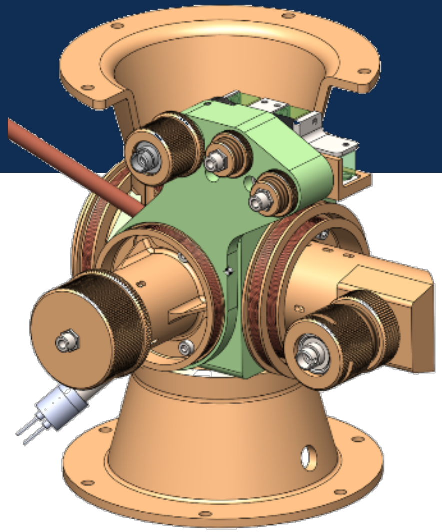
SAND2022-0927C

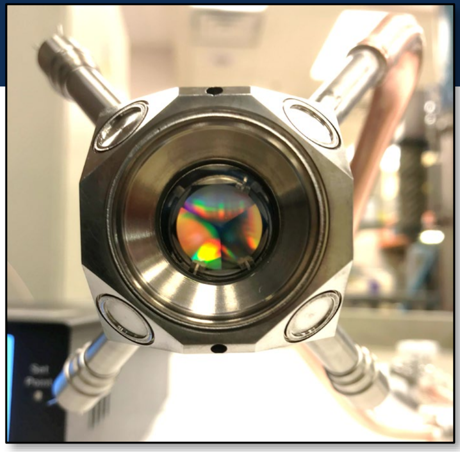
Strategic Inertial Guidance with MAtterwaves

ΣΙΓΜΑ

Exceptional service in the national interest

Sandia National Laboratories

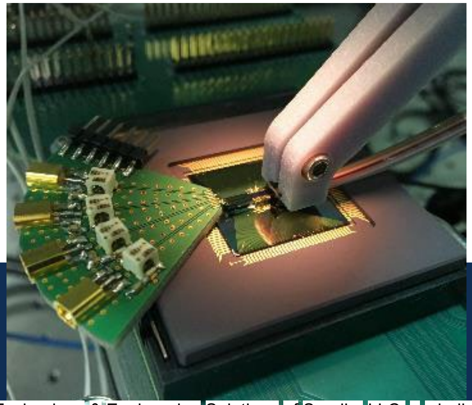


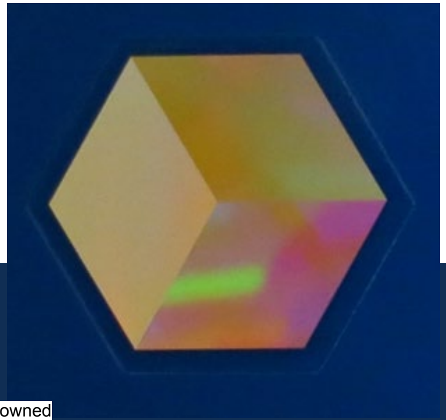


Towards Miniature Cold-Atom Inertial Sensors

Jongmin Lee

jlee7@sandia.gov





U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- Motivation for a compact atom interferometer (AI)
- Integrated photonics for a laser system
- AI demonstration with a grating magneto-optical trap
- Passively pumped vacuum package
- Guided AIs with photonic atom trap integrated platforms
- Conclusion

Motivation

- Atom interferometers (AIs) are excellent inertial sensors
  - Exciting candidate for inertial navigation without GPS aiding
- 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}	

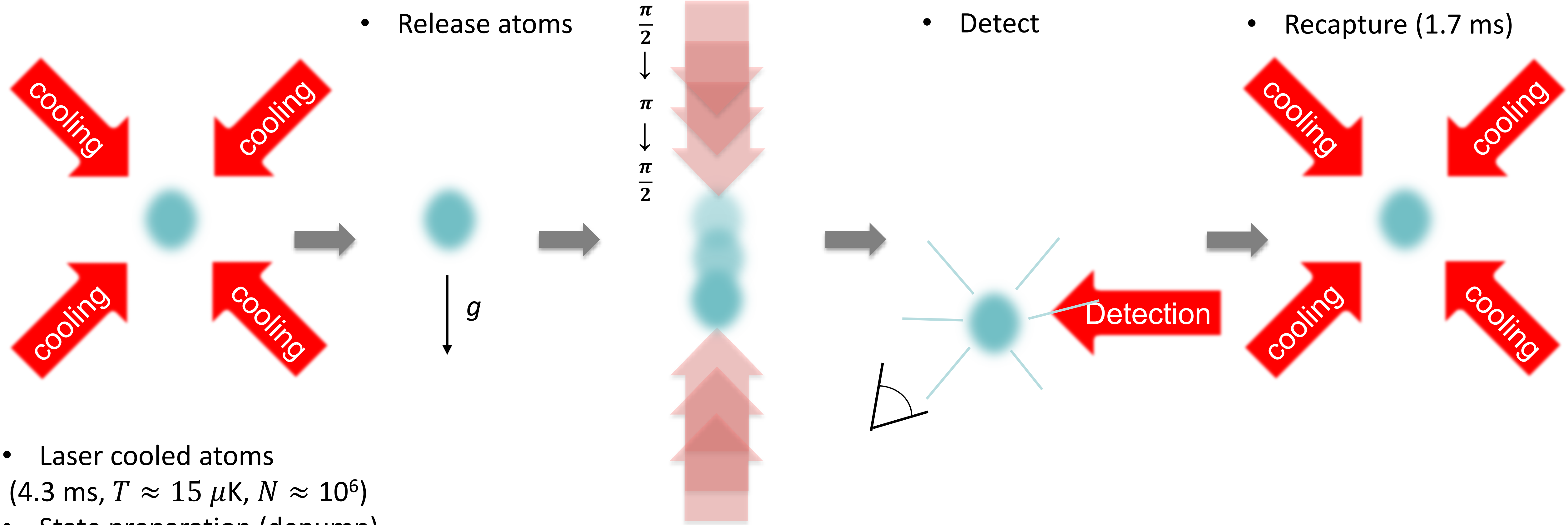
QA: Quartz Accelerometer
RLG: Ring Laser Gyroscope

≈6”

QA (x3) & RLG (x3)

High Data-Rate Atom Interferometry

- Release atoms
- Detect
- Recapture (1.7 ms)



- Laser cooled atoms
(4.3 ms, $T \approx 15\ \mu$K, $N \approx 10^6$)
- State preparation (depump)

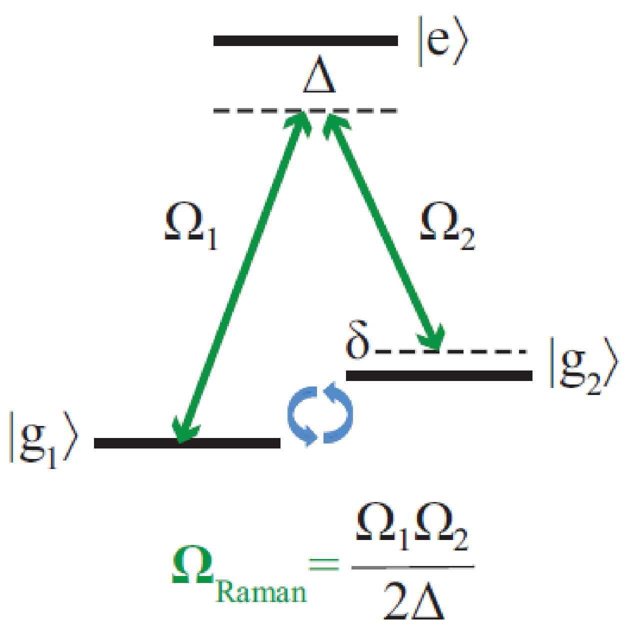
Example, (40 Hz)$^{-1}$ cycle

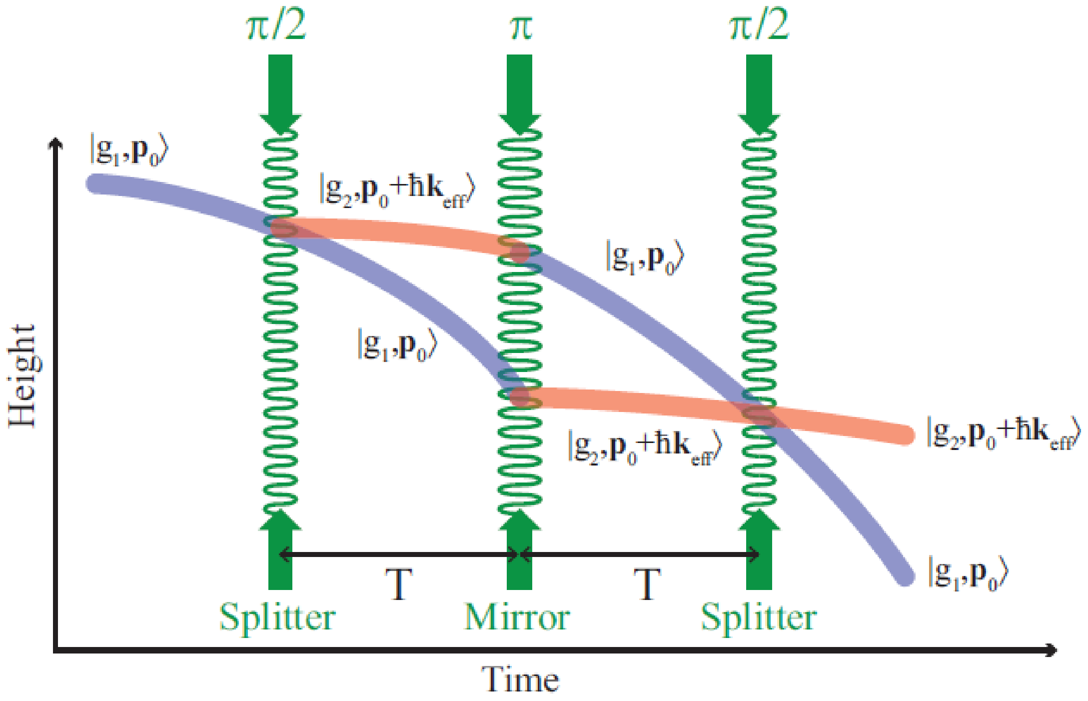
- Raman pulse sequence
(14 ms, T = 7 ms)

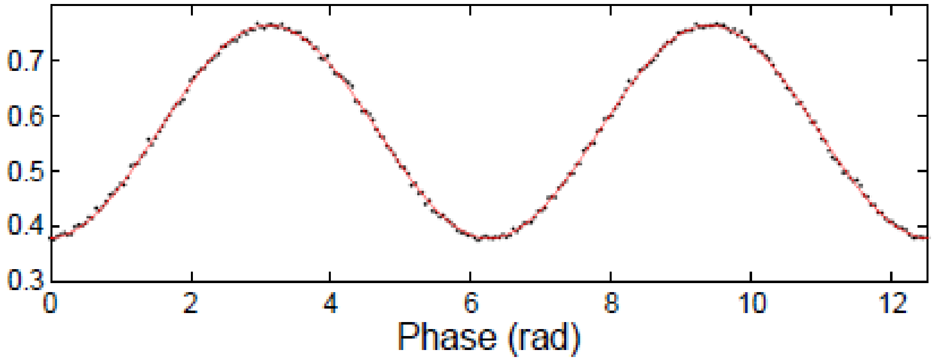
$$\frac{\pi}{2} \rightarrow \mathrm{T} \rightarrow \pi \rightarrow \mathrm{T} \rightarrow \frac{\pi}{2}$$

High data-rate atom interferometry operation for dynamic environments: Reduced sensitivity with a short T, smaller system size, and minimized relative movement between cold atoms and the Raman pulses

Light Pulse Atom Interferometer (LPAI)

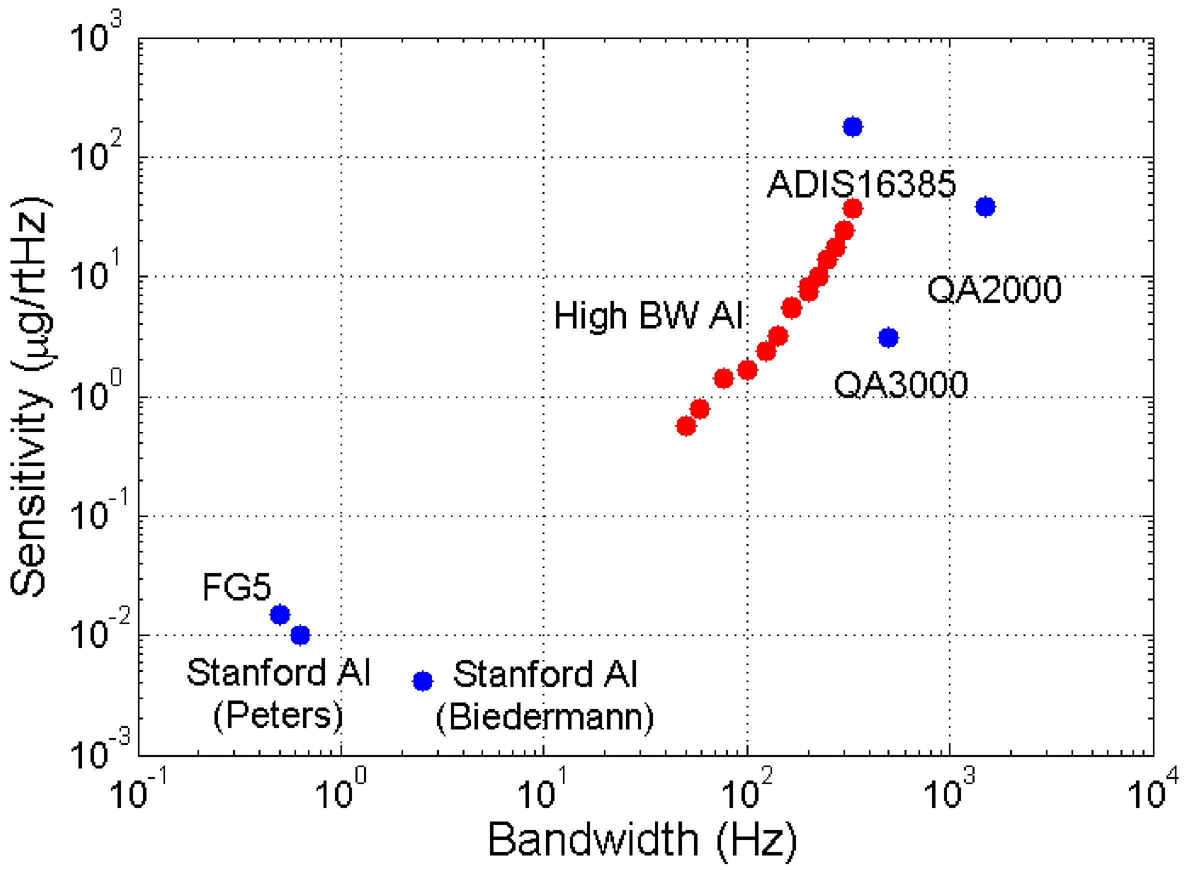


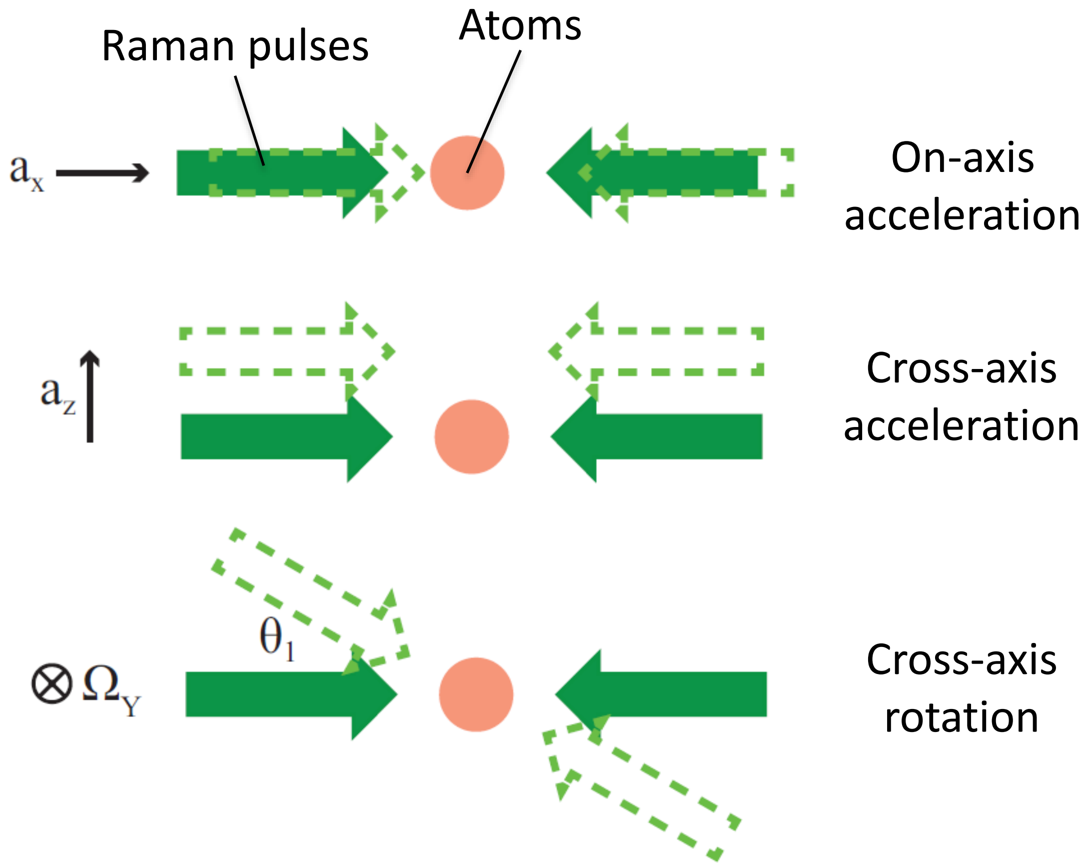




- Stimulated Raman transitions drive state-dependent photon recoils on atoms
- Split (π/2) → Redirect (π) → Recombine (π/2) for matterwave interference
- Atom interferometer accelerometers and gyroscopes

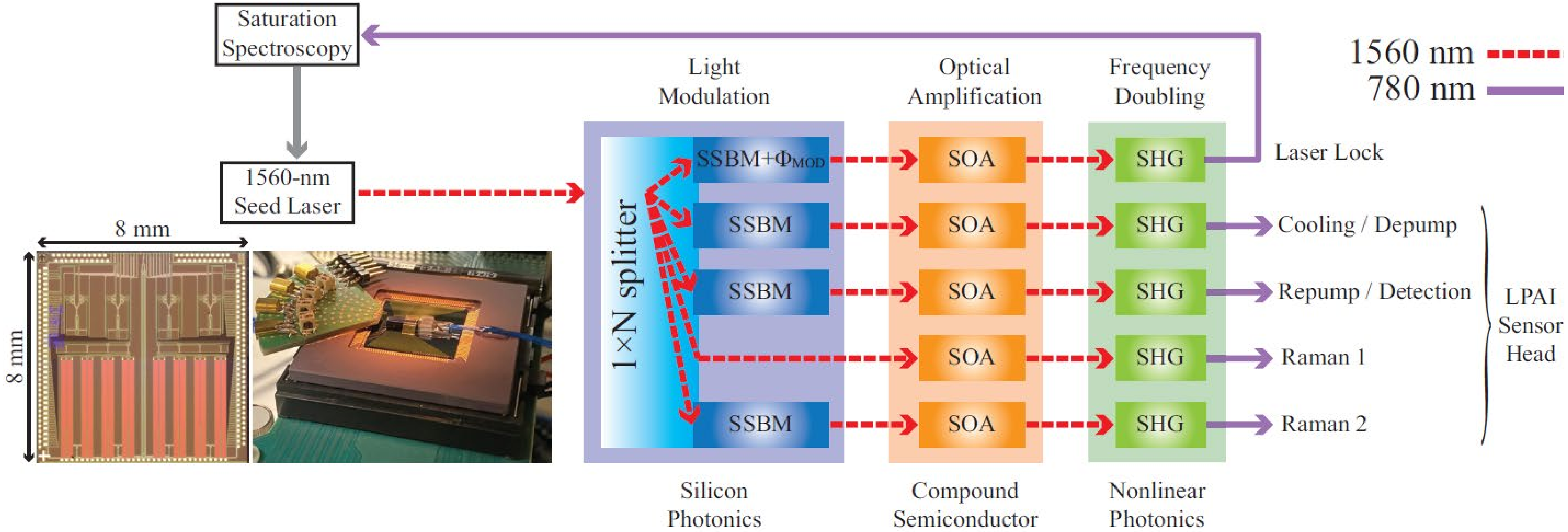
Bandwidth Considerations for Dynamic Environments





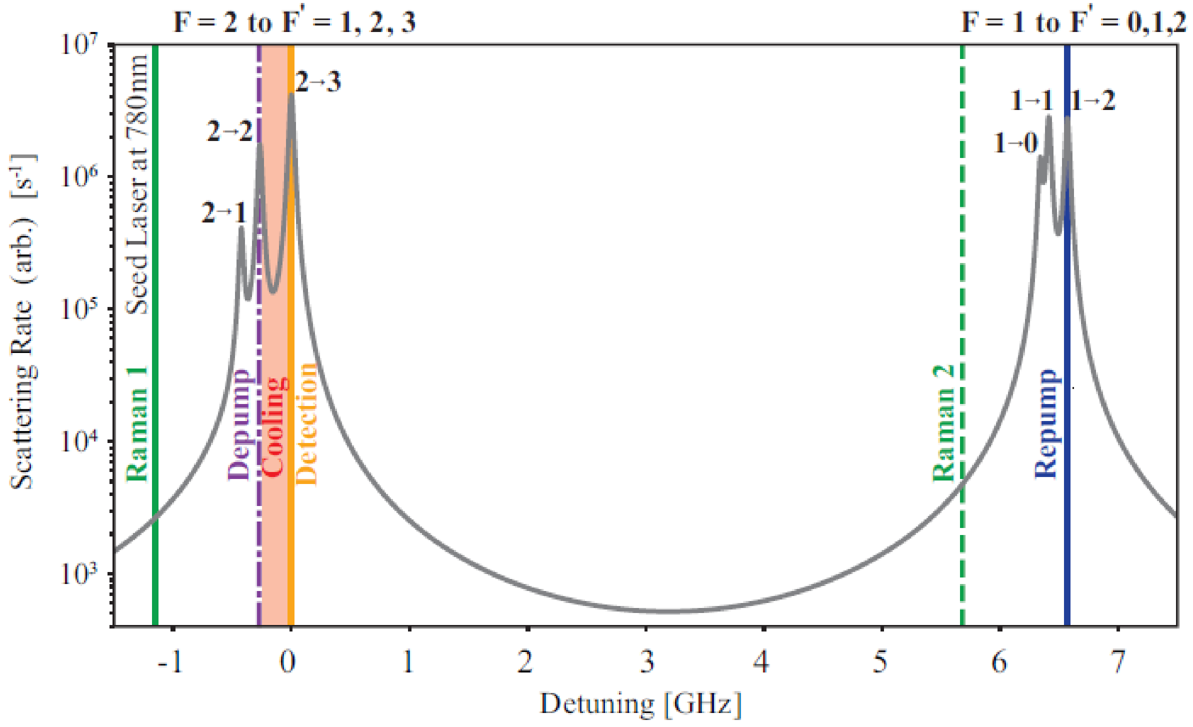
- Bandwidth required for inertial sensor applications
- AI sensitivity reduces with bandwidth & Compact size lends itself to high bandwidth
- Hybrid Inertial Navigation: LPAIs + an inertial measurement unit (IMU) cosensor + feedforward processor

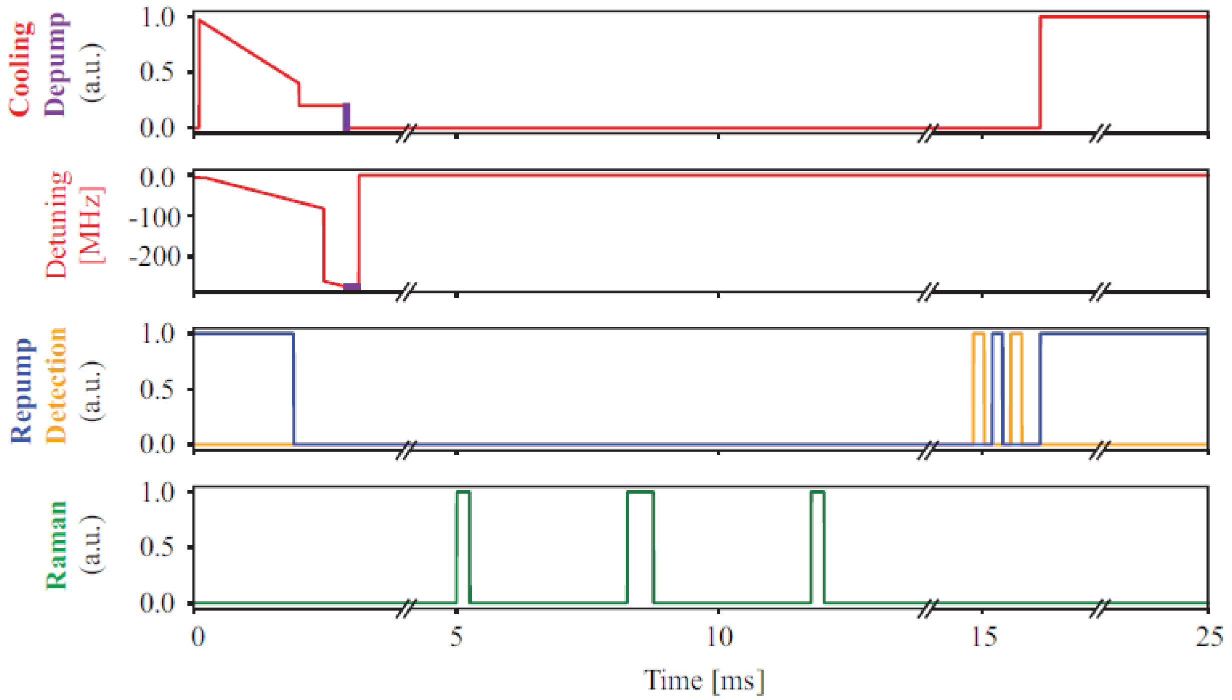
Photonic Integrated Circuit (PIC)-Based Laser System



- Chip-scale PIC-based laser system: 1560-to-780 nm approach, mass-producibility, miniaturization, and ruggedization
- Silicon photonics: Single sideband (SSBM)/phase (Φ_{MOD}) modulators, thermo-optic phase shifters, variable optical attenuators (VOAs), optical filters, and photo-detectors.
- Compound semiconductor: Multi-stage high power semiconductor optical amplifiers (SOAs) and optical switches
- Nonlinear photonics: Second harmonic generation (SHG) for frequency doubling

Integrated Laser Implementation



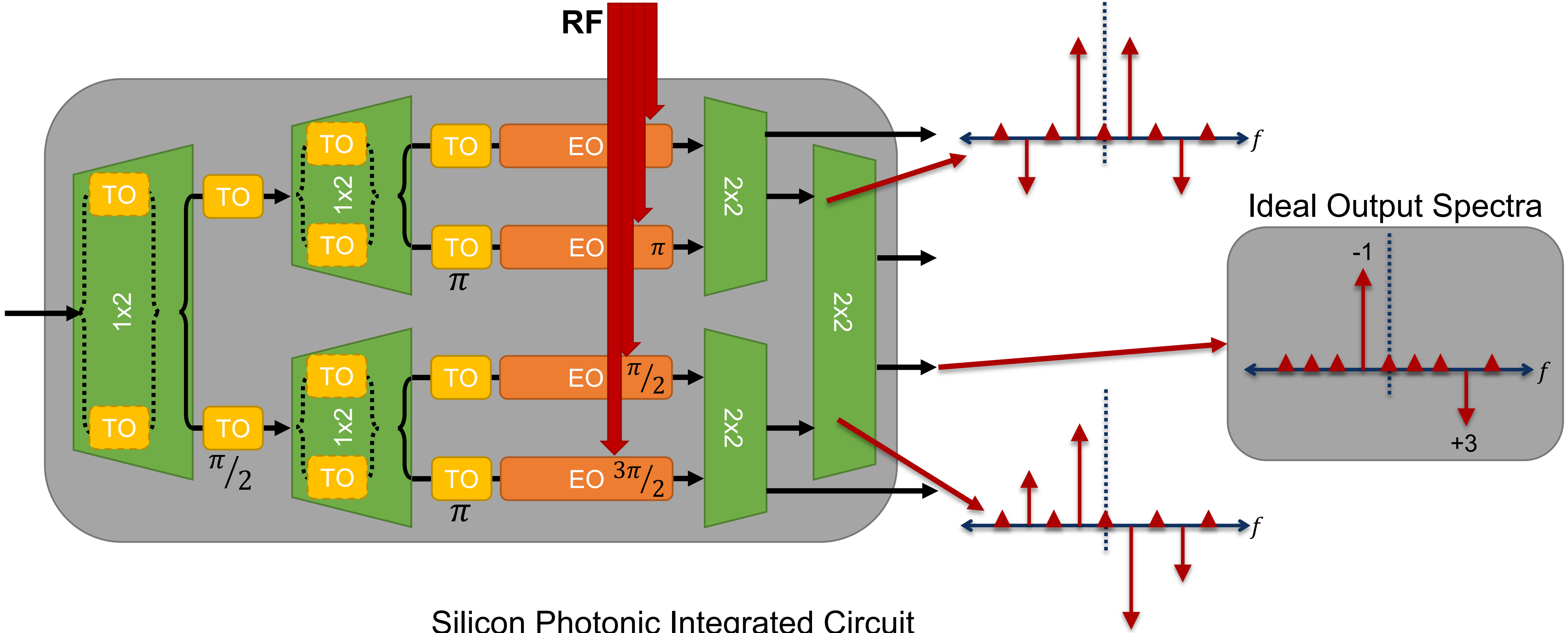


Five laser channels for ^{87}Rb atoms (D2)

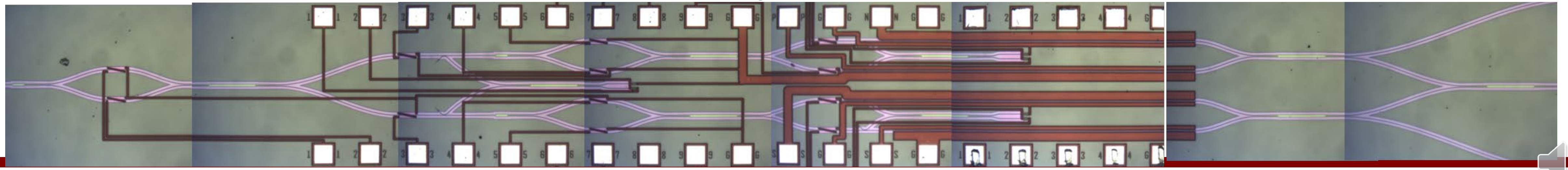
- Ch 1: Laser Lock (saturation spectroscopy)
- Ch 2: Cooling or Depump
- Ch 3: Repump or Detection
- Ch 4: Raman #1 (Seed laser frequency)
- Ch 5: Raman #2

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

Suppressed-Carrier Single Side-Band Modulator

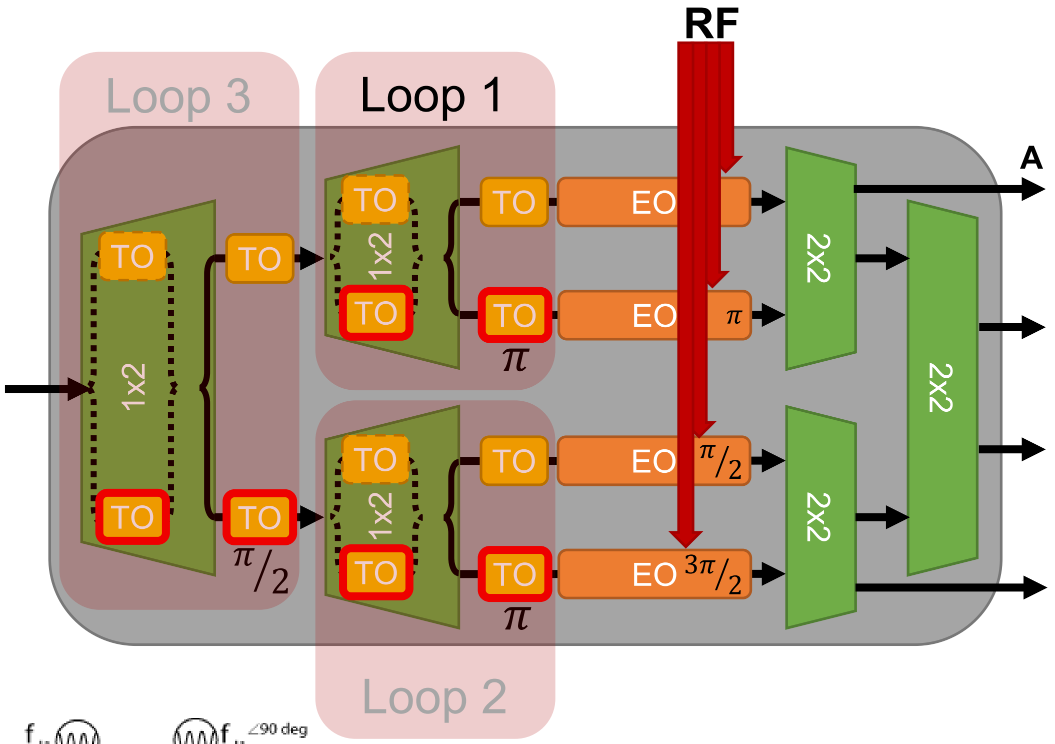


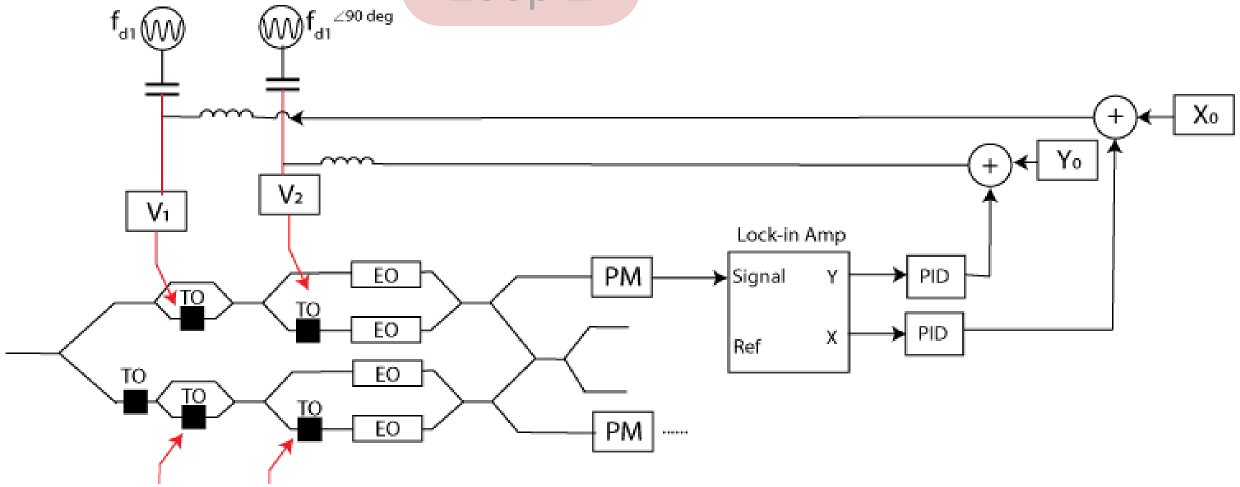
Silicon Photonic Integrated Circuit

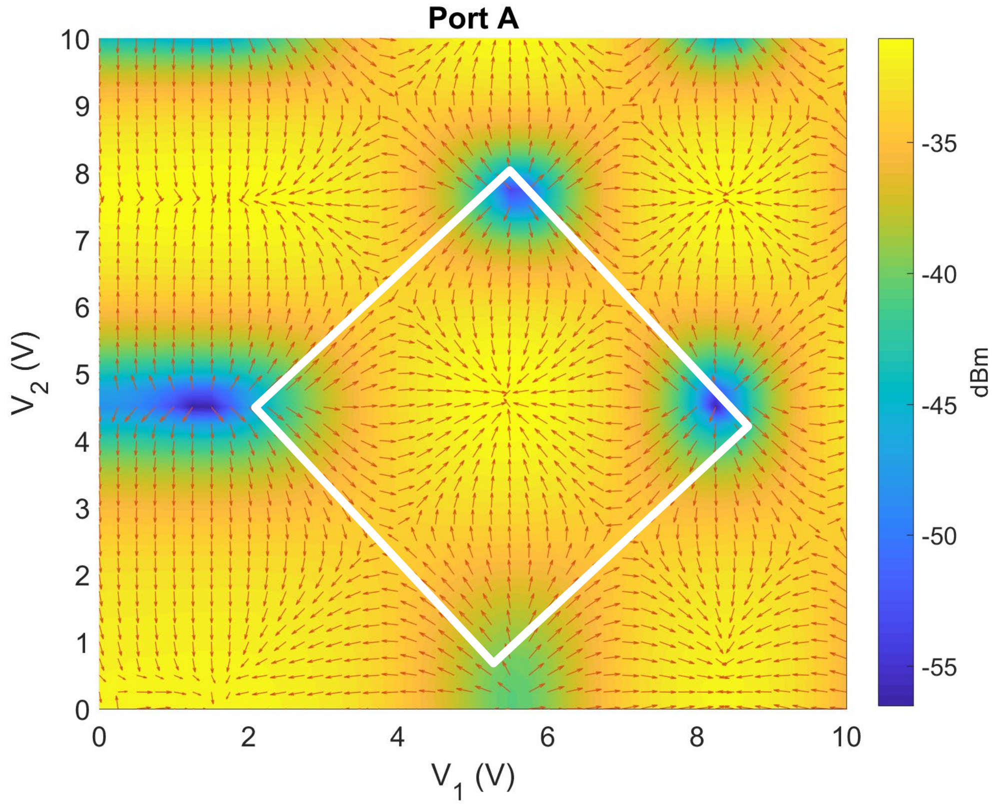


M. Izutsu, et. al. *IEEE J. Quant. Elect.* QE-17 2225 (1981)

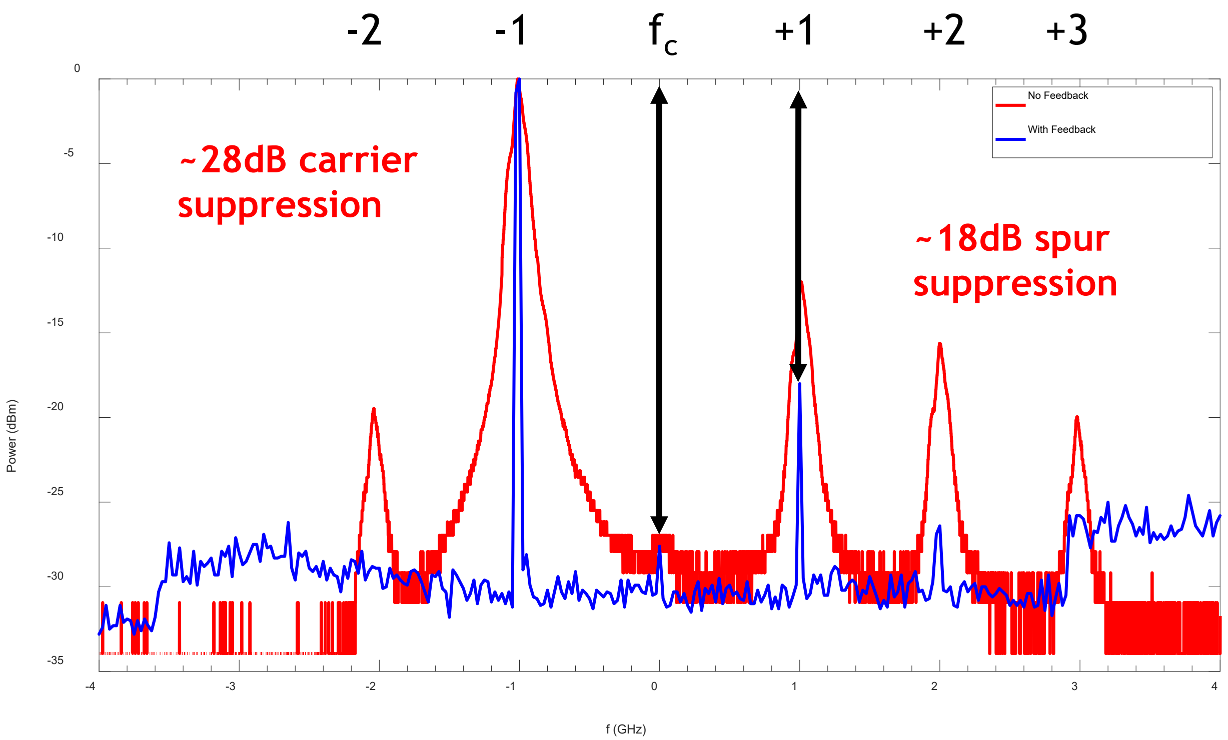
Single Side-Band Modulator Feedback



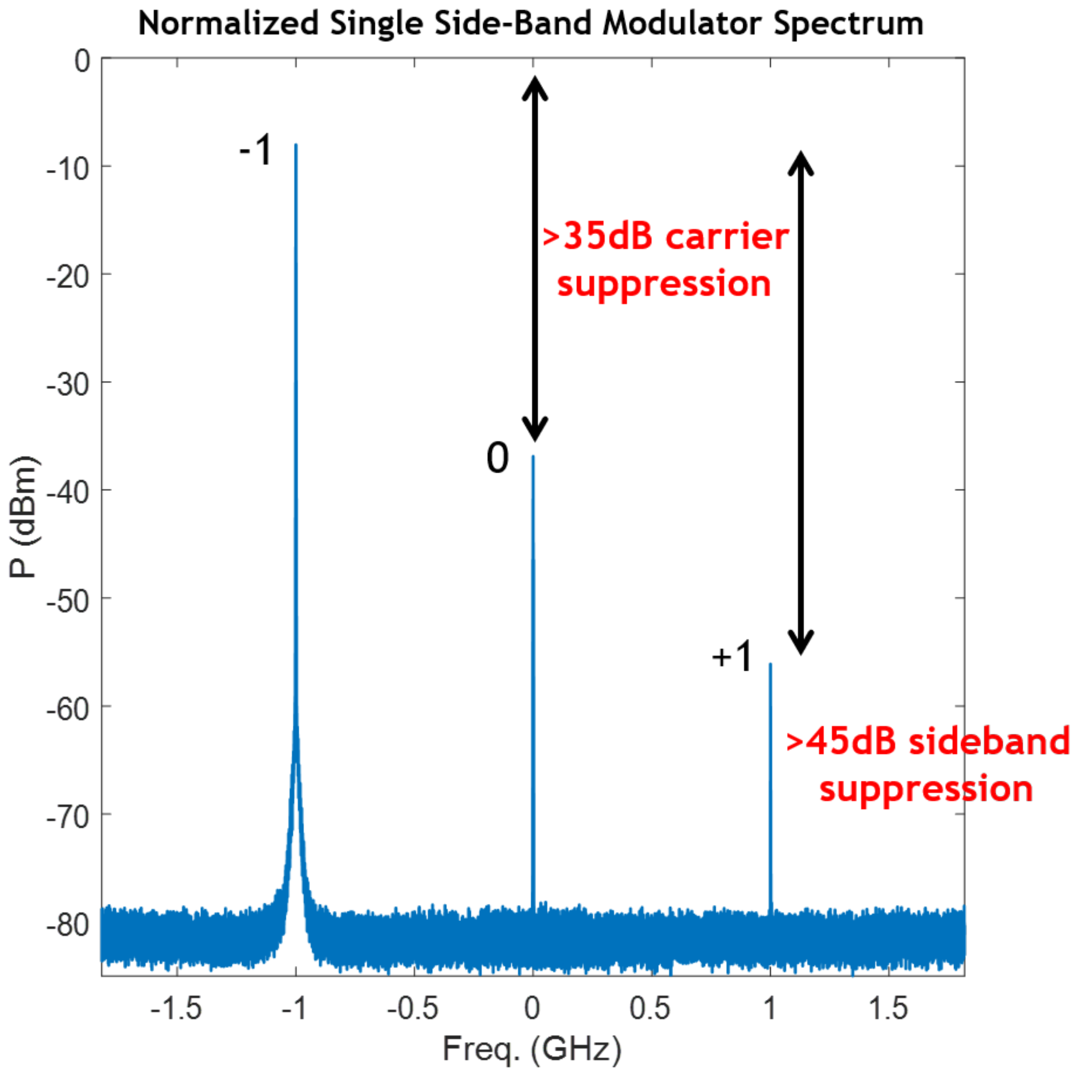




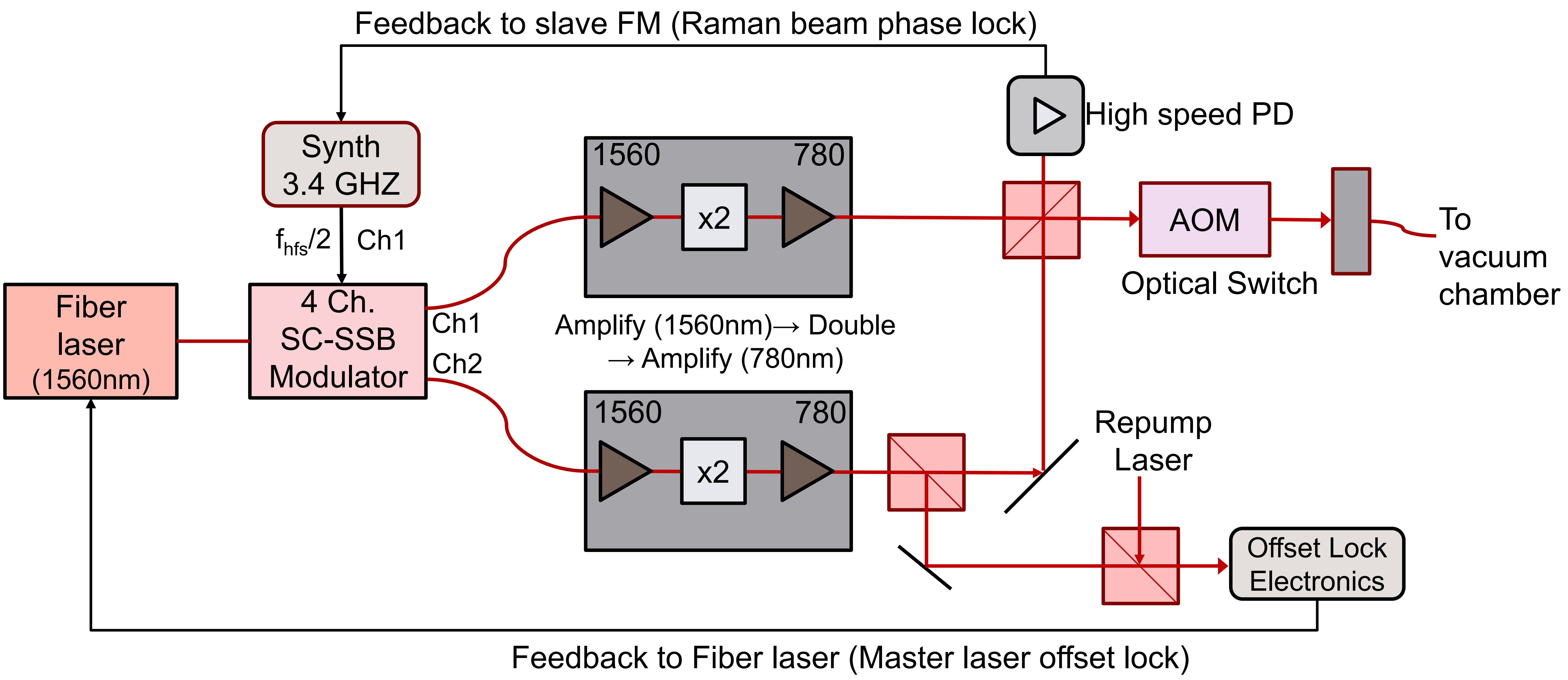
Single Side-Band Modulator Active Control



*implemented higher resolution heterodyne spectral measurement

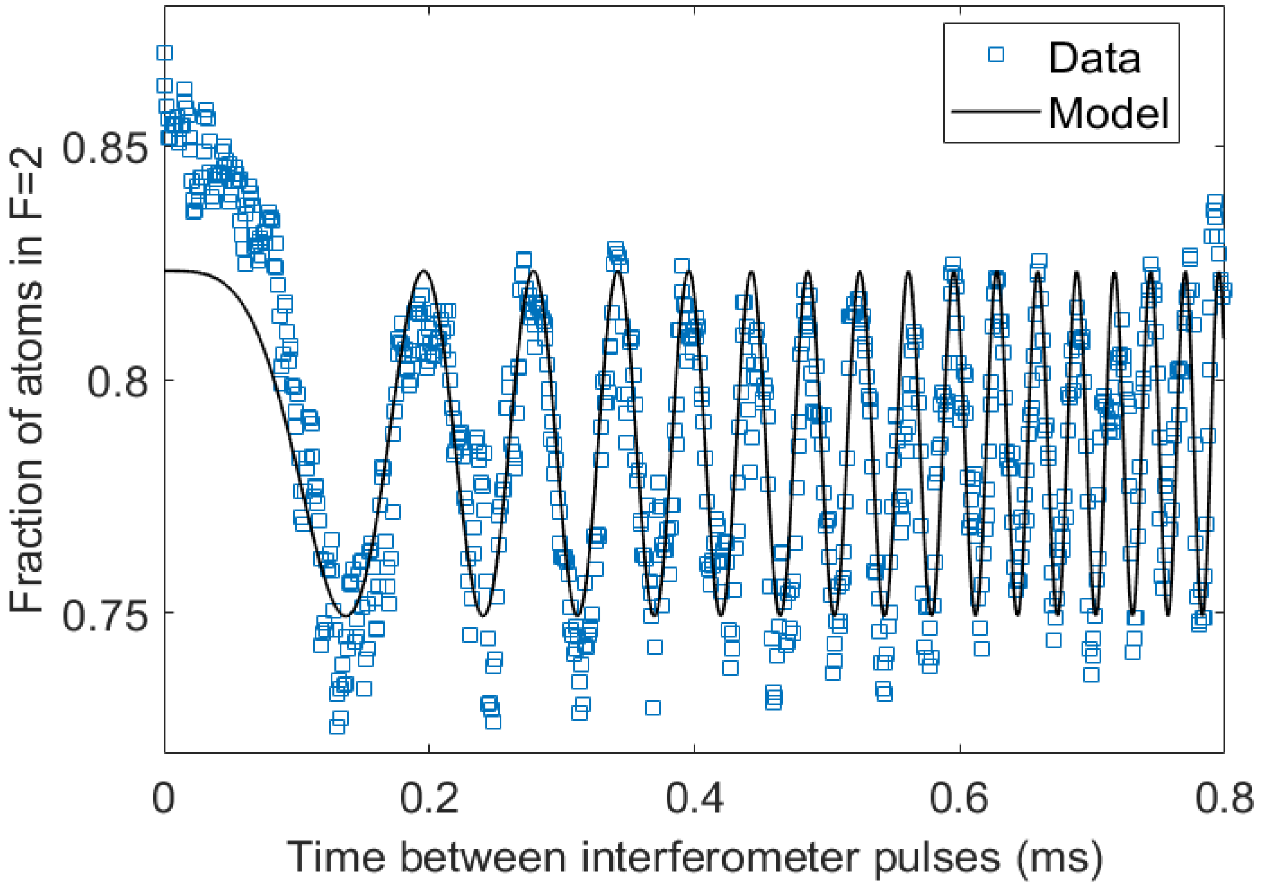


Integrated Photonics Raman Laser Setup

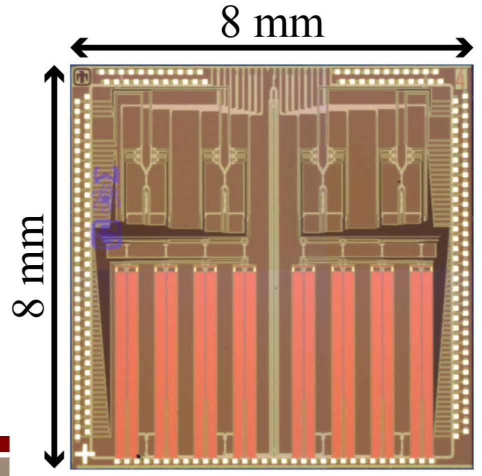


SC-SSB: Suppressed Carrier Single Sideband

AI Demonstration with Integrated Raman Laser Setup

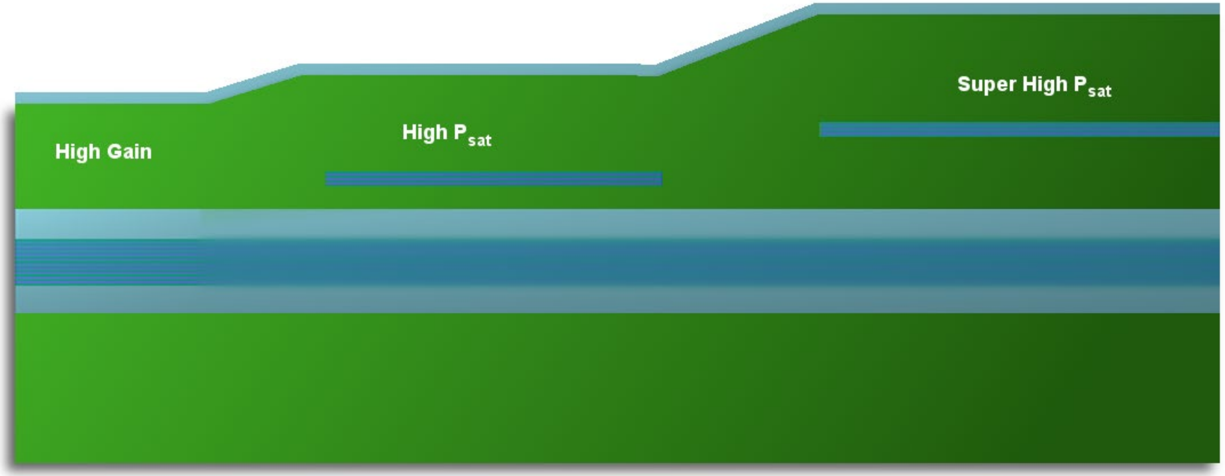


- Demonstrate an AI accelerometer, an atomic gravimeter with SIP Raman laser setup
- $\pi/2 \rightarrow \pi \rightarrow \pi/2$, where $\tau_\pi = 5\ \mu s$
- Measure the chirped fringe from the Doppler-shifted atomic resonance due to gravitational acceleration
- Estimate the gravity with a model: $g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

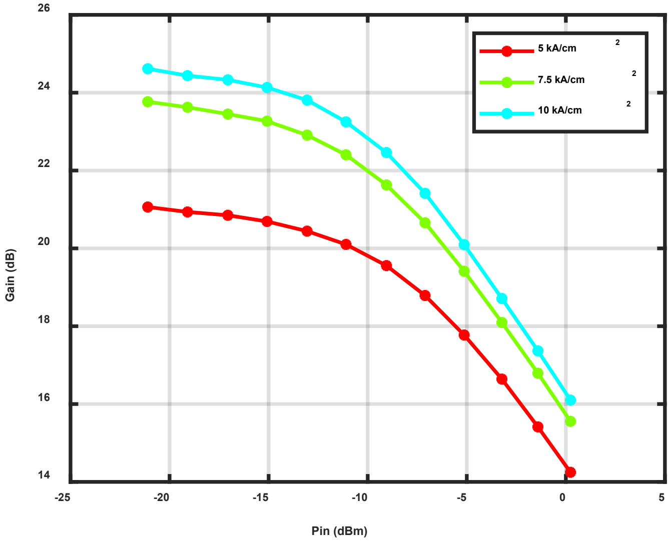


Three-Stage Optical Amplifier in III-V Materials

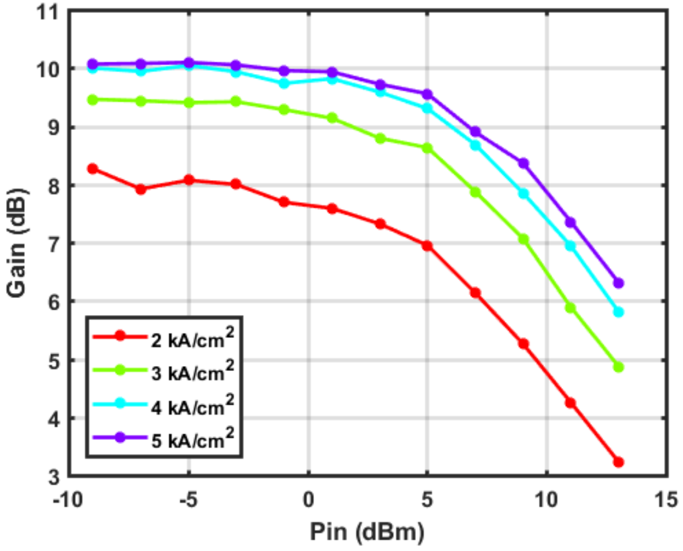
- Demonstrate > 200mW of 1560 nm power
- Large optical power challenging
  - Saturate gain materials
- First two stages successful
- Last stage needs more fabrication development

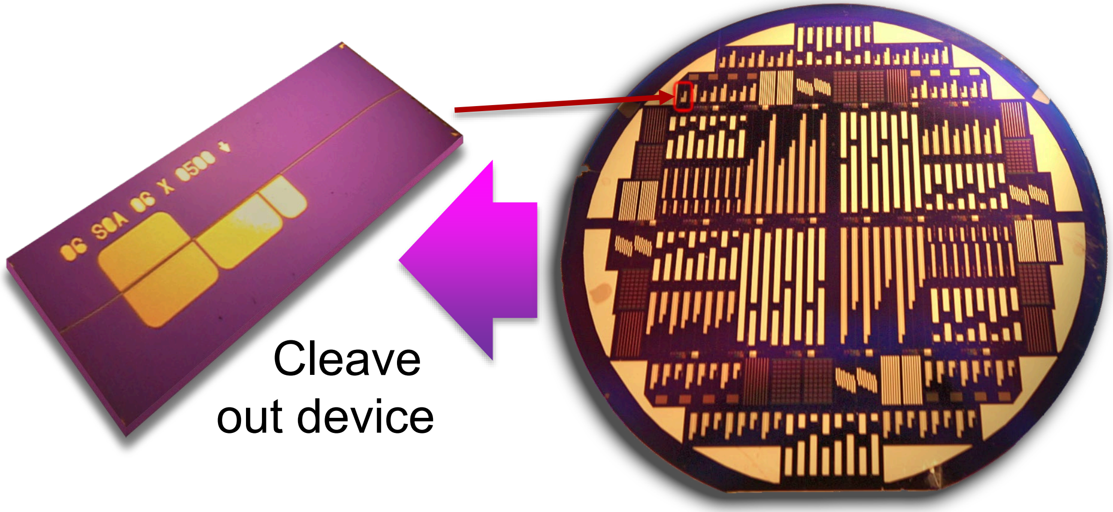


First stage amplifier



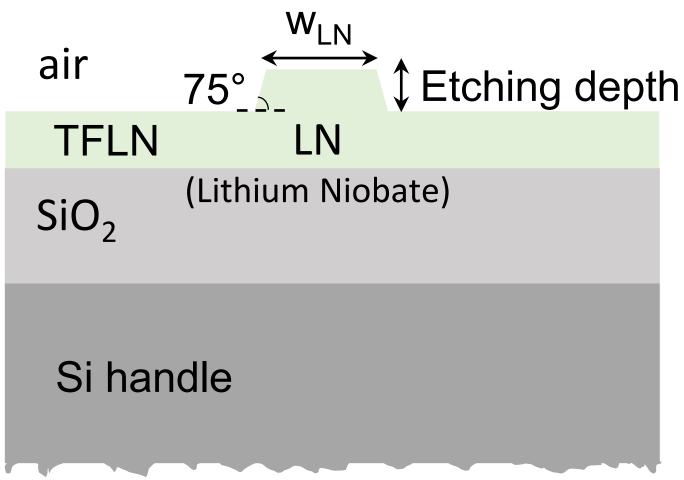
Middle stage amplifier





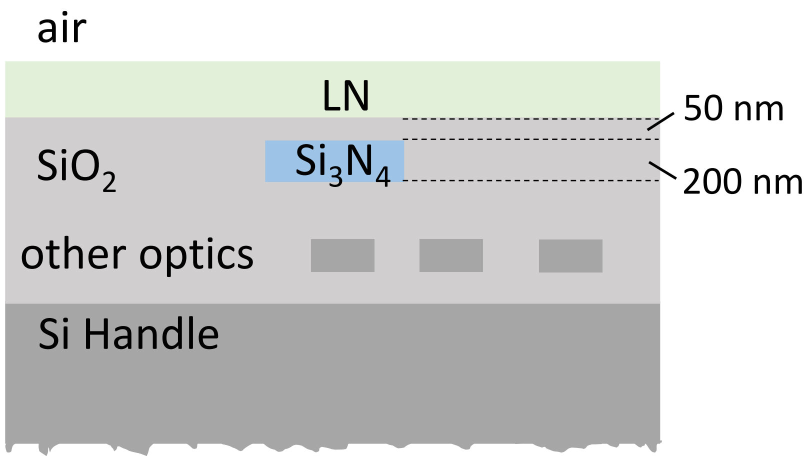
Wafer Complete

Frequency Doubling with Lithium Niobate



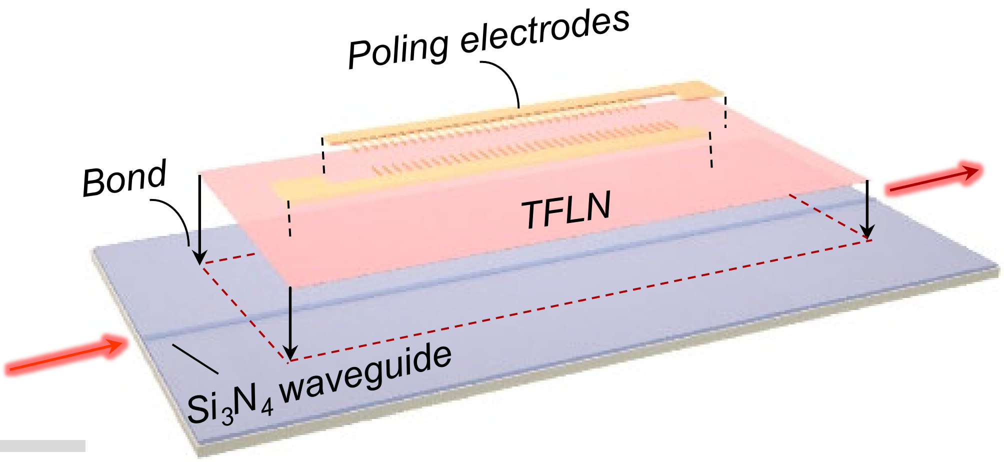
- Disorder-tolerant waveguide design.
- First pole, verify poling quality, and finally, shallow etch.
- Highest waveguide conversion efficiency (939 %/W)

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



- 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)

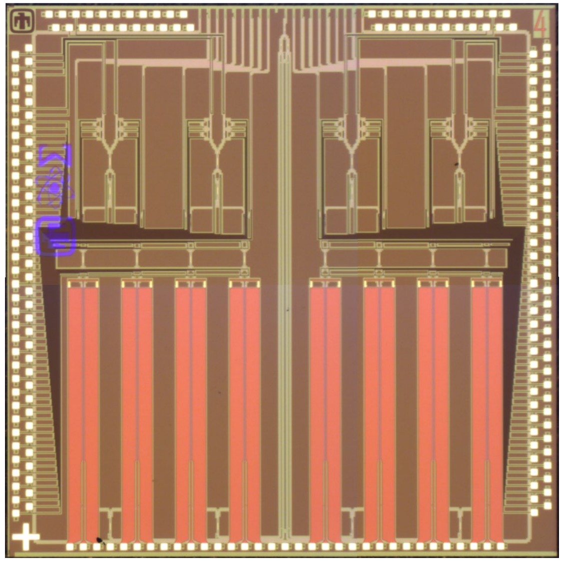


Laser System Architecture using PICs

Silicon Photonics

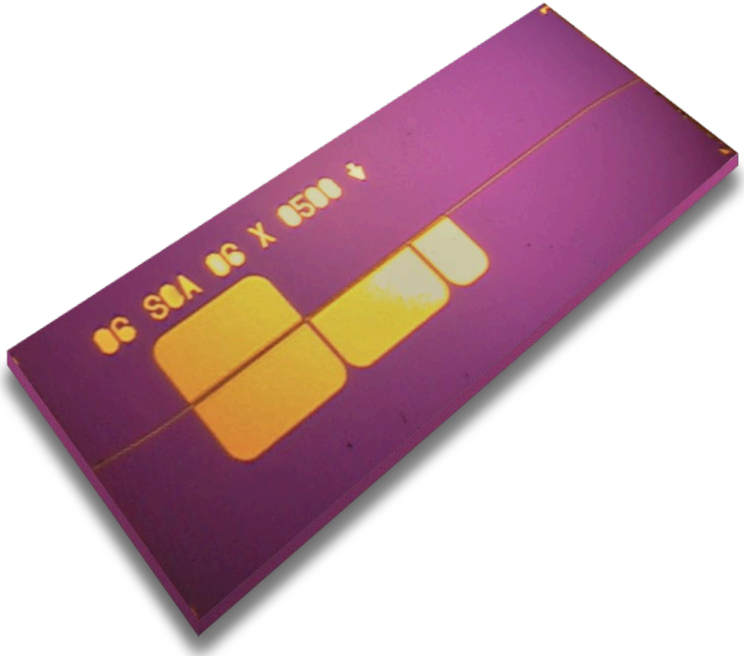
- Modulators & phase shifters
- VOAs & optical filters
- Photo-detectors (Ge)
- HI: III-V or LN on silicon
  (laser & SOA)

HI: Heterogeneous Integration



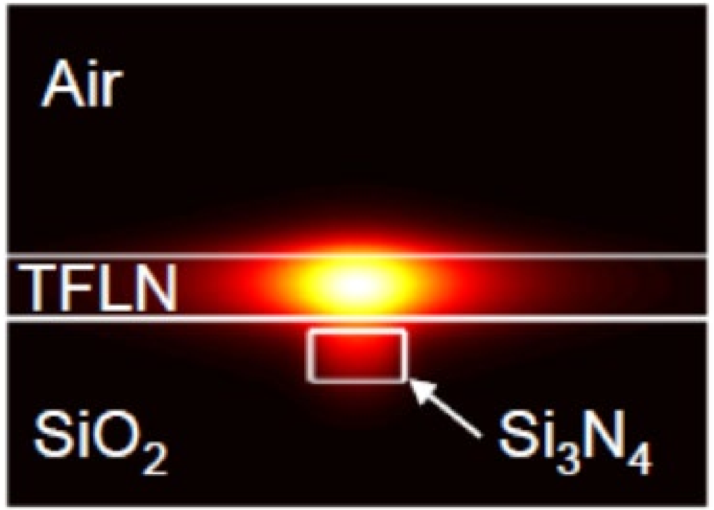
Compound Semiconductor (III-V Photonics)

- 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

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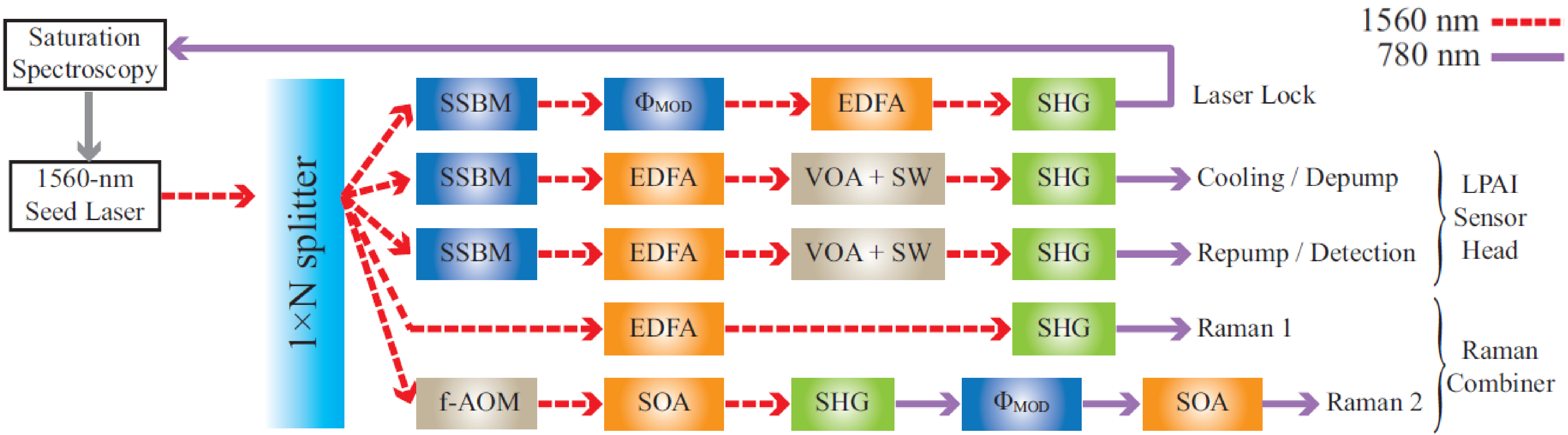
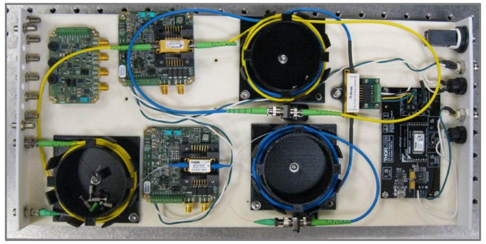
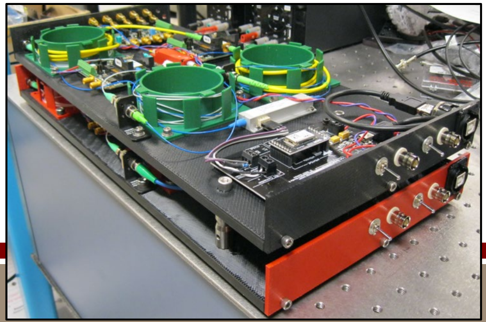
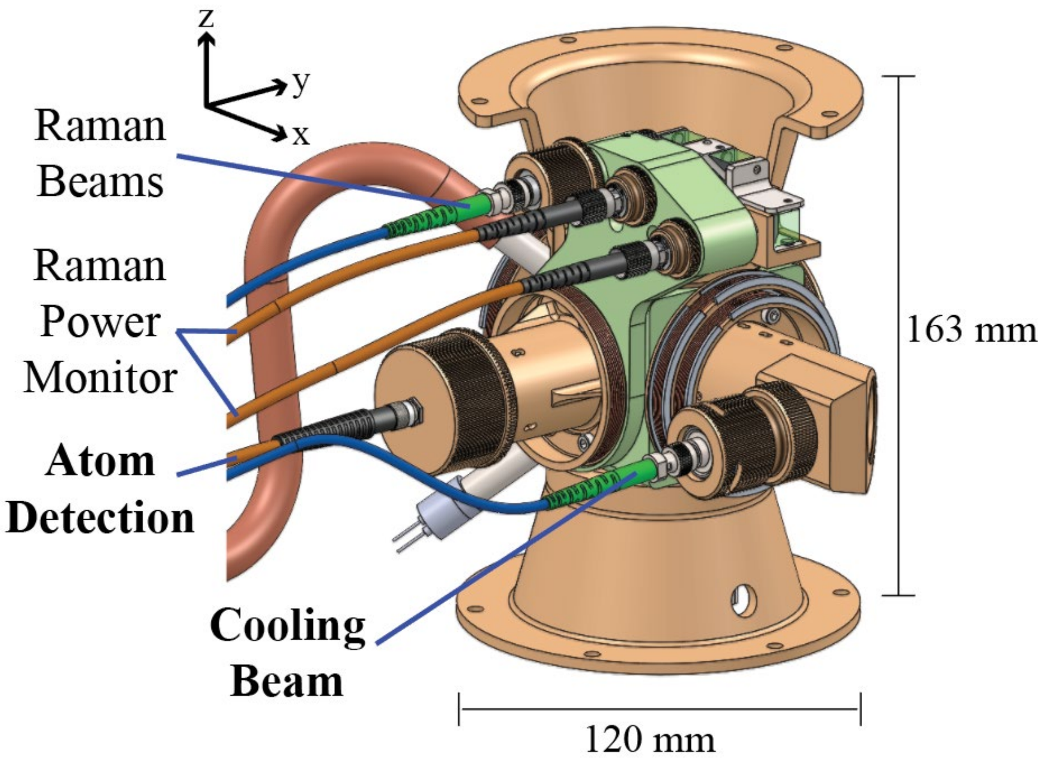


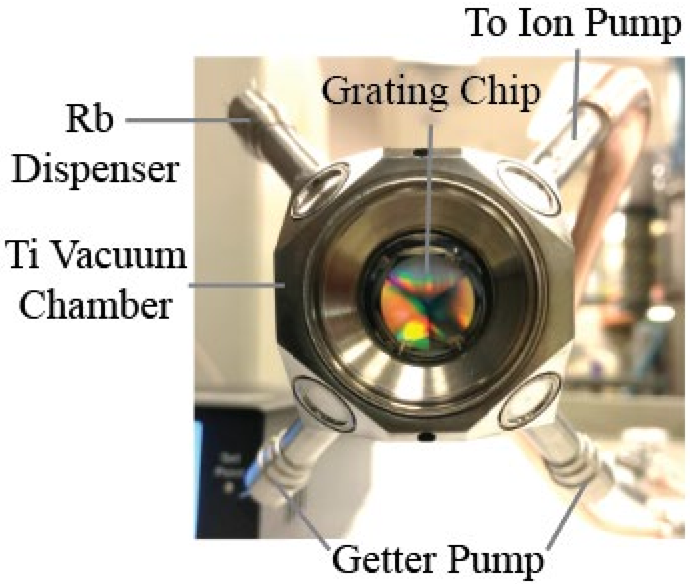


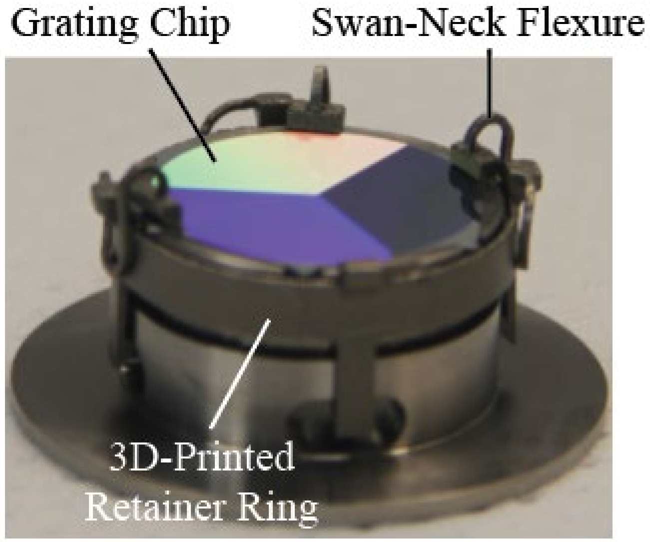


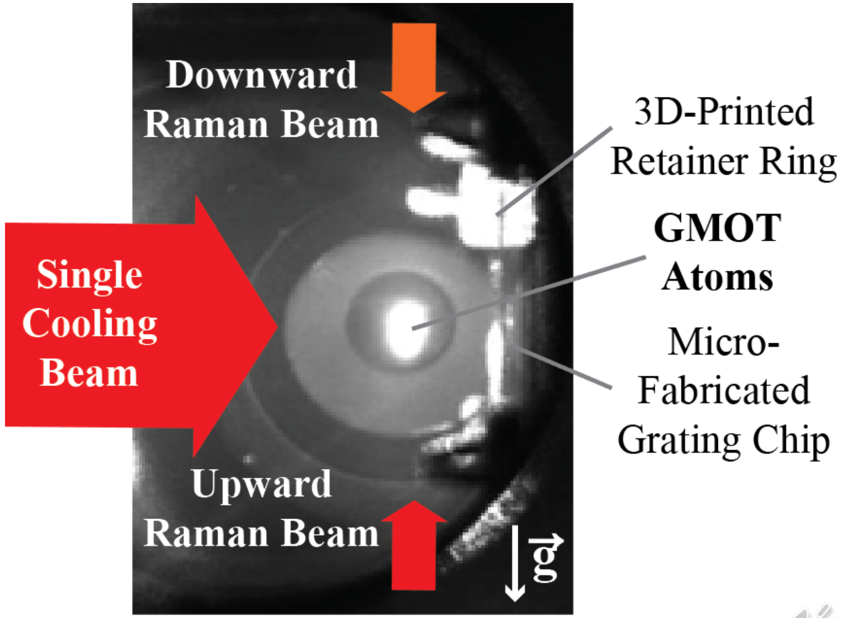
- PIC-compatible laser system: 1560-to-780 nm approach, commercial-off-the-shelf (COTS) components
- Using a PIC-compatible laser architecture validates the functional operation of the PIC-based laser architecture
- SSBM: single sideband modulator; Φ_{MOD} : phase modulator; f-AOM: fiber acousto-optic 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



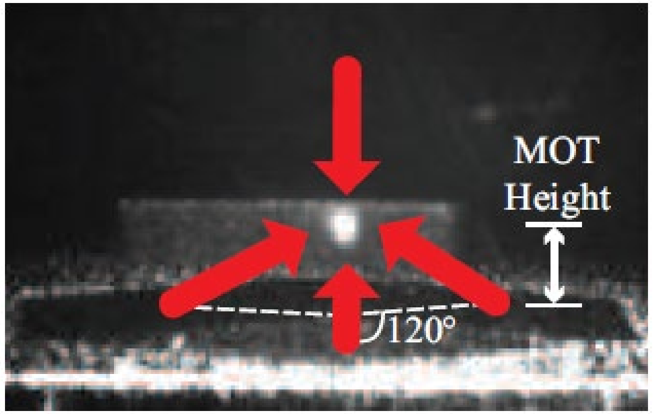


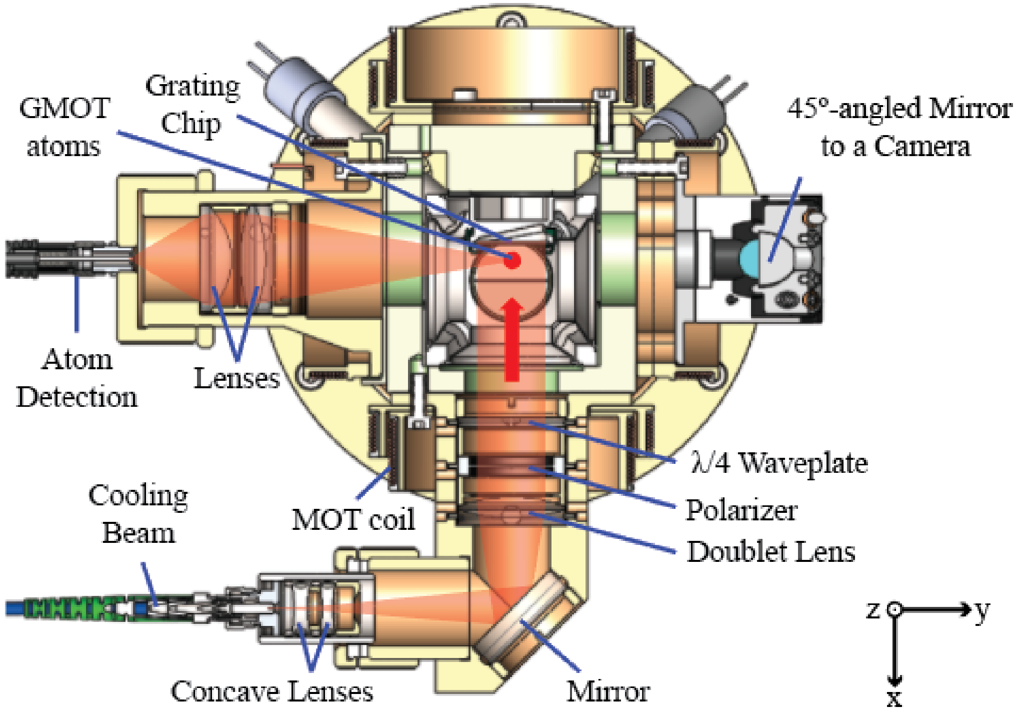


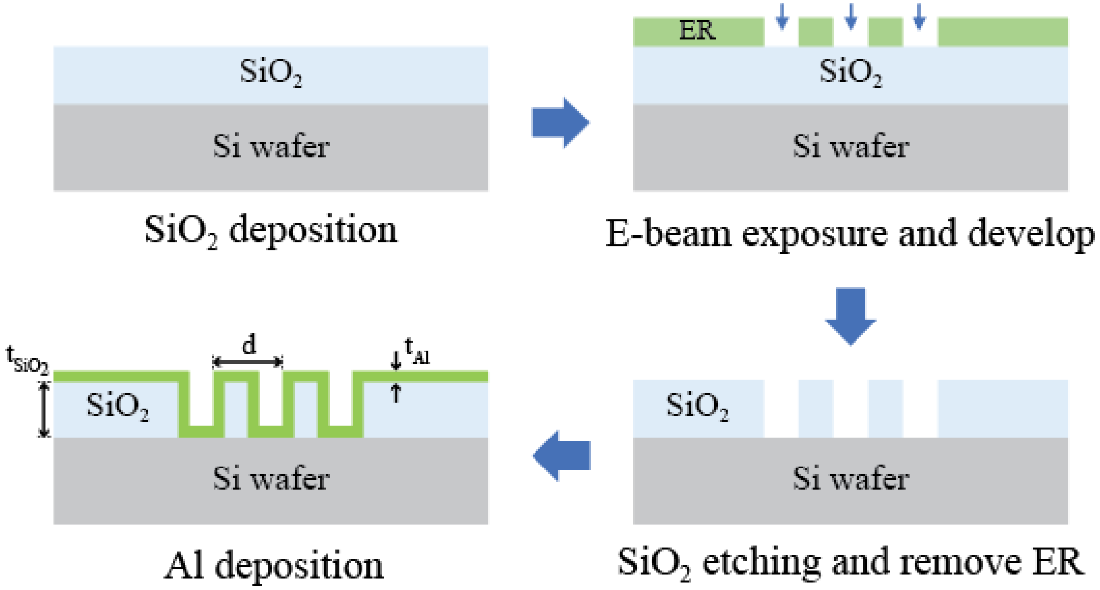


- Compact sensor head with a grating chip and fixed optical components
- Multi-axis cold-atom inertial sensors with grating chips
- 3D-printed retainer ring to hold the grating chip in vacuum
- Vacuum maintained by ion pump, fused silica windows
- Atom number: 10^6-10^7, Sub-Doppler cooling: 15 µK

Grating Magneto-Optical Trap (GMOT)

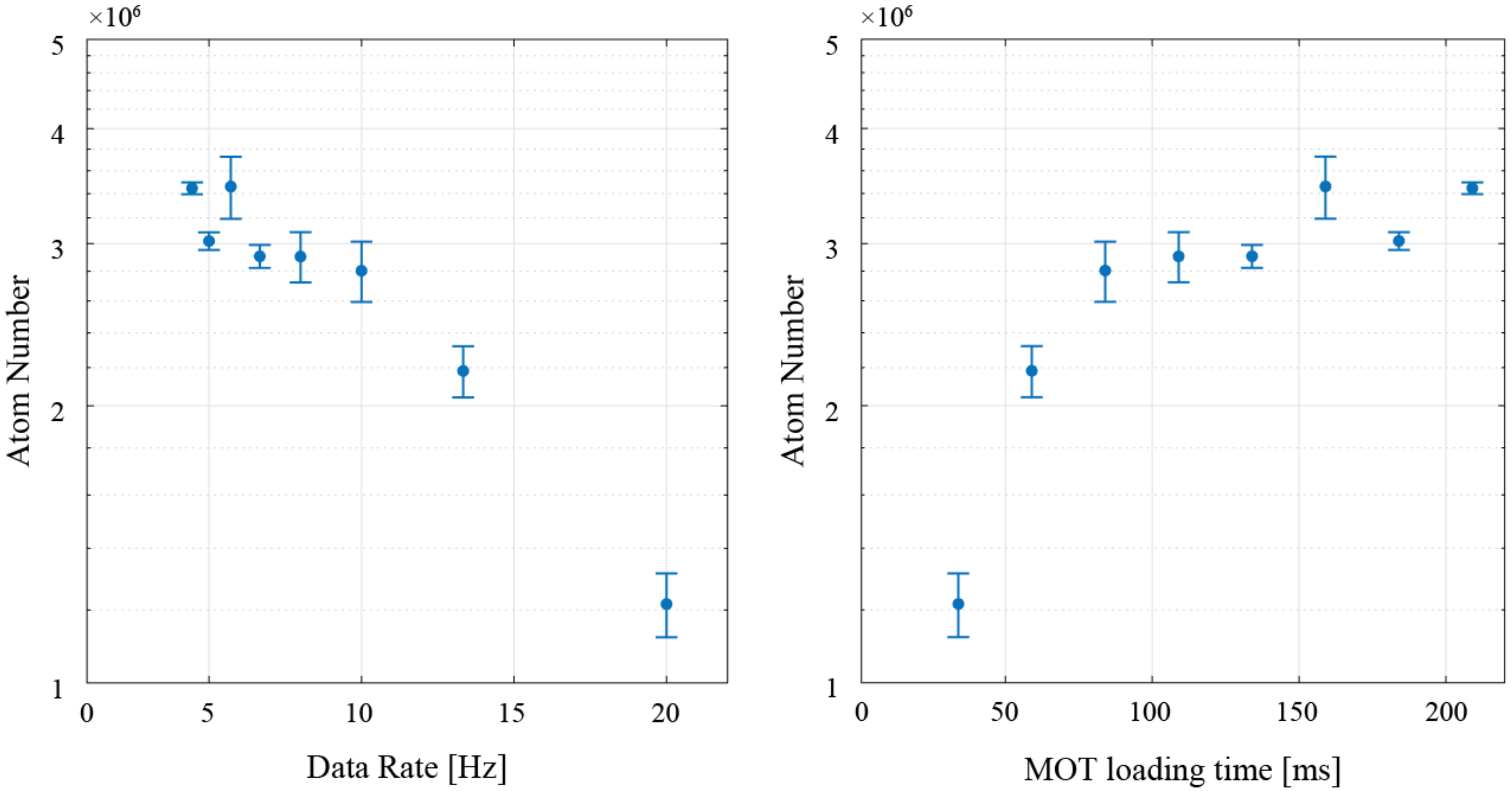






- Sandia-fabricated hexagonal reflective grating chip
  - 1.2 µm pitch, ~50% duty-cycle, and 195nm depth
  - Aluminum coating
- Tetrahedral MOT configuration with a single flat-top cooling beam
- Compact sensor head with fixed alignment optical package to minimize vibration for deployable cold atom inertial sensors

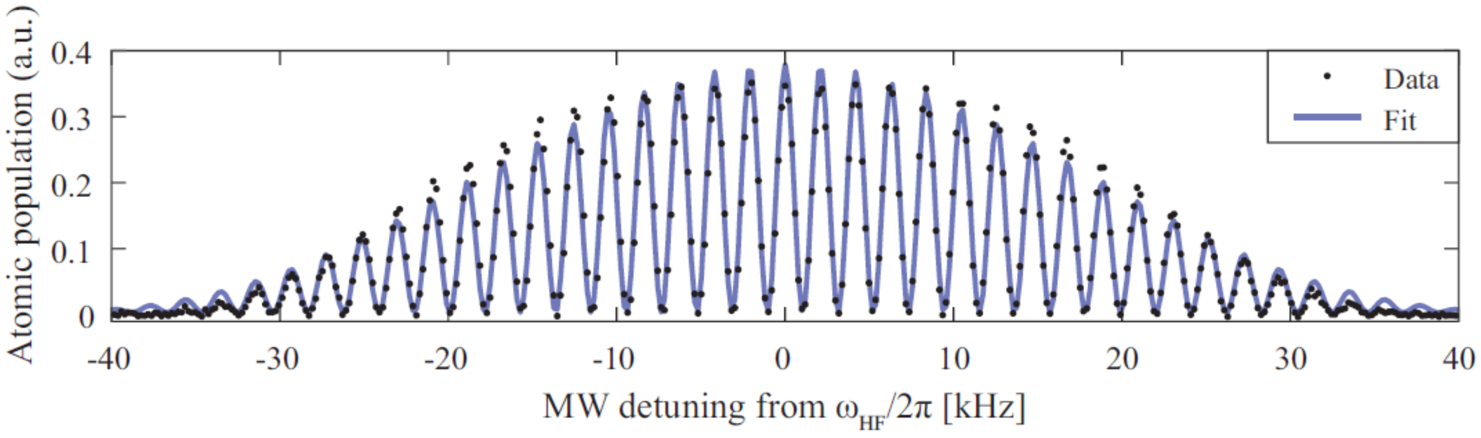
High Data-Rate GMOT



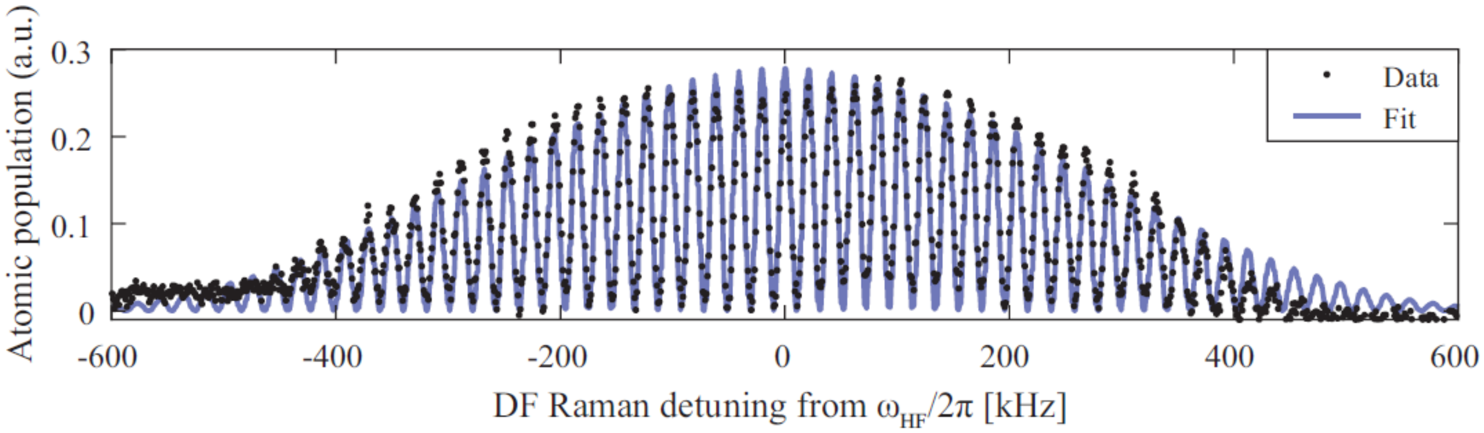
- Sub-Doppler cooled GMOT atoms (T = 15μK)
- High data-rate GMOT operation (> 20Hz)
- Next step: Increase the intensity of the cooling beam

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

Atomic Coherence with GMOT

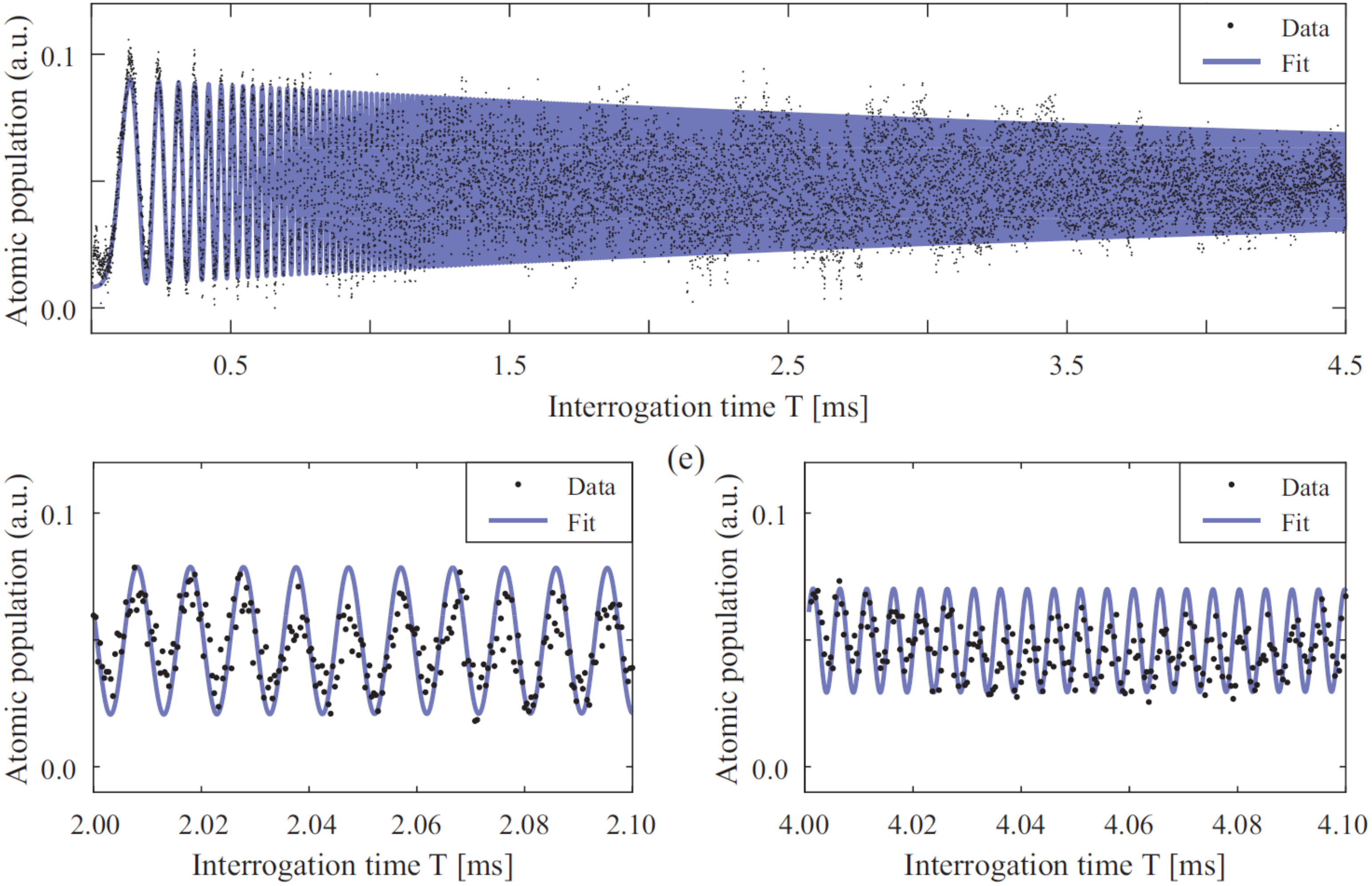


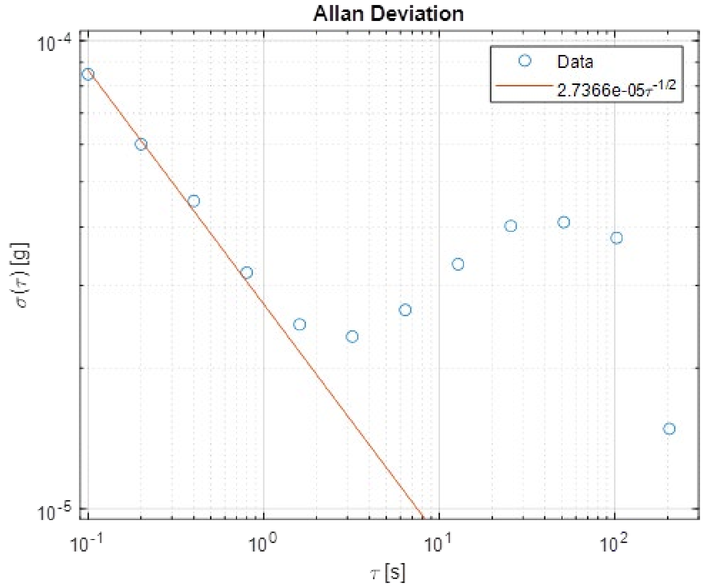
Ramsey sequence with microwave field:
$\frac{\pi}{2} \rightarrow \mathrm{T} \rightarrow \frac{\pi}{2}$ (frequency scan)
Interrogation time $\mathrm{T} = 450\ \mu s$



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

Atom Interferometer Demonstration with GMOT



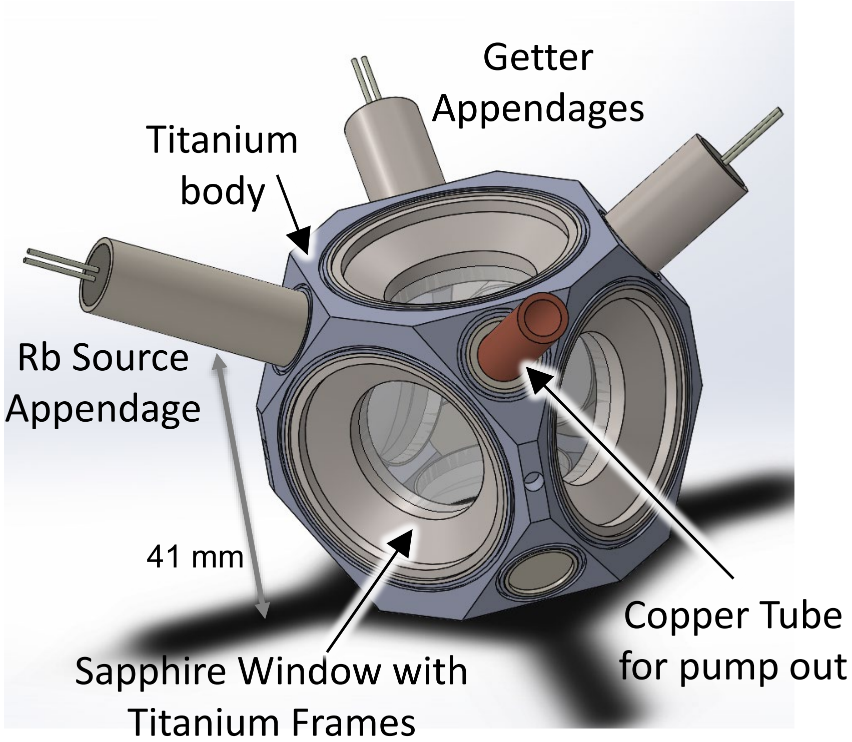


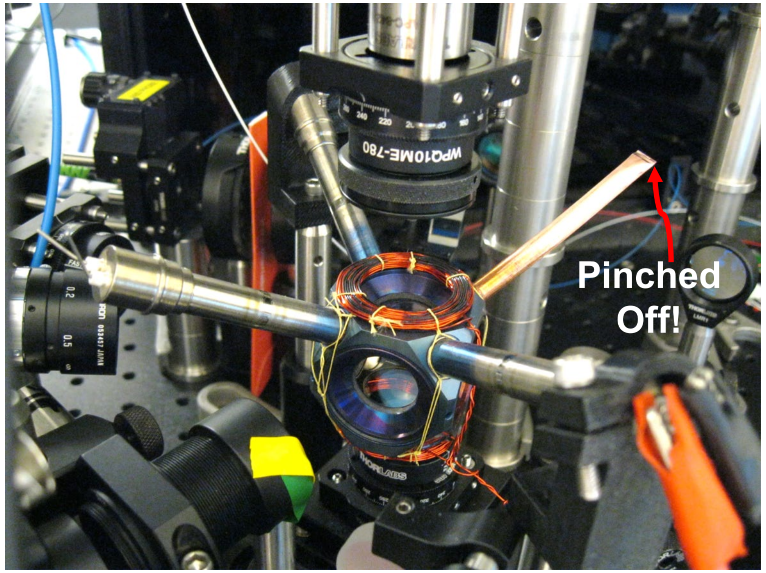
- Sensitivity measurement T = 2.5 ms 27 μ*g*/rt-Hz
- Work needed to improve the data rate and *SNR*

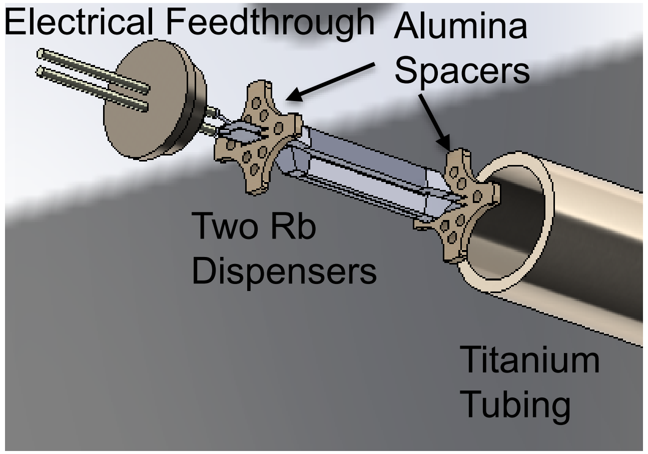
- Raman beam delivered via free space (external from prototype)
- Data rate: 10 Hz. Statistical uncertainty: ~2 μ*g*

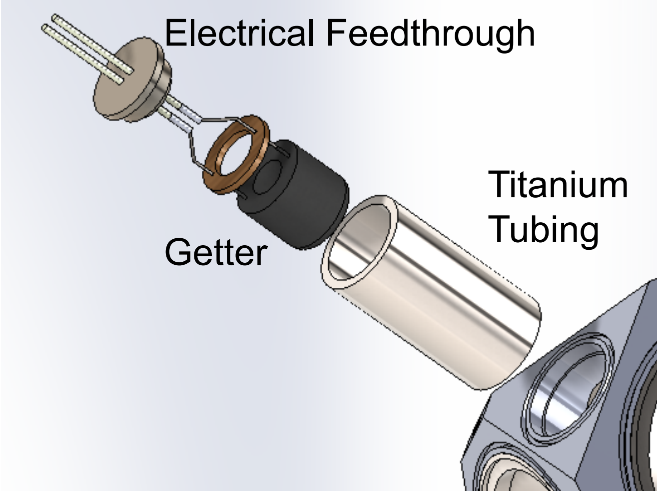
Passively pumped Vacuum Package: Titanium Package Design

- 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



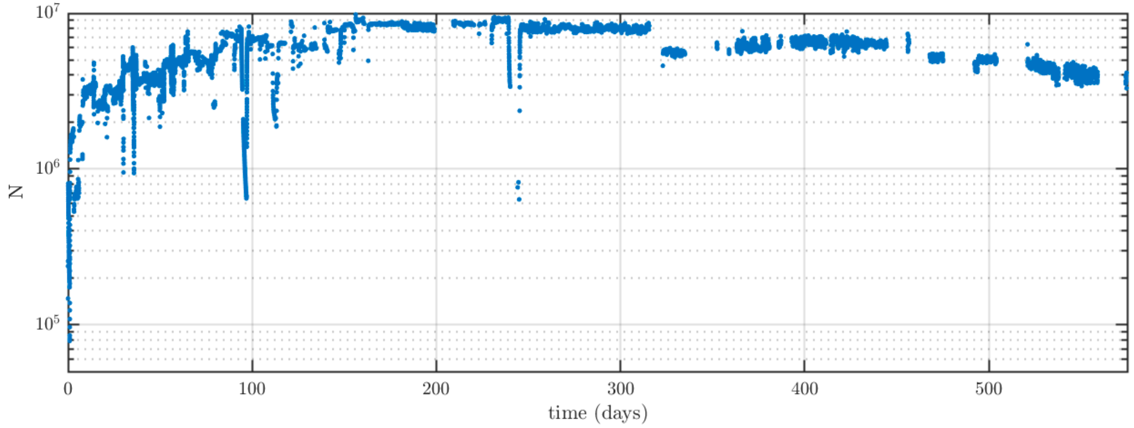


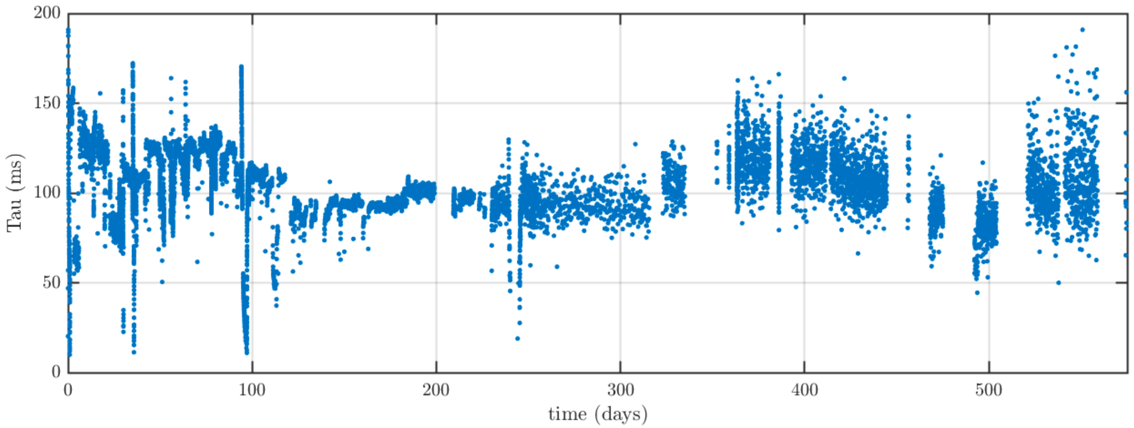




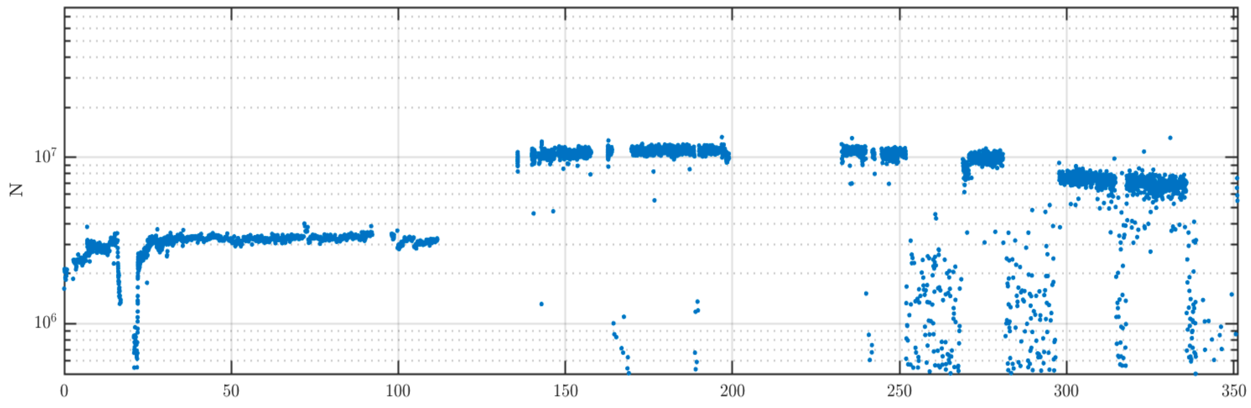
Package operating for 1 year 7 months!

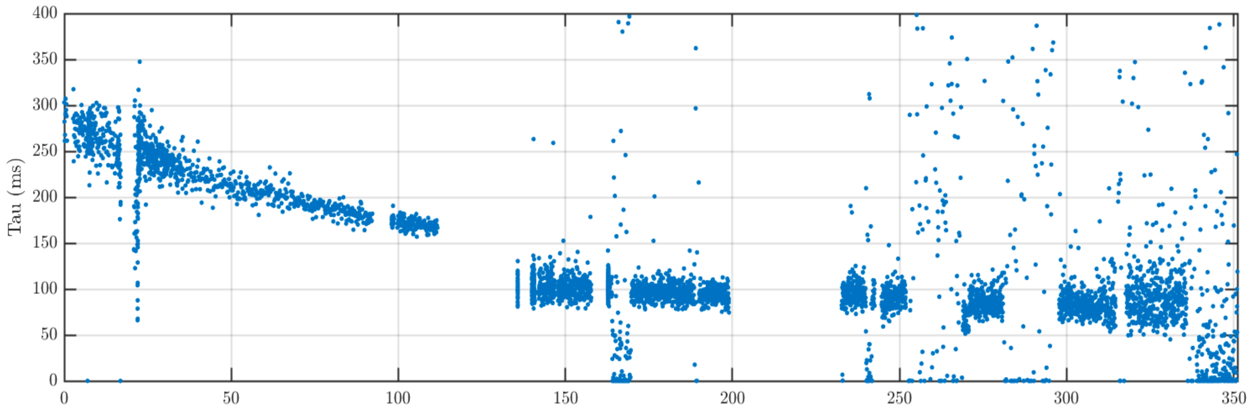
Package 1: 575 days
-On day 231 changed to a Rb-85 MOT





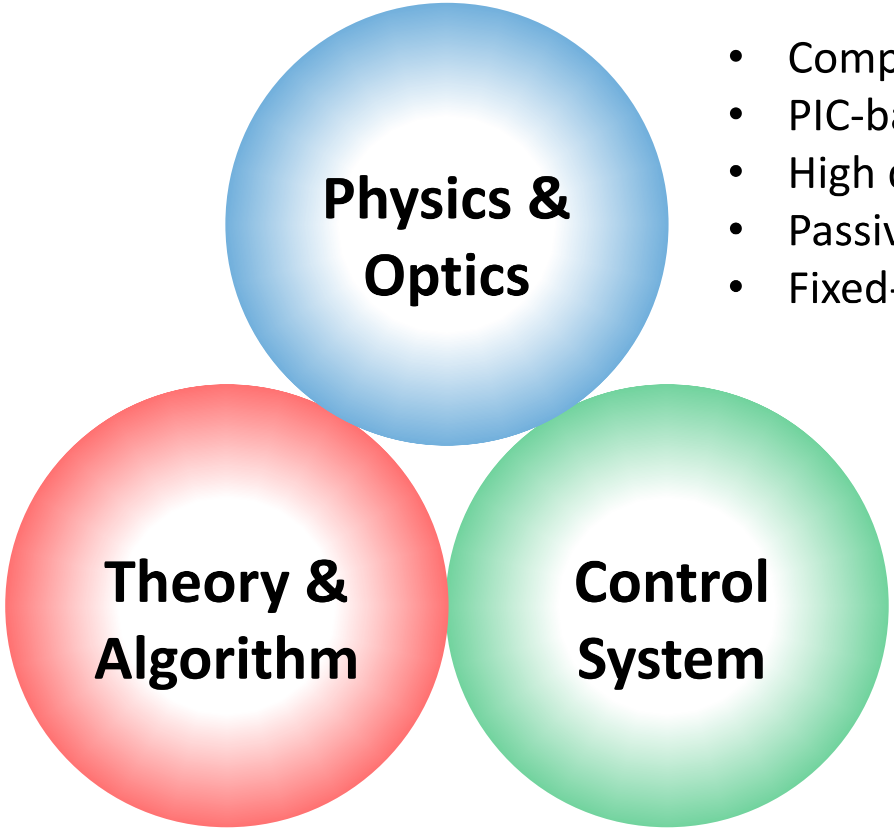
Package 2: 351 days
-Valved off (not pinched)





B. Little et al., *AVS Quantum Sci.* **3**, 035001 (2021)

Towards Deployable Cold-Atom Inertial Sensors



- Compact atom interferometers
- PIC-based & PIC-compatible laser architectures
- High data-rate GMOT
- Passively pumped vacuum chamber
- Fixed-optics sensor head

- Hybrid Inertial Navigation with LPAIs and IMU cosensors
- Physics modeling

\+ IMU cosensor + Kalman filter

- Time-critical control electronics + feedforward processor
- Feedforward hardware implementation for the operation of the LPAI in dynamic environments

Sagnac Matterwave Interferometer using waveguides

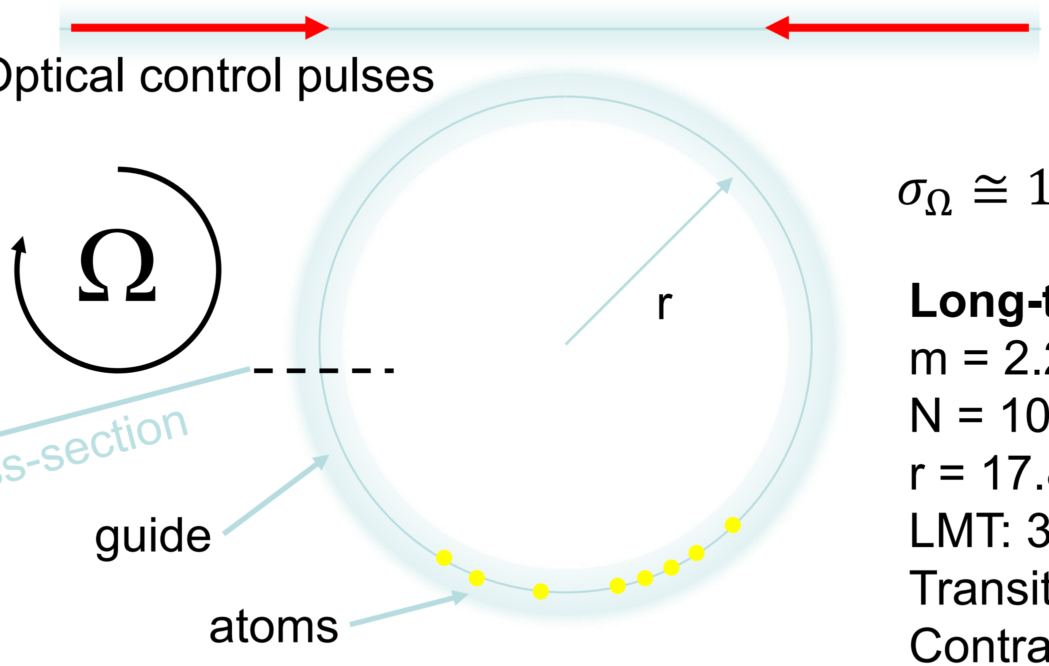
Sandia National Laboratories

DARPA

<u>Concept</u>

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

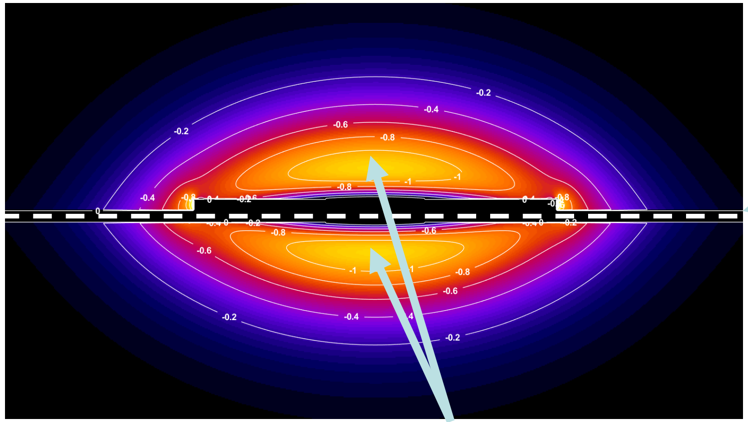
$$\Phi_s = 2\pi\, m\, r^2\, \Omega/\hbar \quad [1]$$



$$\sigma_\Omega \cong 1\ \mu\mathrm{deg}/\sqrt{\mathrm{hr}}$$

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

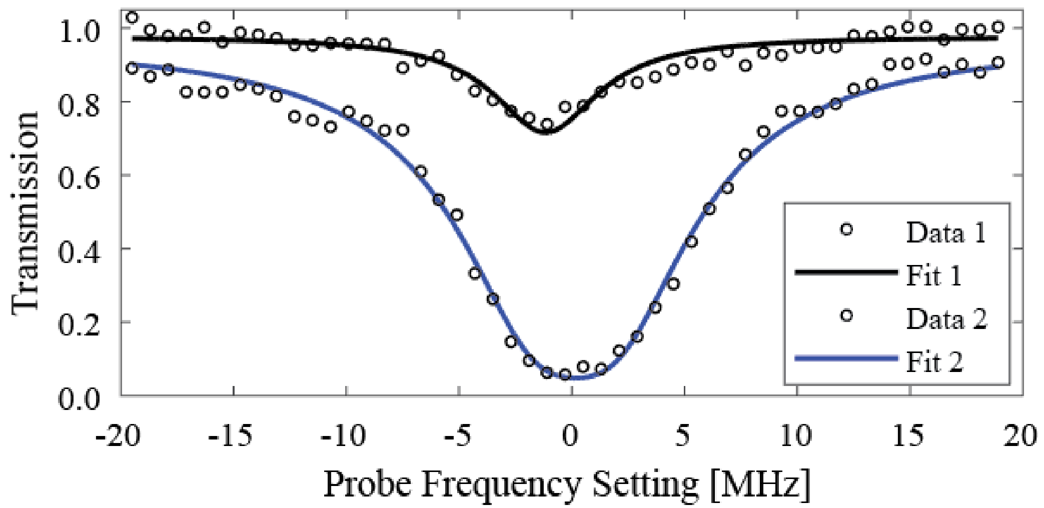
Waveguide Atom Trap Potential

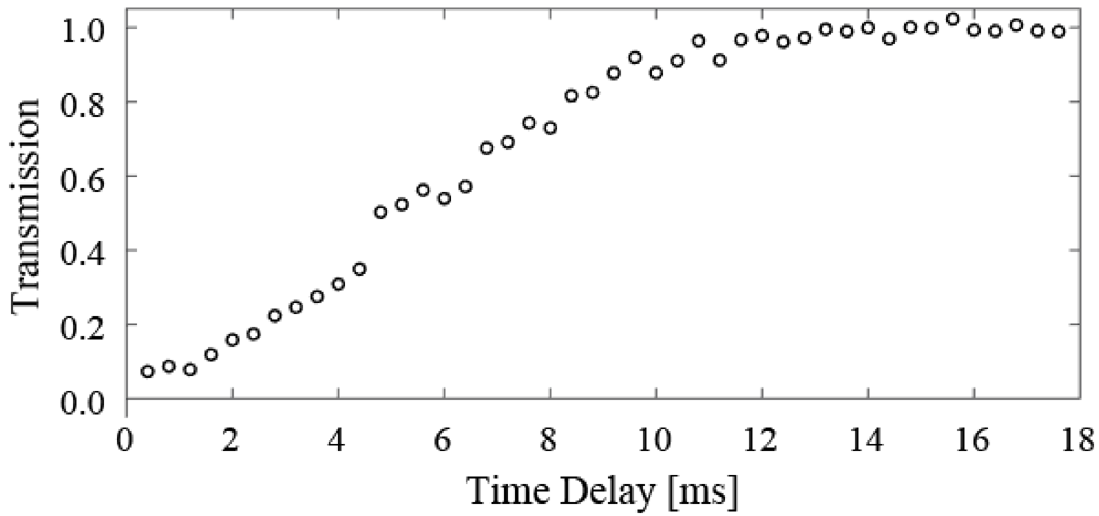


Guide atoms here with the membrane rib waveguide:
Two quasi-TE modes for blue- / red-detuned trap beams

R. Stevenson et al., *PRL* 115, 163001 (2015)

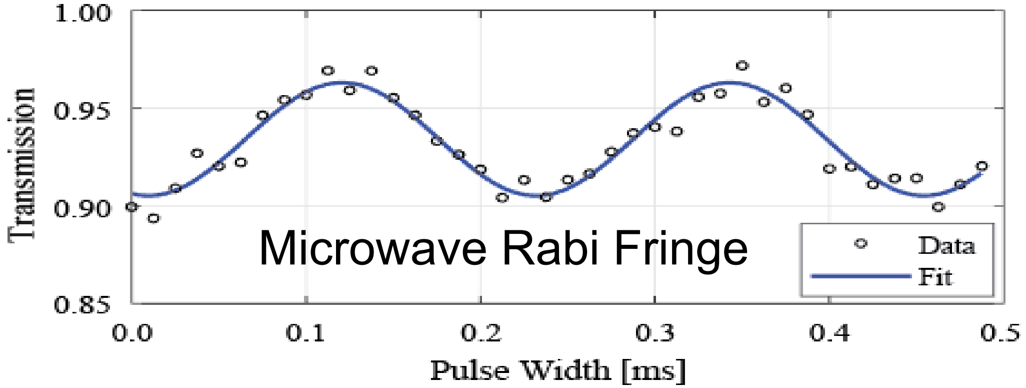
Evanescent-Field Optical Dipole Trap with Nanofibers



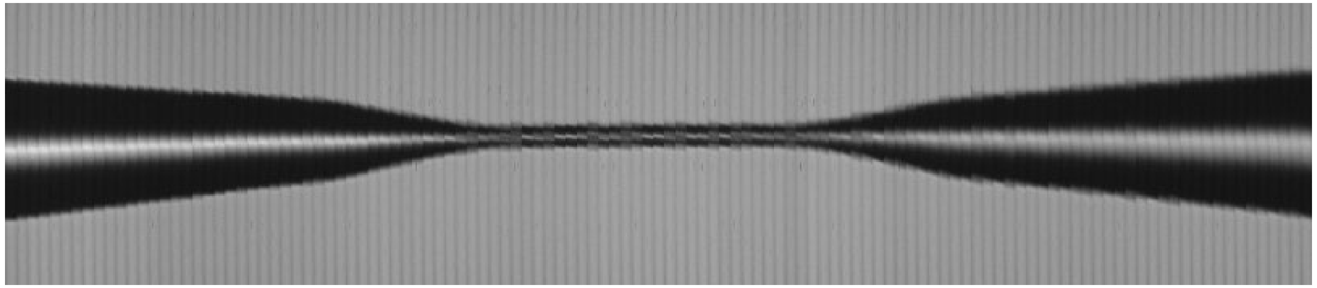


- 685nm and 937nm trapping beams coupled to nanofiber
- Atom number measurement with an absorption probe
  N = 47.2 ± 3.2 for 1-D guided atoms

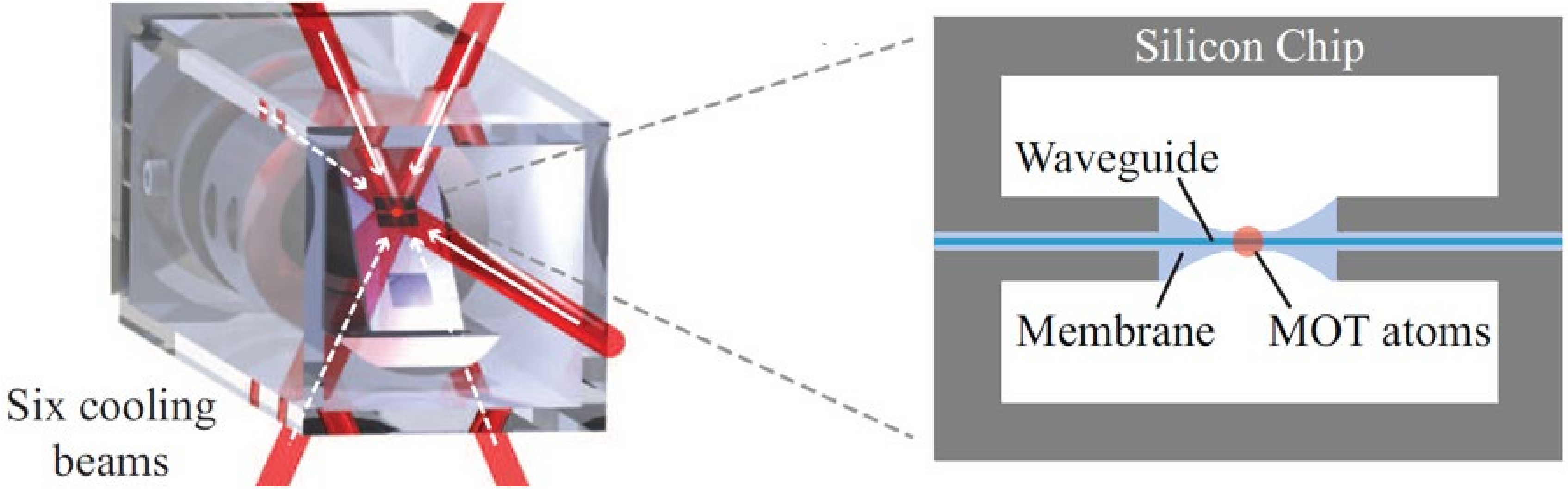
- Lifetime measurement of 1-D guided atoms
  τ = 8.1 ± 0.8 ms

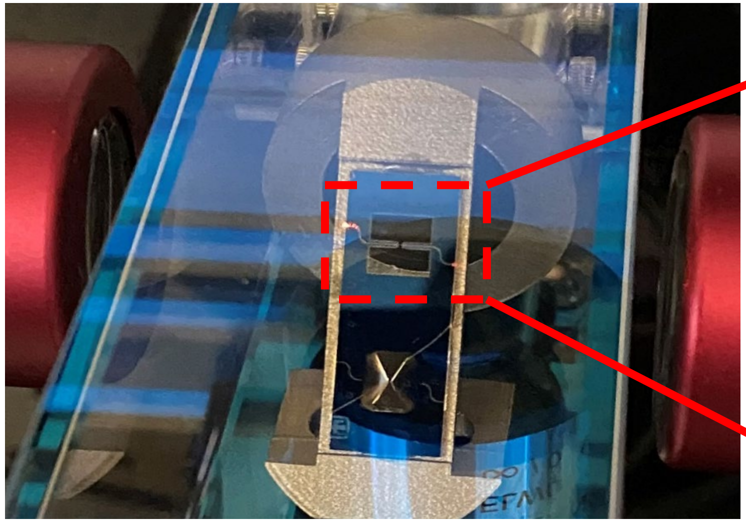


Tapered Fiber

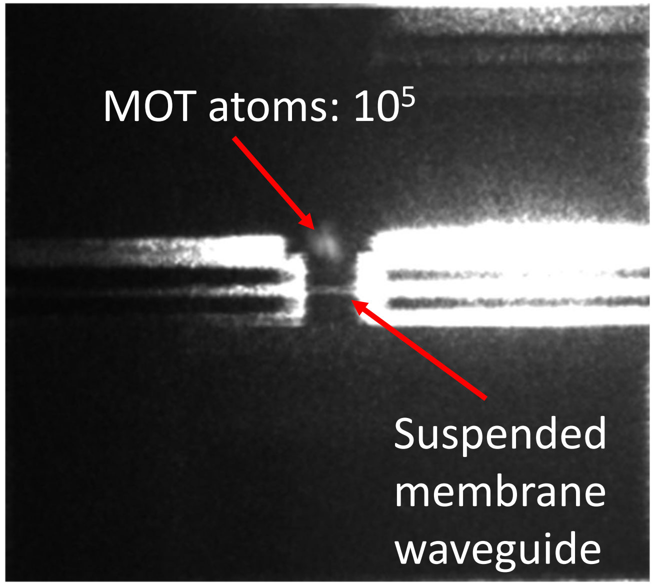


Photonic Atom Trap Integrated Platforms

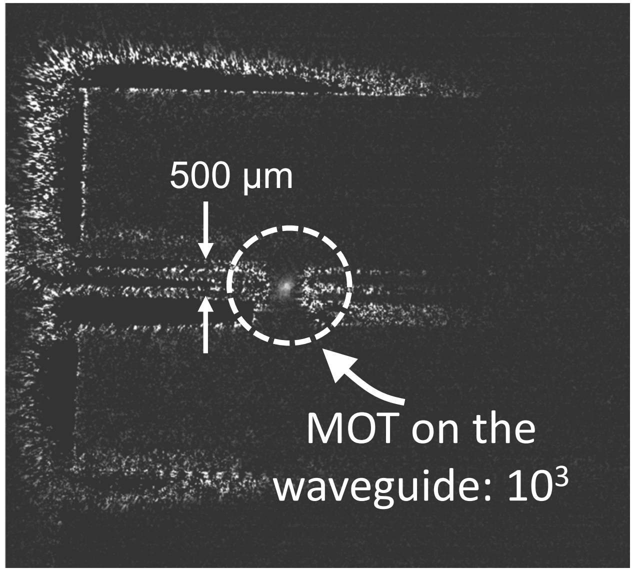


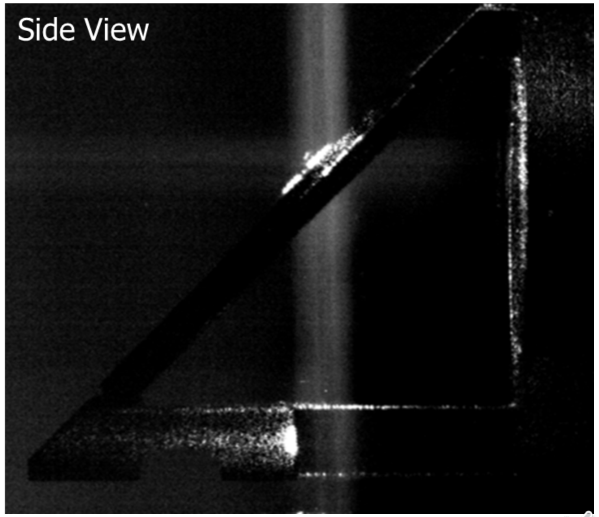


Light-coupled waveguide via high NA objectives



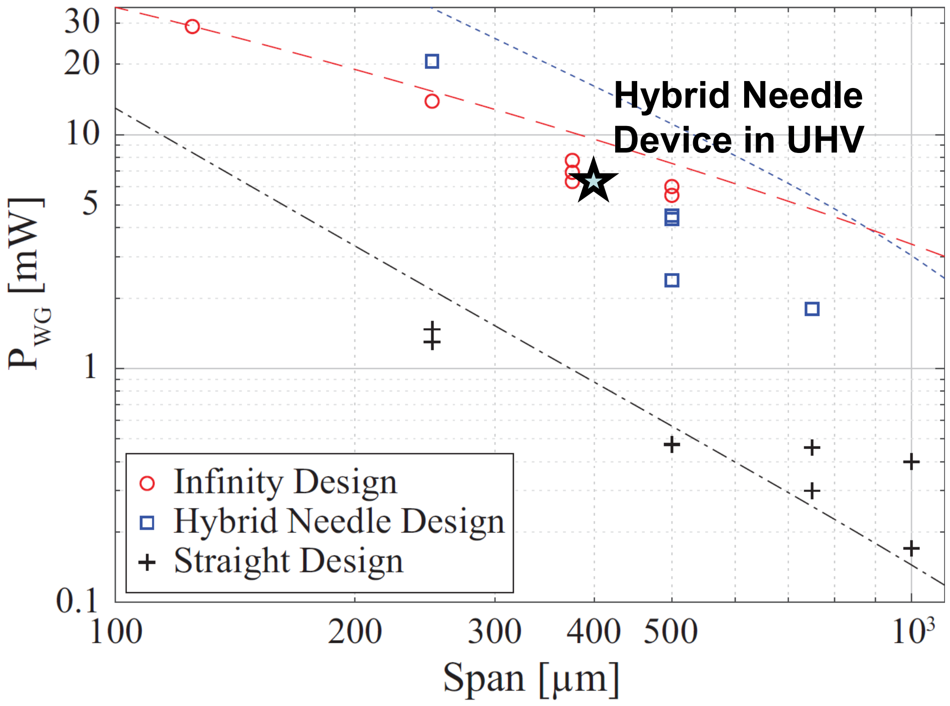
Background subtracted image



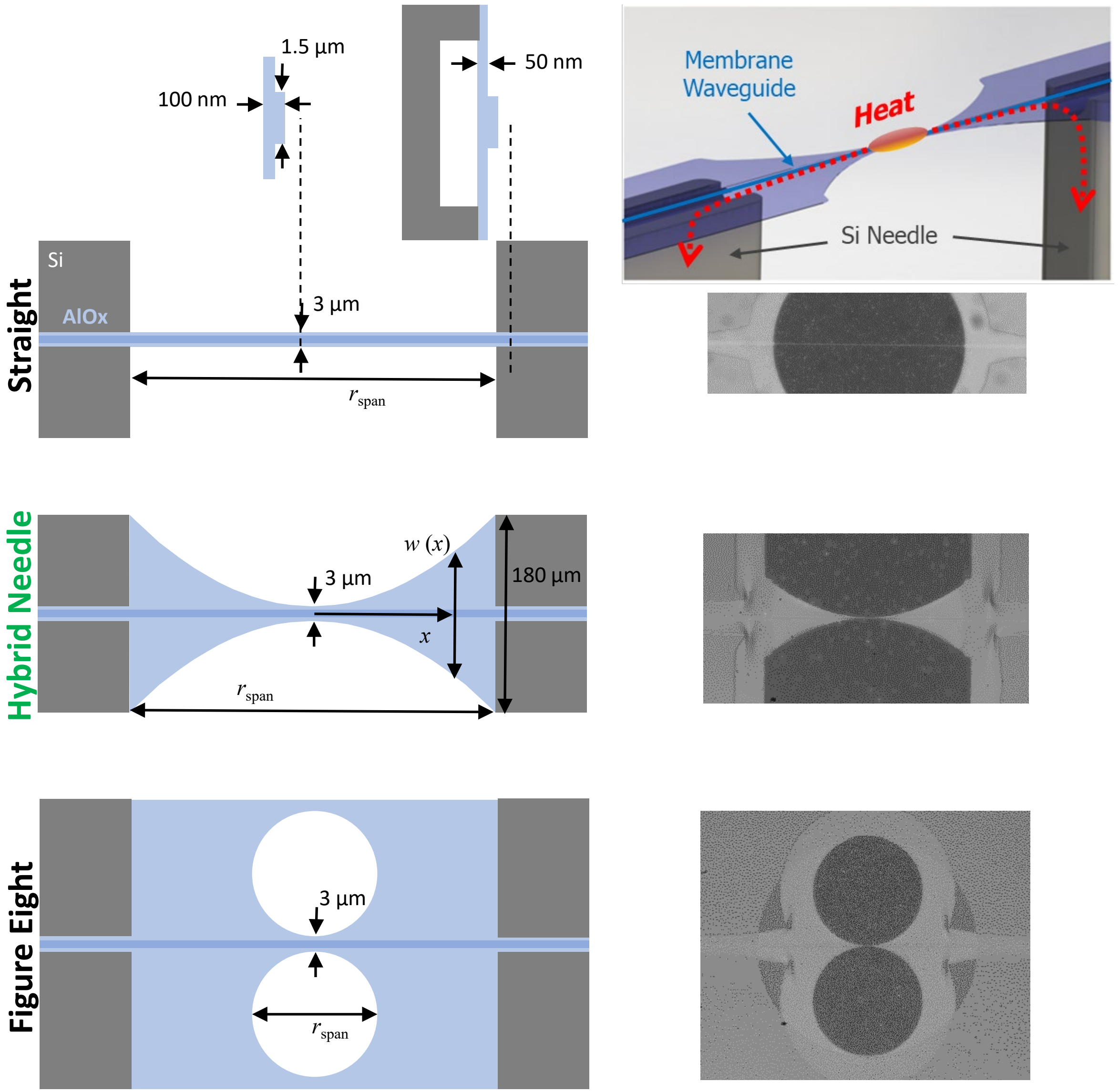


Alumina Waveguides: High Power Optical Handling

- Big challenge: Heat dissipation in vacuum
- Samples were redesigned based on experimental measurements and calibrated thermal simulations
- New designs handle ~30mW at shortest lengths and **> 6mW in target design**



M. Gehl et al., *Opt. Express* 29 (9), 13129 (2021)
J. Lee et al., *Scientific Reports* 11, 8807 (2021)



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- A Compact Atom Interferometer (SIGMA GC)

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Conclusion

Sandia National Laboratories

- Multifaceted programs towards miniature cold-atom inertial sensors
  - Integrated photonics laser system
    - Single sideband modulator with suppressed carrier
    - Demonstrated atom interferometry
  - Compact atom interferometer sensor head
    - High data-rate GMOT
    - Initial atomic gravimeter demonstration
  - Vacuum package development
    - Passively pumped operation for > 1.5 years
  - Guided atom interferometers towards multi-axis, arrayed atomic sensors
    - Photonic atom trap integrated platforms

Strategic Inertial Guidance ΣΙΓΜΑ with MAtterwaves

- Future work
  - Combine integrated photonics platform with atom interferometer prototype
- Funding

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT