

Strategic Inertial Guidance

ΣΙΤΜΑ

with MAtterwaves

Towards Miniature Cold-Atom Inertial Sensors

Jongmin Lee



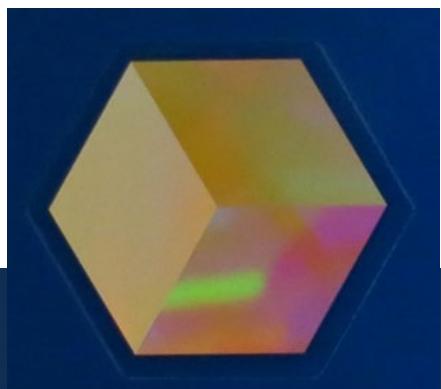
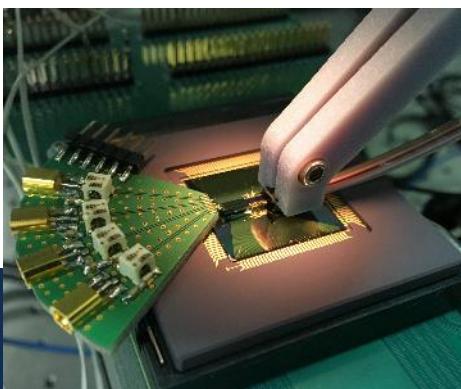
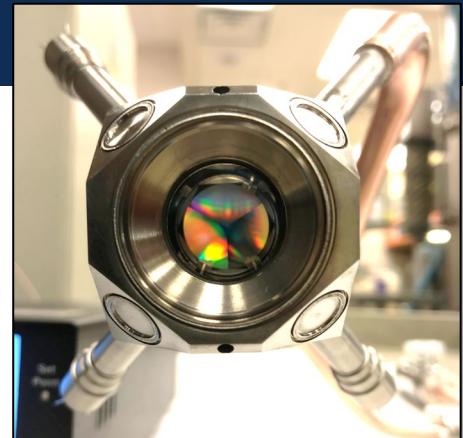
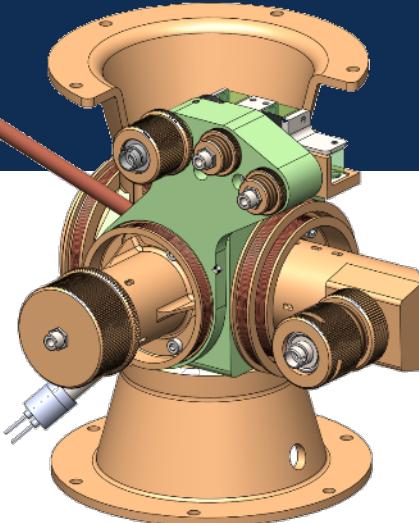
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Outline

- 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 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 (1 σ) [μg]	< 25	< 10^{-4}	<0.25
Accel SF (1 σ) [PPM]	< 100	< 10^{-4}	1
Accel Random Walk [$\mu g/\sqrt{Hz}$]	not reported QA ~ 10	10^{-5}	<1
Gyro Bias (1 σ) [deg/hr]	< 0.003	< 7×10^{-5}	
Gyro SF [PPM]	< 5	< 5	
Gyro Random Walk (1 σ) [deg/ \sqrt{hr}]	< 0.002	2×10^{-6}	

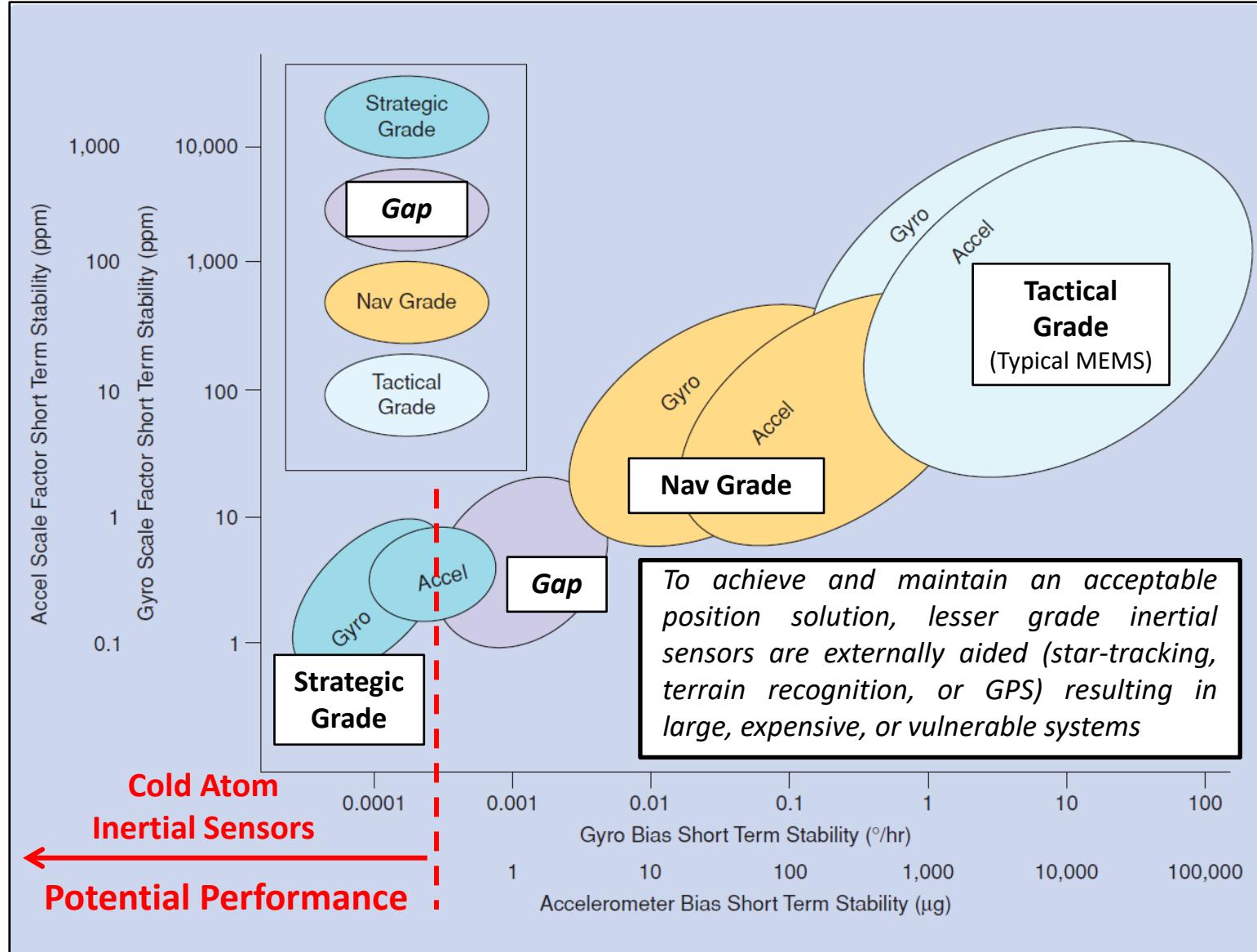
QA: Quartz Accelerometer

RLG: Ring Laser Gyroscope



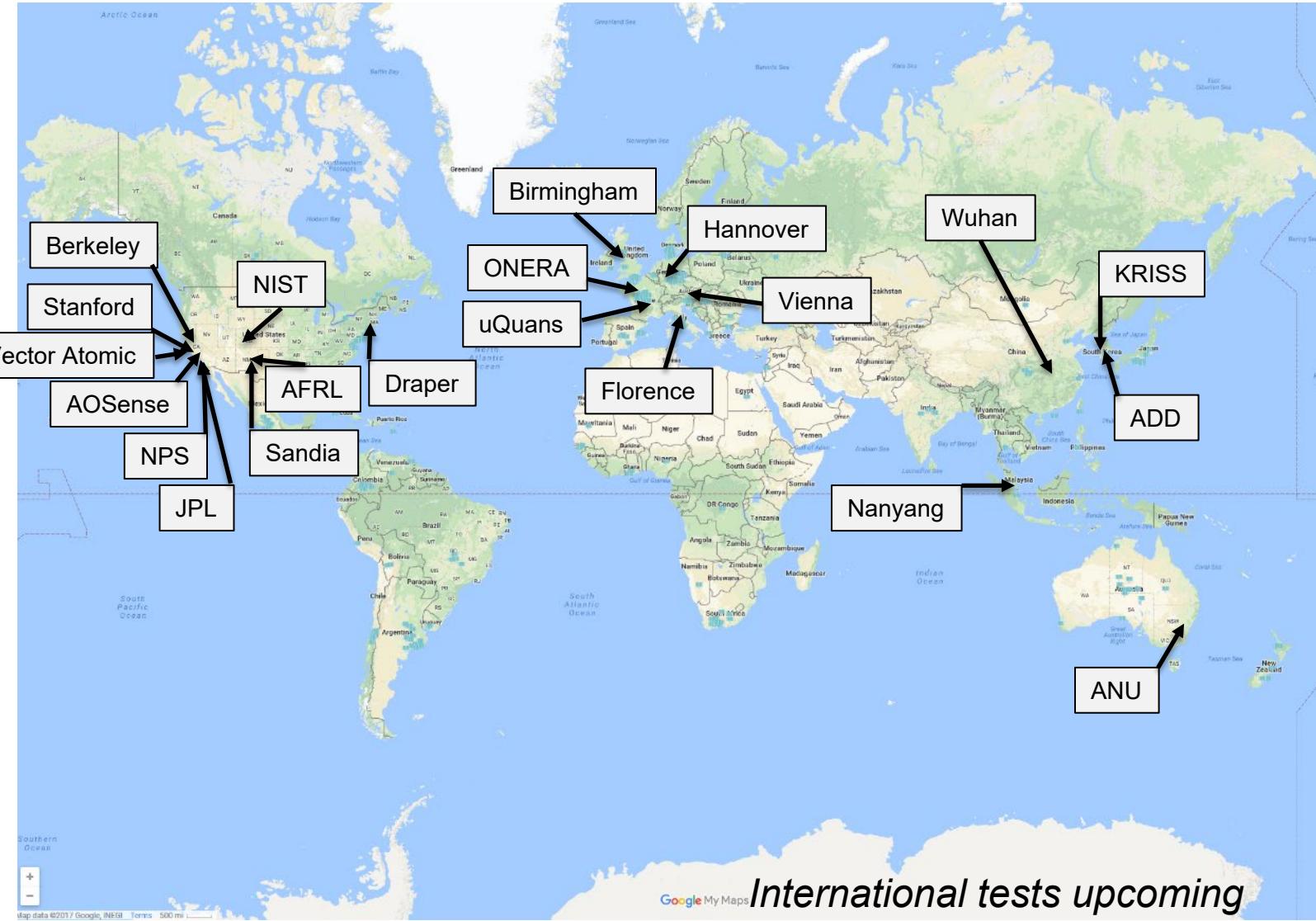
QA (x3) & RLG (x3)

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

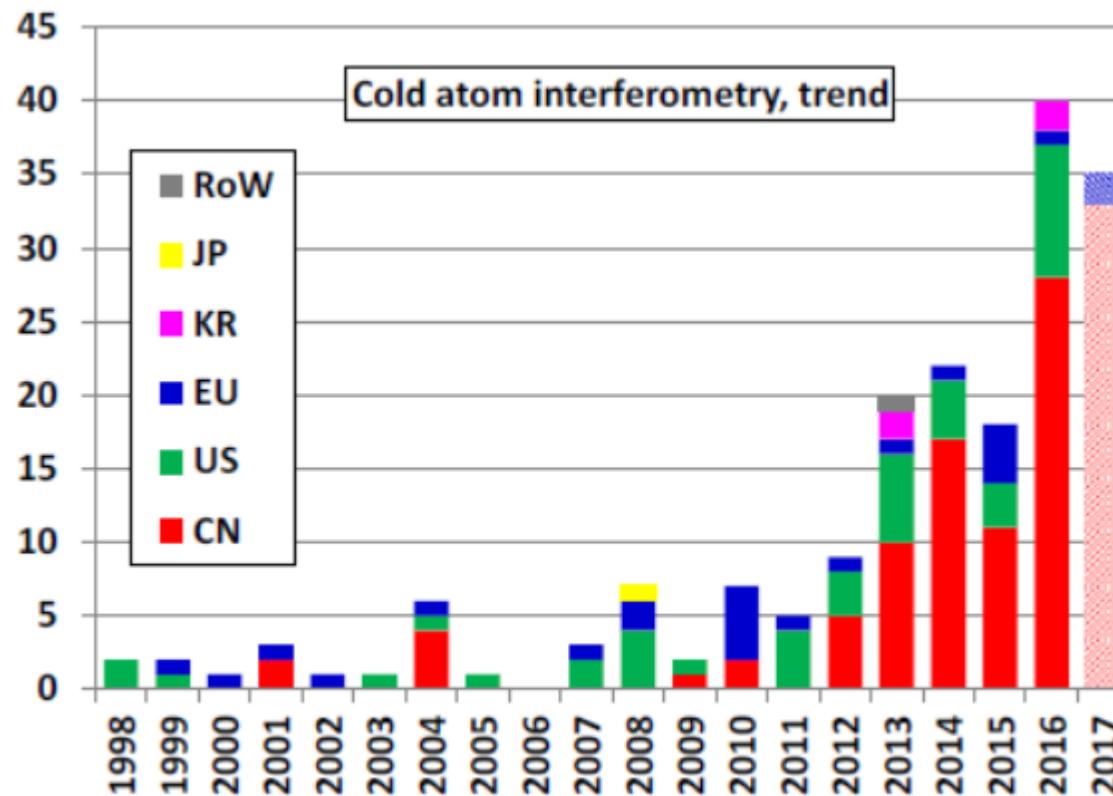
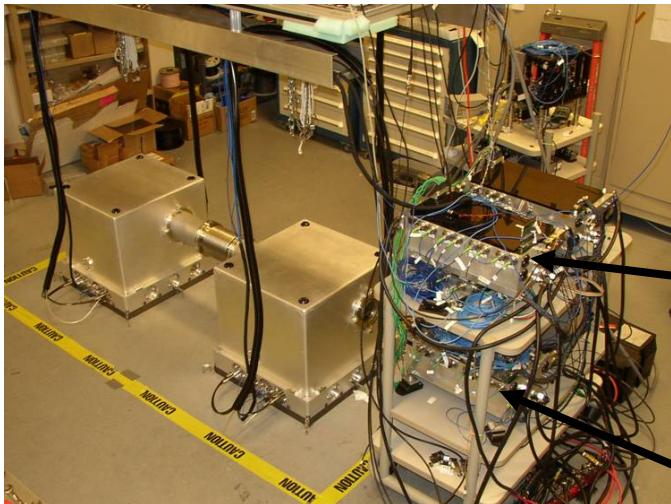


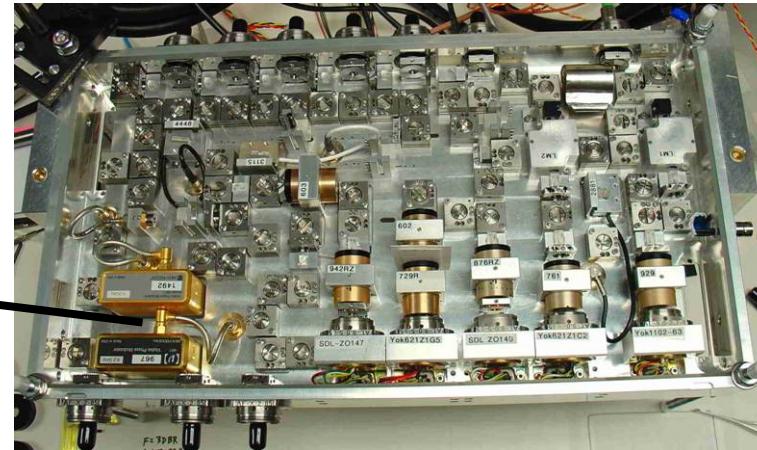
Fig. 32: time evolution of patent applications on cold atom interferometry³⁷.

“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>

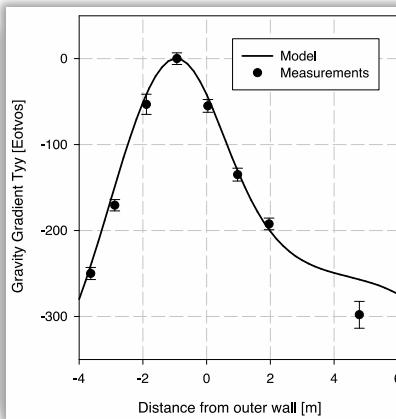
Mobile atom interferometer



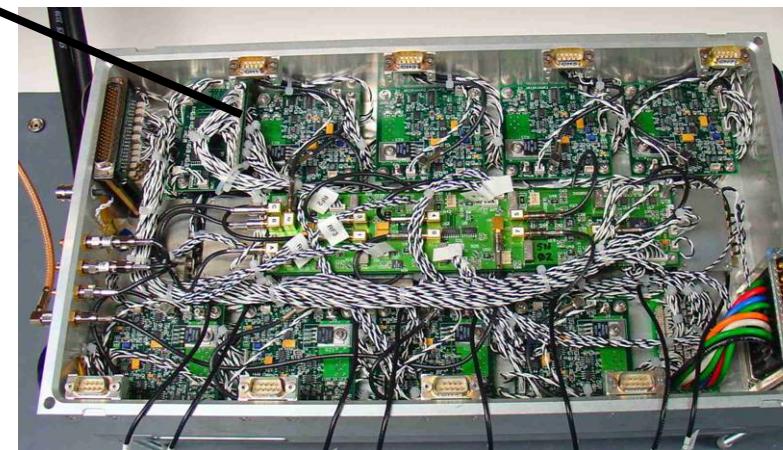
Biedermann, Ph.D. Thesis, Stanford, 2007



lasers 9" x 15"

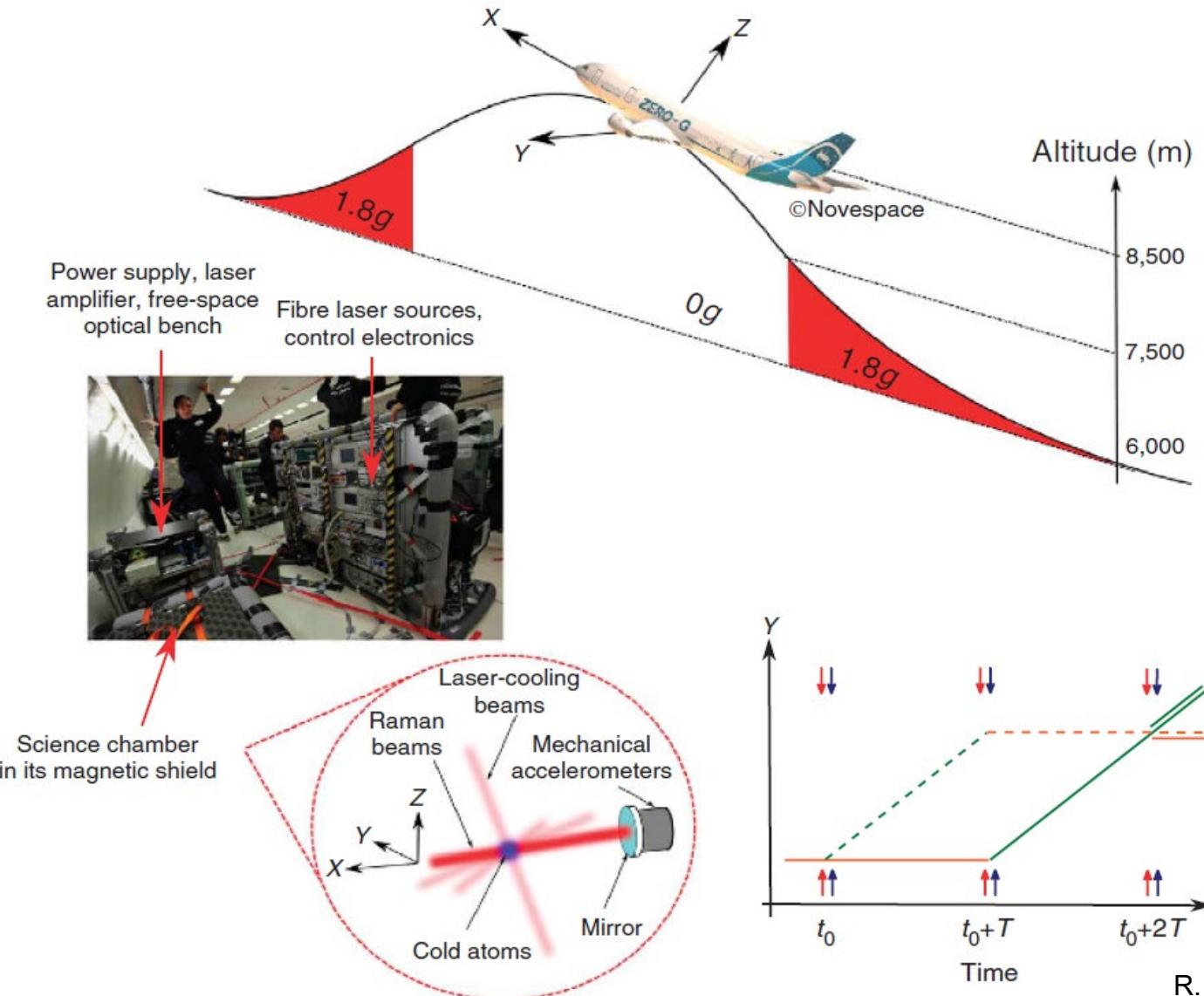


Wu, Ph.D. Thesis, Stanford, 2009



electronics 9" x 15"

Portable Atom Interferometers for Aircraft (France)



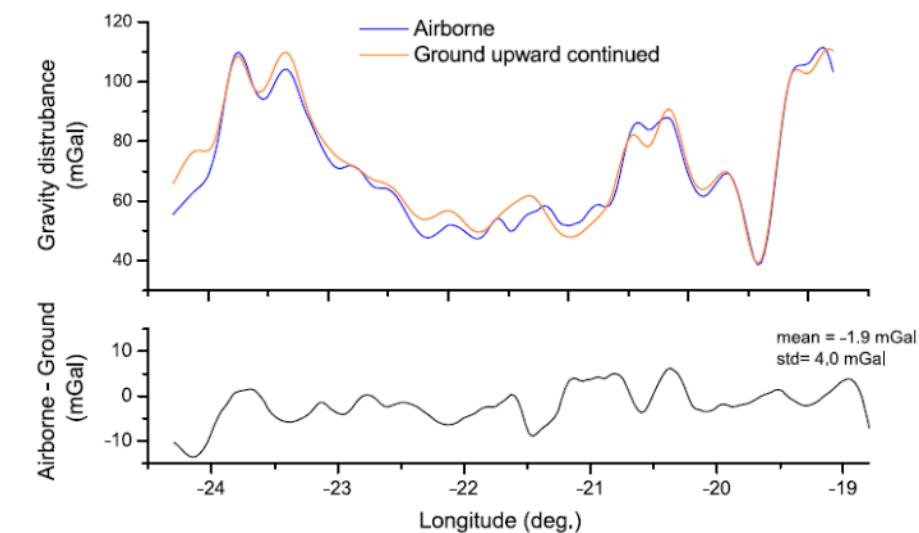
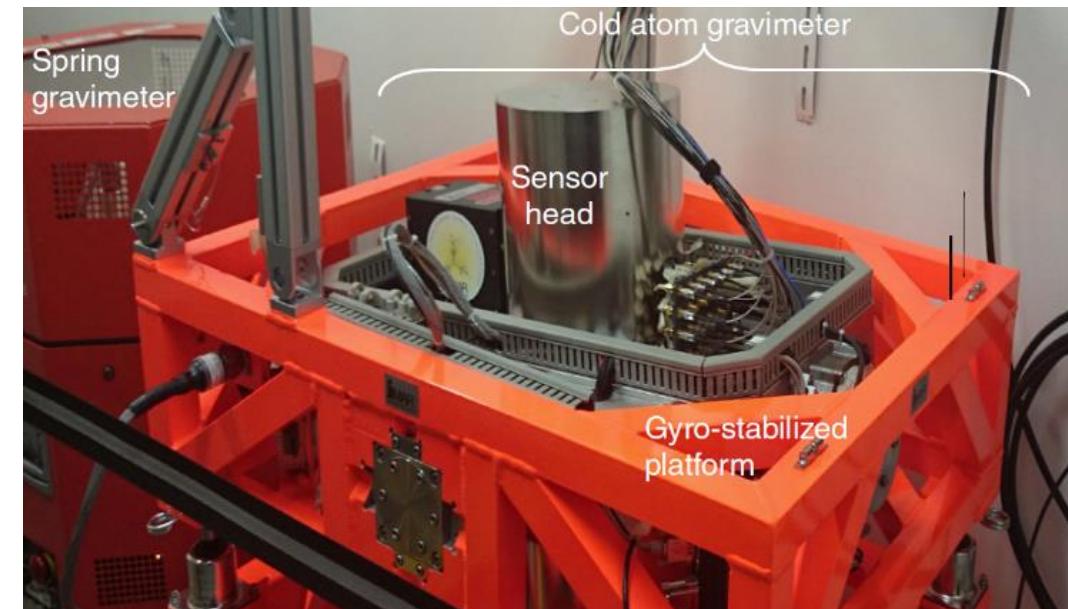
R. Geiger, nature communications, 2:474 (2011)
K. Bongs et. al, Nature Reviews, Physics 1 (2019)

Airborne Gravimetry with an Atom Interferometer

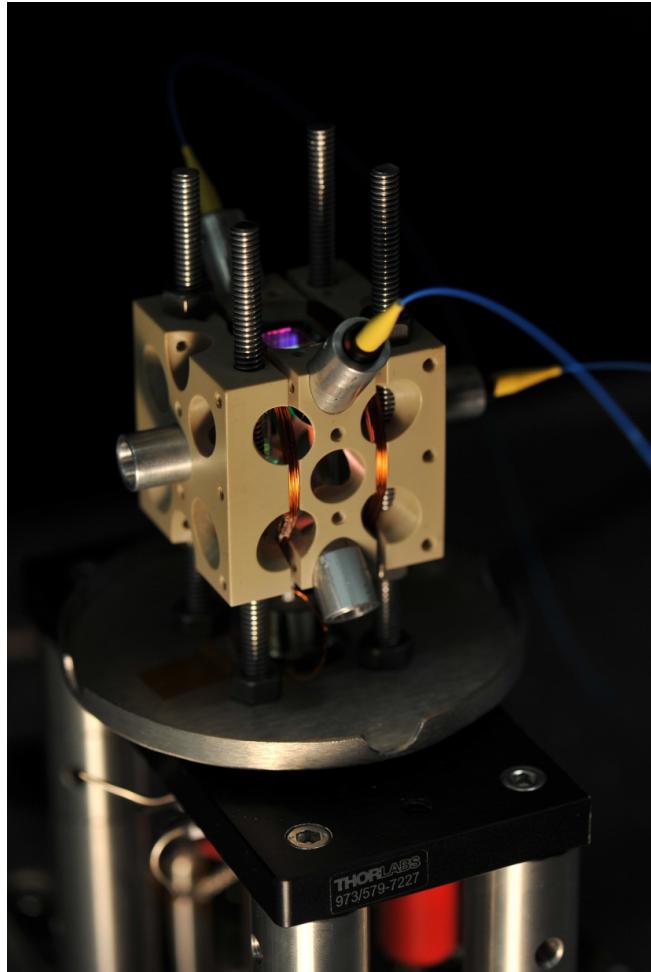
- Gravity measurements over Iceland
- Gimbaled platform to maintain vertical
- Feed forward technique
 - Dynamic range = 1000 fringes or $\sim 0.1 g$ at $T = 20$ ms
- Data rate = 10 Hz
- Errors: 1.7 to 3.9 μg
- ONERA – The French Aerospace Lab

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

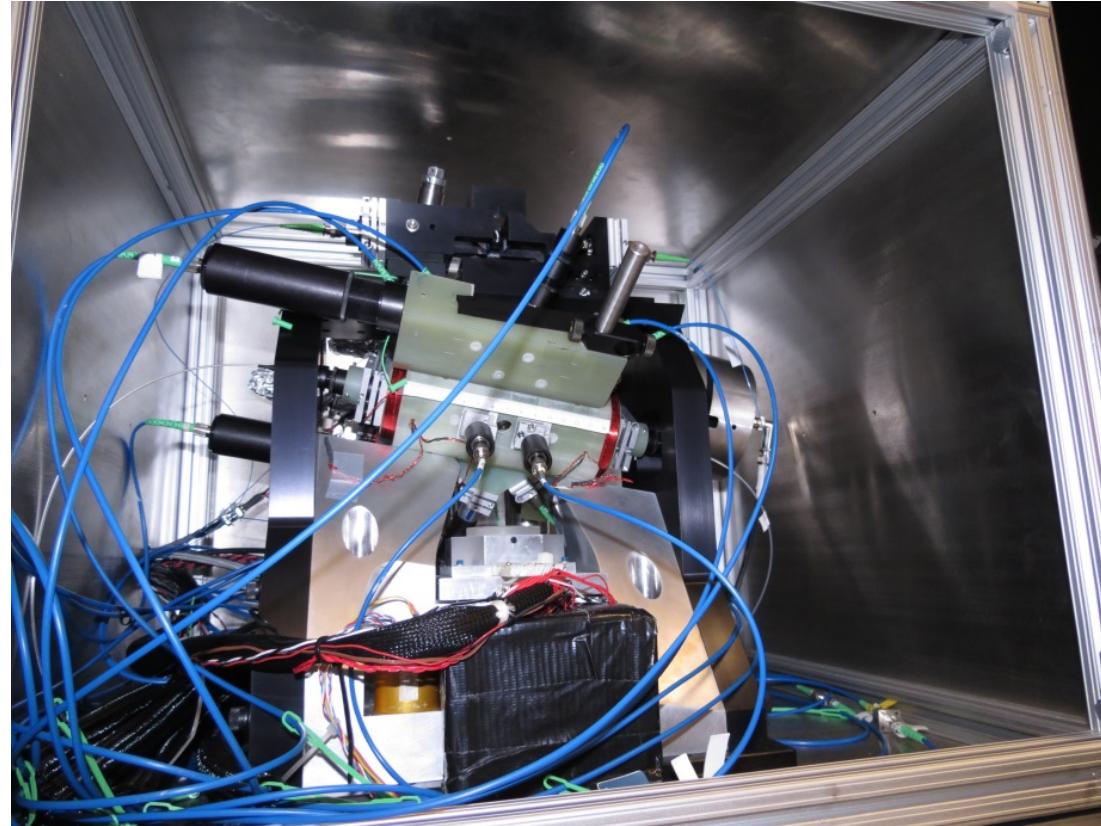
Ship: Bidel, Y., Zahzam, N., Blanchard, C. *et al.* Absolute marine gravimetry with matter-wave interferometry. *Nat Commun* **9**, 627 (2018).



Compact atom interferometers

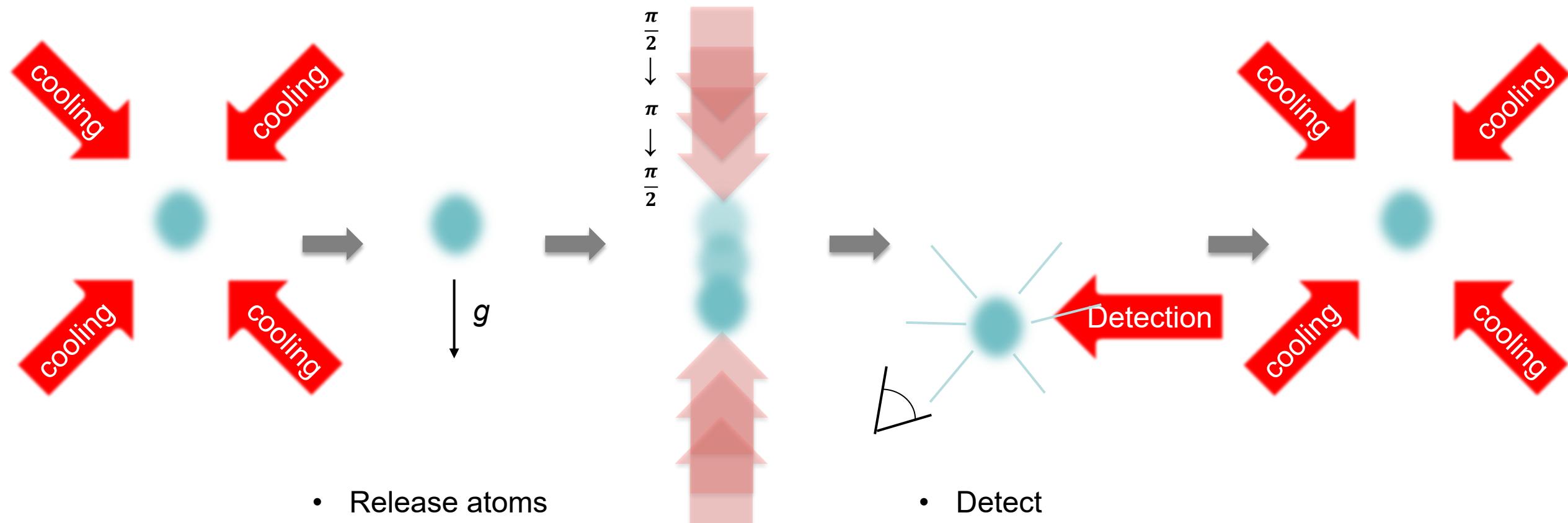


NIST accel/gyro



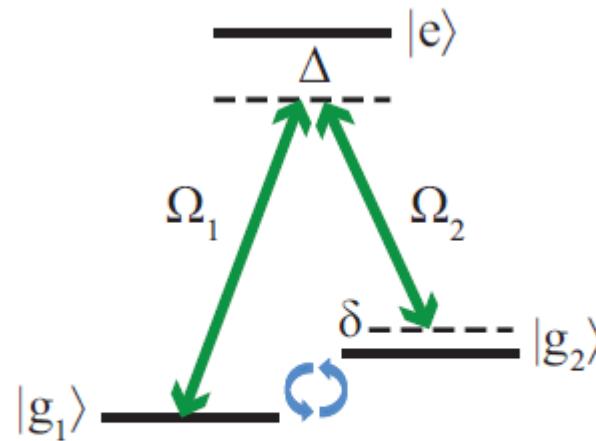
Sandia accel/gyro

High Data-Rate Atom Interferometry

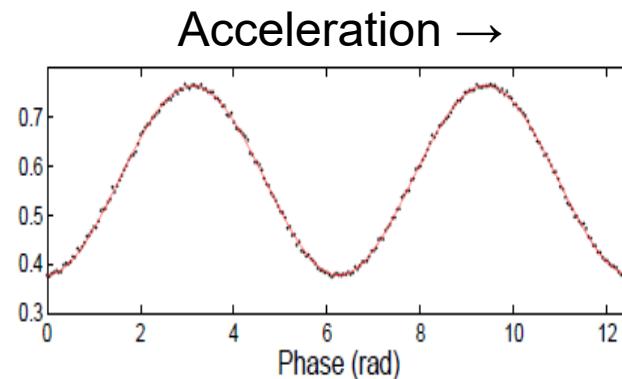
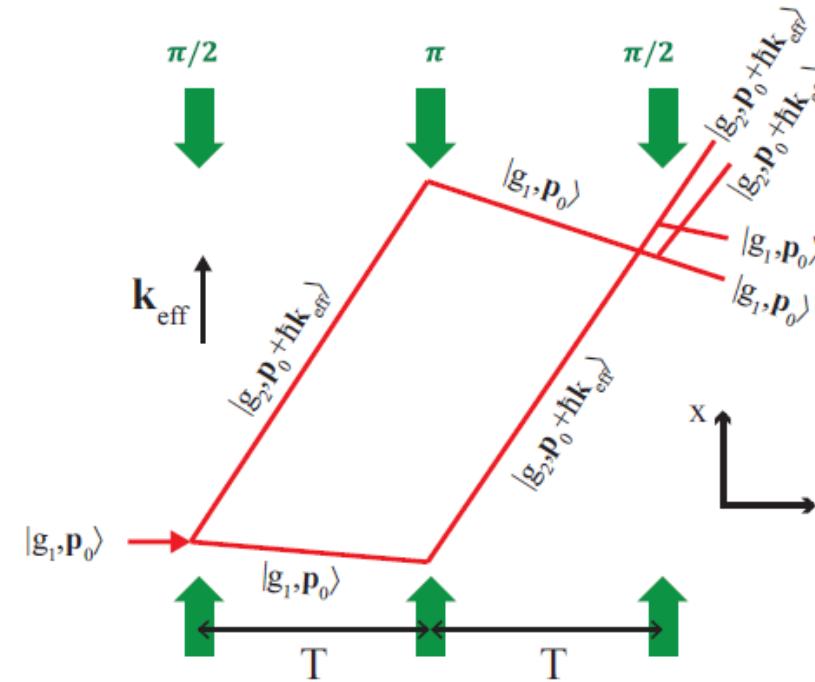


Example, $(40 \text{ Hz})^{-1}$ cycle

Light Pulse Atom Interferometer



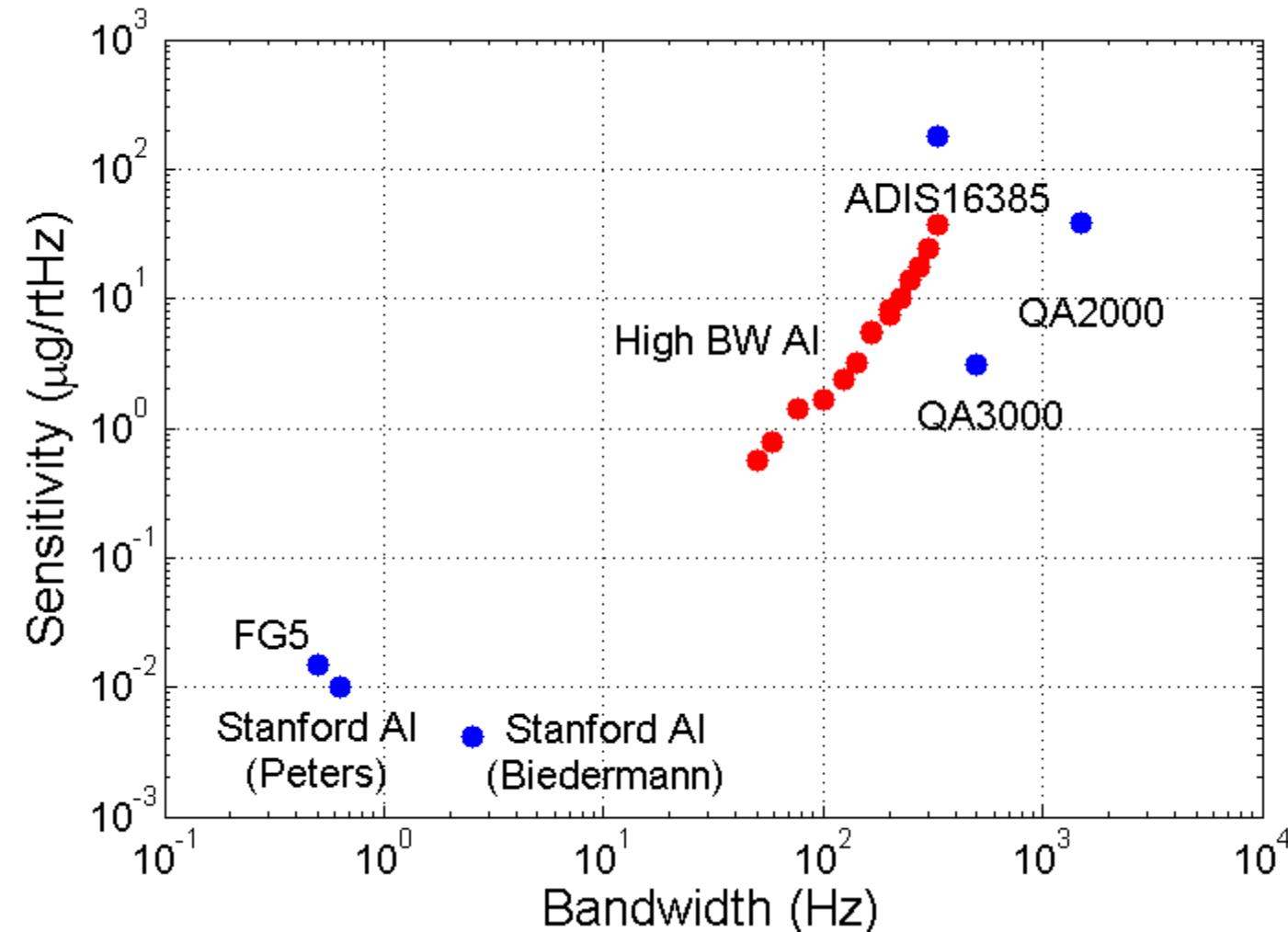
$$\Omega_{\text{Raman}} = \frac{\Omega_1 \Omega_2}{2\Delta}$$



- 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

Bandwidth considerations

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



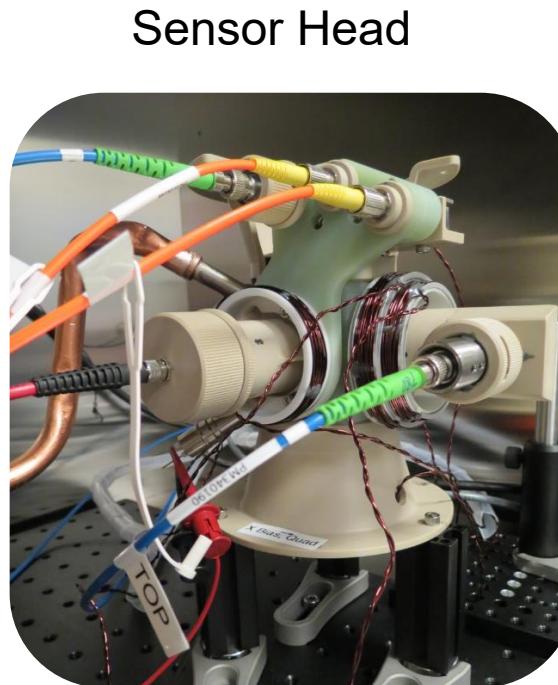
INTEGRATED PHOTONICS

Challenges to miniaturization

- Physics takes place in a few cubic centimeters

Challenge level

1. Laser system
 - Very complex
 - Large system
2. Sensor head
3. Control electronics



Sensor Head

Control and
Power
Electronics

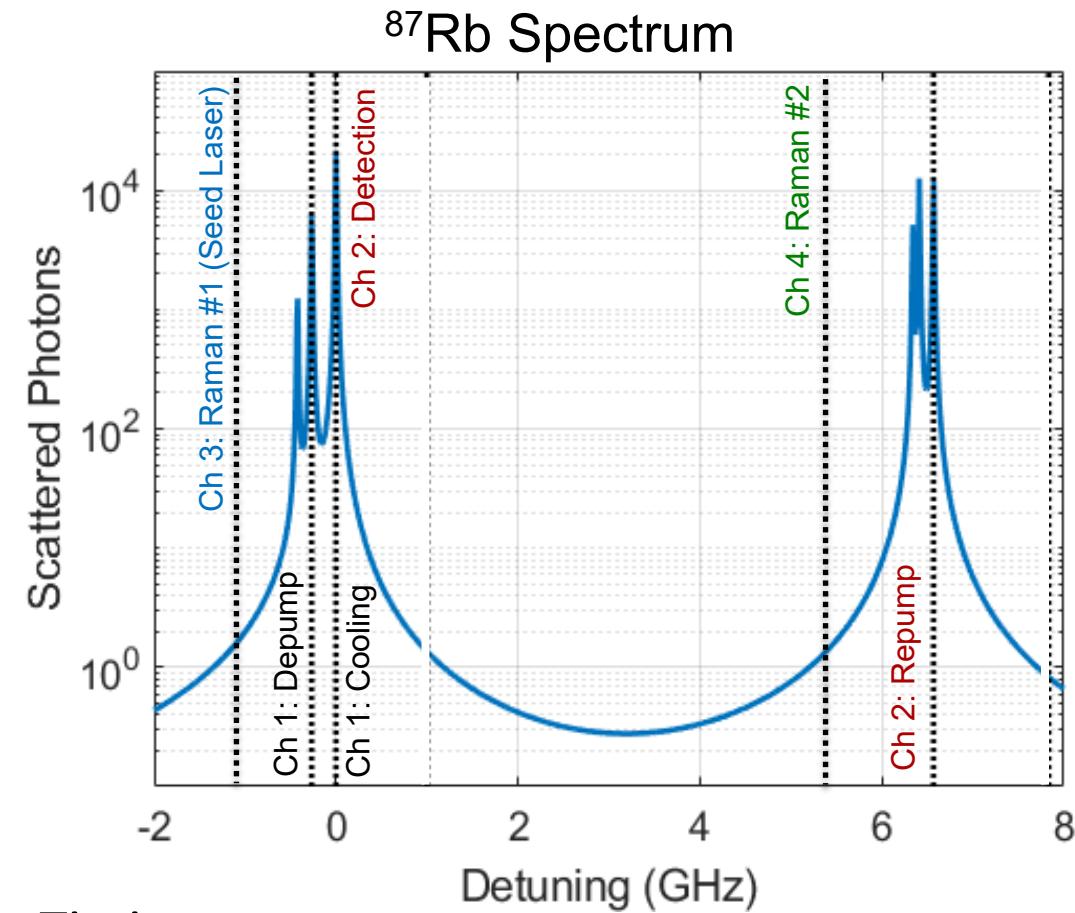
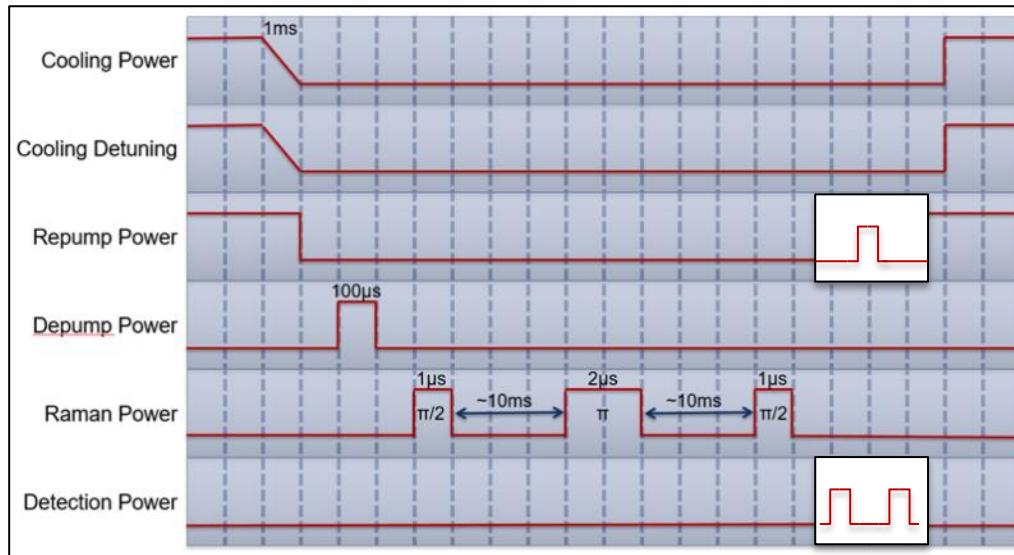
Laser
System



Integrated Laser Implementation

Five laser channels

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

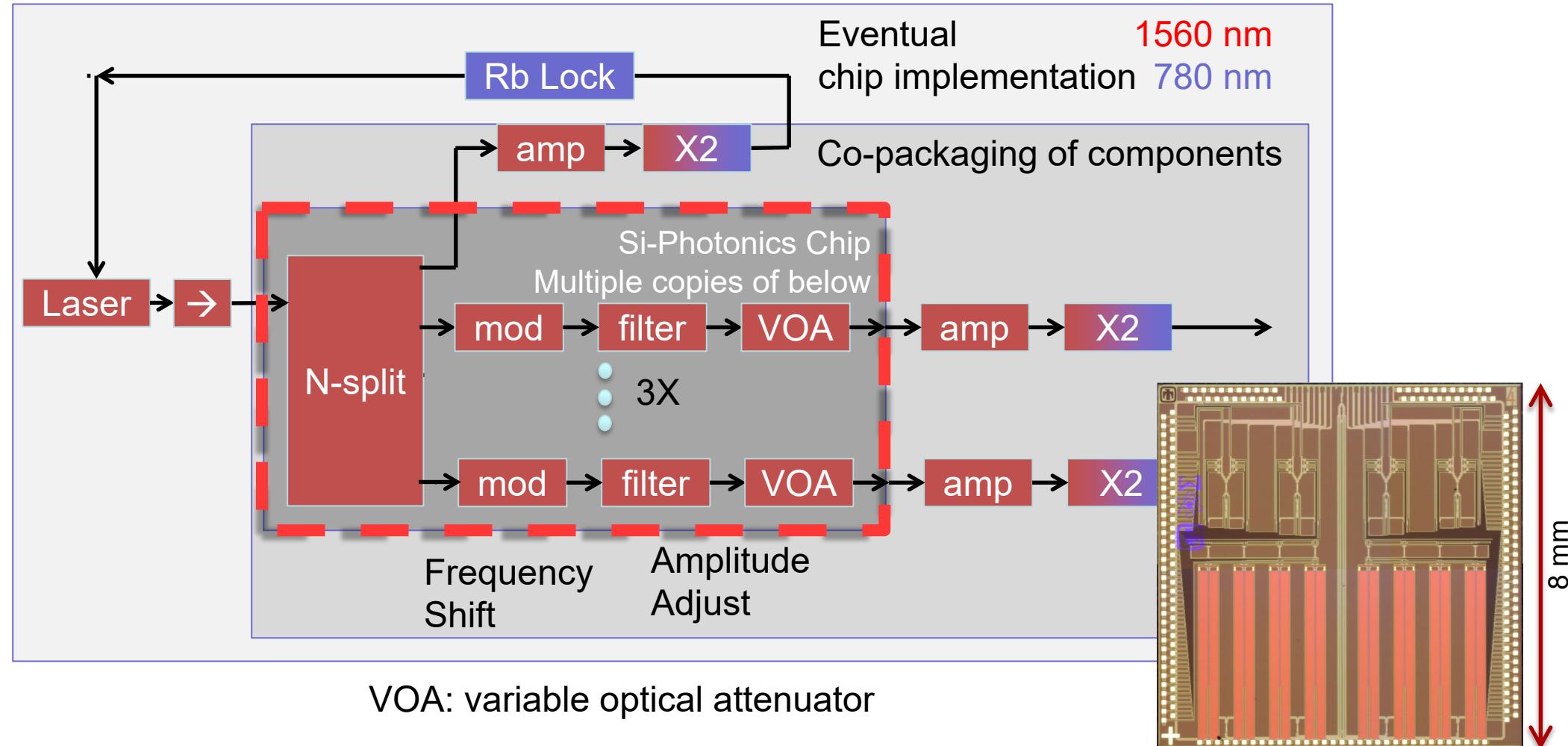


Timing

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

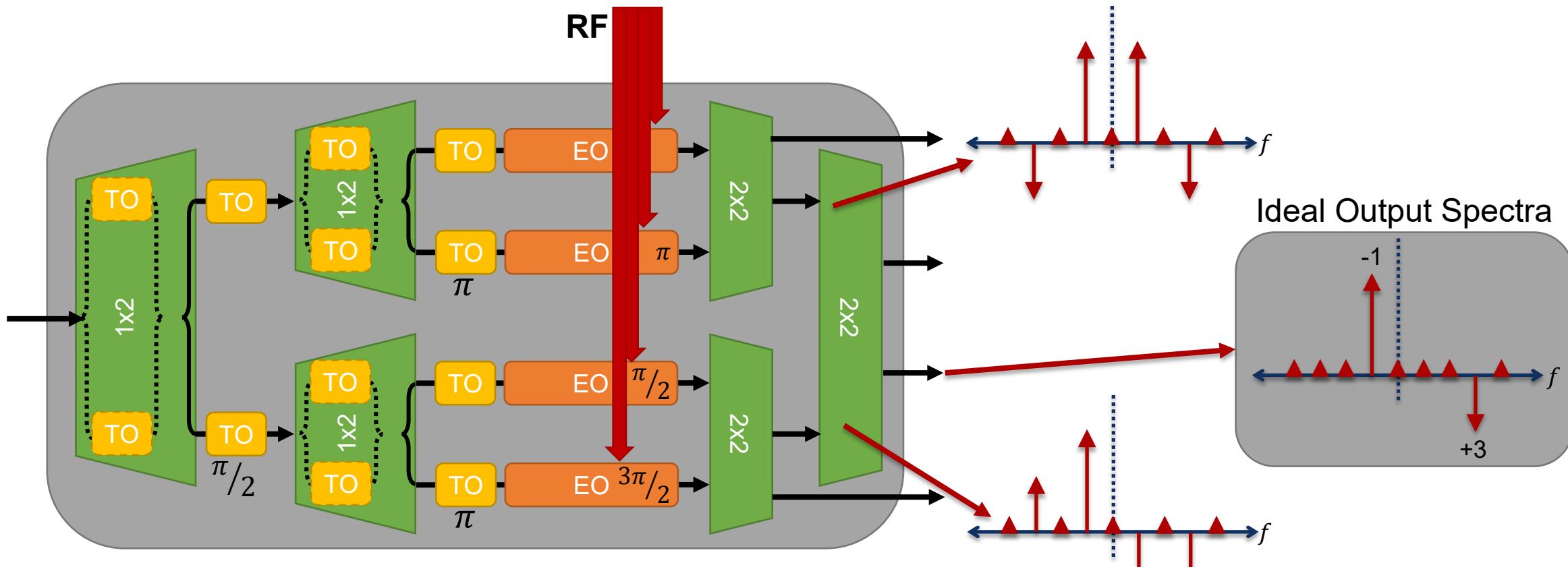
Integrated Photonics Overview

Scalable Photonic Architecture

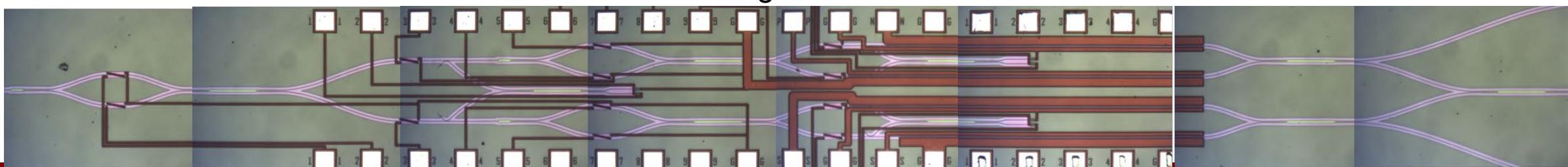


Patent application: Compact Laser Source with Frequency Modulators Generating Multiple Lines, Appl. No. 16/831,350

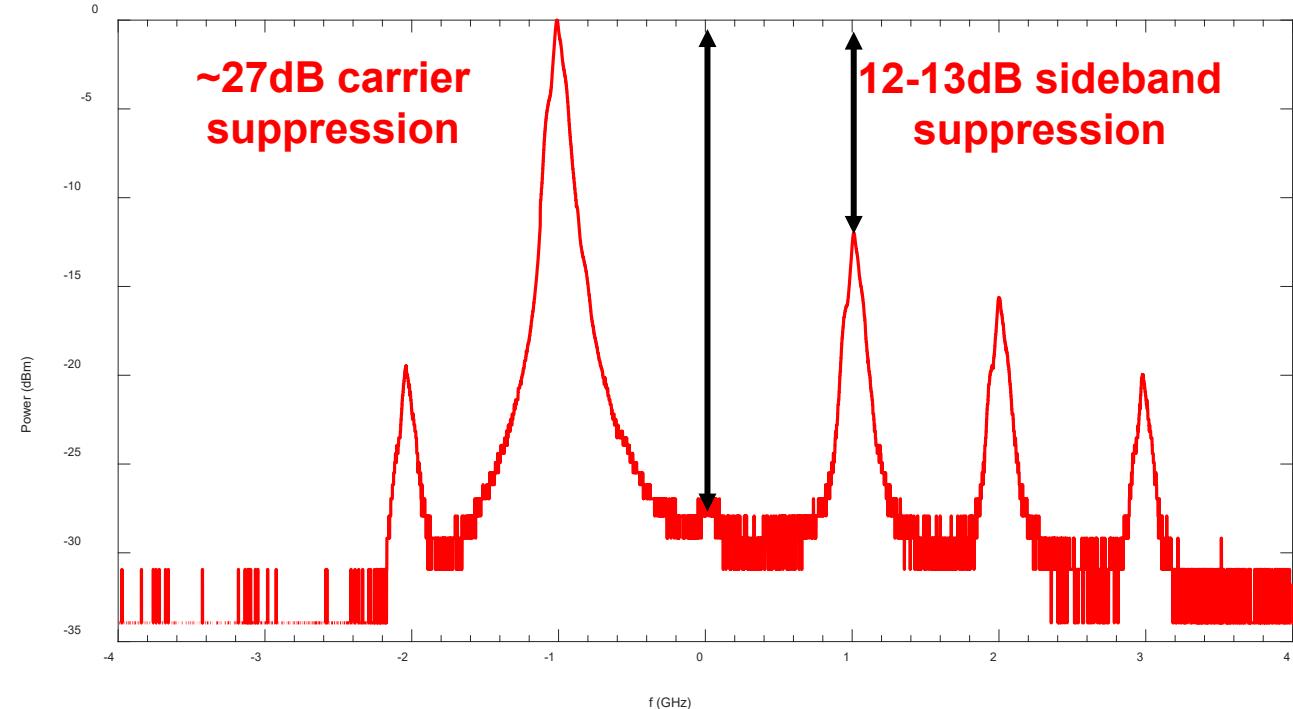
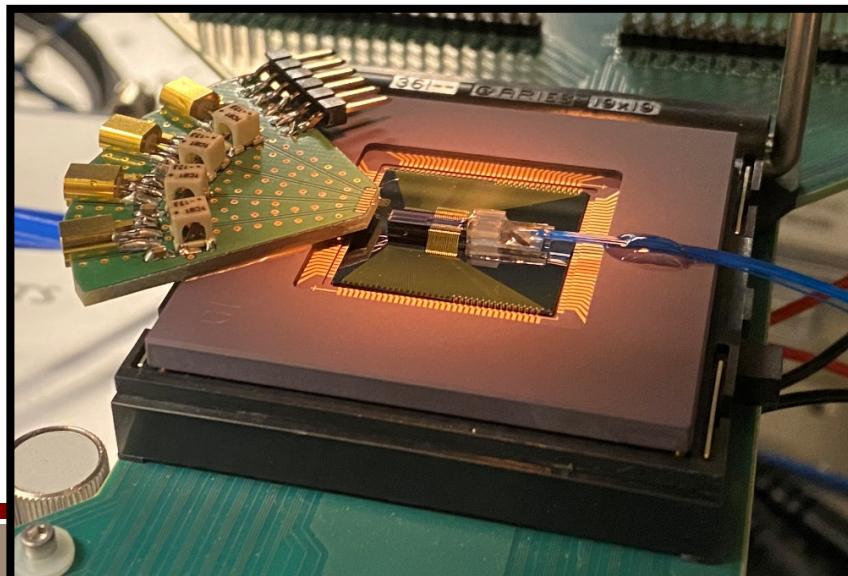
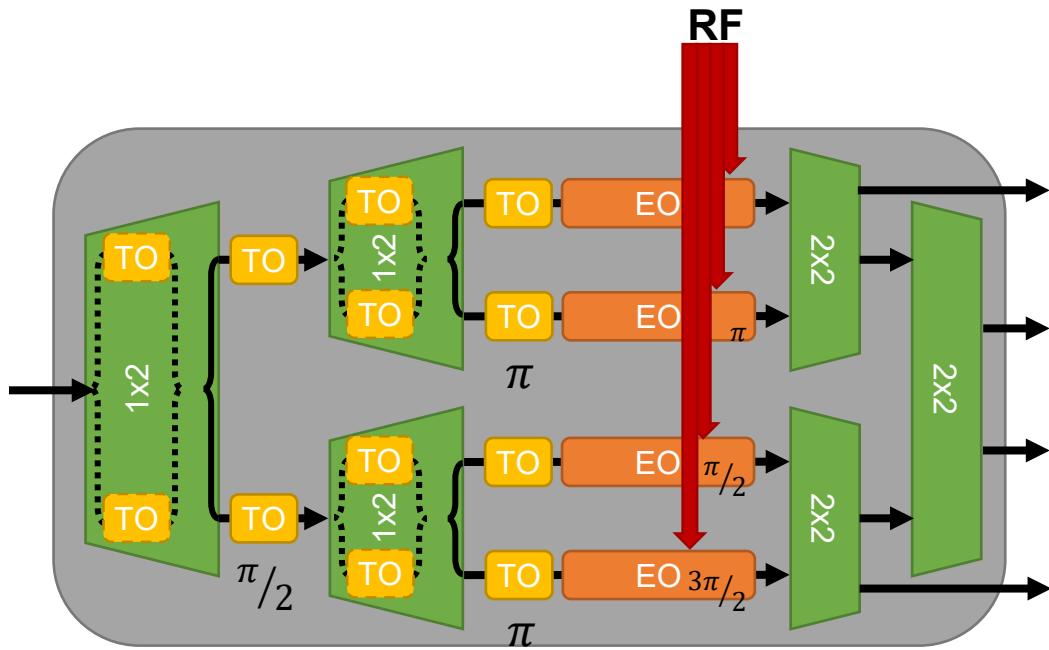
Suppressed-Carrier Single Side-Band Modulator



Silicon Photonic Integrated Circuit

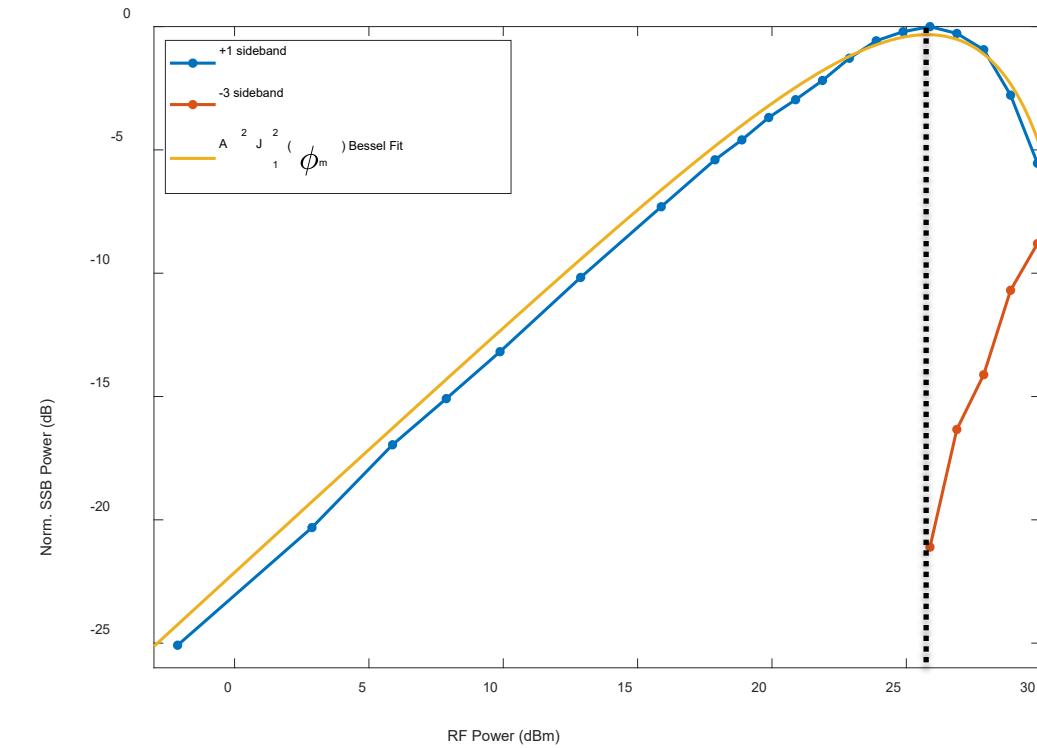
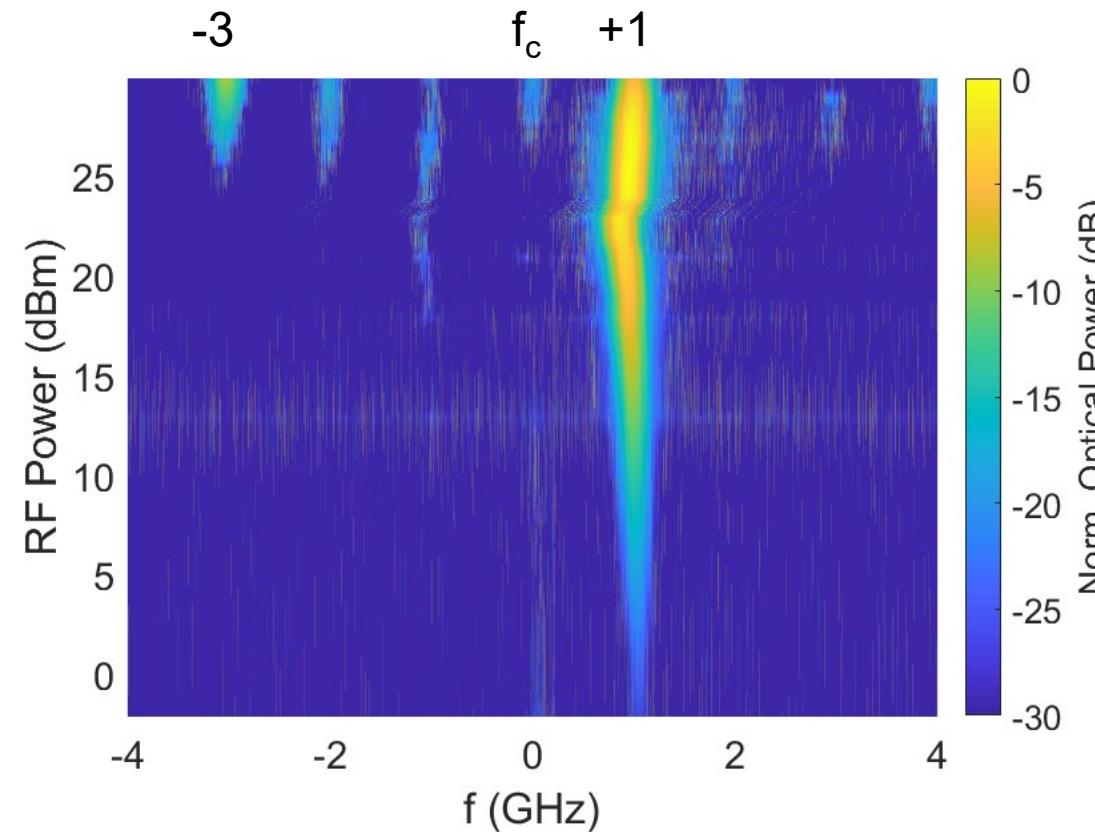


Single Side-Band Modulator Spectrum



A. Kodigala et. al., "Silicon Photonic Single-Sideband Generation with Dual-Parallel Mach-Zehnder Modulators," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, 2019), paper STh4N.6.

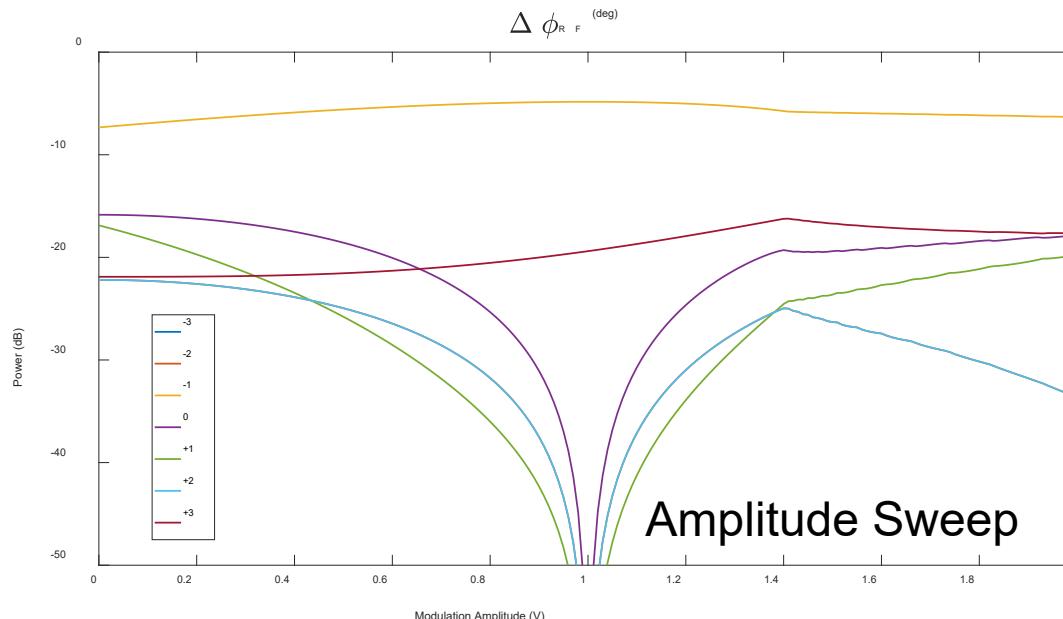
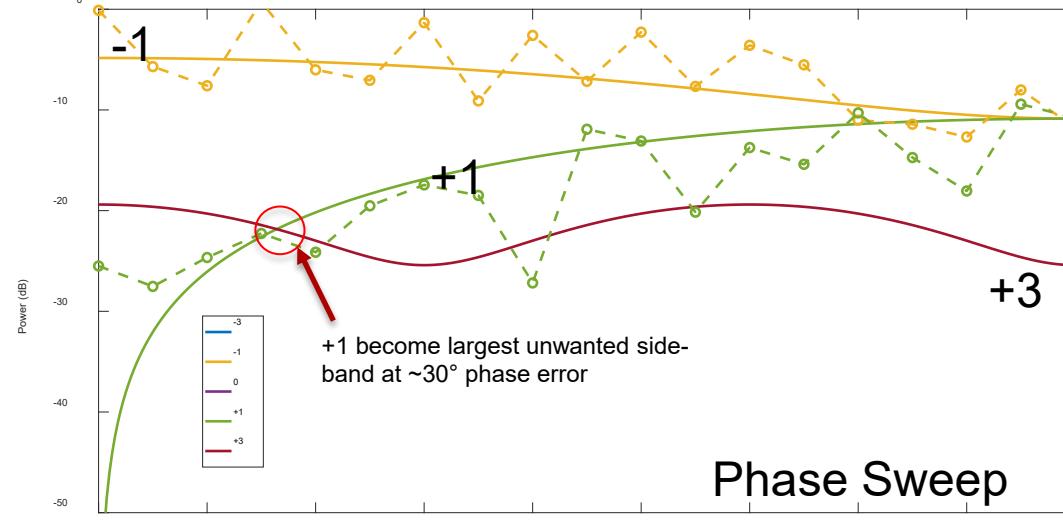
Single Side-Band Modulator Gen II Results



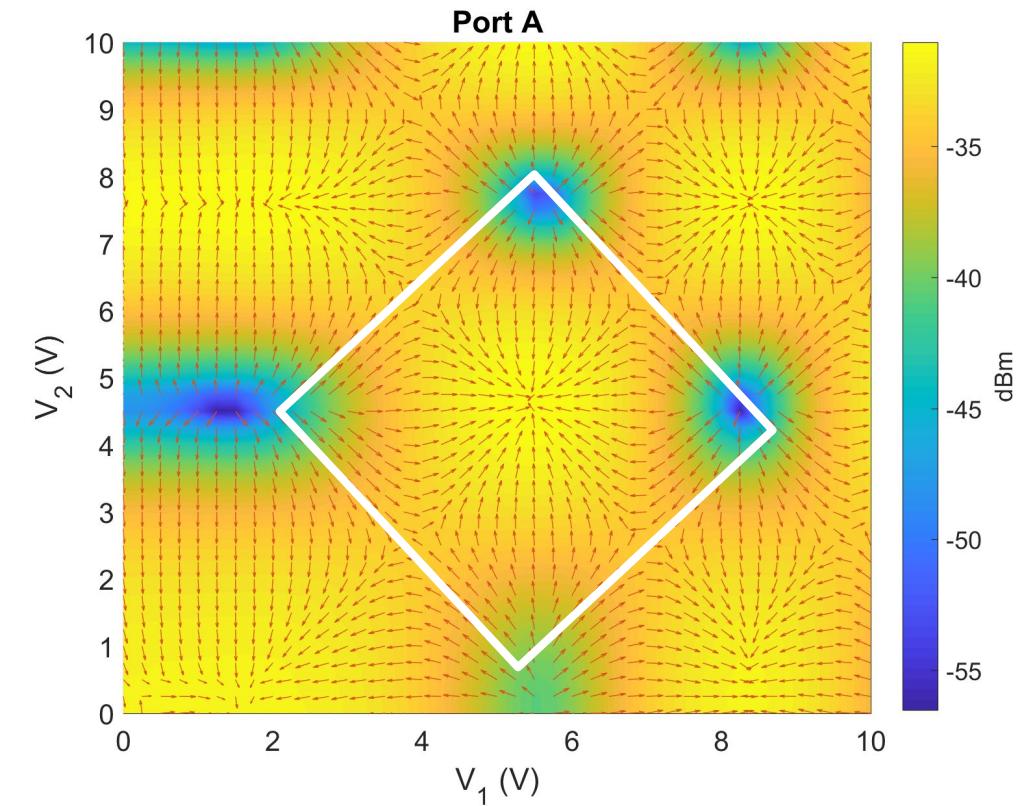
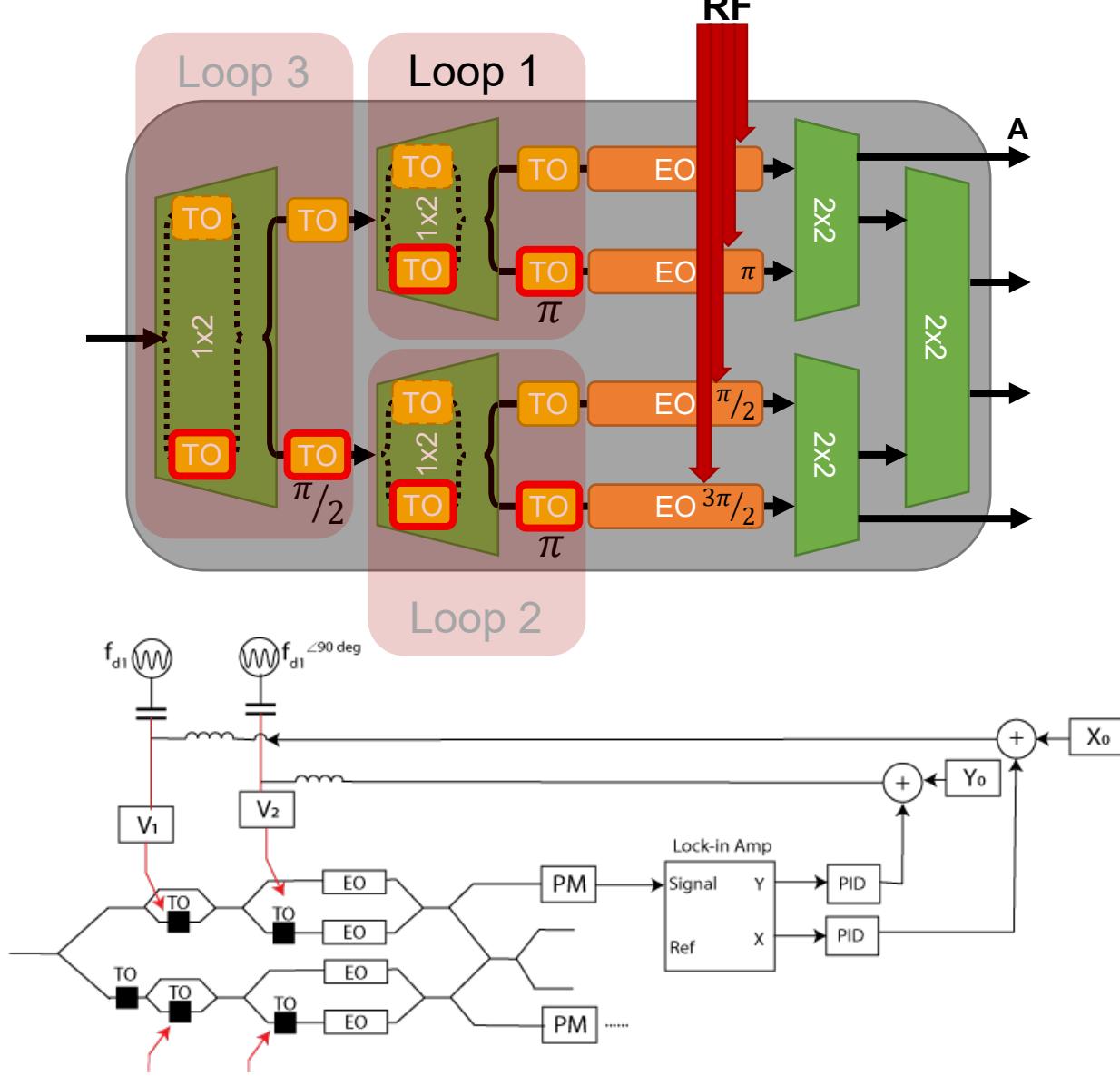
Optimum at RF powers close to ~400mW
Bessel Fit Provides $-V_{\text{TL}} = 0.557 \text{ V} \times \text{cm}$

Single Side-Band Modulator Modeling

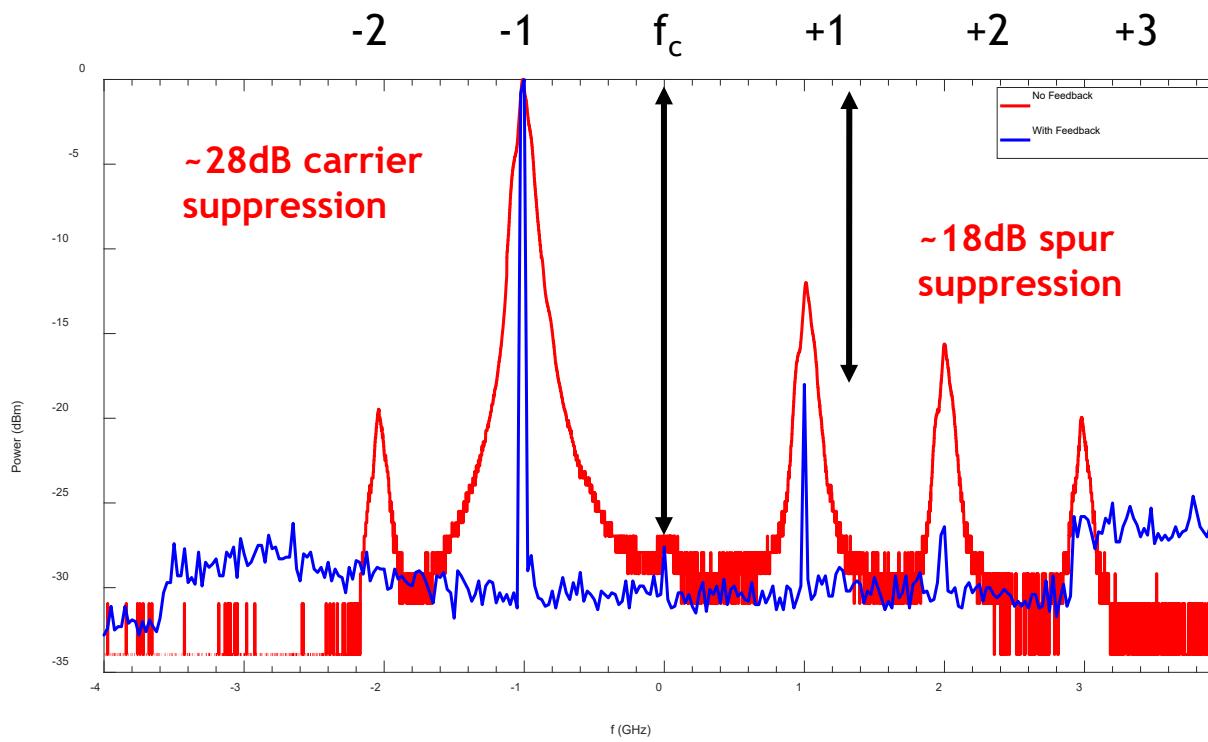
- Implemented 4 channel RF source for independent phase and amplitude control of modulator
- Comparison to previous modeling work in progress
 - Relatively insensitive to RF phase
 - $\pm 30^\circ$ before extra spurs become dominate
 - Very sensitive to RF amplitude
 - ± 0.3 dB required to maintain >35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



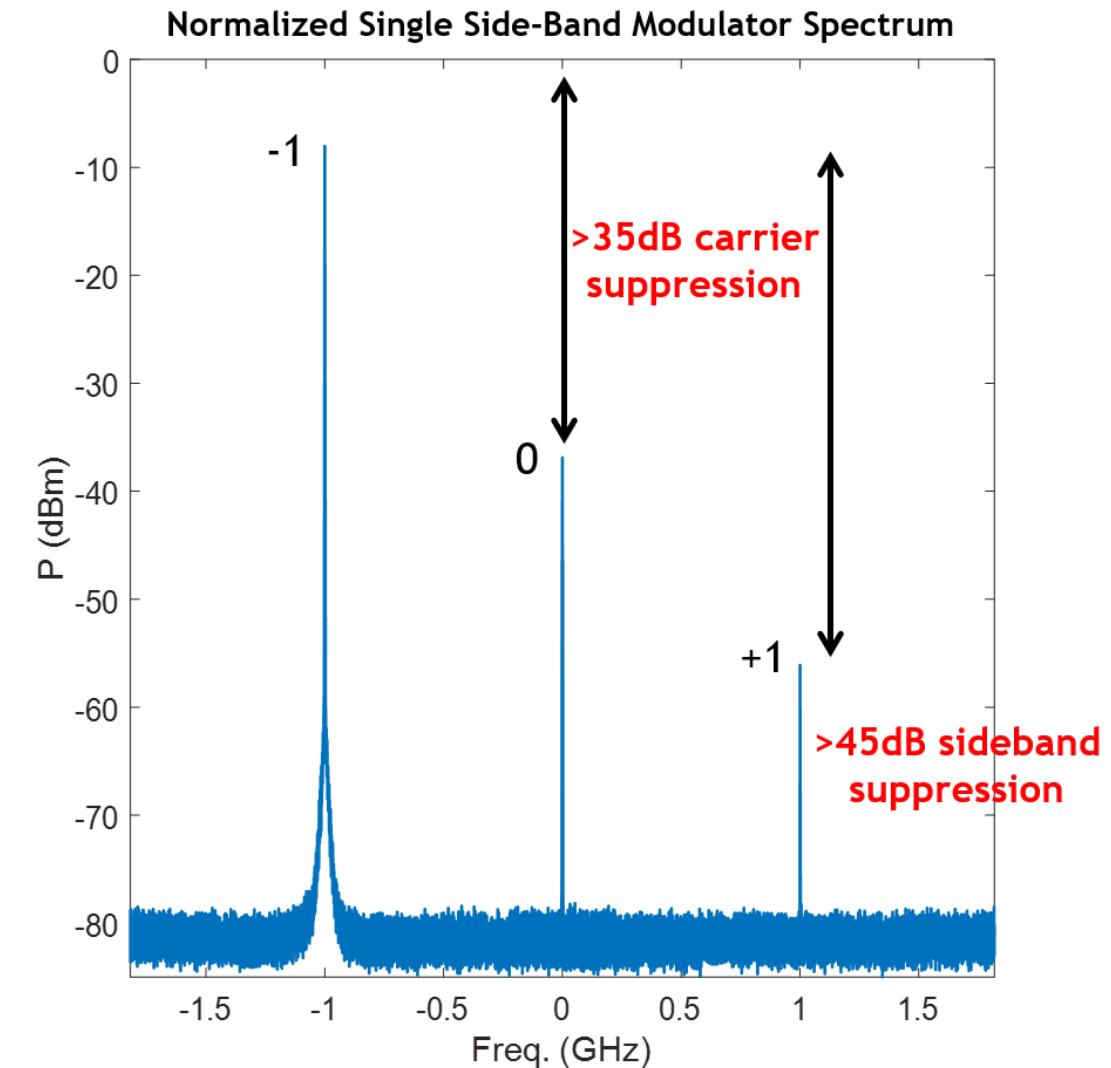
Single Side-Band Modulator Feedback



Single Side-Band Modulator Active Control



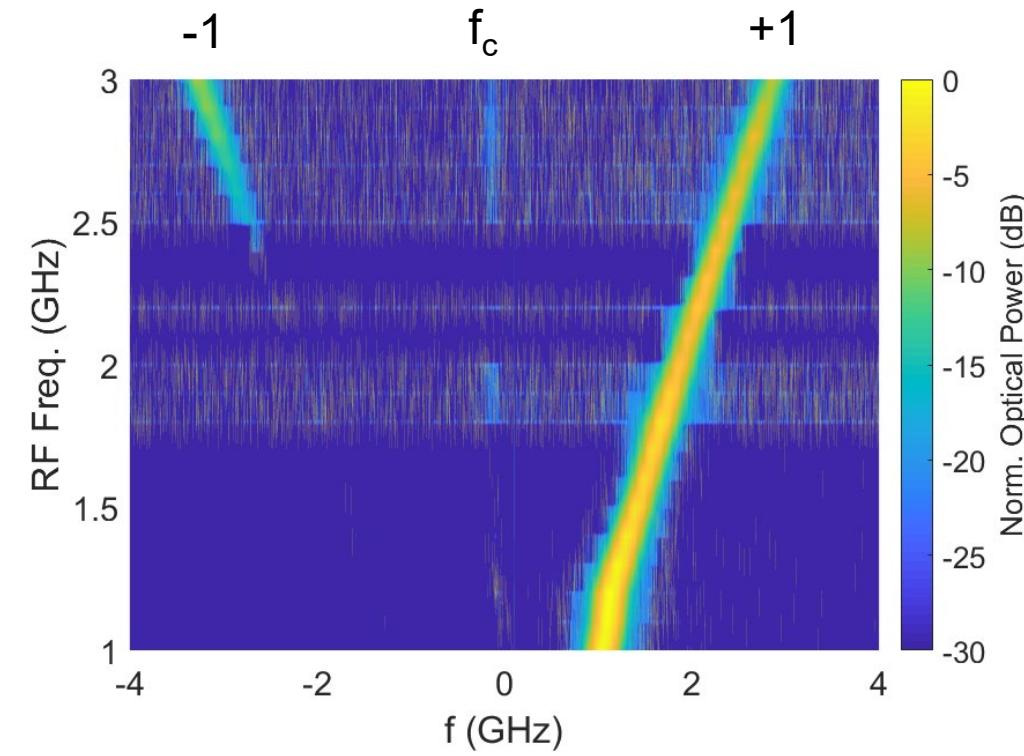
*implemented higher resolution heterodyne spectral measurement



Frequency Response

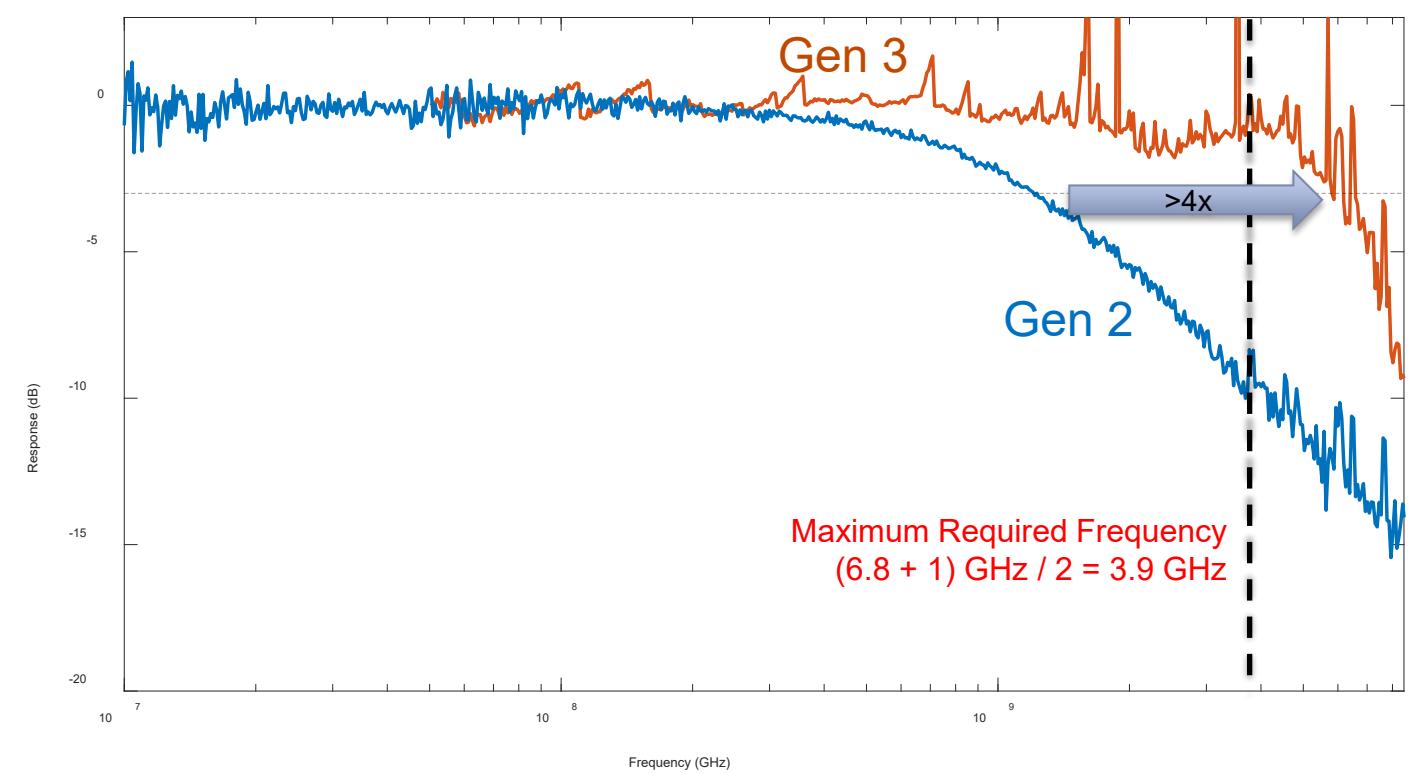
■ Generation 2

- Lumped element modulators



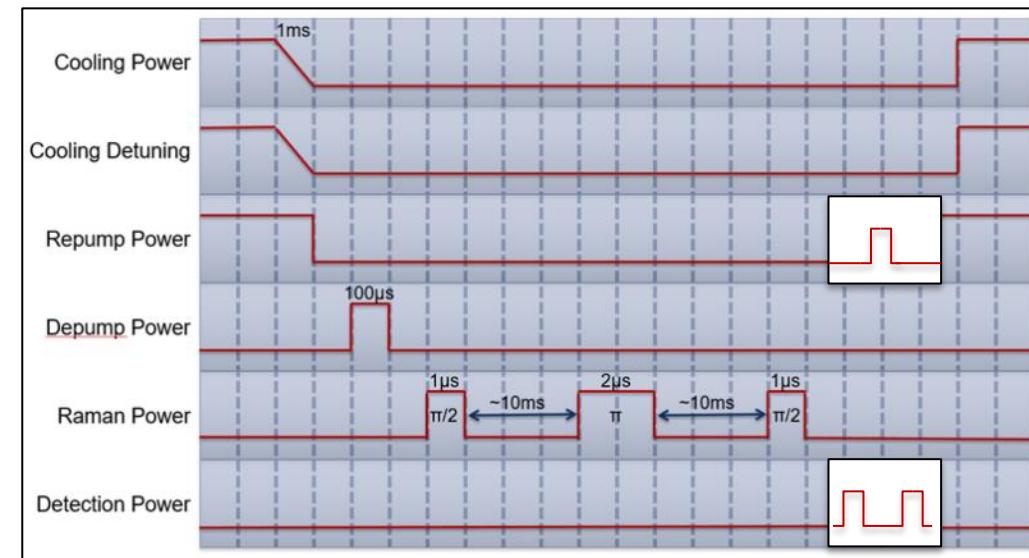
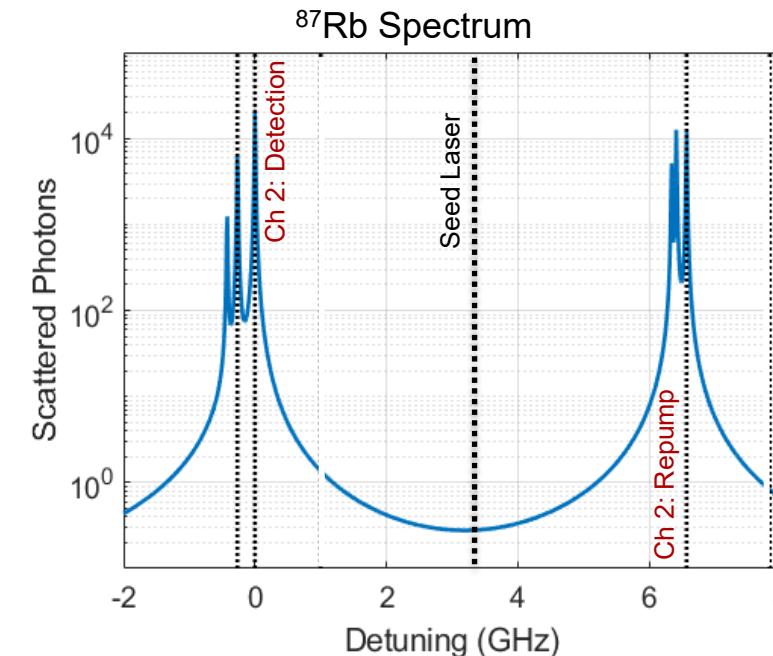
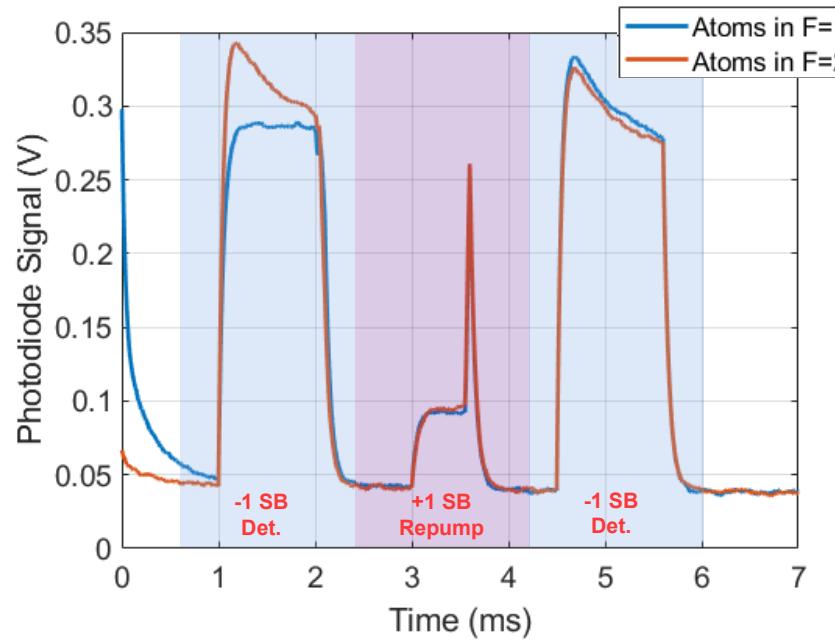
■ Generation 3

- Traveling wave modulators

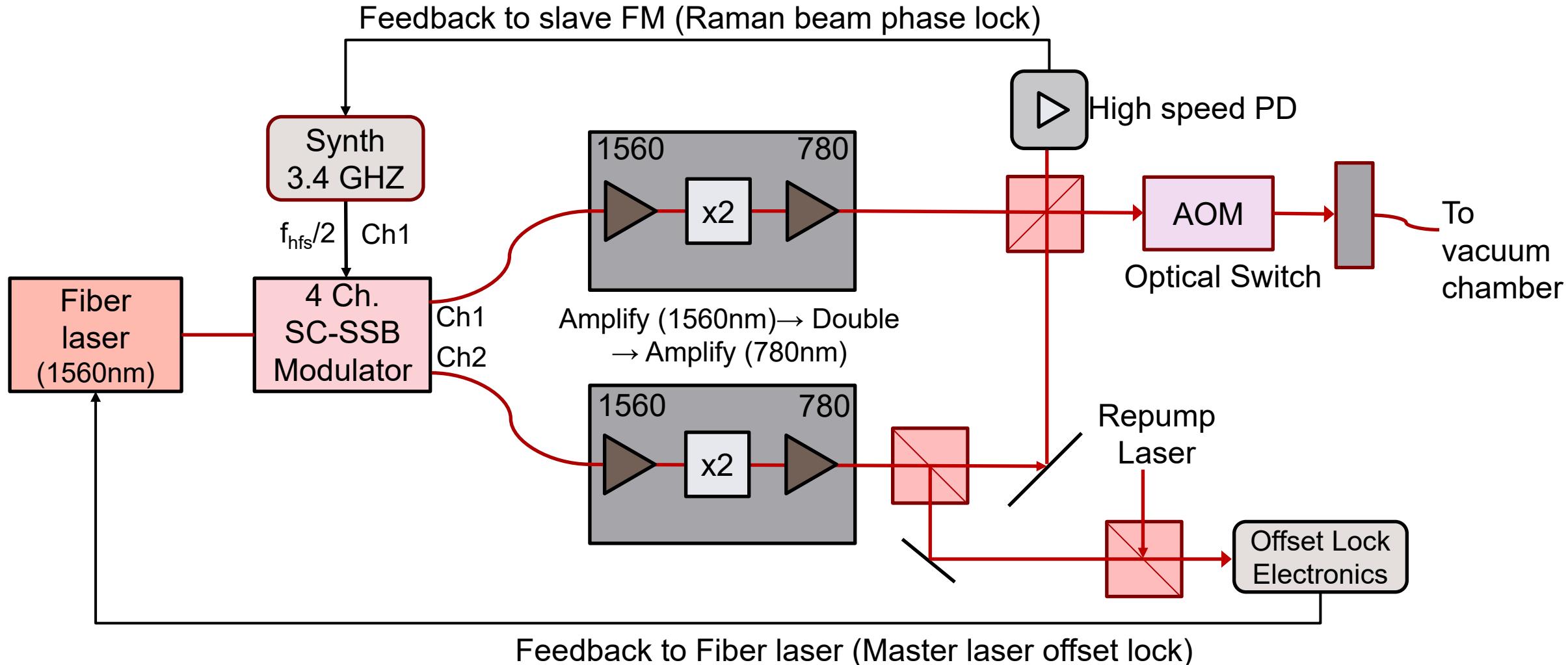


Packaged SSBM Demonstration

- 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**

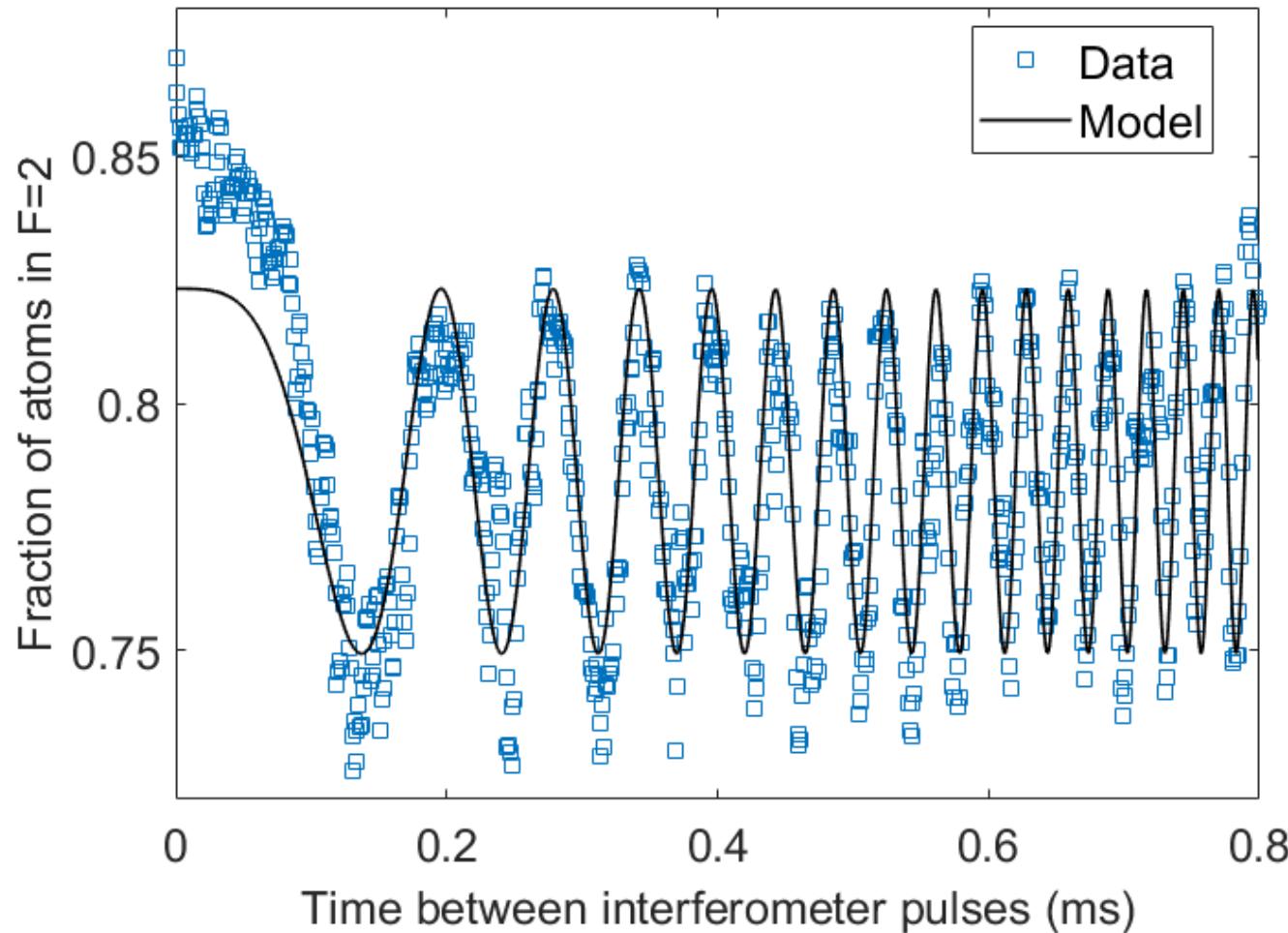


Integrated Photonics Raman Laser Setup



SC-SSB: Suppressed Carrier Single Sideband

AI Demonstration with Integrated Raman Laser Setup

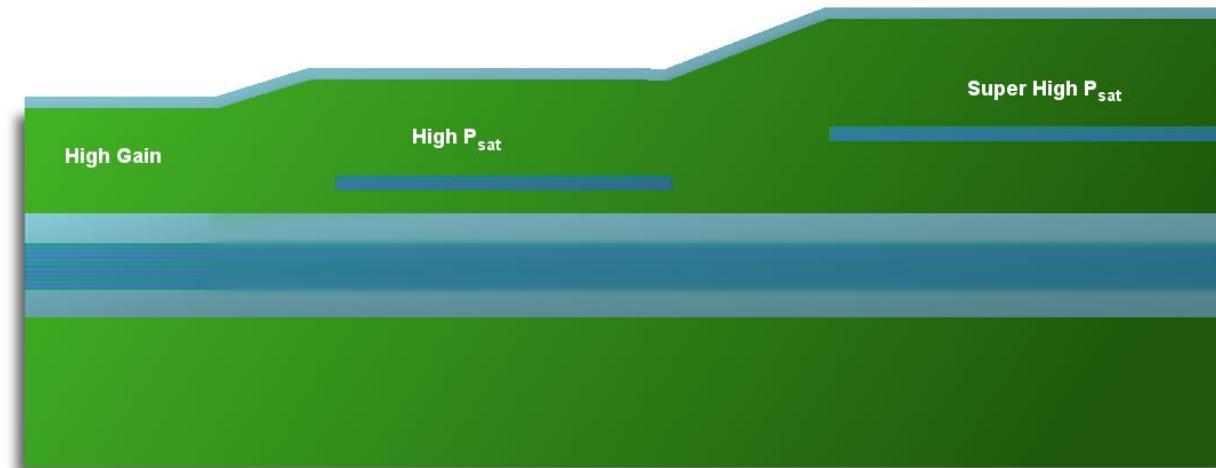


- Demonstrate an AI accelerometer, an atomic gravimeter with SIP Raman laser setup
- $\pi/2 \rightarrow \pi \rightarrow \pi/2$, where $\tau_\pi = 5 \mu\text{s}$
- Measure the chirped fringe from the Doppler-shifted atomic resonance due to gravitational acceleration
- Estimate the gravity with a model: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

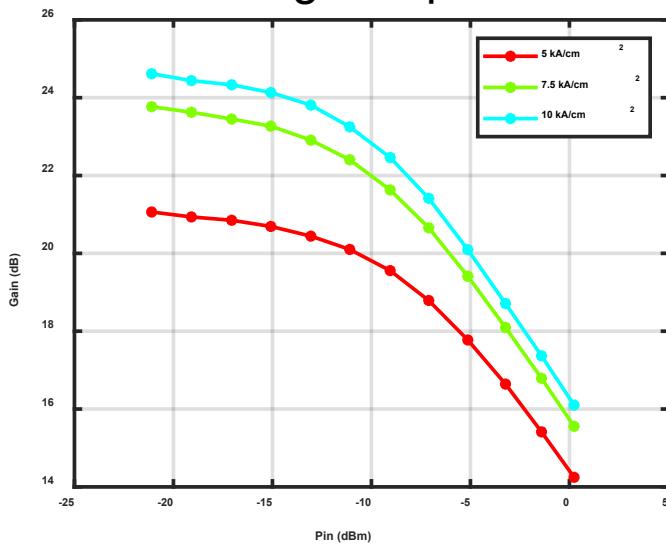
AMPLIFIER AND FREQUENCY DOUBLER

Three-stage optical amplifier in III-V materials

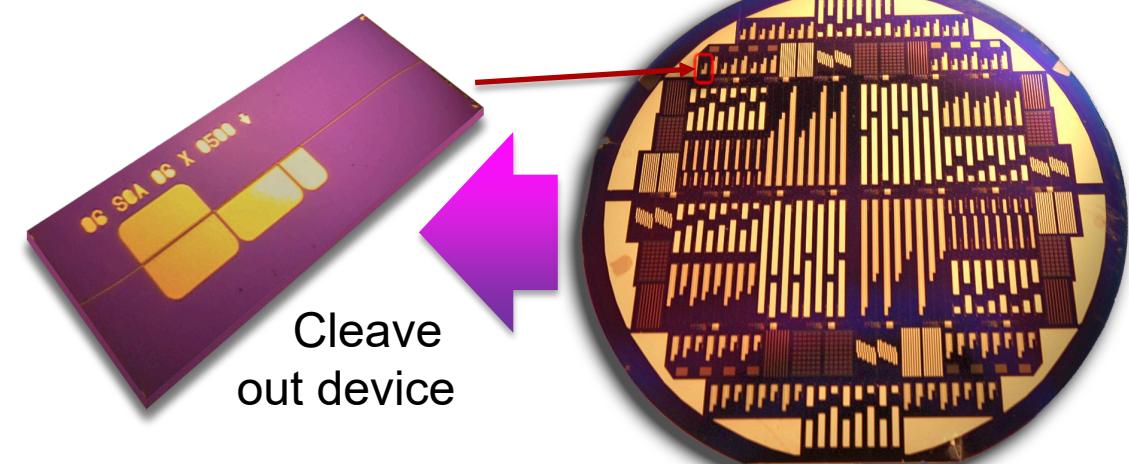
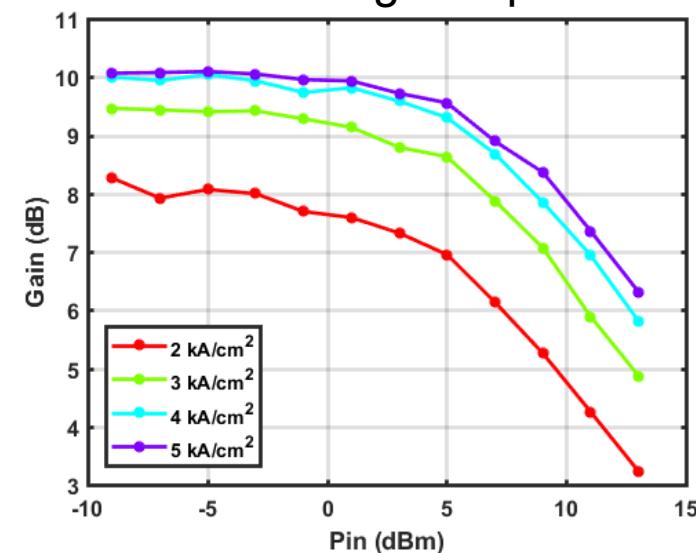
- Need nearly 1 W of 1560 nm power
- Large optical power challenging
 - Saturate gain materials
- First two stages successful
- Last stage needs more fabrication development



First stage amplifier



Middle stage amplifier

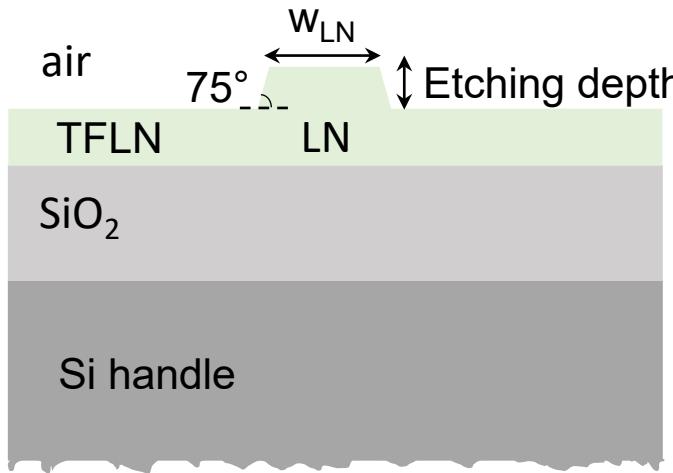


Cleave out device

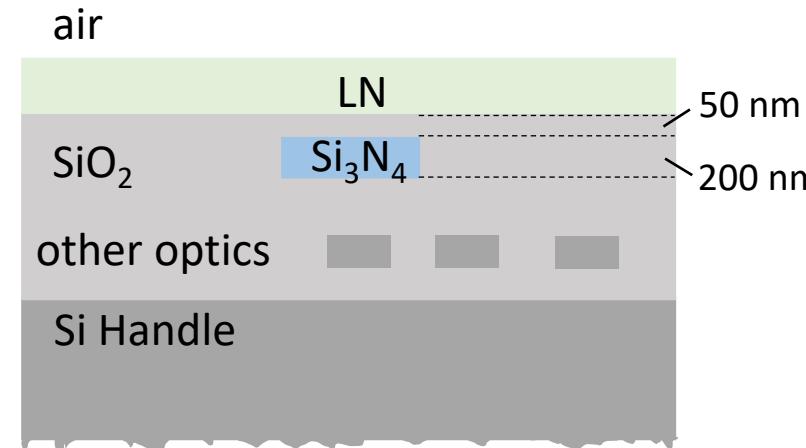
Wafer Complete

Frequency Doubler with Lithium Niobate: Two approaches to Waveguides

Rib-etched LNOI



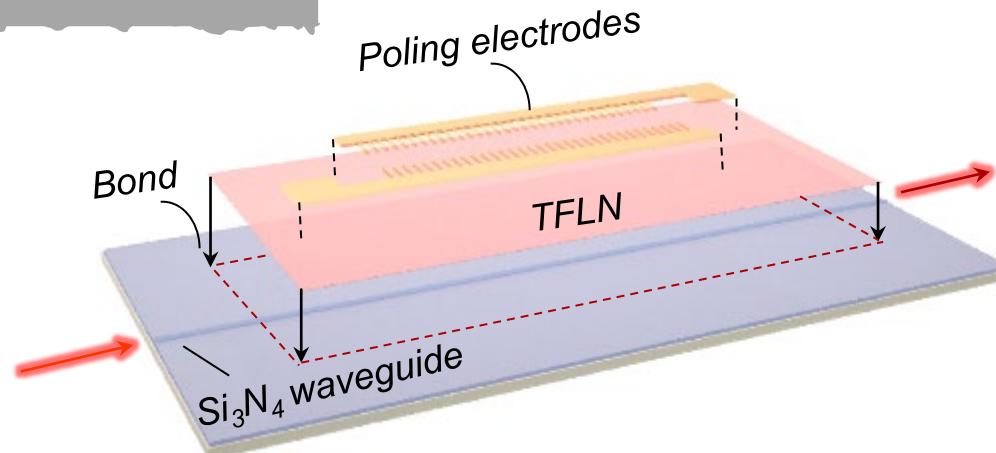
Strip-loaded, bonded LNOI



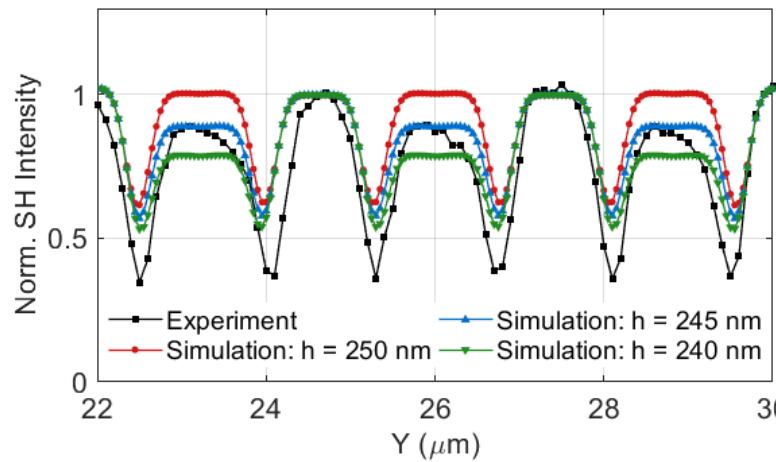
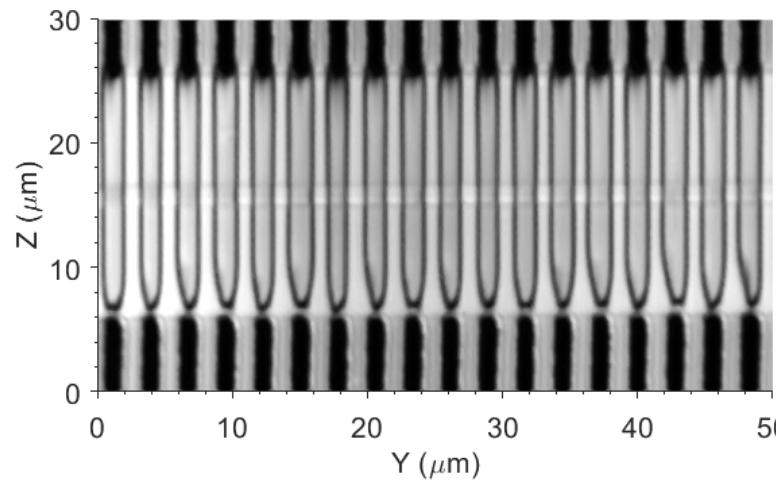
- Disorder-tolerant waveguide design.
- First pole, then verify poling quality, and finally, shallow etch.
- Etched at Univ. Rochester, collaboration w/ Qiang Lin's group. Other options now exist.

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 Sandia e.g., N. Boynton et al. Opt. Express 28, 1864 (2020).

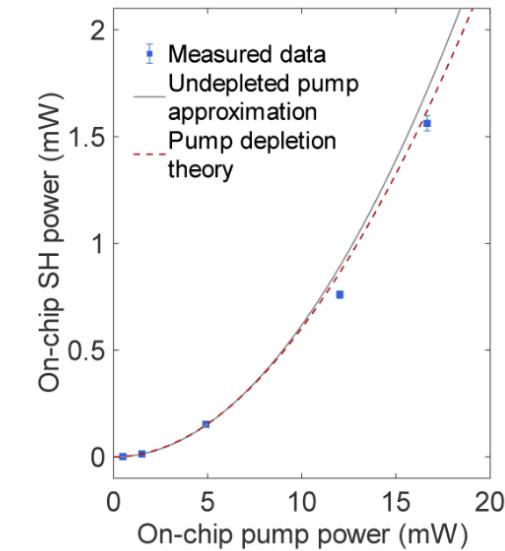
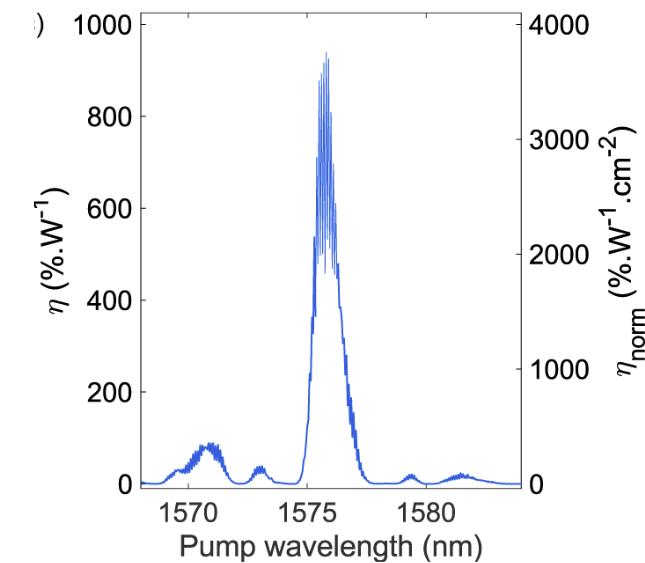


Imaging of domain walls and record doubling efficiency



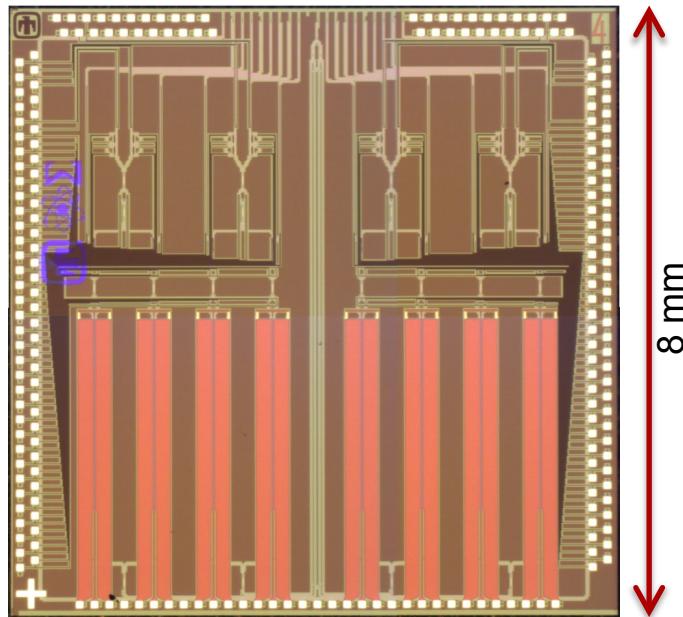
- Jie Zhao, et al. Phys. Rev. Lett. 124, (2020)
- M. Ruesing, et al. J. of App. Phys., Vol. 126, 114105 (2019)

- 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



Development of key components: hybrid integration in single Si chip

Silicon Photonic Single Sideband Modulator

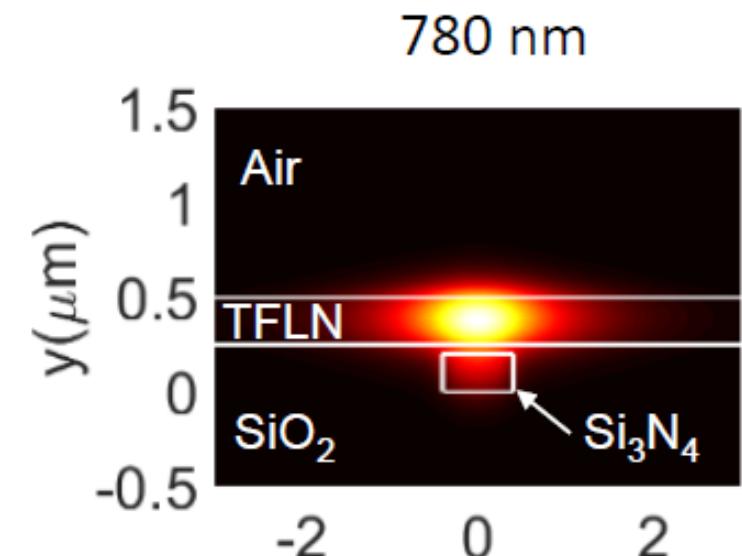


Amplifier

- 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

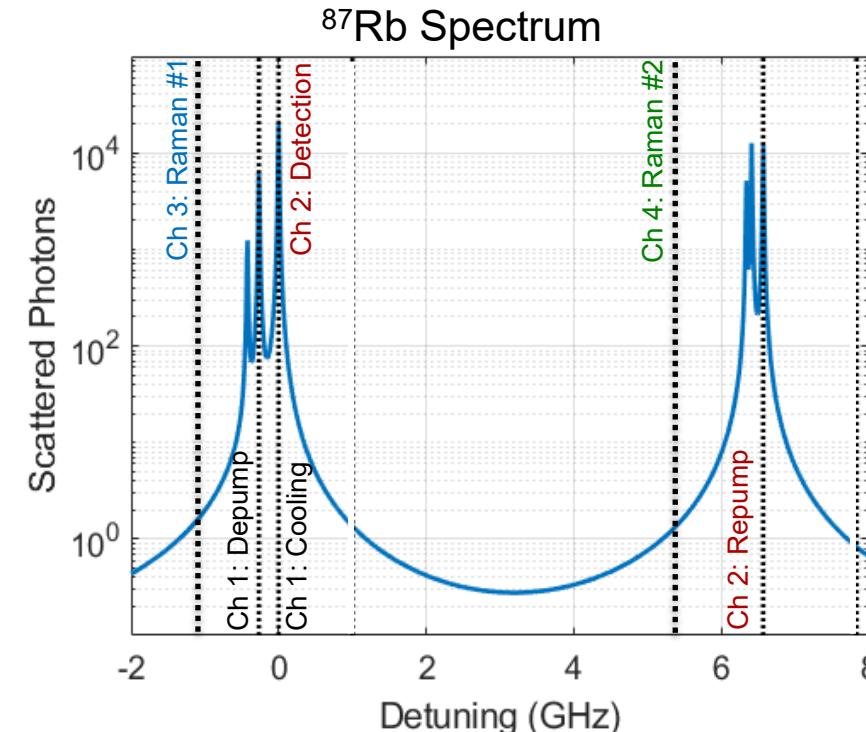
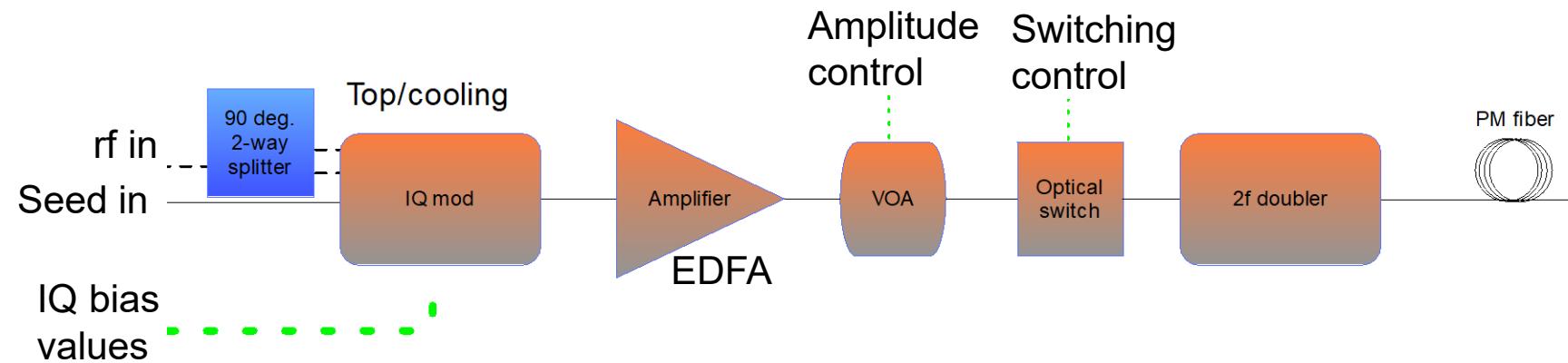
COMPACT ATOM INTERFEROMETER SENSOR HEAD

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

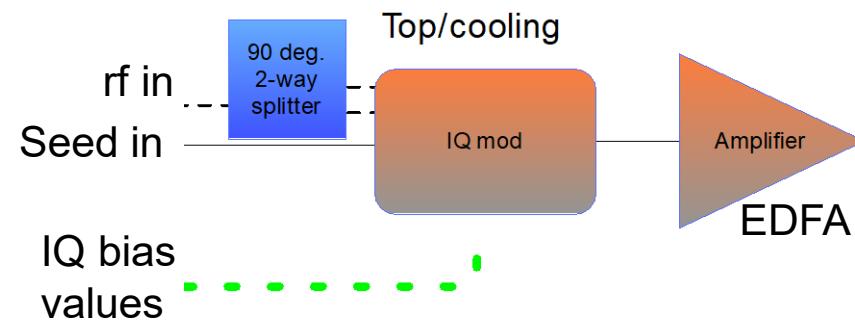


Commercial off the Shelf (COTS) Laser Architecture

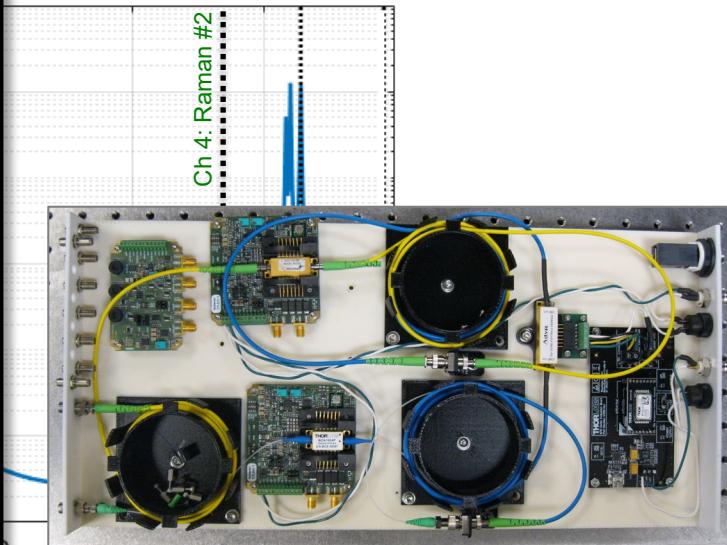
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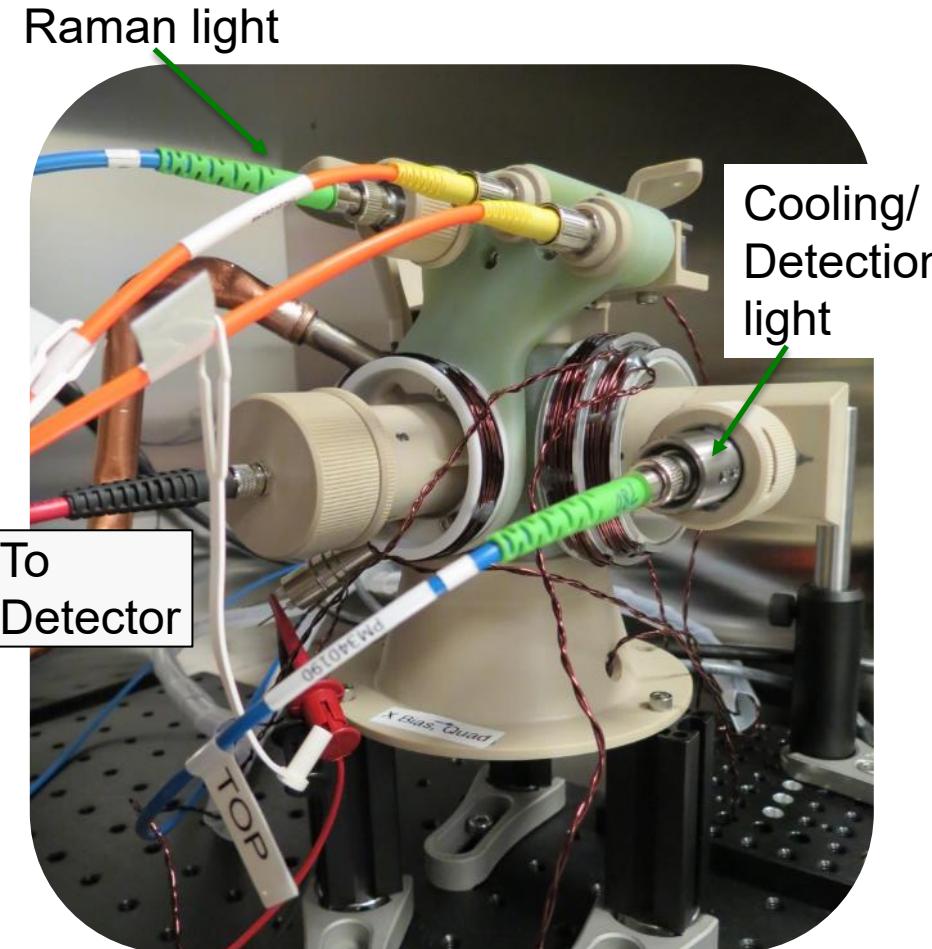
Seed : NP Photonics Rock Fiber Las



Spectrum

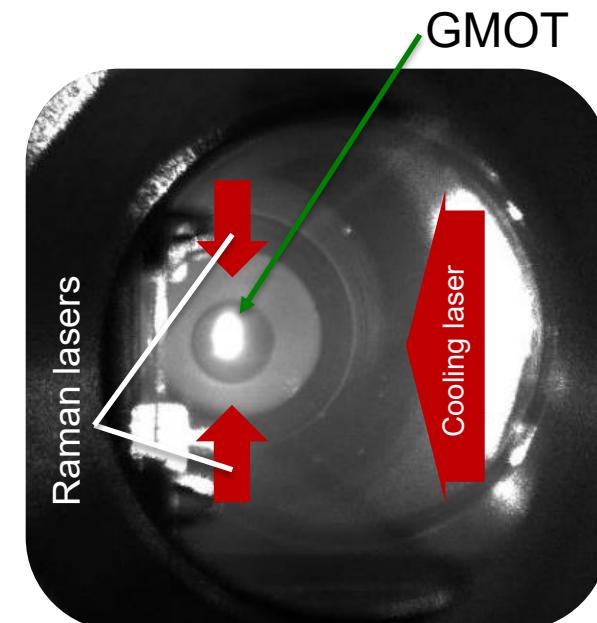


Compact Atom Interferometer Sensor Head

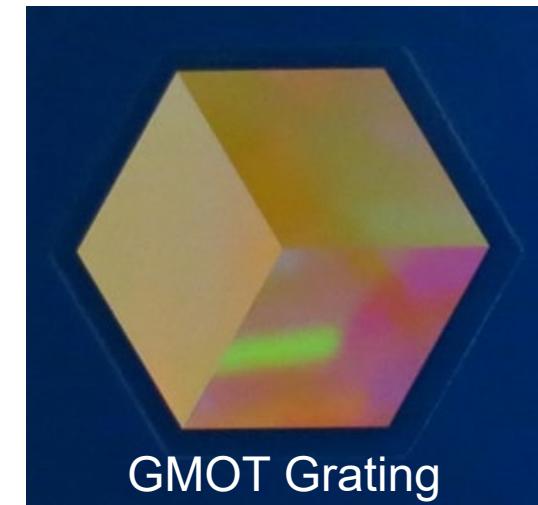
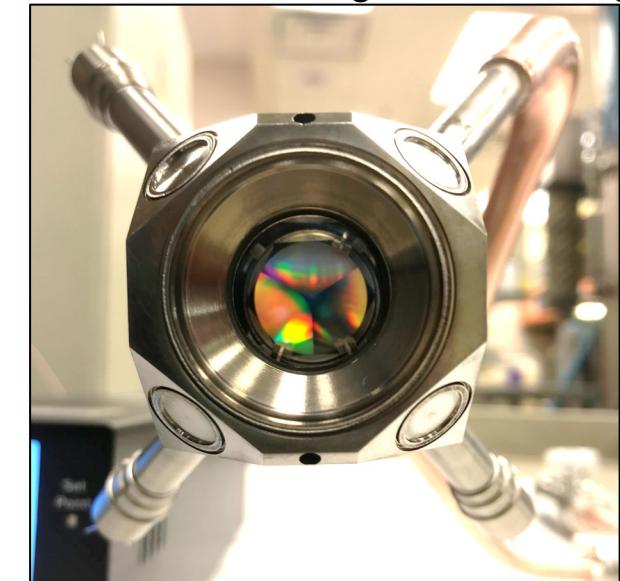


Patent Applications:
Compact Laser Source with Frequency Modulators Generating Multiple Lines, Appl. No. 16/831,350
Compact Grating-Based Magneto-Optical Trap Sensor Head for Cold Atom Inertial Sensors in Dynamic Environments, Appl. No. 63/109,535

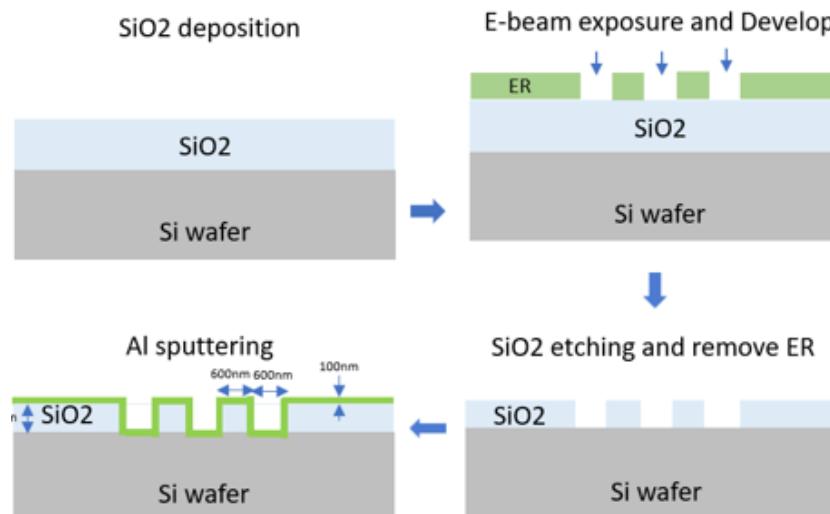
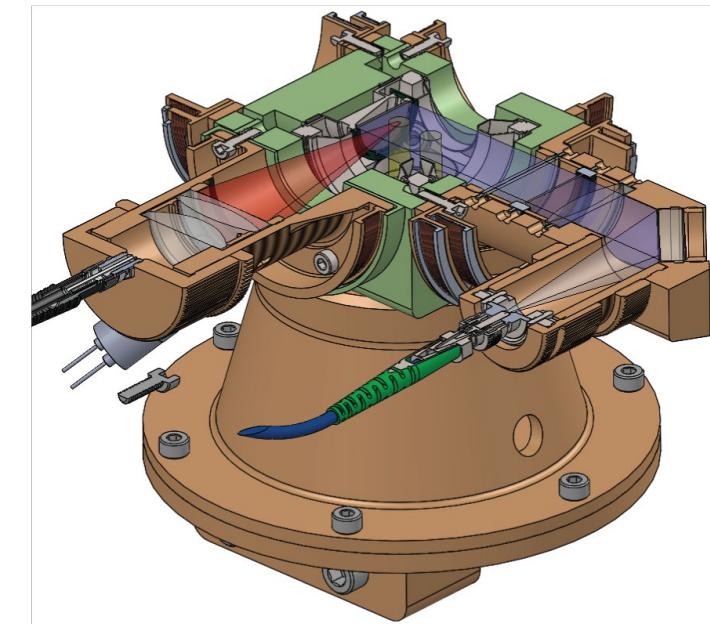
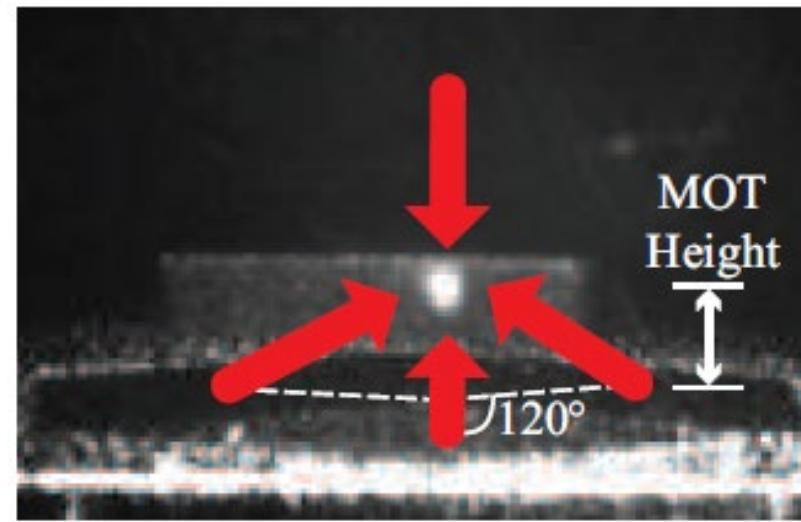
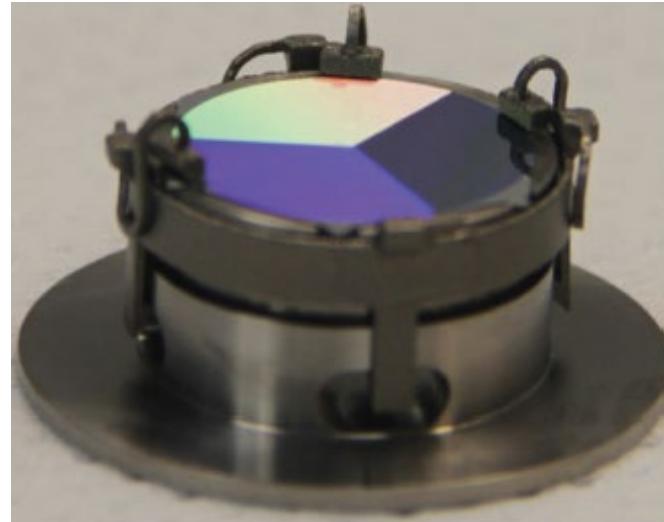
- Grating magneto optical trap (GMOT)
- Grating replaces one window of vacuum package
- Vacuum maintained by ion pump, fused silica windows
- Atom number: 10^6 - 10^7 , Sub-Doppler cooling: $18 \mu\text{K}$.



Ti Vacuum Package with Grating

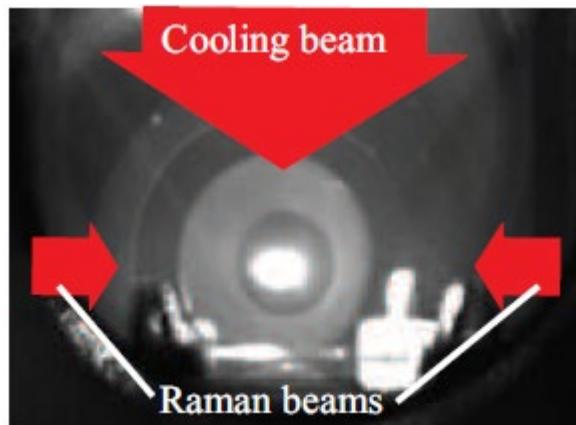


Grating-mirror Magneto-Optical Trap (GMOT)

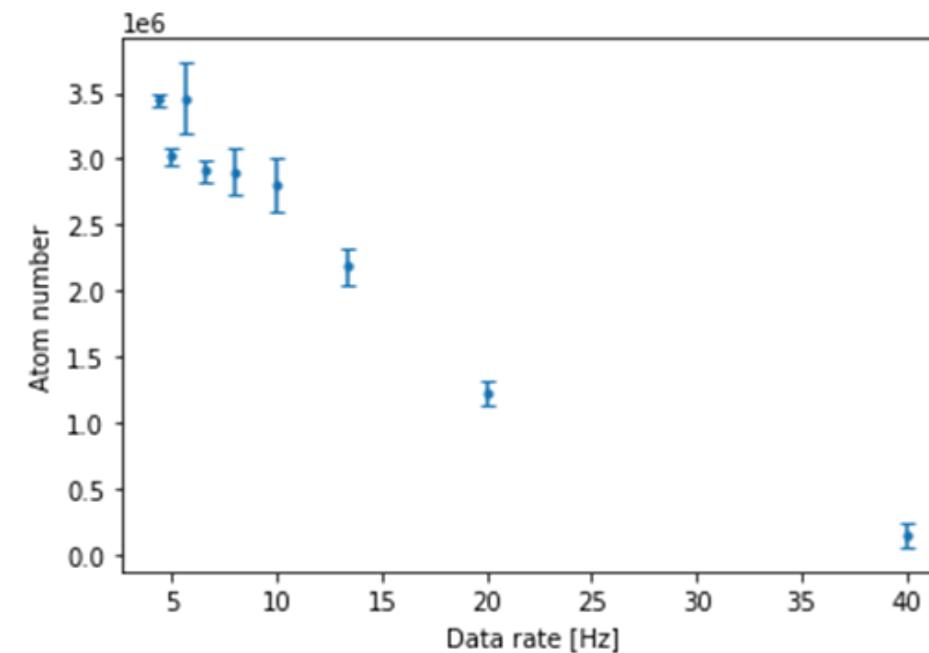
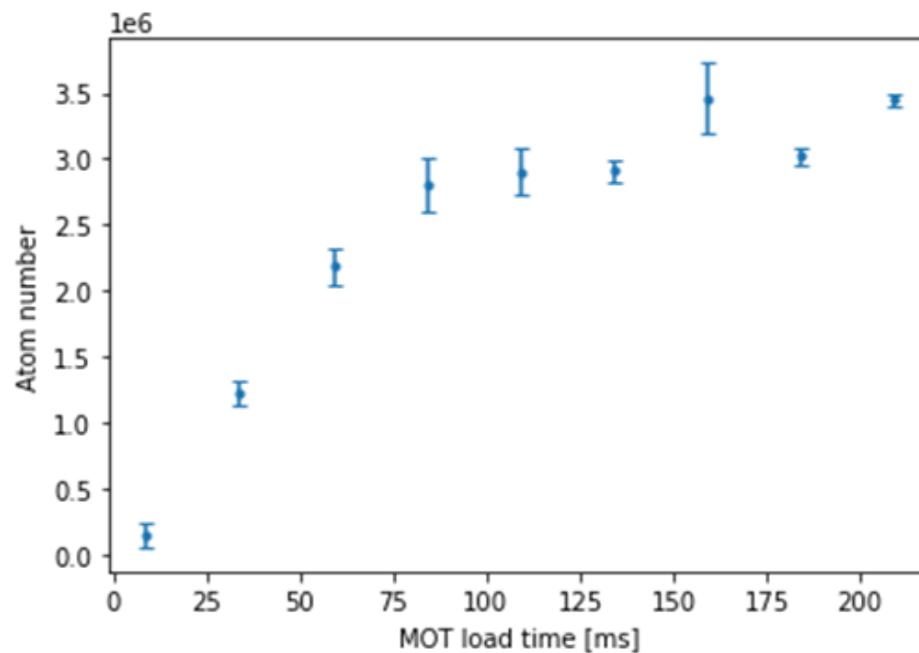


- Sandia-fabricated hexagonal reflective grating chip
 - 1.2 μm pitch, ~50% duty-cycle, and 195nm depth
 - Aluminum coating
- 3D-printed retainer ring to hold the grating chip for high dynamics
- Single-beam tetrahedral MOT configuration
- Compact sensor head with fixed alignment optical package to minimize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

Grating-mirror Magneto-Optical Trap (GMOT)

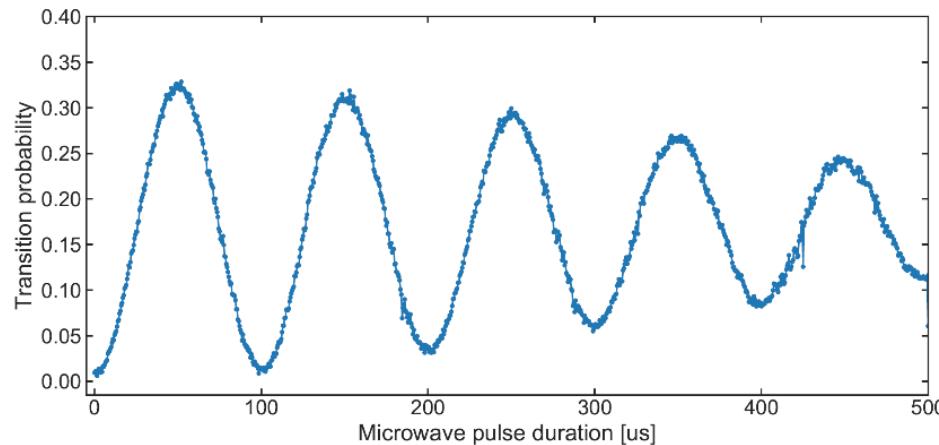


- Sub-Doppler cooled GMOT atoms ($T = 15\mu\text{K}$)
- High data-rate GMOT operation
- Atom interferometry with Doppler-sensitive Raman beams



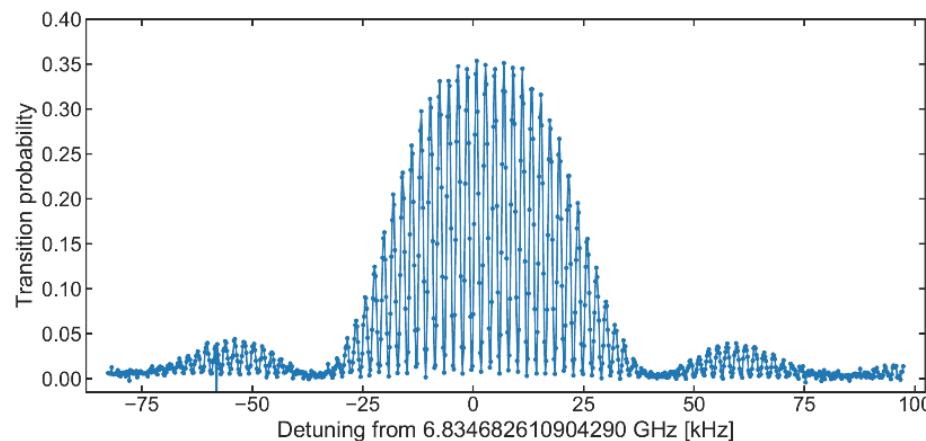
Atomic Coherence with GMOT

- Rabi oscillation with a microwave horn



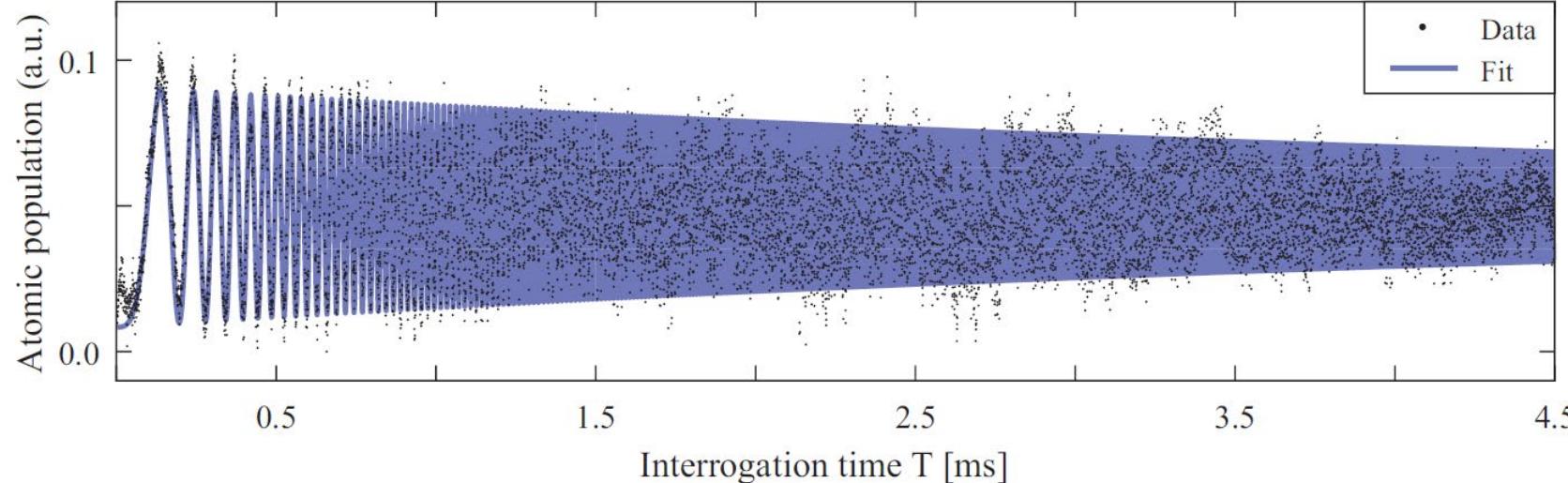
Rabi oscillation:
Rabi frequency $\simeq 10$ kHz

- Ramsey interferometry with a microwave horn

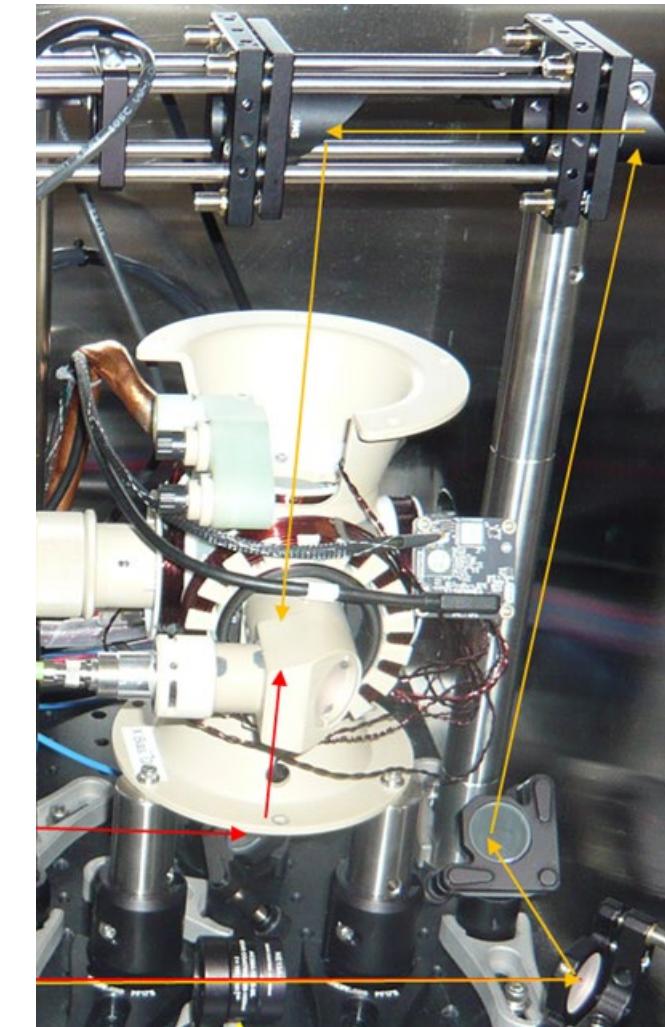
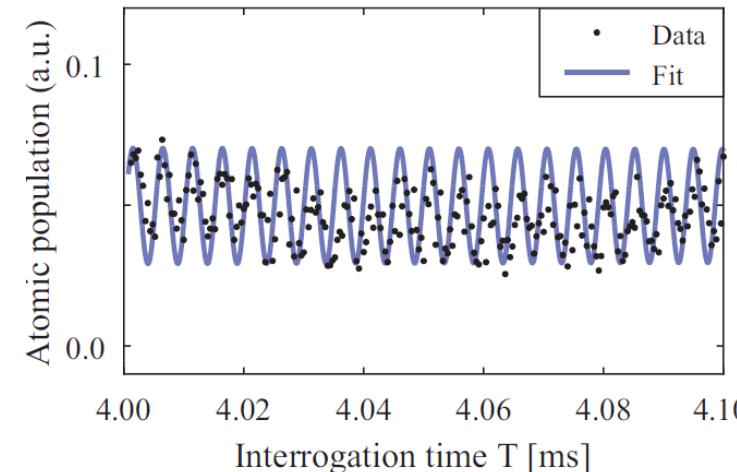


Ramsey sequence:
 $\frac{\pi}{2} \rightarrow T \rightarrow \frac{\pi}{2}$ (frequency scan)
Interrogation time $T = 450$ μs

Atom Interferometer Demonstration with GMOT



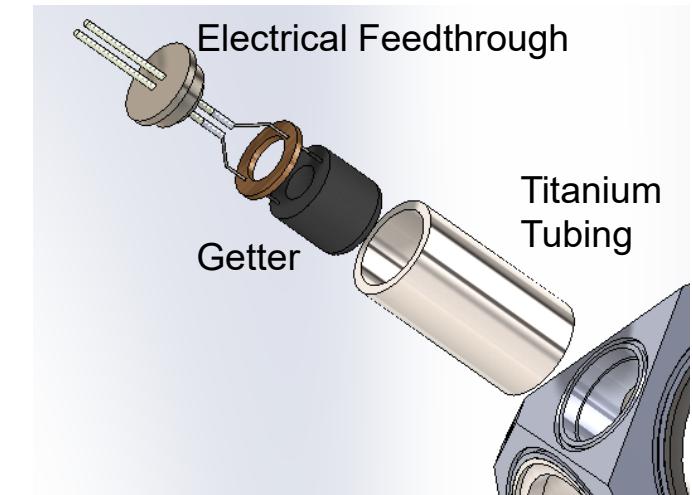
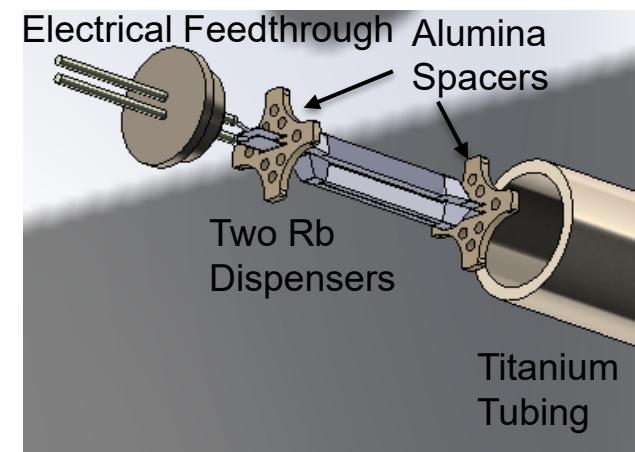
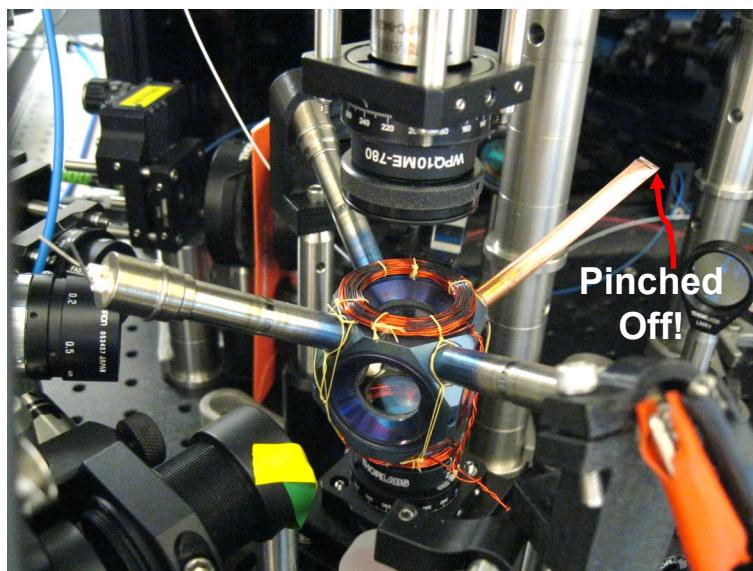
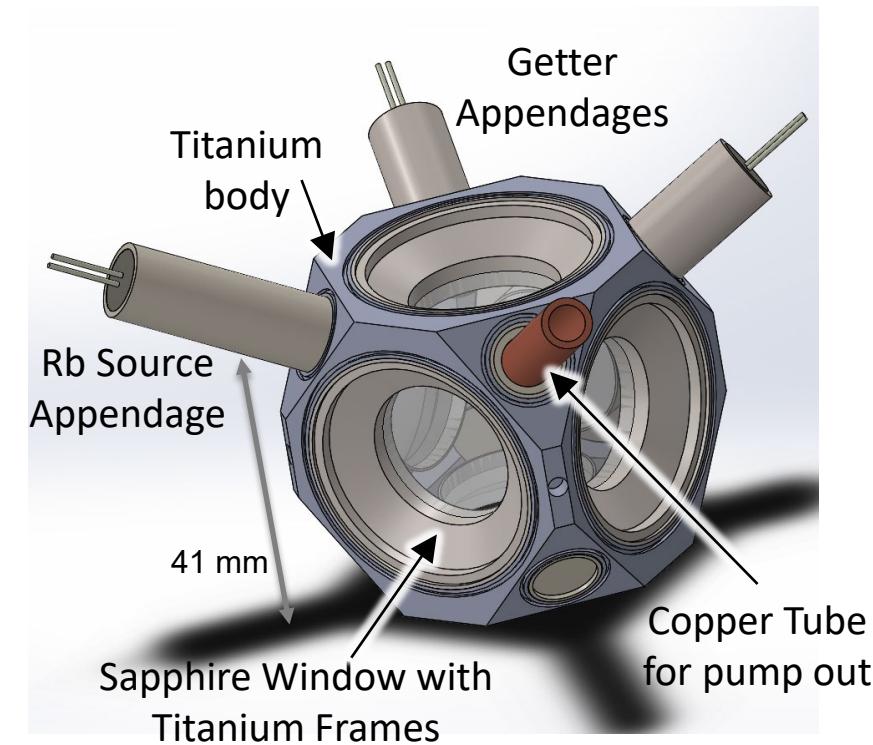
- Atomic accelerometer (atomic gravimeter) in compact prototype
- Used conventional optics for Raman beams
- Data rate: 10 Hz
- Statistical uncertainty: $< 2 \mu\text{g}$



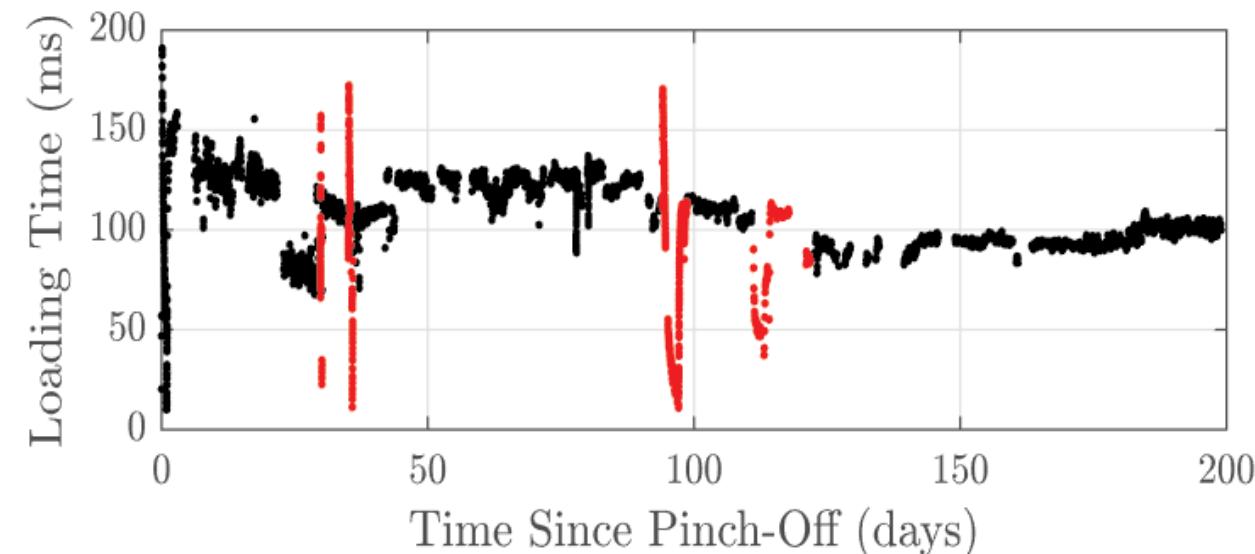
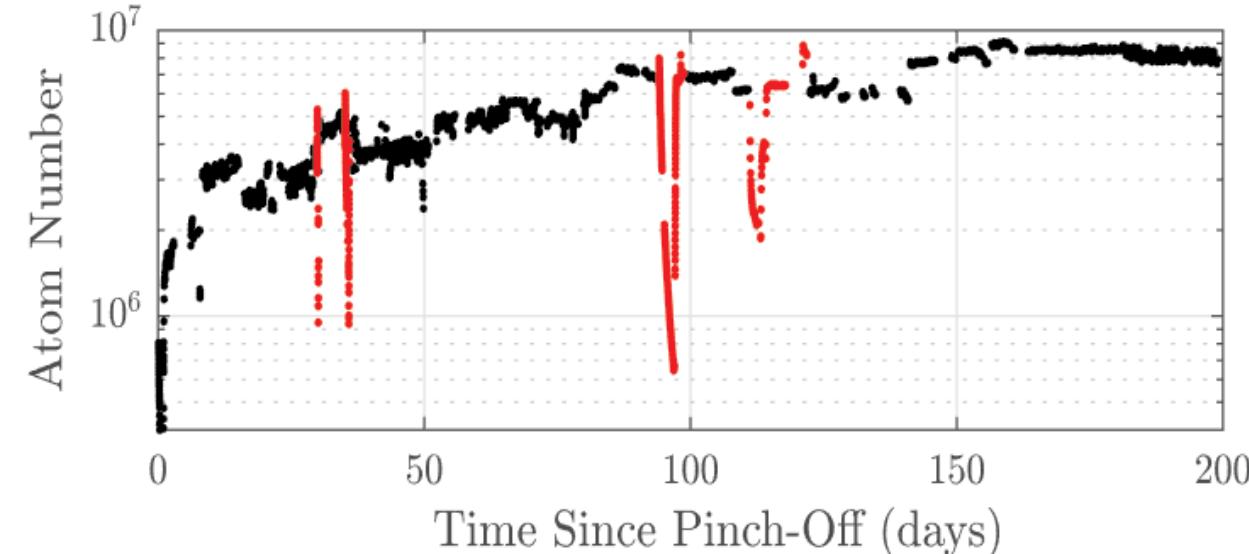
PASSIVELY PUMPED VACUUM PACKAGE

Passively pumped Vacuum Package: Titanium Package Design

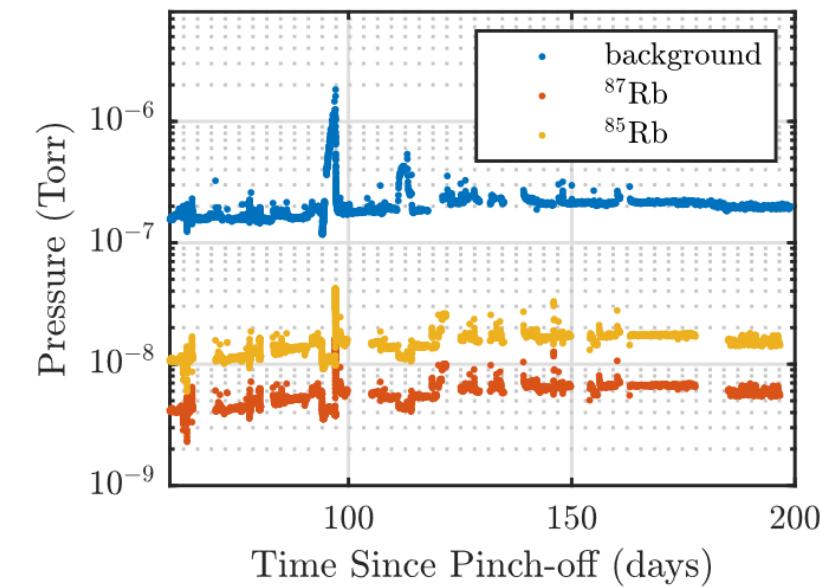
- Passive pumping: SAES St172 getters
- C-cut sapphire windows, AR-coated
 - No helium permeation (or very low)
- Rb dispenser: SAES Rb-dispensers.
- Copper pump-out tube for eventual pinch-off seal.
- Sealing: laser welding and brazing
- Preparation: 400 °C bake-out in vacuum furnace



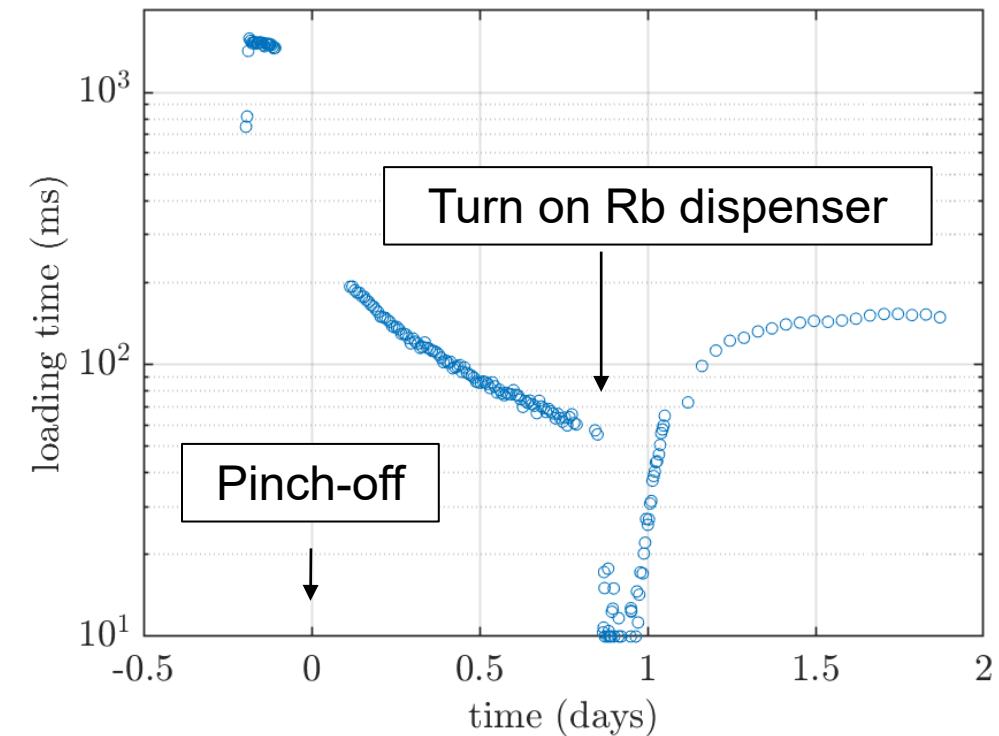
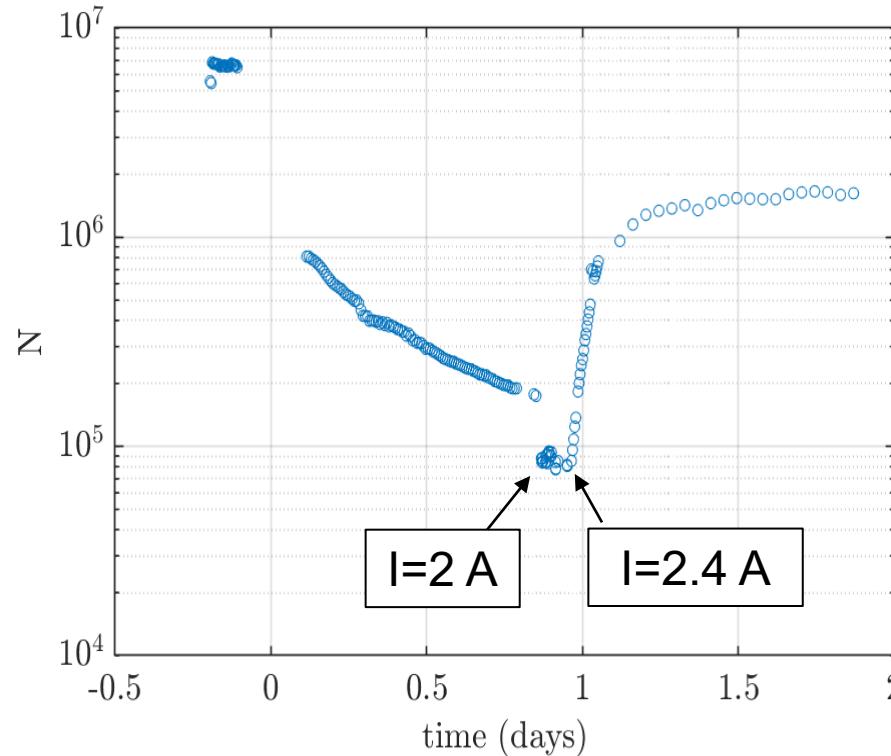
MOT in the Passively Pumped Chamber



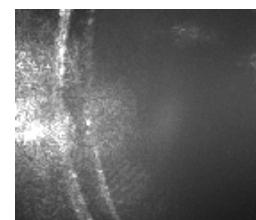
- Sustaining Cold Atoms for More Than 200 Days
- MOT seems happier with “pinch-off” rather than “pump off”.
 - $(N\tau)_{\text{pinch-off}} \approx 3 \times 10^5 \text{ atoms} \cdot \text{s}$ vs $(N\tau)_{\text{pump-off}} \approx 0.7 \times 10^5 \text{ atoms} \cdot \text{s}$.
- Estimate pressure to be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



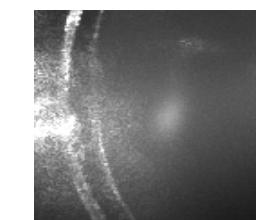
$N - \tau$ Evolution After Pinch-off



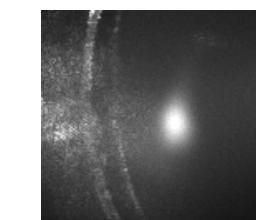
- After pinch-off, $N - \tau$ decay slower than with “pump off”.
- Driving the dispenser hard enough still improves vacuum.



$t_{\text{exp}} = 4$ ms



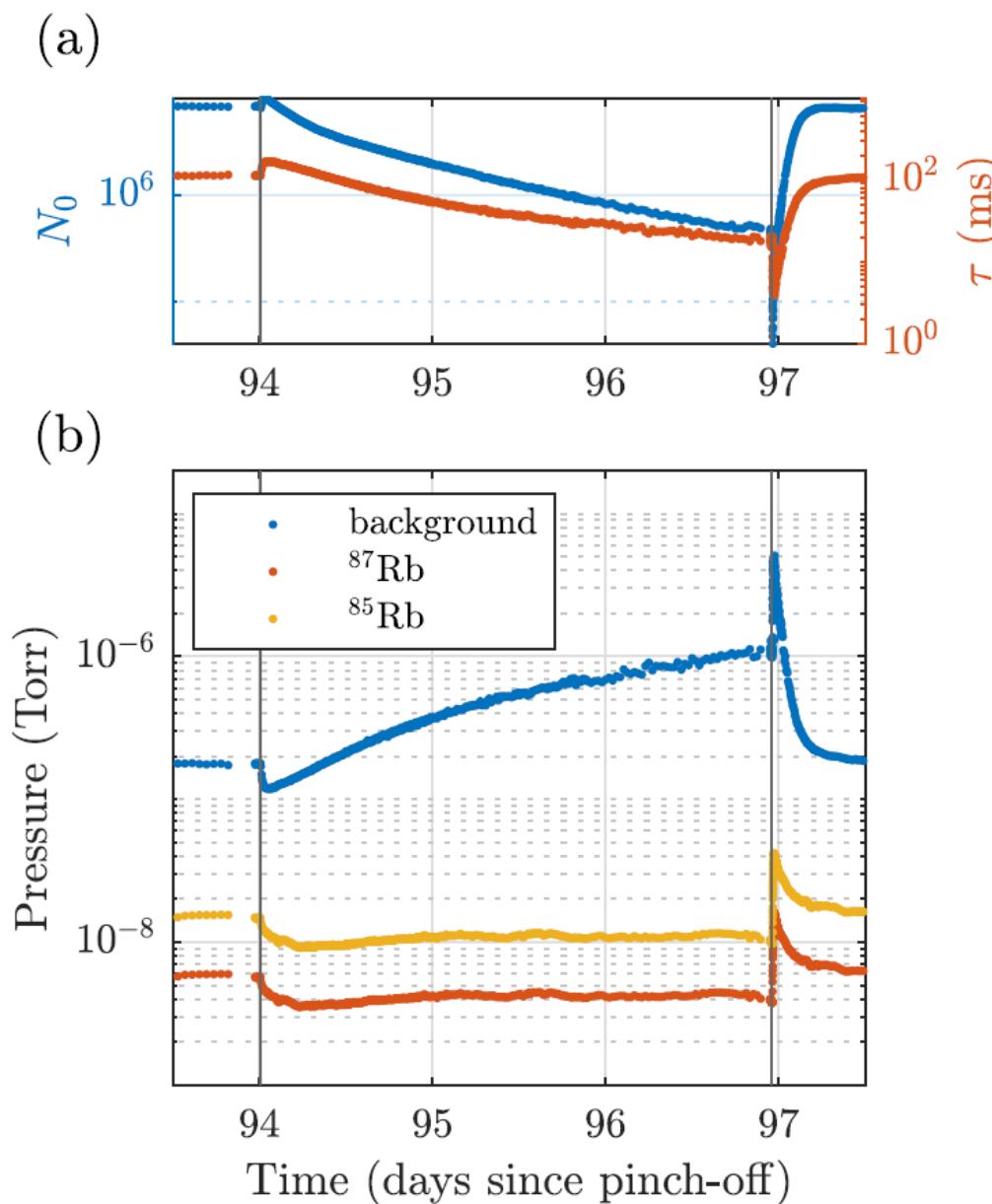
$t_{\text{exp}} = 4$ ms



$t_{\text{exp}} = 2$ ms

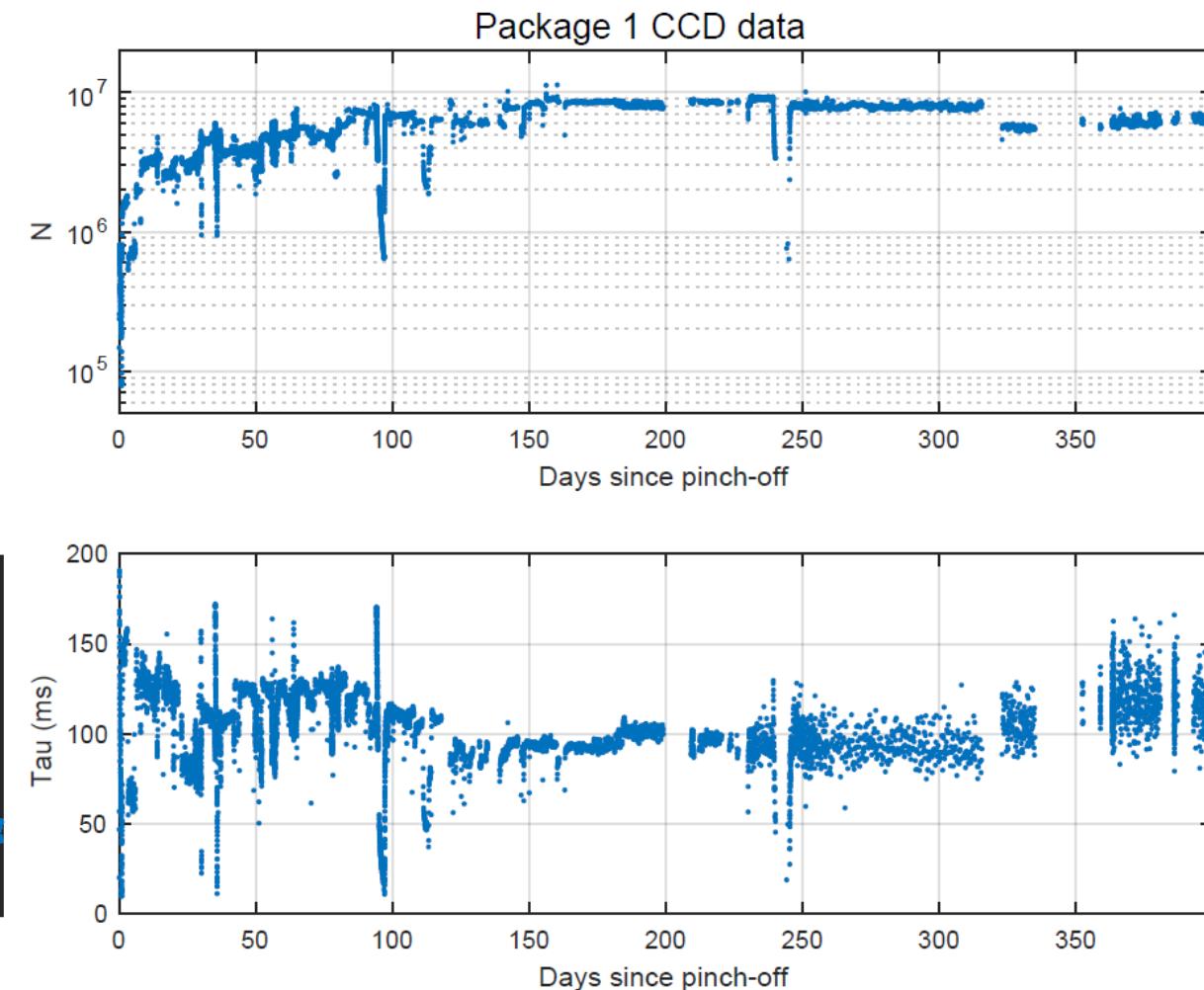
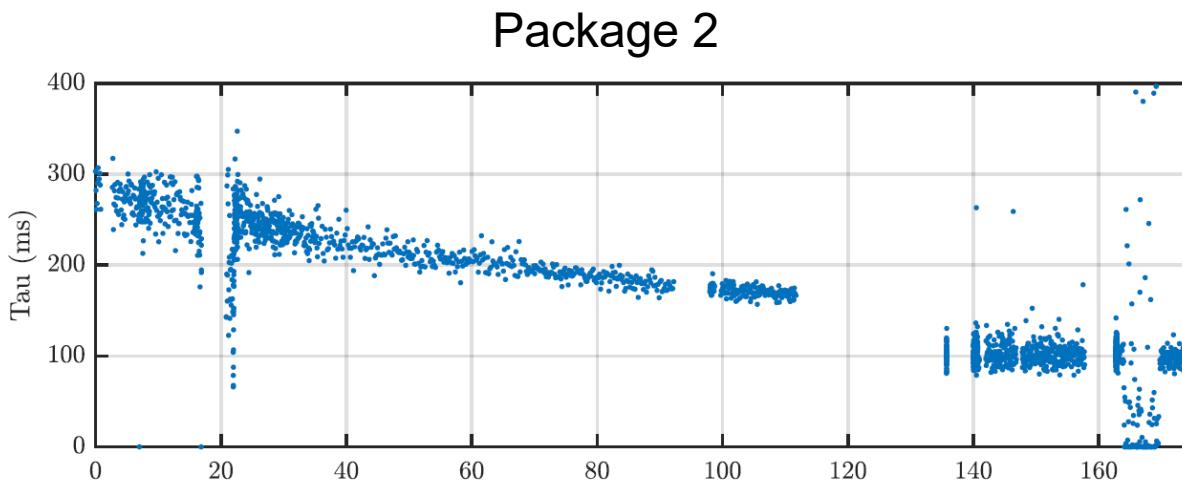
Effect of Rb dispenser

- 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 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)
 - Vacuum conditions converging to similar value



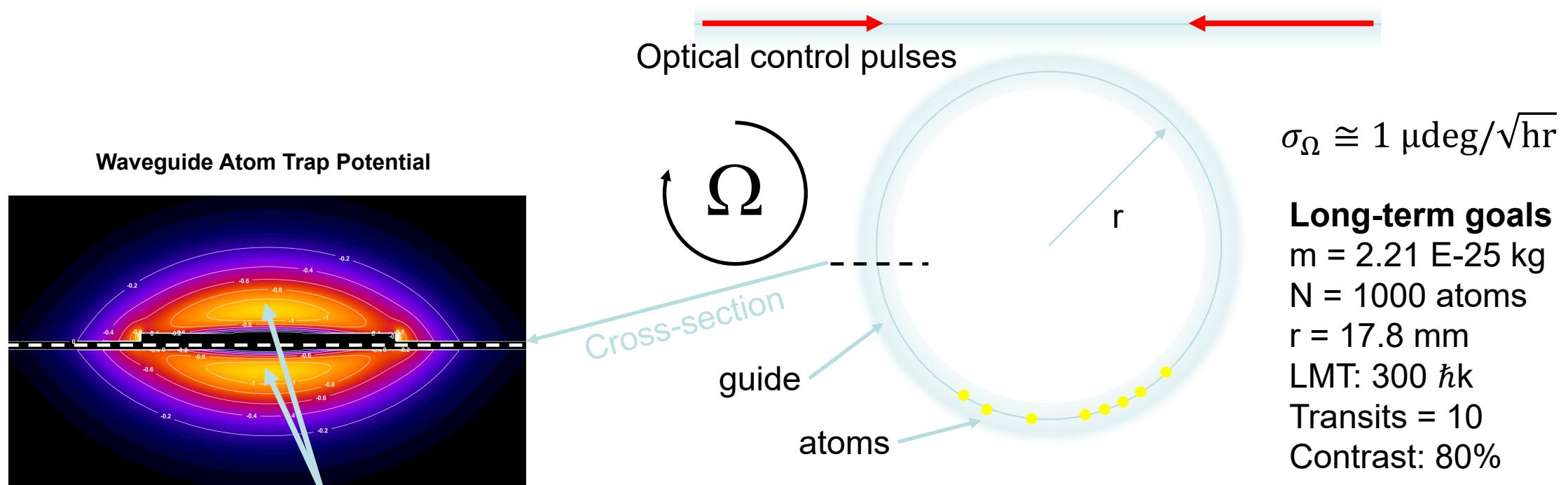
TOWARD GUIDED ATOM INTERFEROMETRY

Sagnac matterwave interferometer using optical waveguides

Concept

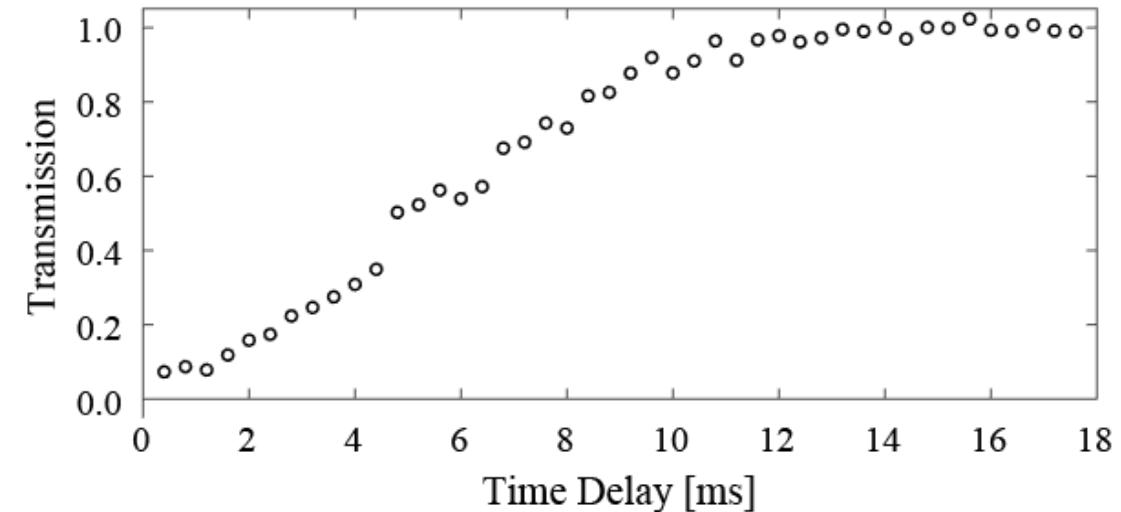
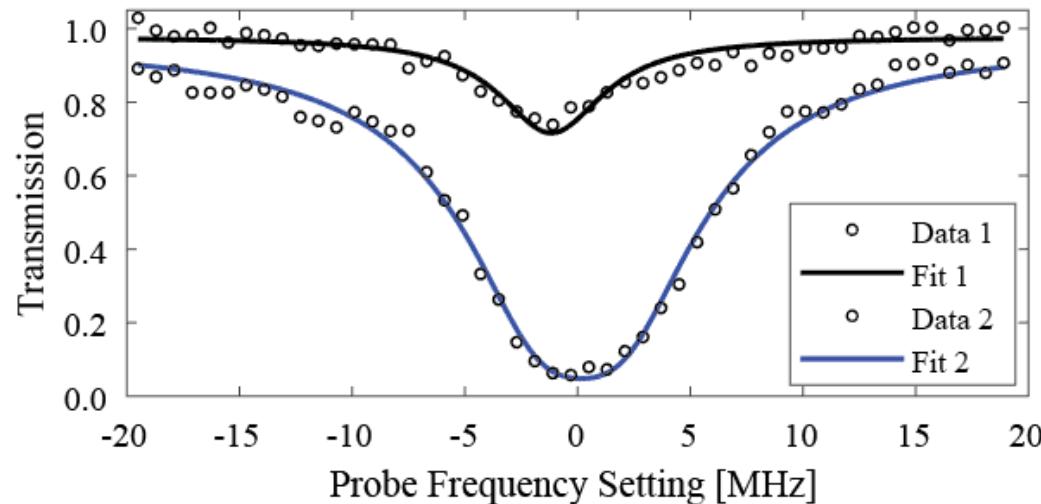
1. Guide atoms along the evanescent-field optical trap (EFOT)
2. Separate atomic wavepacket with resonant light pulses: $\frac{\pi}{2} \rightarrow \frac{\pi}{2}$
3. Measure interferometric phase with the state-dependent optical probe

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



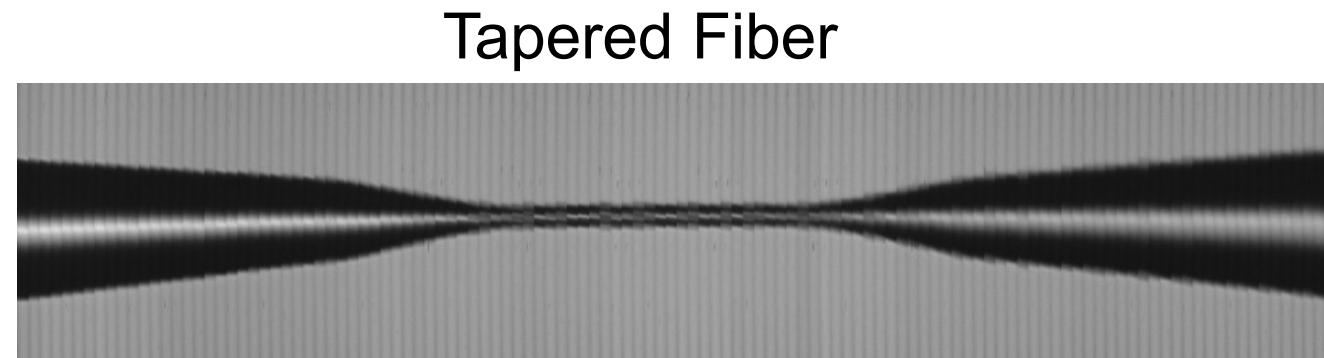
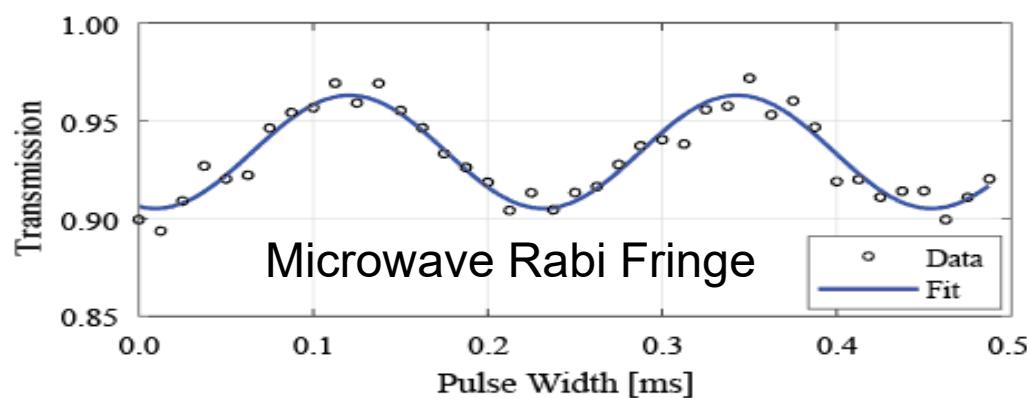
Guide atoms here with the membrane rib waveguide:
Two quasi-TE modes for blue- / red-detuned trap beams

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



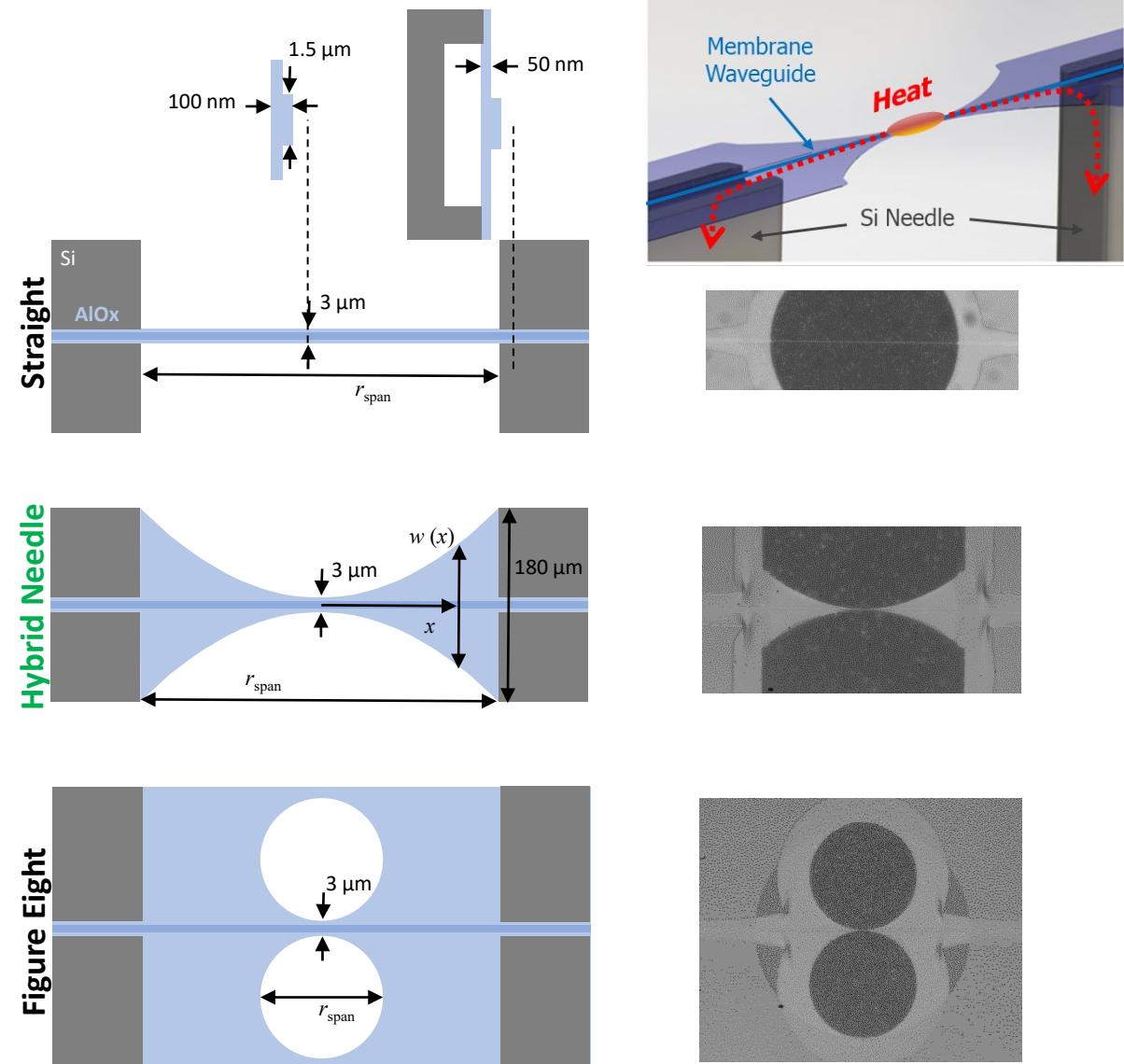
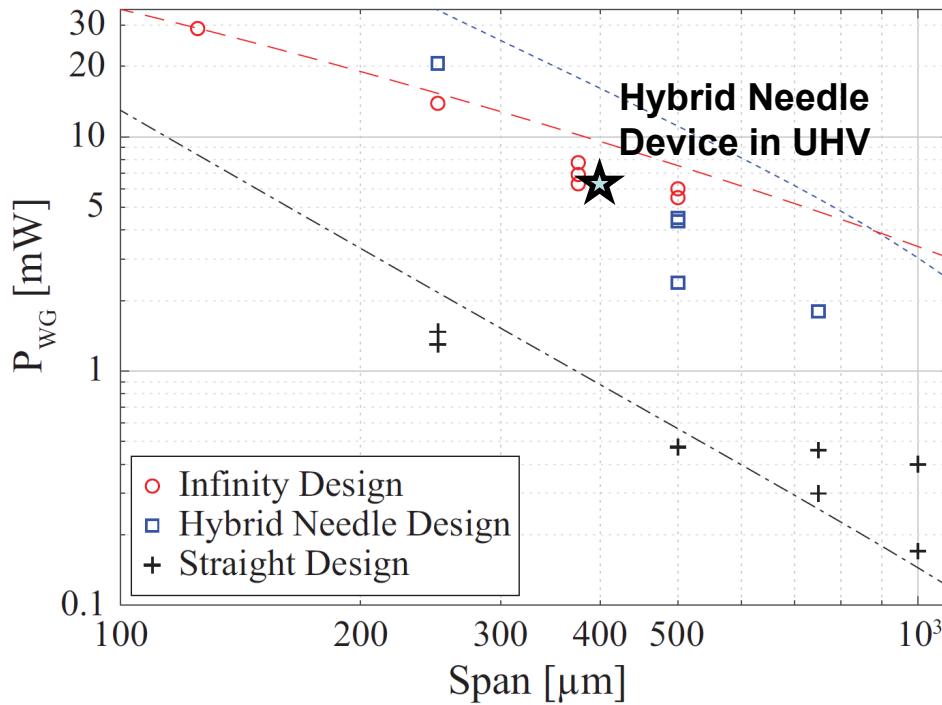
- 685nm and 937nm trapping beams coupled to nanofiber
- Atom number measurement with an absorption probe
 $N = 47.2 \pm 3.2$ for 1-D guided atoms

- Lifetime measurement of 1-D guided atoms
 $\tau = 8.1 \pm 0.8$ ms

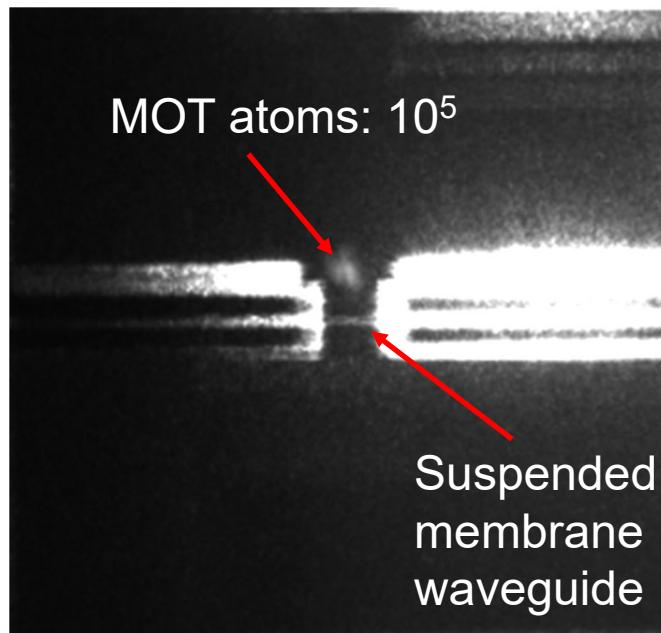
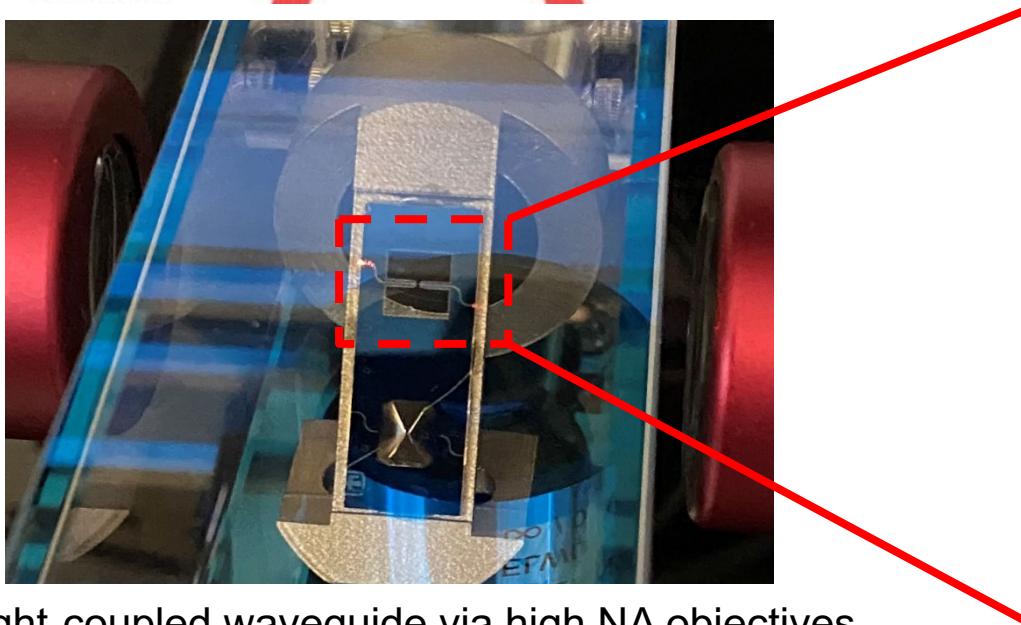
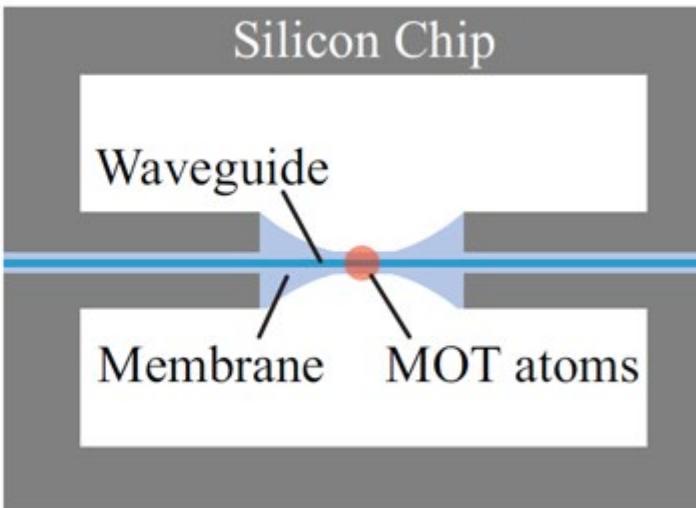
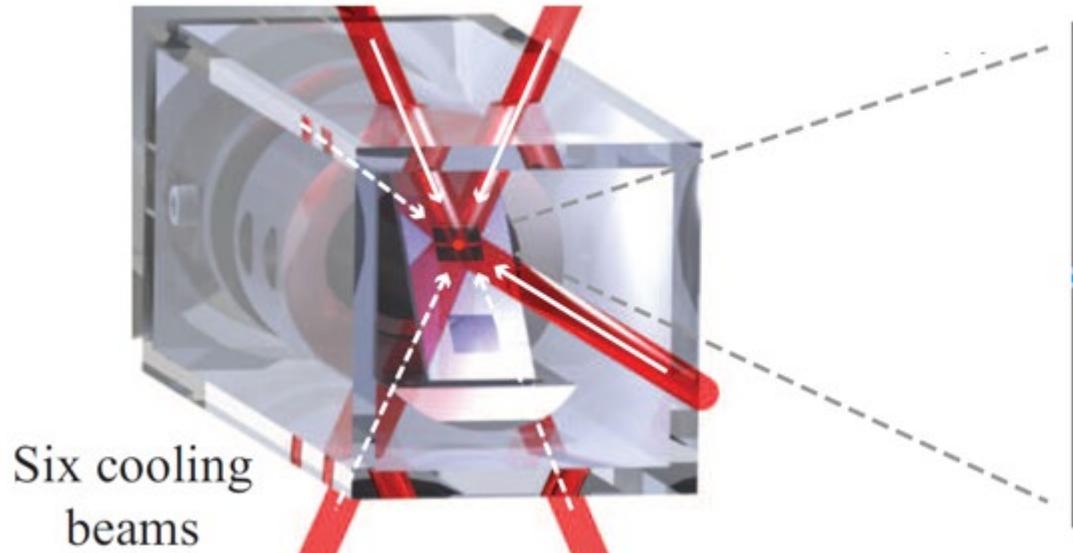


Aluminum Oxide Waveguides: High Optical Power Handling

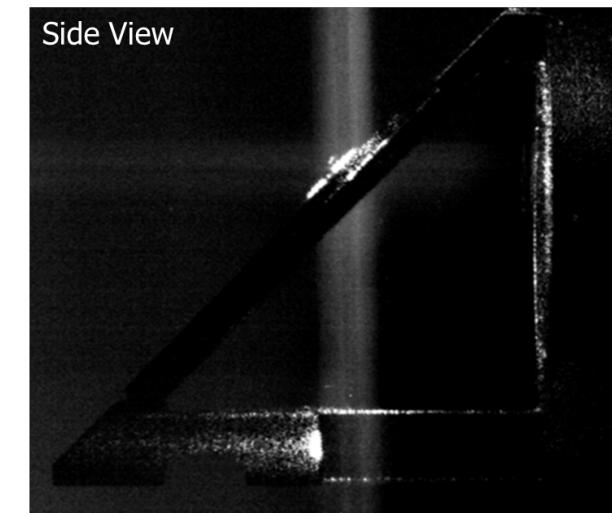
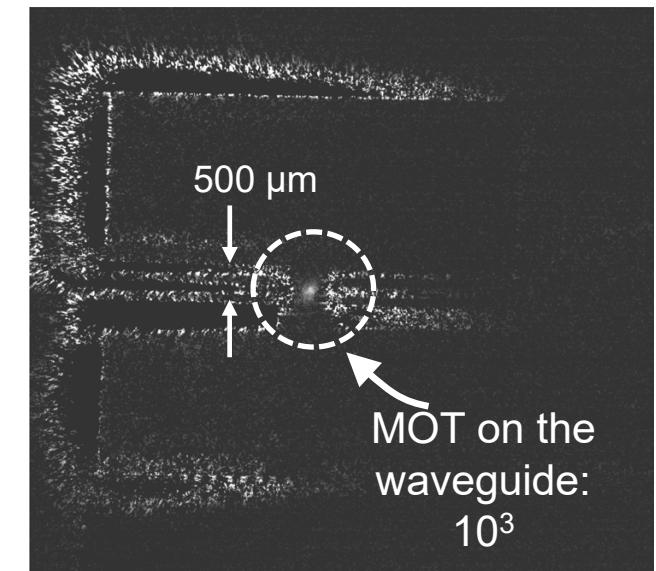
- Big challenge: heat dissipation
- Samples were redesigned based on experimental measurements and calibrated thermal simulations
- New designs handle $\sim 30\text{mW}$ at shortest lengths and **>6mW in target design**
- Publication accepted to *Optics Express* 2/22/21



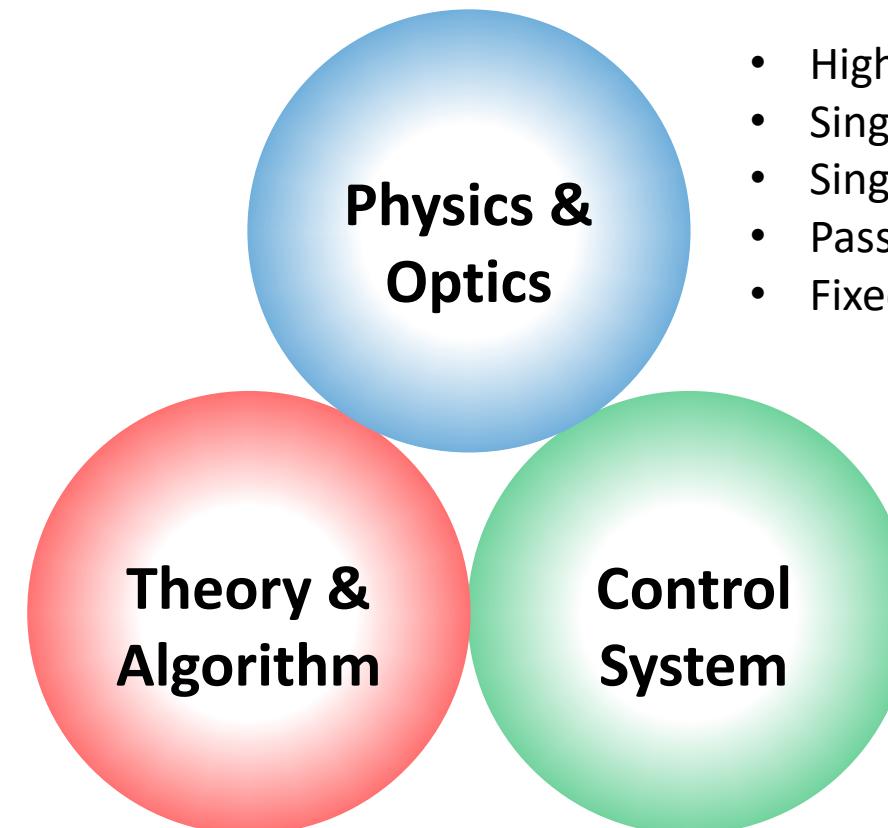
Atom Trap Integrated Platforms with Membrane Integrated Photonics



Background subtracted image



CONCLUSION



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

- 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

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

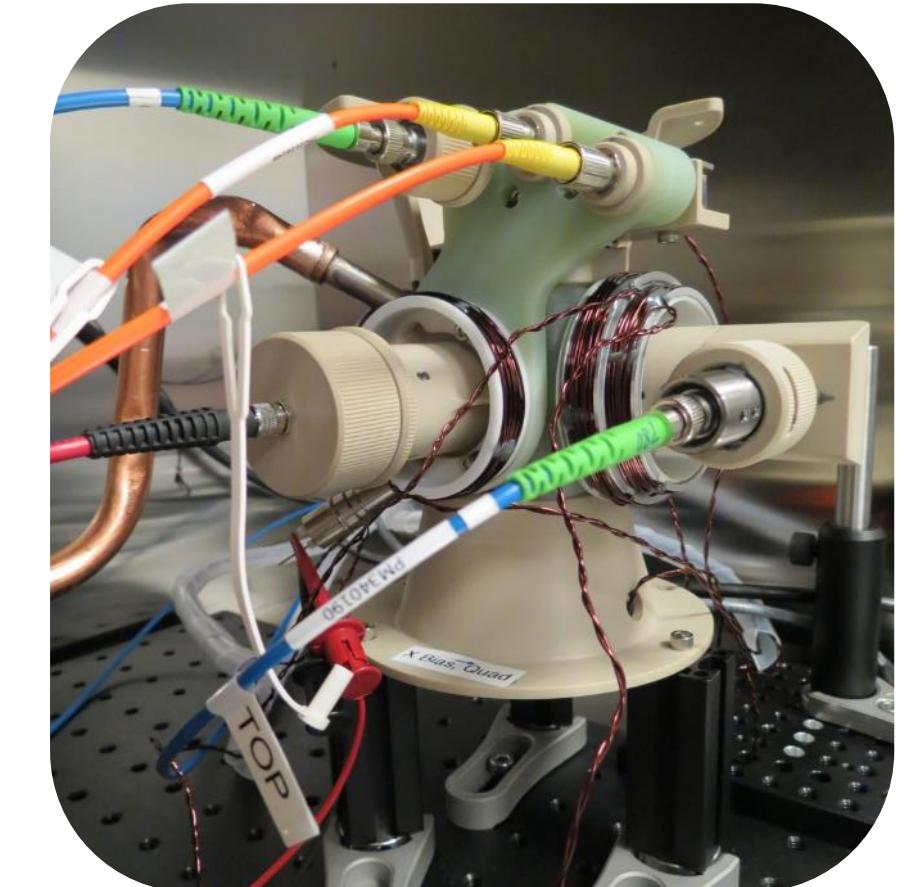
COTS: Commercial-off-the-shelf

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



Abstract: Towards Miniature Cold-Atom Inertial Sensors



The extreme miniaturization of cold-atom inertial sensors requires the development of novel technologies and architectures for the interferometer subsystems. First, we developed a custom, compact titanium vacuum package containing a microfabricated grating chip for a tetrahedral grating magneto-optical trap (GMOT) using a single cooling beam. The vacuum package is integrated into the optomechanical design of a compact sensor head with fixed optical components. In addition, a multichannel laser system driven by a single seed laser has been implemented with time-multiplexed frequency shifting using single sideband modulators. To develop a chip-scale laser system, we also developed a silicon photonic single-sideband modulator operating near 1550 nm. Based on these technologies, we have demonstrated atom interferometers. In addition, guided atom interferometry platforms have been explored with evanescent fields of photonic integrated circuits and nanofibers. We designed the atom trap integrated platforms (ATIPs) with membrane integrated photonics and membrane/needle MOT devices. All these efforts are progressing towards miniature cold-atom inertial sensors under large amplitude motional dynamics.

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