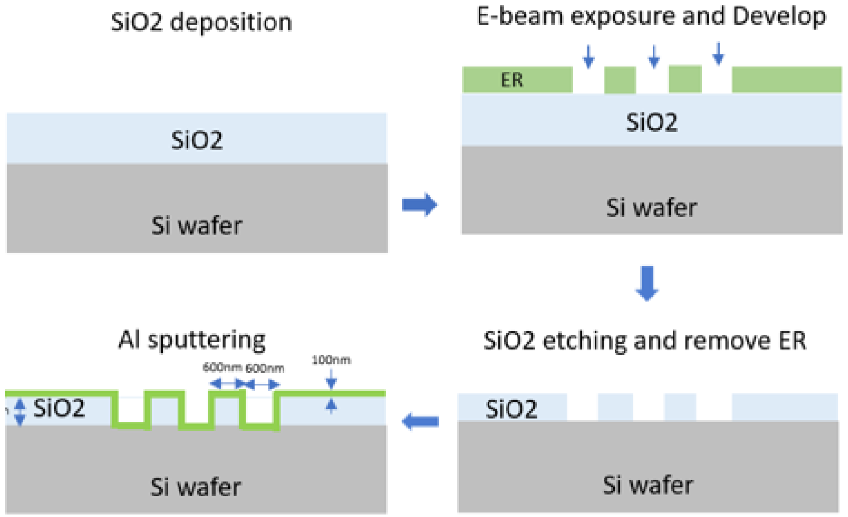

GMOT Grating

Grating-mirror Magneto-Optical Trap (GMOT)



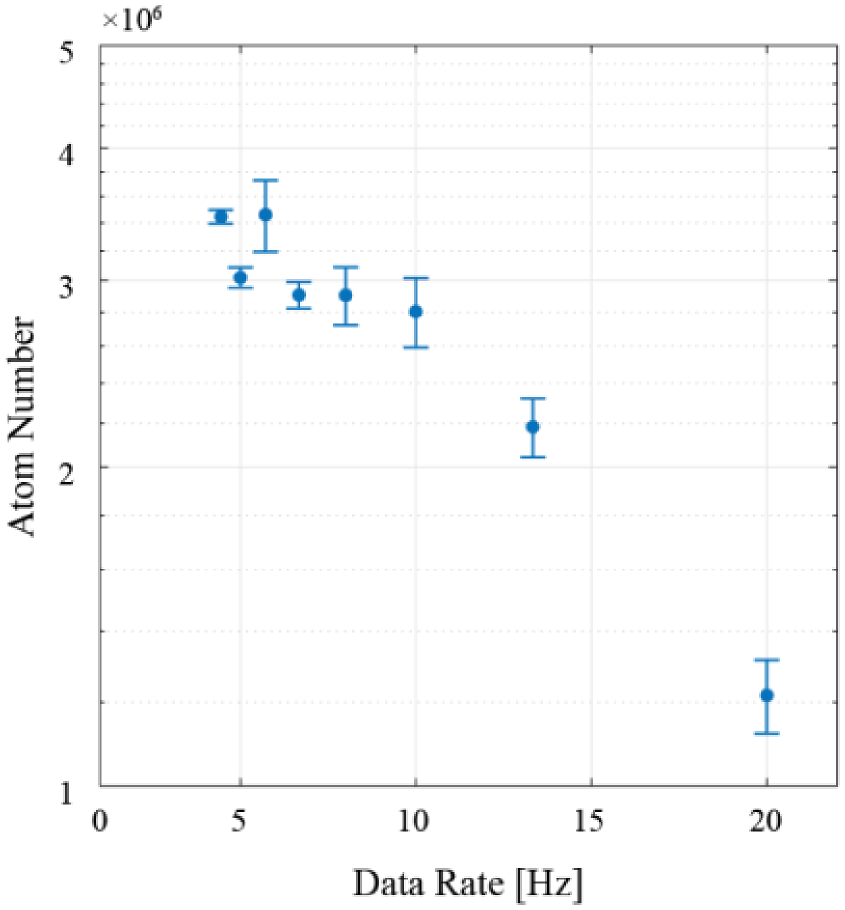


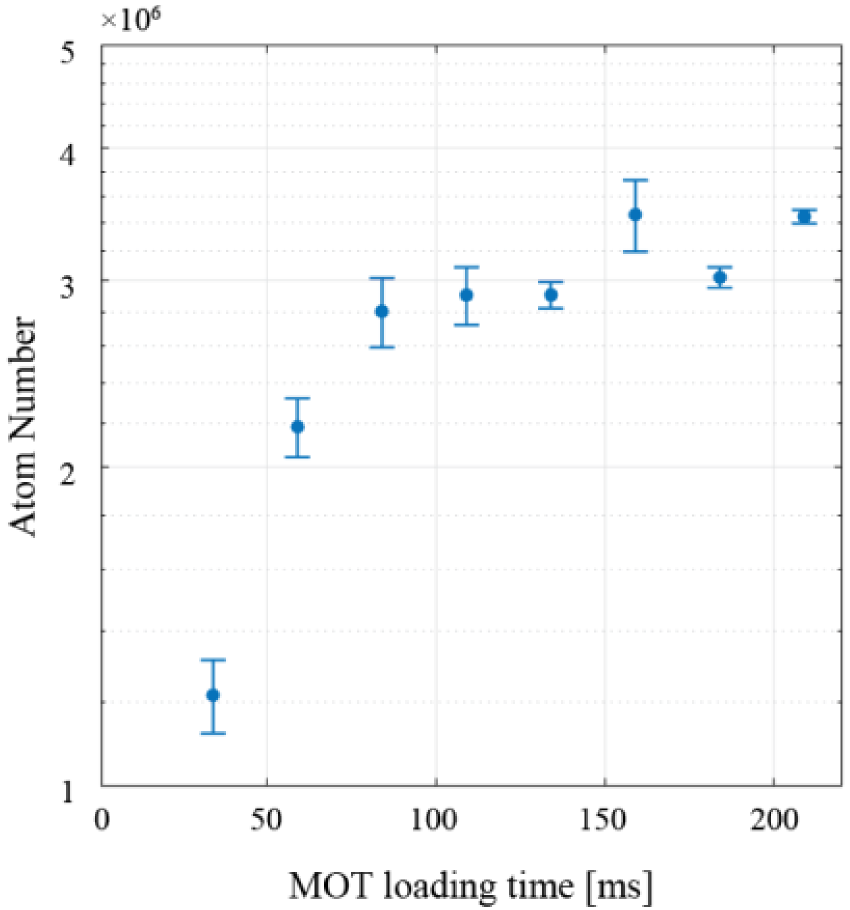




- Sandia-fabricated hexagonal reflective grating chip
  - 1.2 μm pitch, ~50% duty-cycle, and 195 nm depth
  - Aluminum coating
- 3D-printed retainer ring to hold the grating chip for high dynamics
- Single-beam tetrahedral MOT configuration
- Compact sensor head with fixed alignment optical package to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

High Data-Rate GMOT

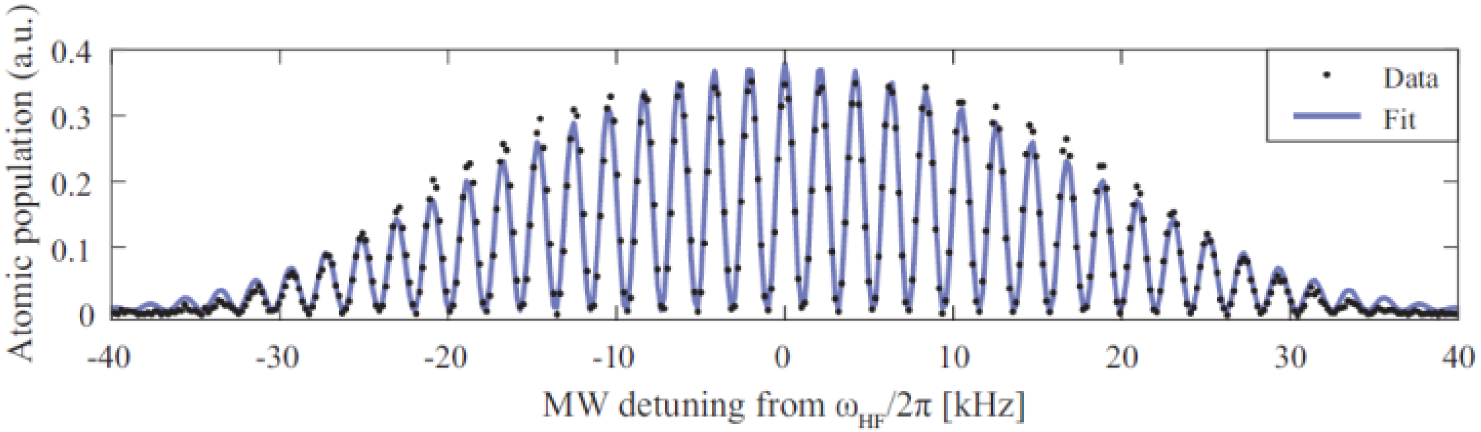




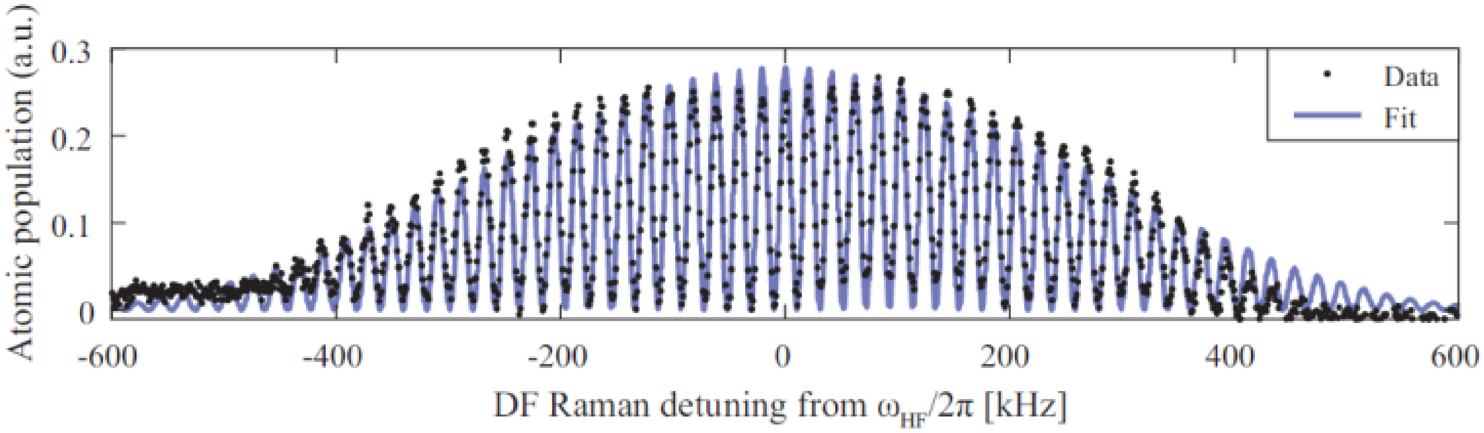
- Sub-Doppler cooled GMOT atoms (T = 15μK)
- High data-rate GMOT operation (> 20Hz)
- Next step: Increase the intensity of the cooling beam

J. Lee et al., arXiv:2107.04792 (2021)

Atomic Coherence with GMOT



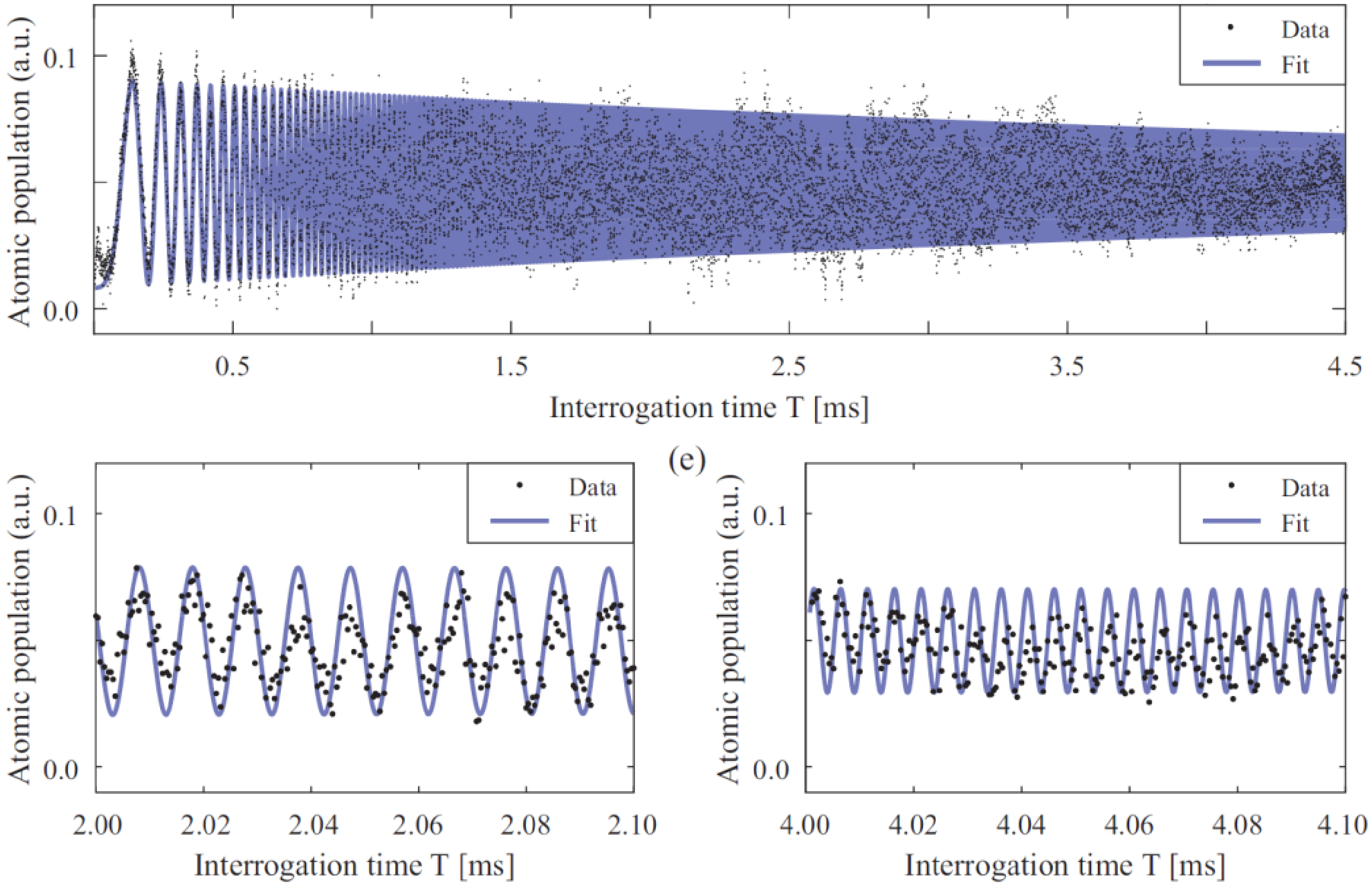
Ramsey sequence with microwave field:
$\frac{\pi}{2} \rightarrow \mathrm{T} \rightarrow \frac{\pi}{2}$ (frequency scan)
Interrogation time $\mathrm{T} = 450\ \mu\mathrm{s}$

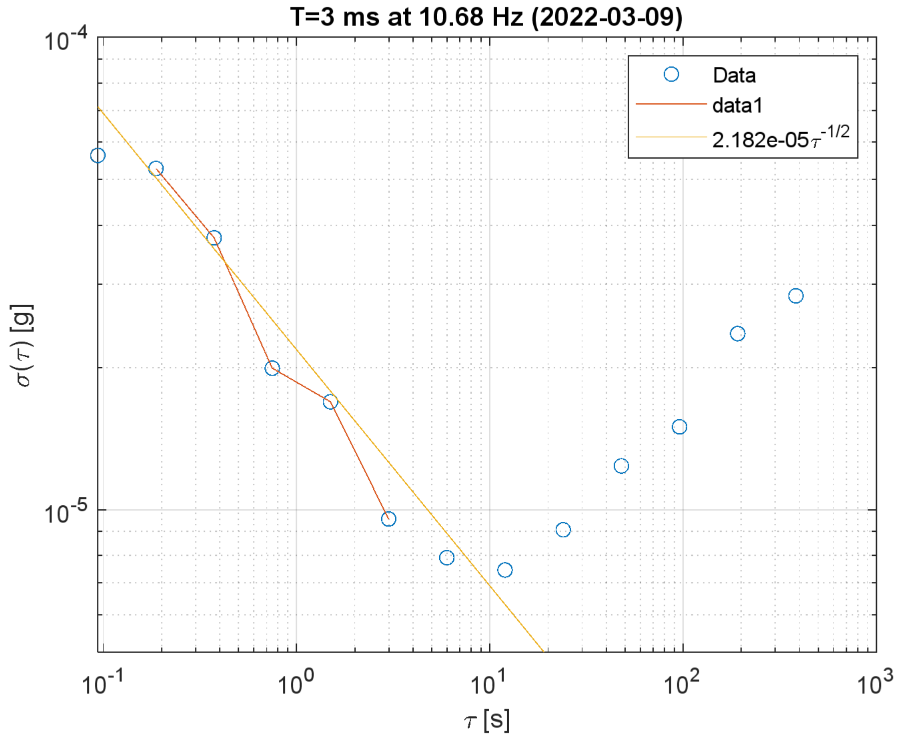


Ramsey sequence with Doppler-free Raman beams:
$\frac{\pi}{2} \rightarrow \mathrm{T} \rightarrow \frac{\pi}{2}$ (frequency scan)
Interrogation time $\mathrm{T} = 48.08\ \mu\mathrm{s}$

J. Lee et al., arXiv:2107.04792 (2021)

Atom Interferometer Demonstration with GMOT



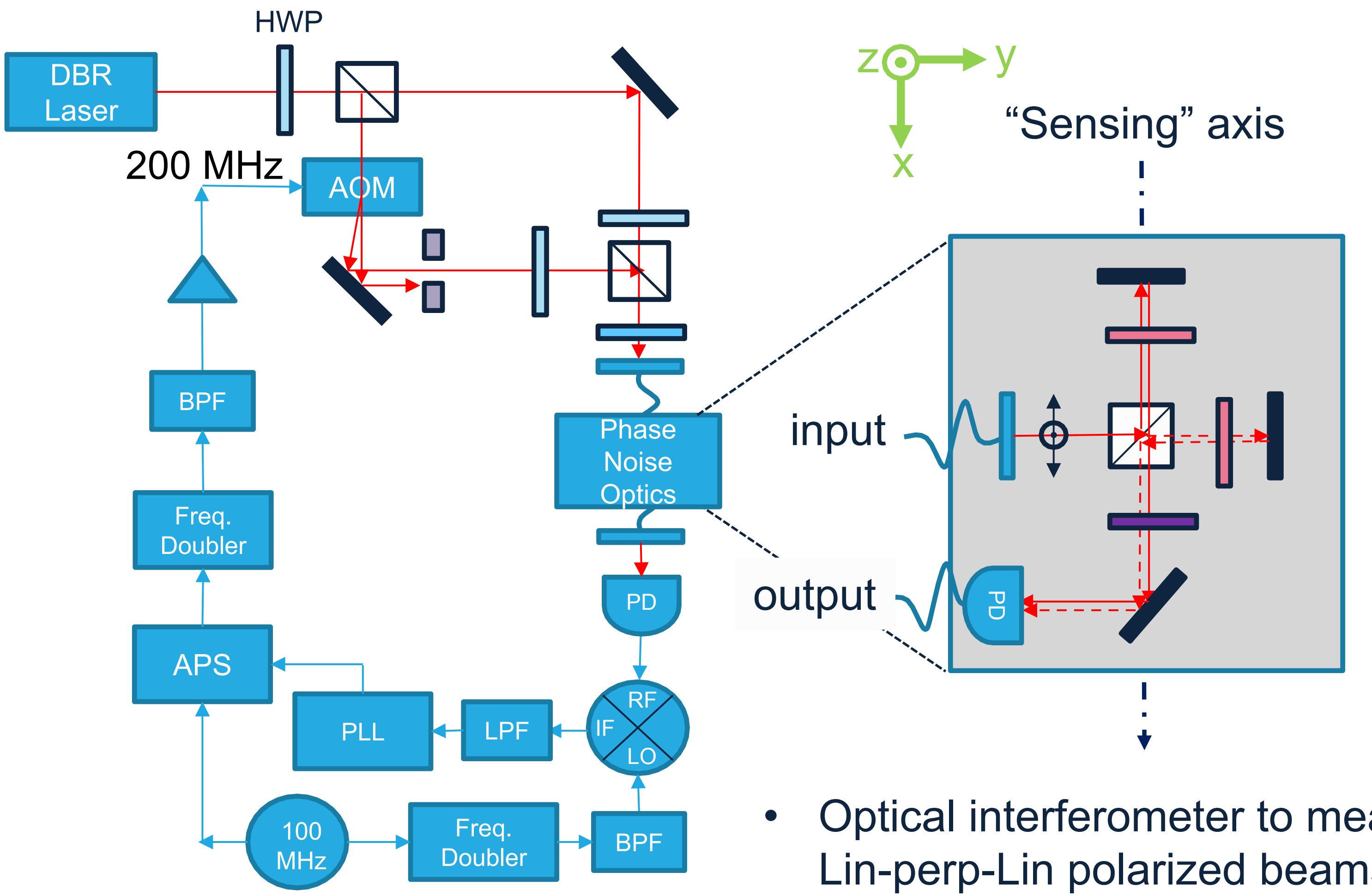


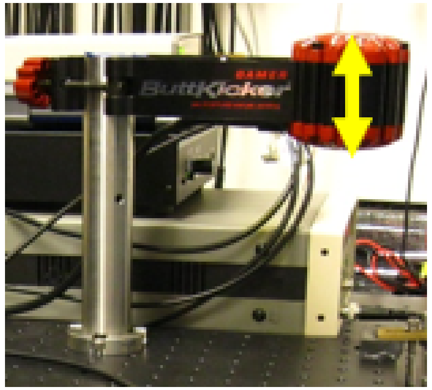
- Sensitivity measurement T = 3 ms
- 22 μ*g*/rt-Hz
- Work needed to improve the data rate and *SNR*

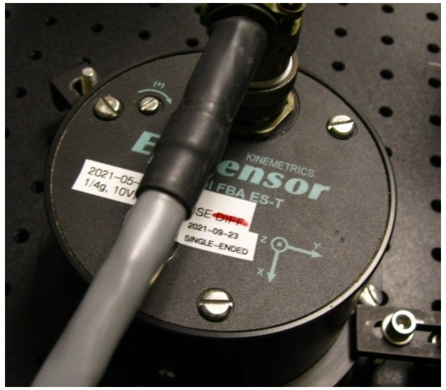
- Raman beam delivered via free space (external from prototype)
- Data rate: 10 Hz. Statistical uncertainty: ~2 μ*g*

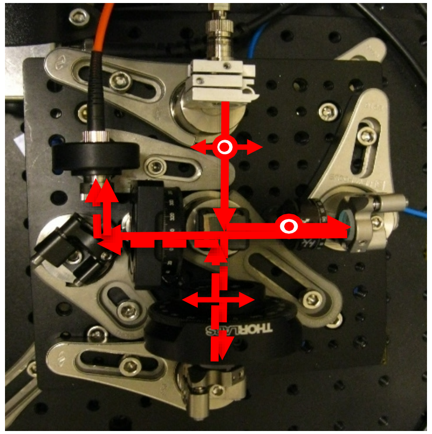
Phase Noise Measurement Setup with Phase Lock

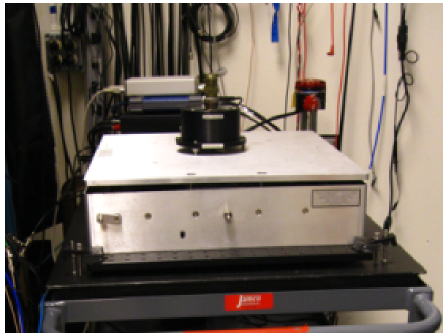
Sandia National Laboratories







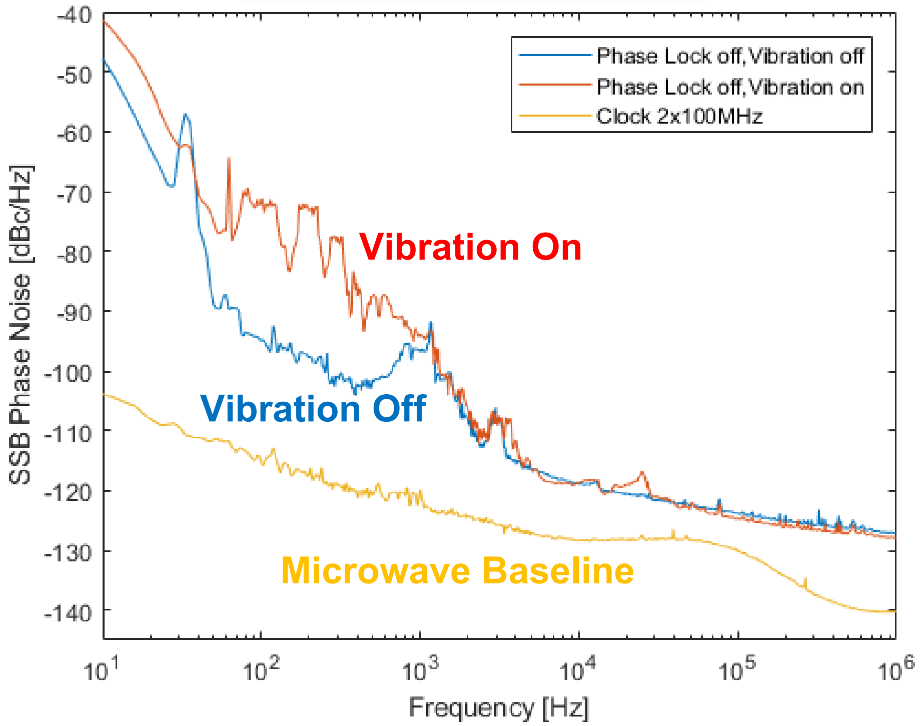




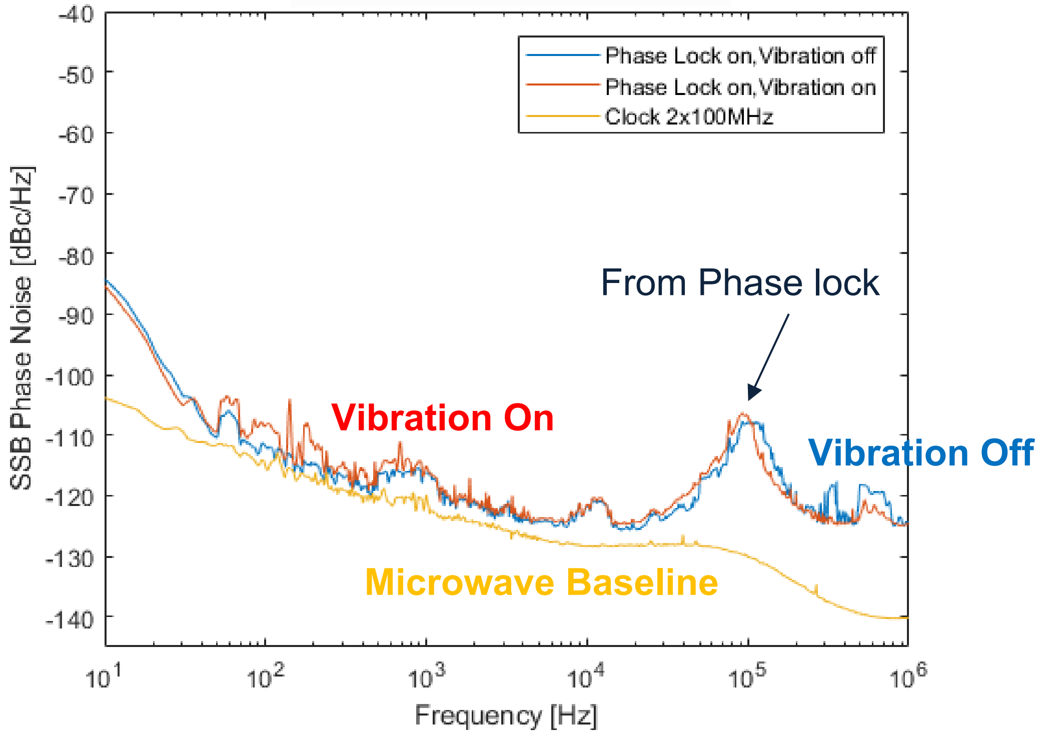
- Optical interferometer to measure phase noise with phase lock (two Lin-perp-Lin polarized beams)
- Phase noise optics like Raman beam optics on a sensor head
- Acousto-Optic Modulator (AOM); Analog Phase Shifter
- *Ephi Sensor (a 3-axis accelerometer)*

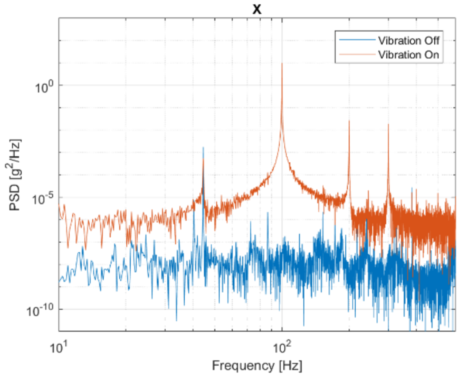
Effect of phase lock

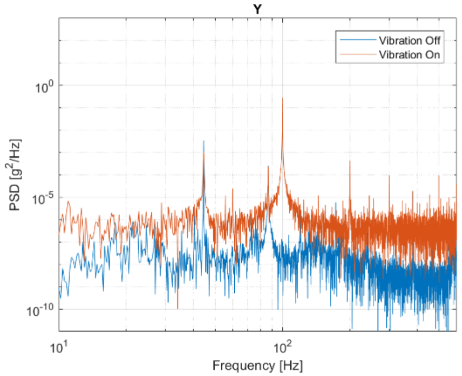
Phase Lock Off

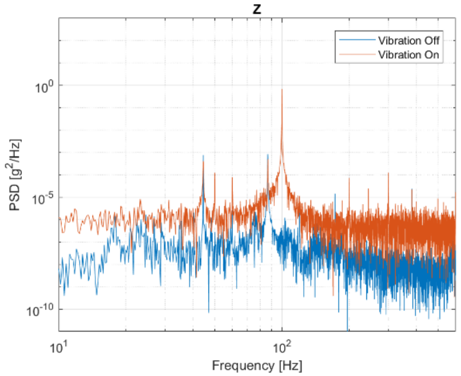


Phase Lock On



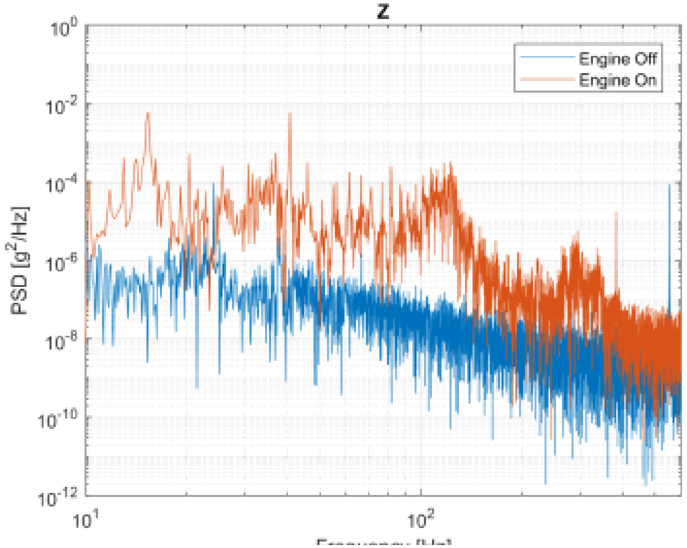


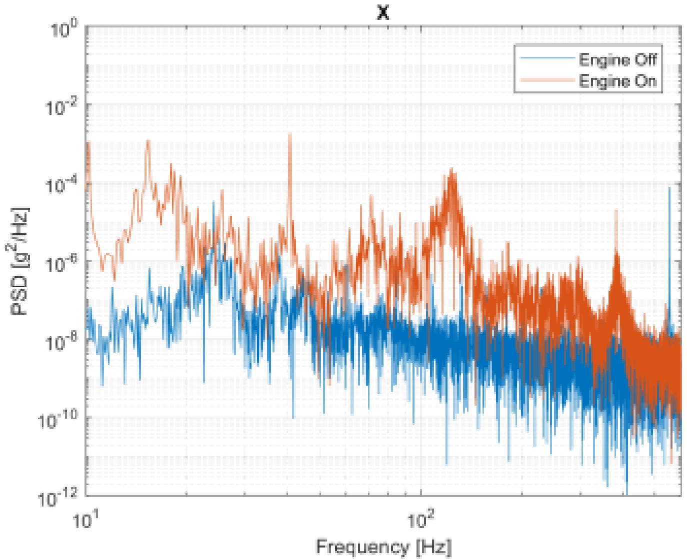


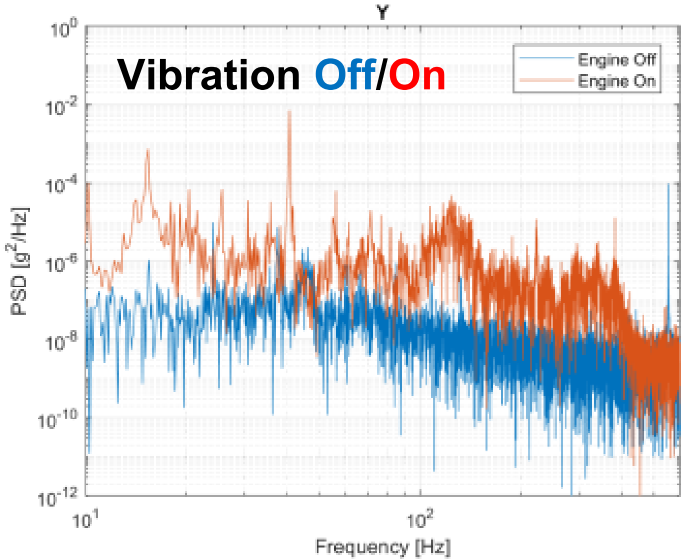


Ephi sensor in Laboratory Condition (Vibration Off/On)

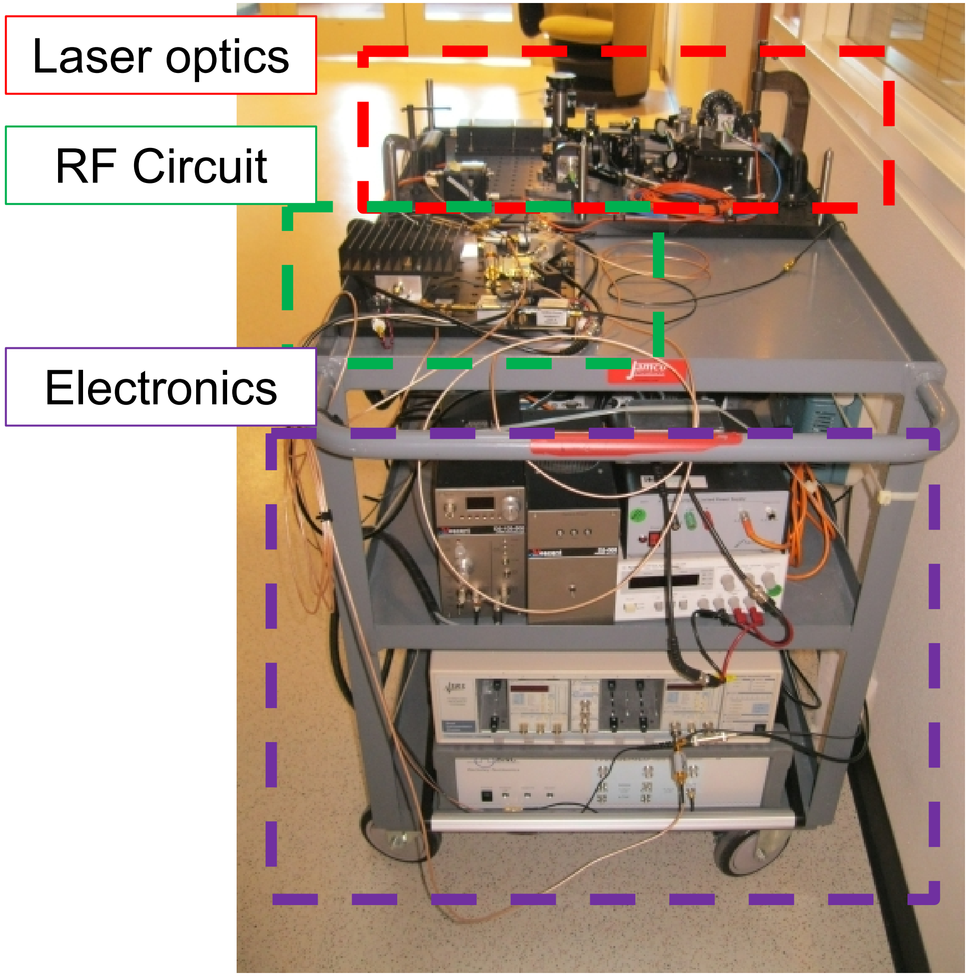
Phase noise measurements in a moving vehicle



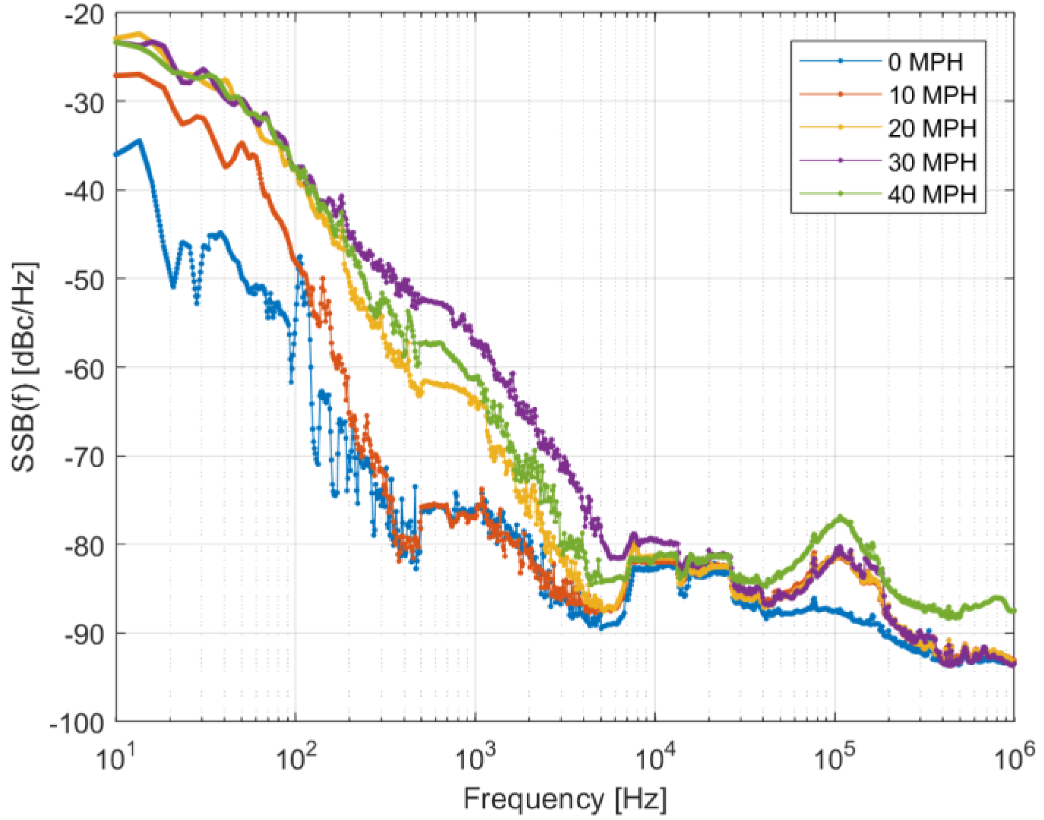


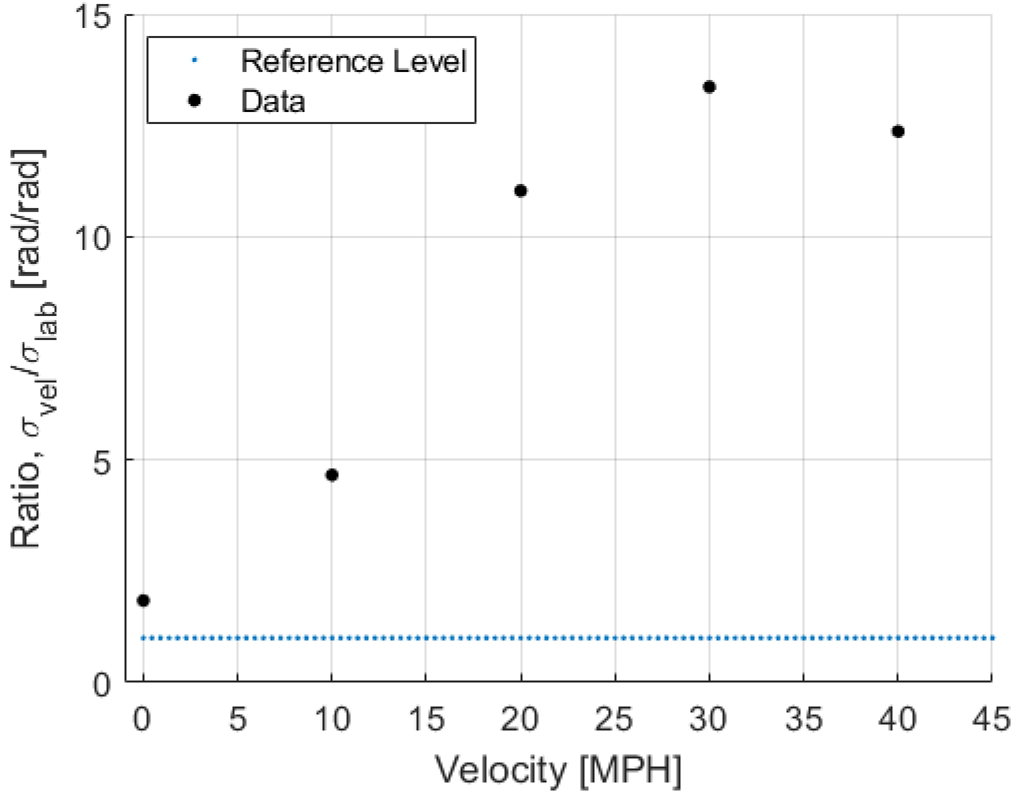


- All electronics and laser optics are on a single cart
- Phase noise of a beat note was measured for different constant van velocities



Measured vibration and Inferred change in sensitivity

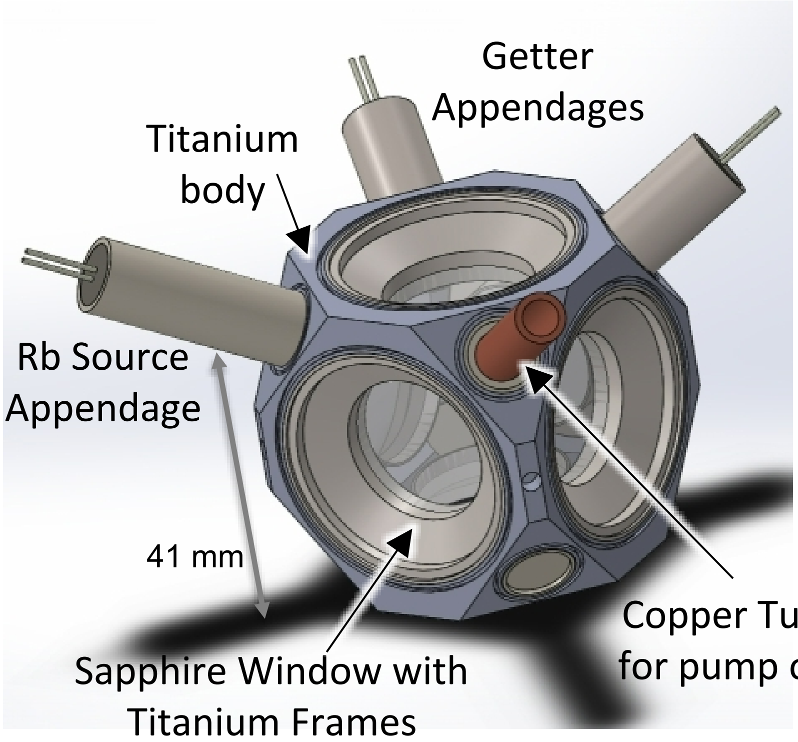


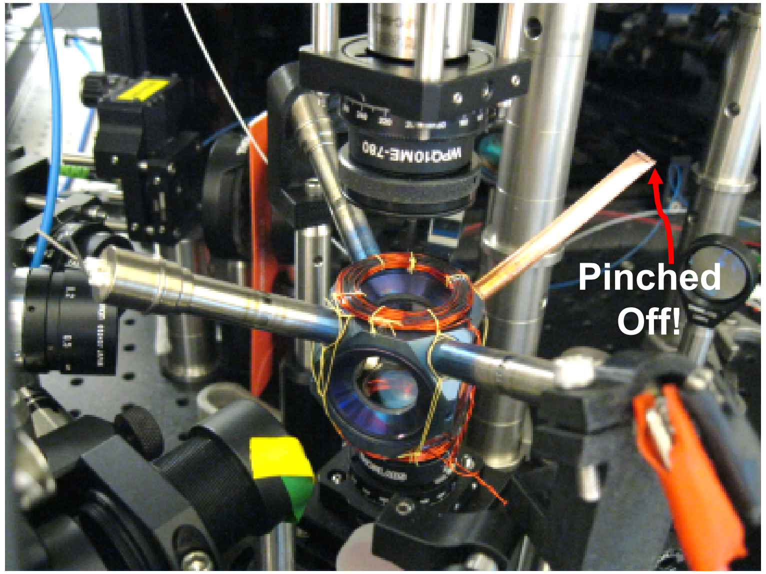


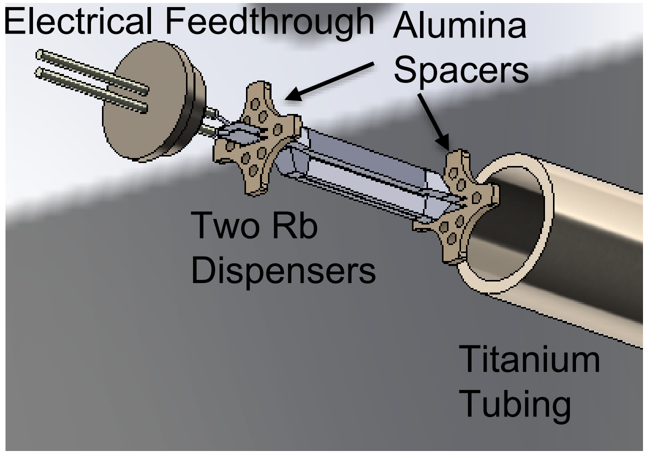
- Interferometer phase noise is approximated using the measured phase PSD
  - P. Cheinet et. al, IEEE Trans. Instrum. Meas. **57**, 1141 (2008)

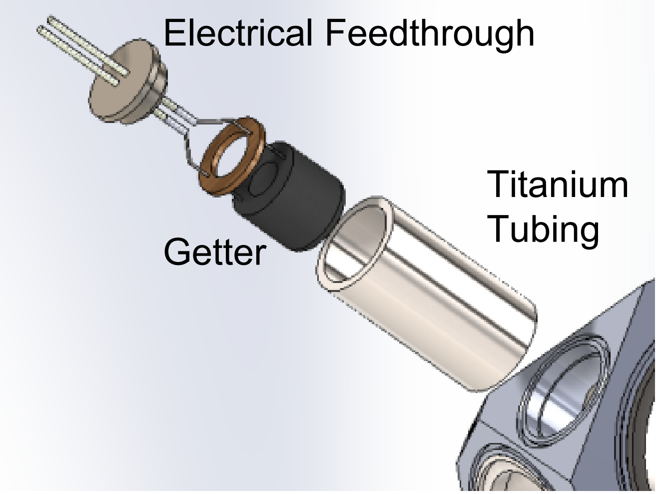
Passively pumped Vacuum Package: Titanium Package Design

- C-cut sapphire windows, AR-coated
  - No helium permeation (or very low)
- Passive pumping: SAES St172 getters
- 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

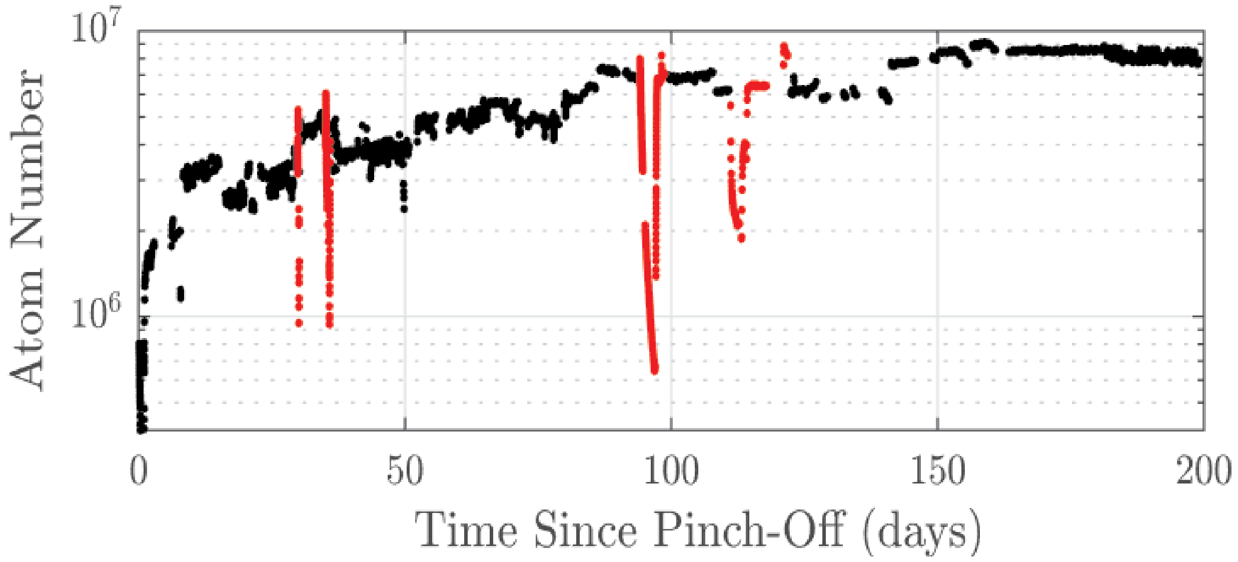


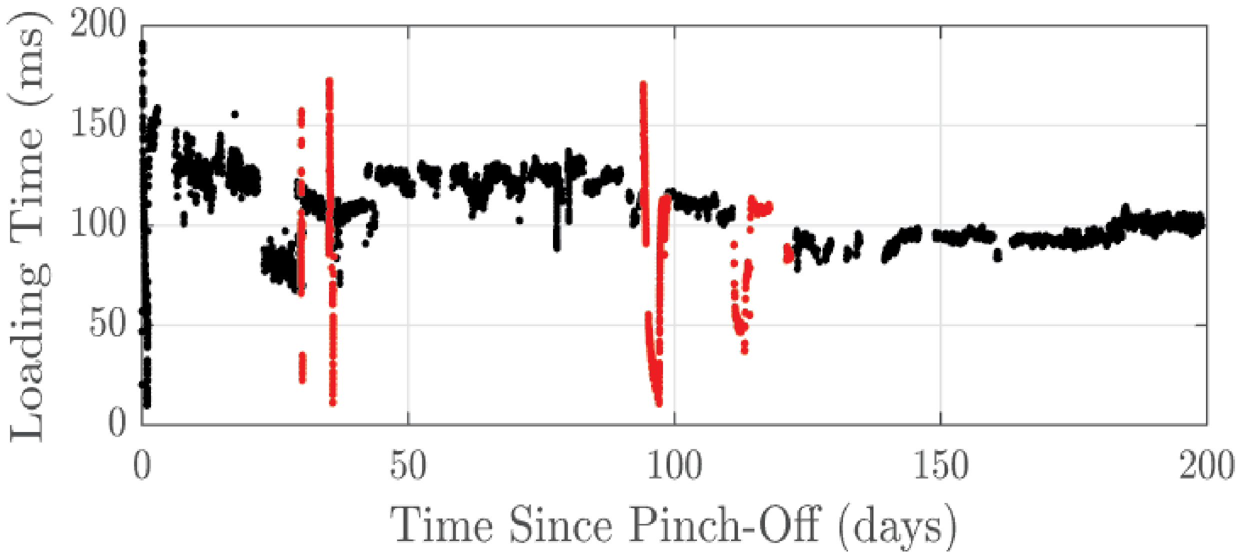




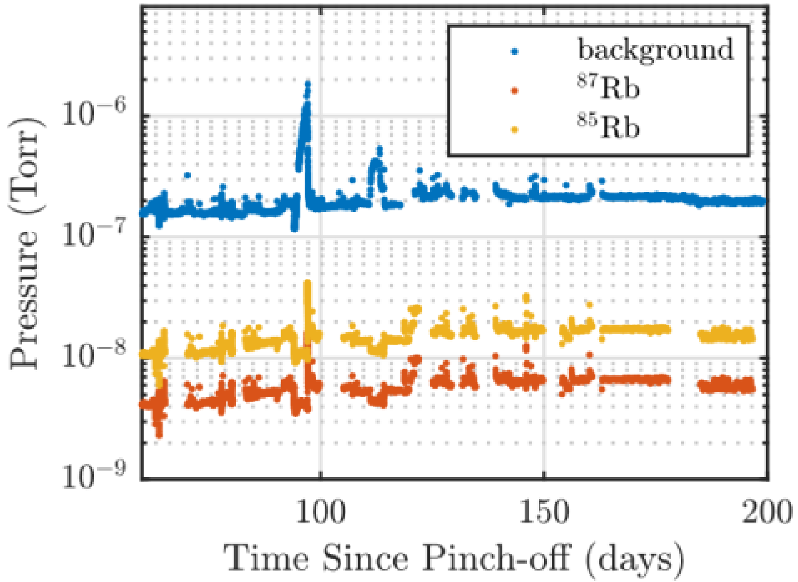


MOT in the Passively Pumped Chamber

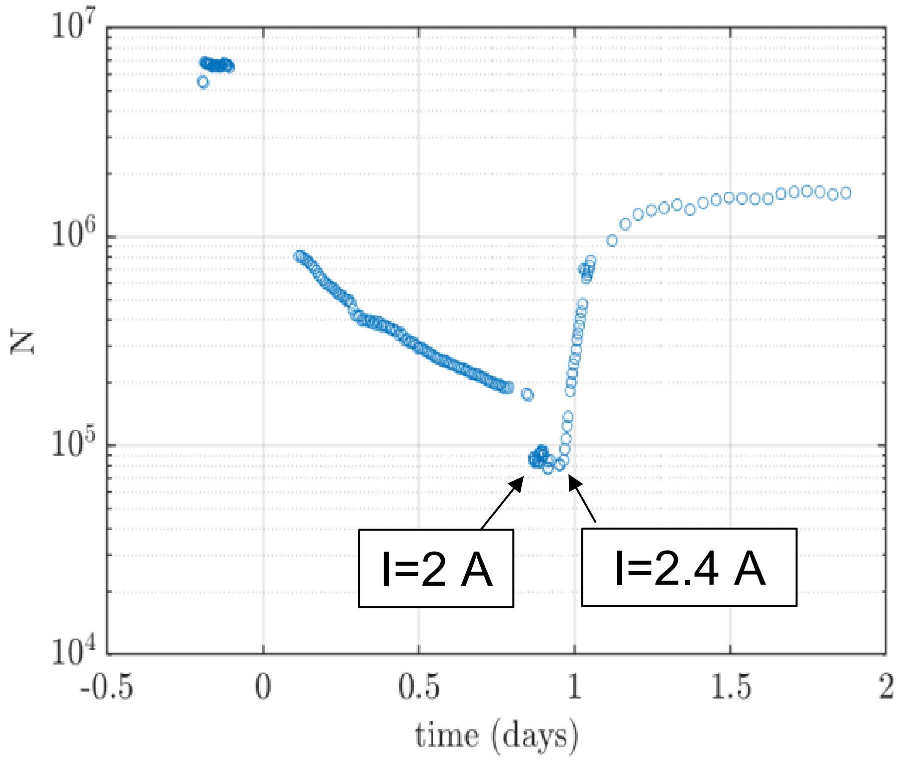


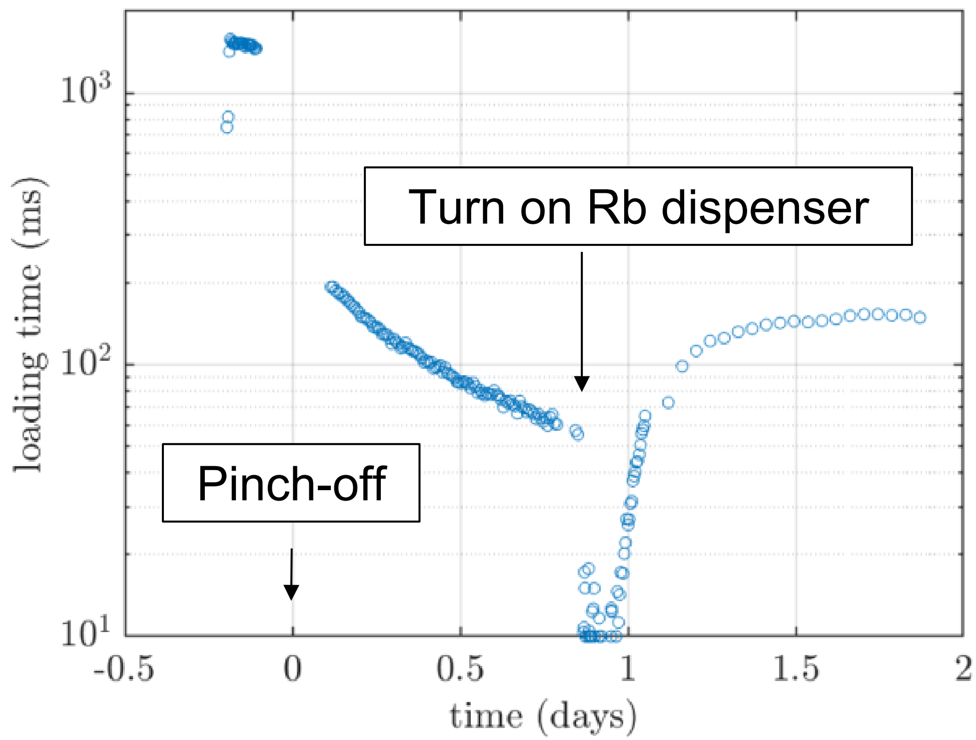


- Sustaining Cold Atoms for More Than 200 Days
- MOT seems happier with "pinch-off" rather than "pump off".
  - $(N\tau)_{\text{pinch-off}} \approx 3 \times 10^5$ atoms $\cdot$ s vs $(N\tau)_{\text{pump-off}} \approx 0.7 \times 10^5$ atoms $\cdot$ s.
- Estimate pressure to be ~2×10^{-7} Torr. P_{Rb}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



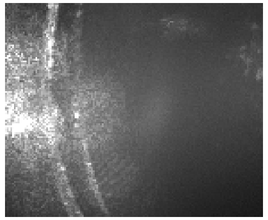
N-τ Evolution After Pinch-off





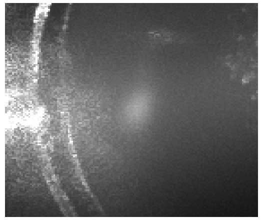
- After pinch-off, $N-\tau$ decay slower than with "pump off".
- Driving the dispenser hard enough still improves vacuum.

I= 2 A



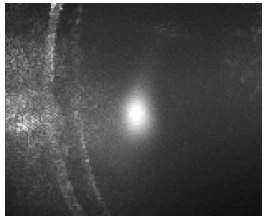
t_{exp}= 4 ms

I=2.4 A + 20 min



t_{exp}= 4 ms

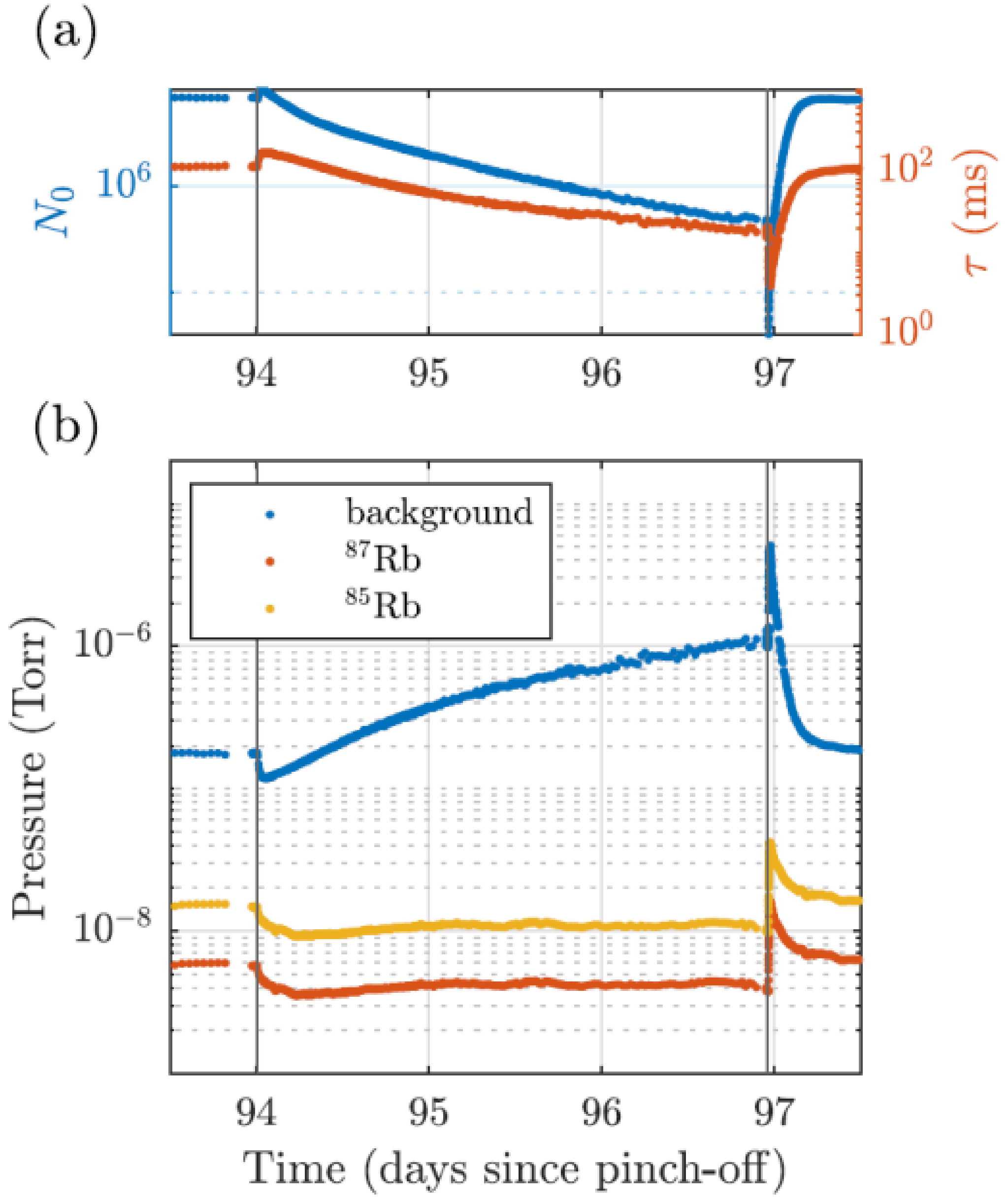
I=2.4 A + 90 mins



t_{exp}= 2 ms

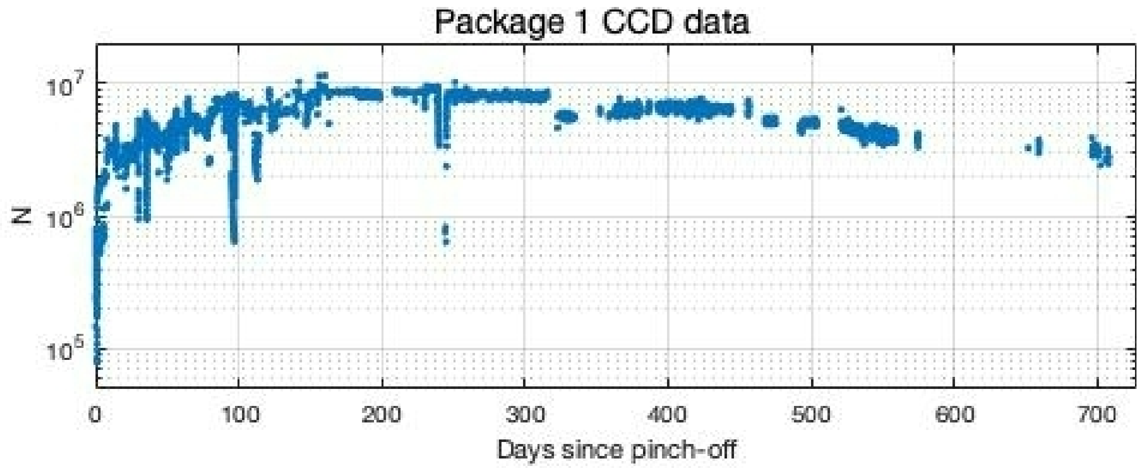
Effect of Rb dispenser

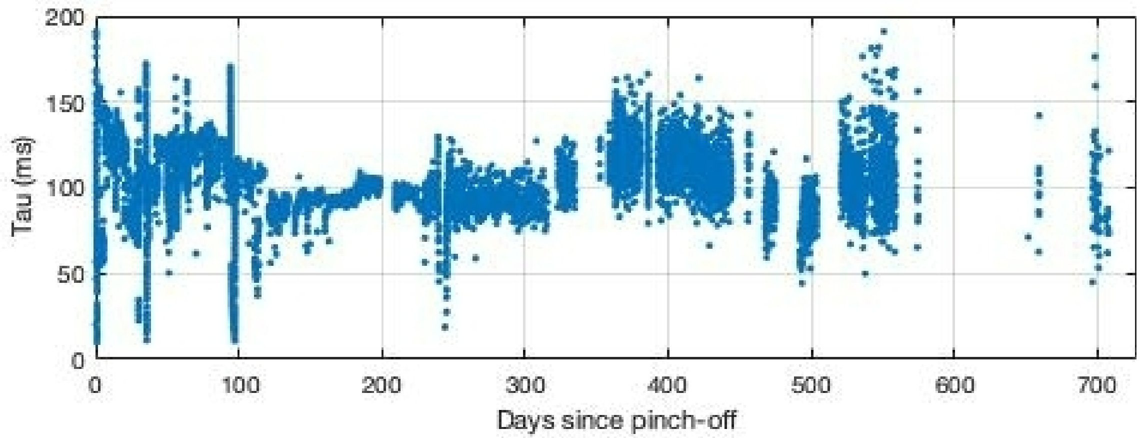
- Switch dispenser off
- Atom number decreases (expected)
- Load time decreases (not expected)
- Substantial pumping effect from the dispenser.
  - P. della Porta, C. Emili, and J. Hellier, in IEEE Conference on Tube Techniques (IEEE, 1968)



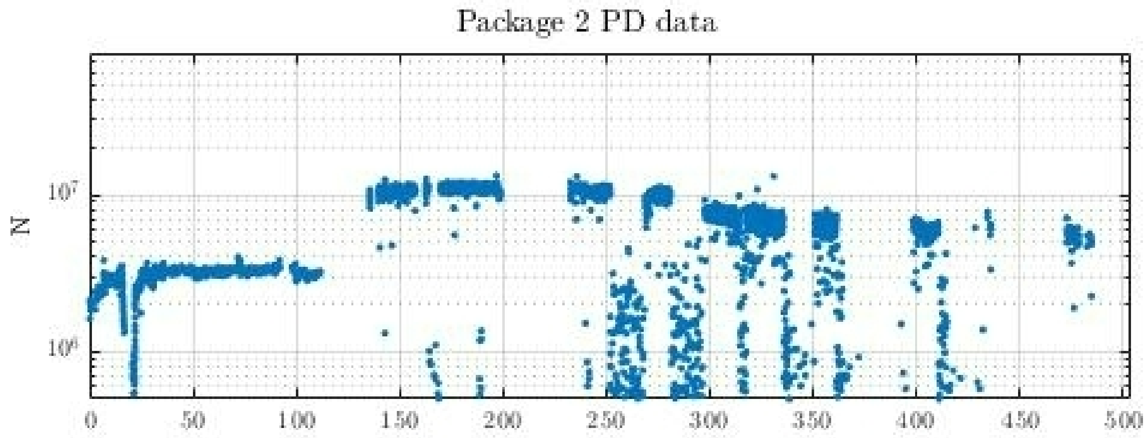
Package operating for 2 years!

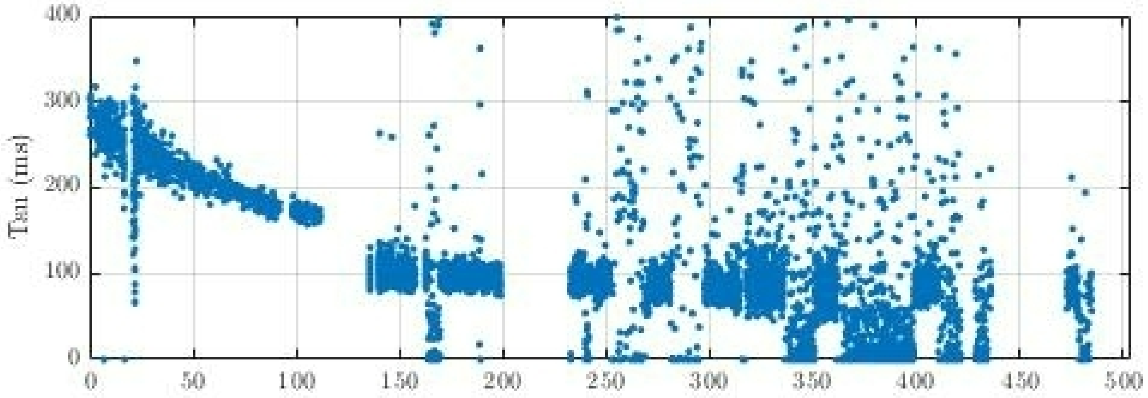
Package 1: ~730 days
-On day 231 changed to a Rb-85 MOT





Package 2: ~470 days
-Valved off (not pinched)





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 > 2 years
- Future work
  - Combine integrated photonics platform with atom interferometer prototype
- Postdoc position available
- Funding

Strategic Inertial Guidance with MAtterwaves

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT