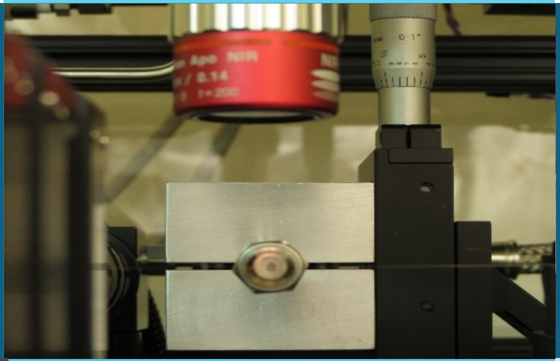
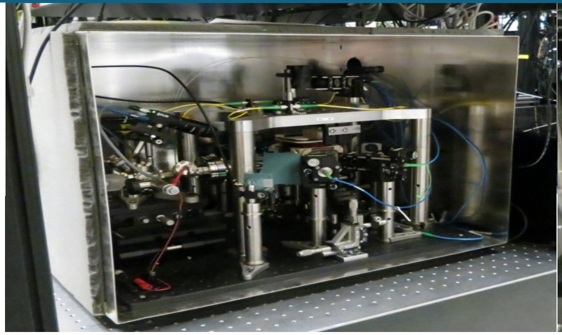
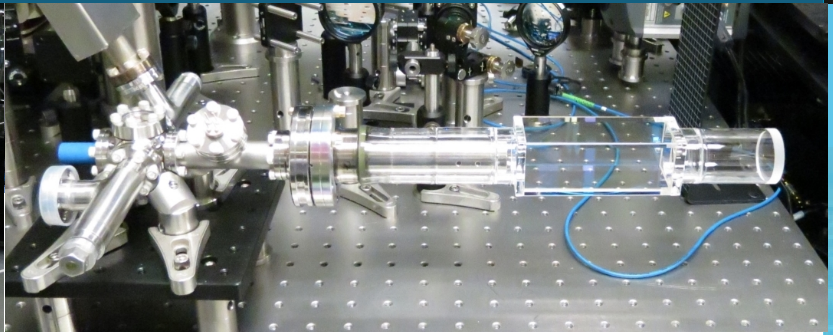
SAND2023-04449C

Nanofiber testbed for atom interferometry on chip







DAMOP 2023

Adrian Orozco[1,2]

Team: William Kindel[1], Jonathan Sterk[1], Weng Chow[1], Yuan-Yu Jau[1], Grant Biedermann[3], Nicholas Kar[1], Michael Gehl[1], and Jongmin Lee[1]

1. Sandia National Laboratories

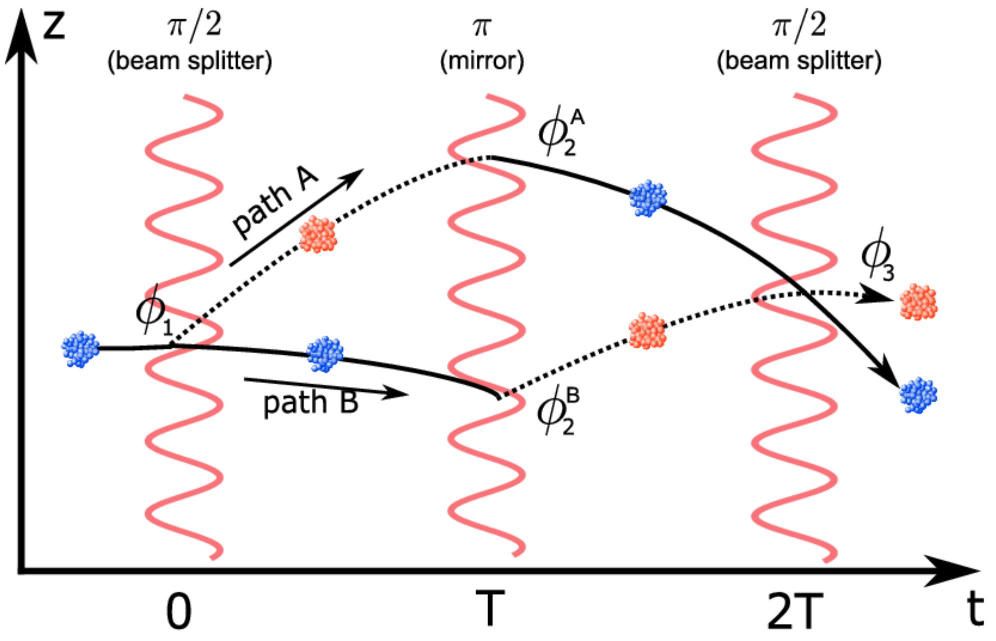
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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.

Nanofiber testbed for atom interferometry on chip

Nanofiber testbed for atom interferometry on chip

Atom interferometers are analogous to Mach-Zehnder interferometers



$$P_e(\Delta_\phi) = \frac{1}{2}(1 - \cos(\Delta_\phi))$$

$$\Delta\phi = \phi_1 - 2\phi_2 - \phi_3$$
$$= -2kgT^2$$

- Raman transition with counterpropagating beams imparts a momentum kick
- Atomic wavepackets separate in space
- Laser phase is imprinted onto the wavepacket

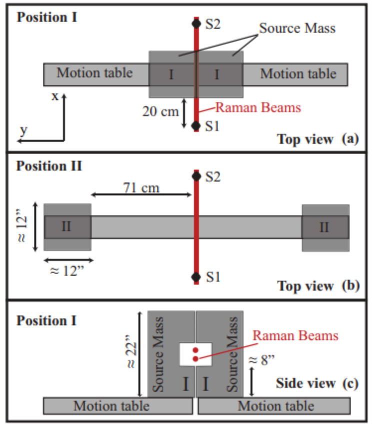
M. Hauth et al., Atom interferometry for absolute measurements of local gravity (2014)

Atom interferometry for precision measurements

- Atom interferometry allows the measurement of acceleration with high precision

Fundamental Physics

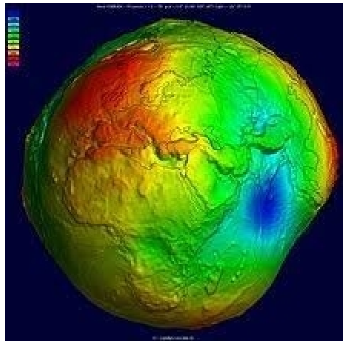
$$U = -G\frac{m_1 m_2}{r}$$



Gravity gradients

- Gravitational constant –ISL violation
- Test Weak equivalence principle

Geophysics



Gravity and gravity gradients

- Geoid – shape of earth
- Underground structures
- Oil deposits
- Shifted tectonic plates

Inertial Navigation

Acceleration and rotation rates

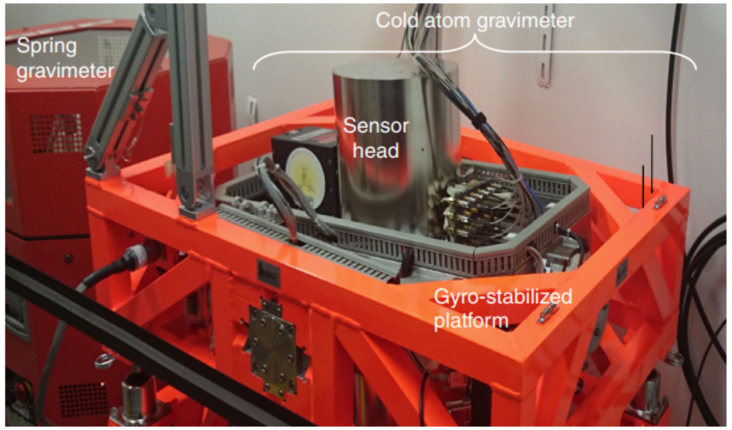
- Position determination for GPS denied environments
- Autonomous vehicles

G. Biedermann et al., Testing Gravity with Atom Interferometry (2015)

Mobile atom interferometers require SWaP Conditions

- Mobile gravimeters are commercially available from MuQuans, AOSense
- These systems make measurements while stationary
- Dynamic measurements performed on a ship with a compact sensor (T = 20 ms) with on a gyroscope stabilizer that kept interferometer aligned with gravity

www.muquans.com



- In higher dynamic environments atoms ca escape the interaction region
  - Higher data rate (see Roger Ding's Poster (Session V01: Poster Session III)
  - Confining atoms using optical potentials

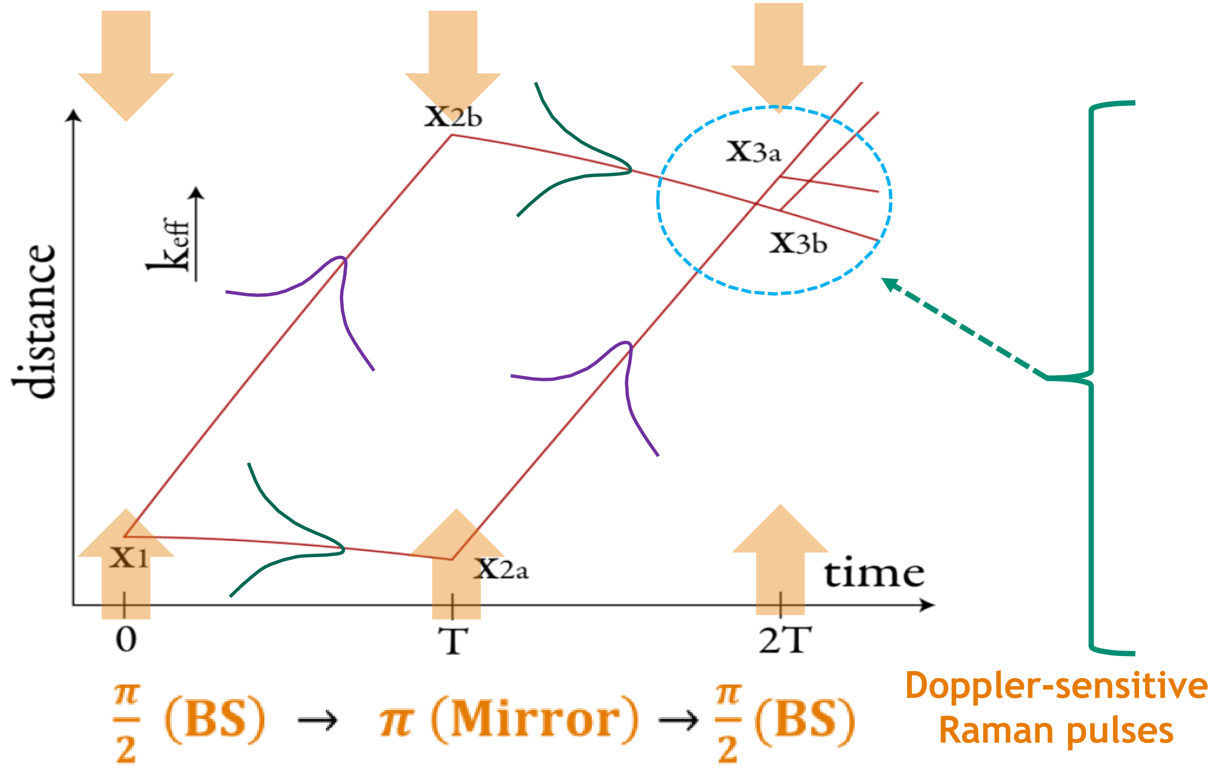
Y. Bidel et al., Absolute marine gravimetry with matter-wave interferometry(2018)

Advantages of using optical potentials

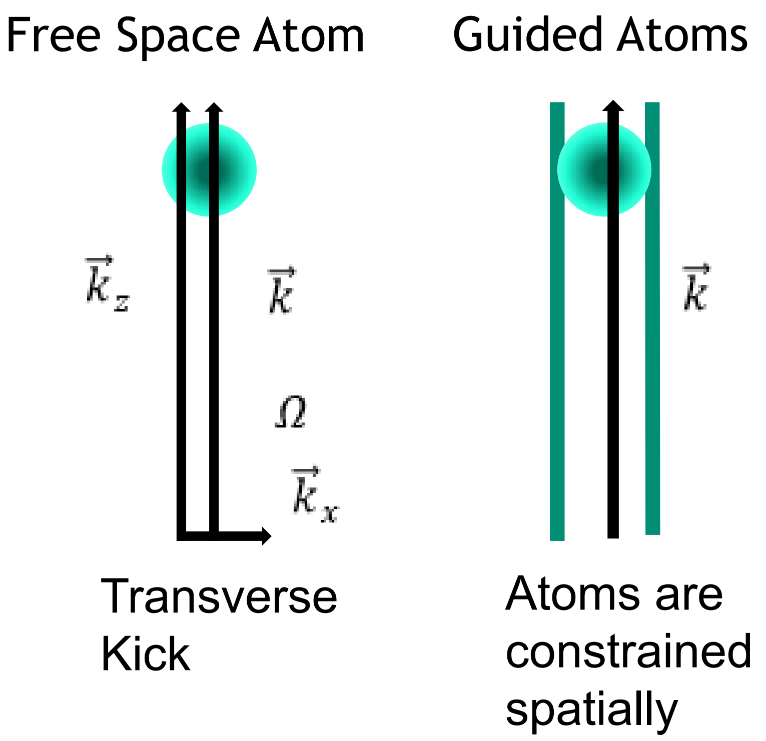
- Optical potentials are inherently smooth (unlike magnetic potentials)
- Reduce power requirements for atom interferometry
- Atoms are confined spatially
- Waveguide modes can be used to drive interferometry pules

- Problems with approach
  - Guided modes typically have spatial intensity gradients exacerbating dephasing effects – need to study coherence with guided modes
  - Waveguide polarization can limit transfer efficiency

Motivation: Tight spatial confinement



Unguided Configuration fails in dynamic environments

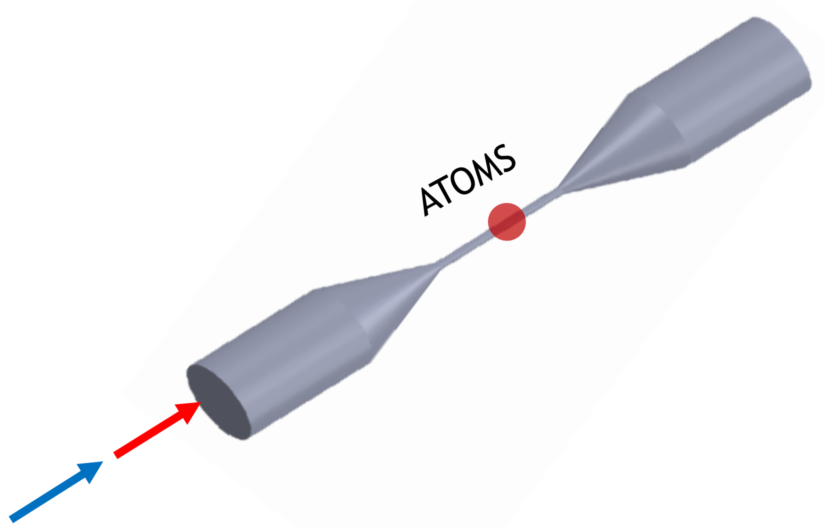


- Light Pulse Atom Interferometry (LPAI) is analogous to optical Mach-Zehnder interferometer
- Dynamic platforms cause wavepacket (phase) mismatch
- Transverse kick results in a wavepacket separation* $\delta x = 4v_r \Omega T^2$
- Relative atom/platform transverse motion is limited by radial confinement

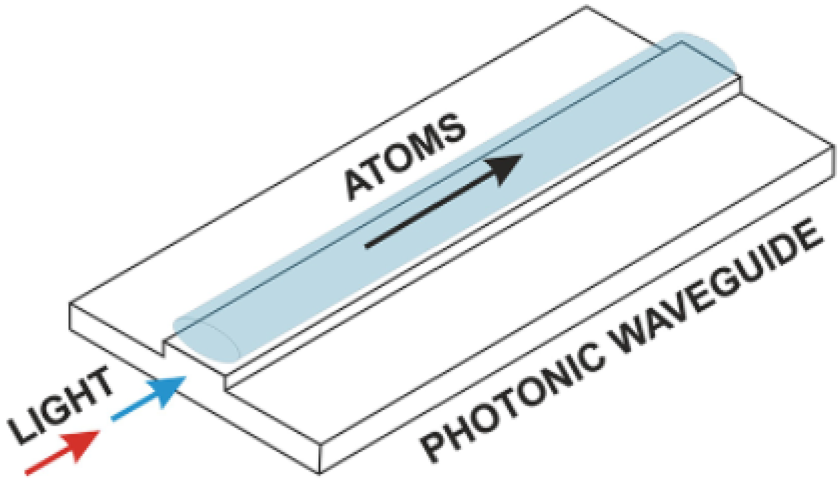
* PRL 108, 090402 (2012)

Nanofabricated Optical Waveguides

Optical Nanofiber WG



Optical Rib WG on chip

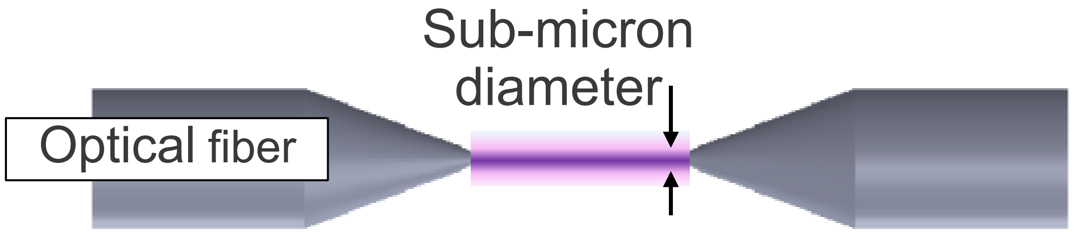


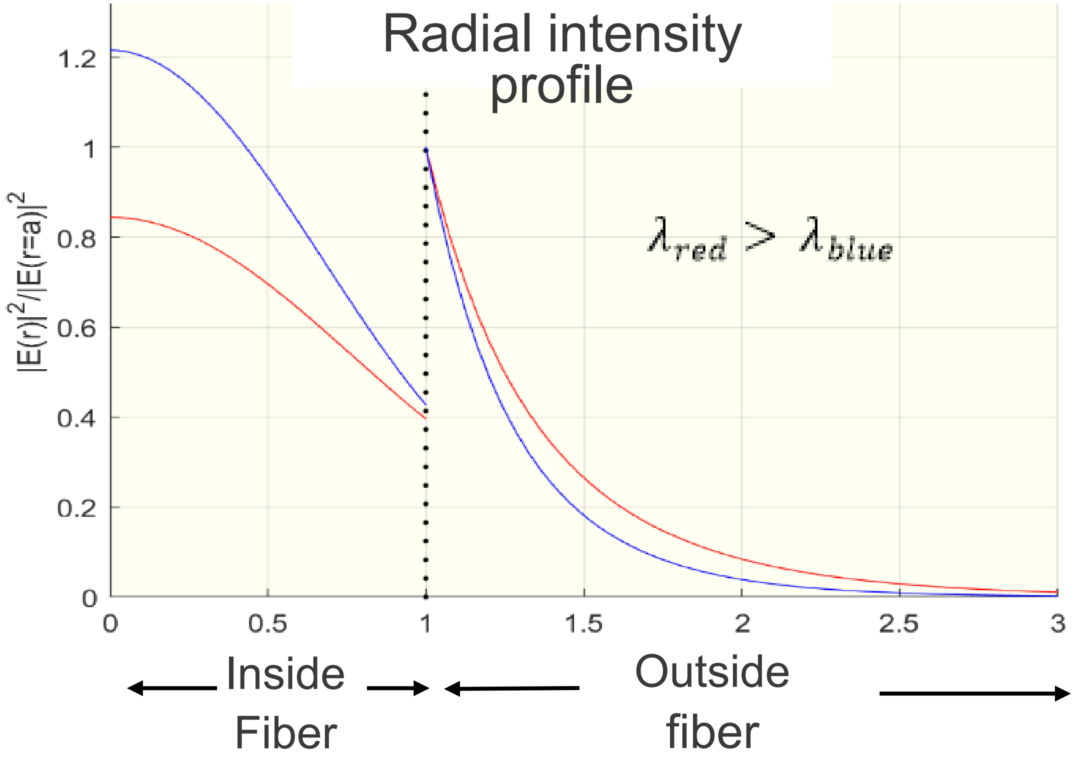
Y. B. Ovchinnikov, Appl. Phys. Lett. 120, 010502 (2022)

- >100 mW transmission
- Platform has been successful for trapping atoms
- Fundamental mode is quasi-polarized
- sensitive to vibrations

- Sandia has fabrication capabilities
- Small and rigid
- Intricate waveguide designs are possible
- Guided light polarization is well defined
- Limited power transmission

What is a Nanofiber?





- A nanofiber is an optical fiber with a sub-micron diameter
- The fundamental mode has an evanescent tail that decays radially away from the nanofiber surface
- Effective mode area is ~1μm^2
- Resonant scattering cross section for Alkali's ~0.1 μm^2
- Optimal interaction efficiency occurs with nanofiber radius = 0.23*guided light

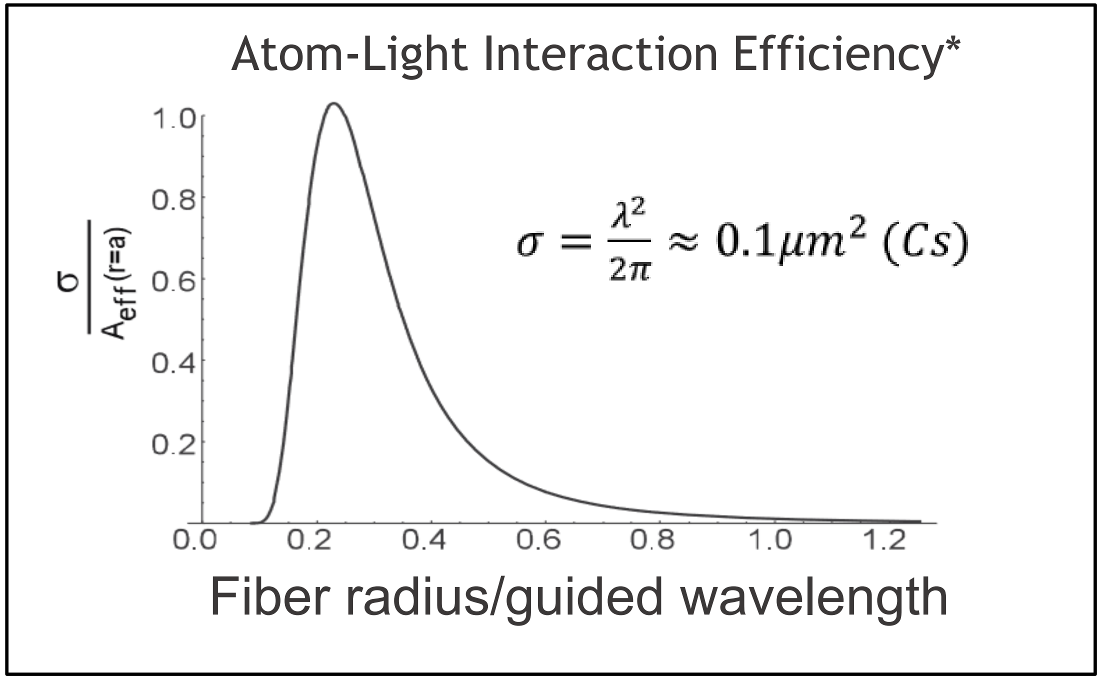
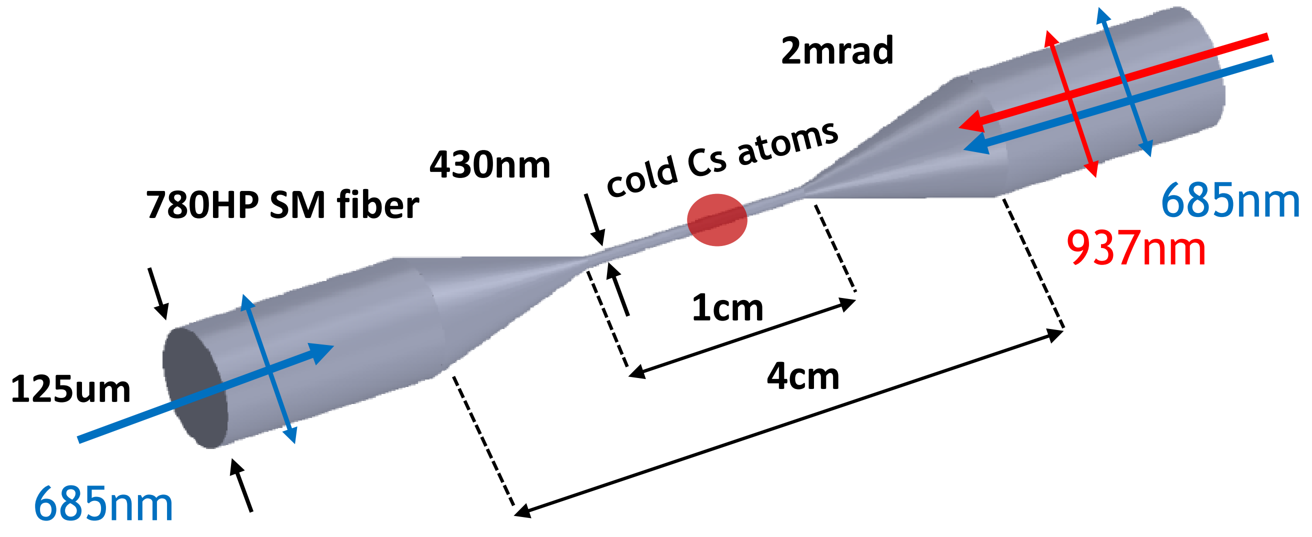
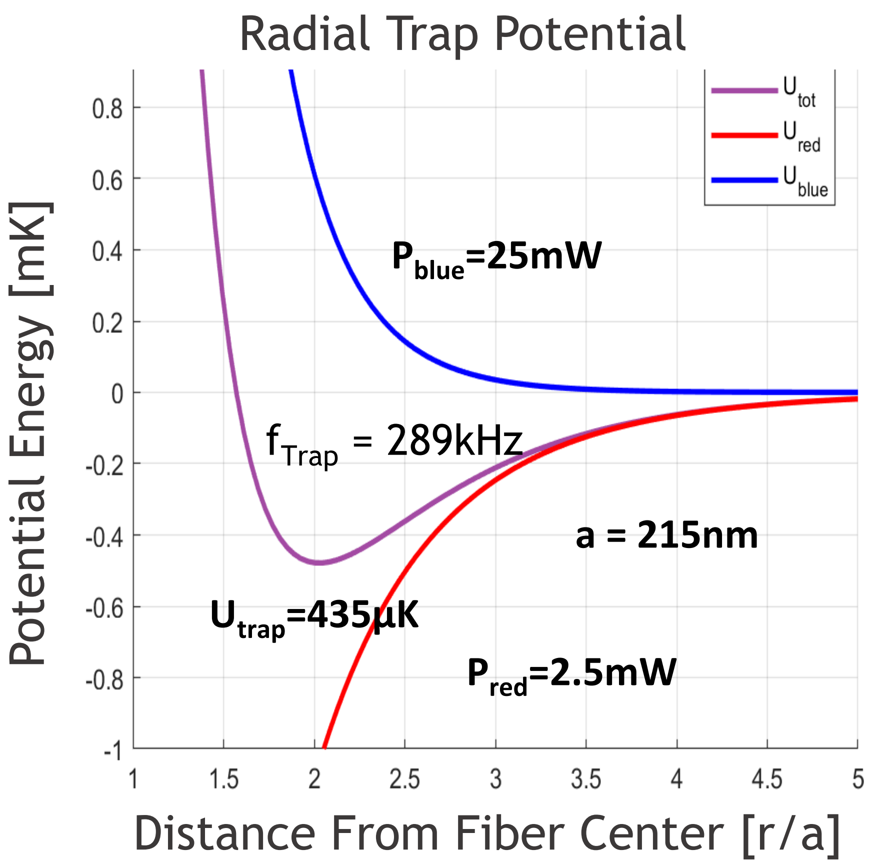


*figure borrowed from Eugene Vetsch PhD Thesis

1D trap on a nanofiber



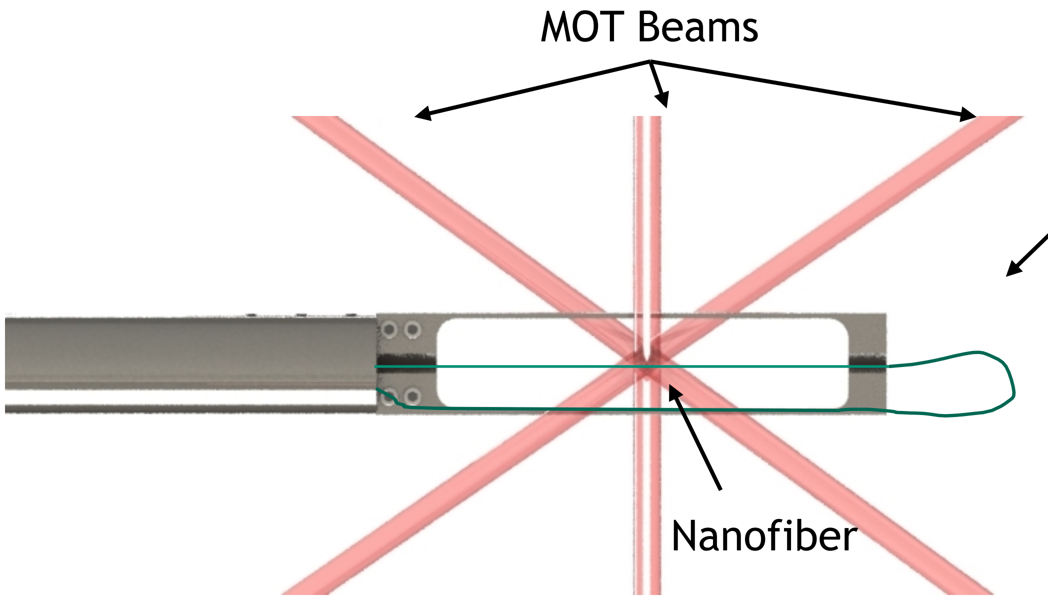


- No confinement along fiber axis
- Two trapping lasers: red (attracts) and blue (repels) detuned beams with parallel polarizations
- Magic wavelengths used for 6S1/2->6P3/2 Cs transition to eliminate differing light shifts between ground and excited state
- Fiber radius is 215 nm; nanofiber section is 1 cm long
- Trap depth is ~435uK

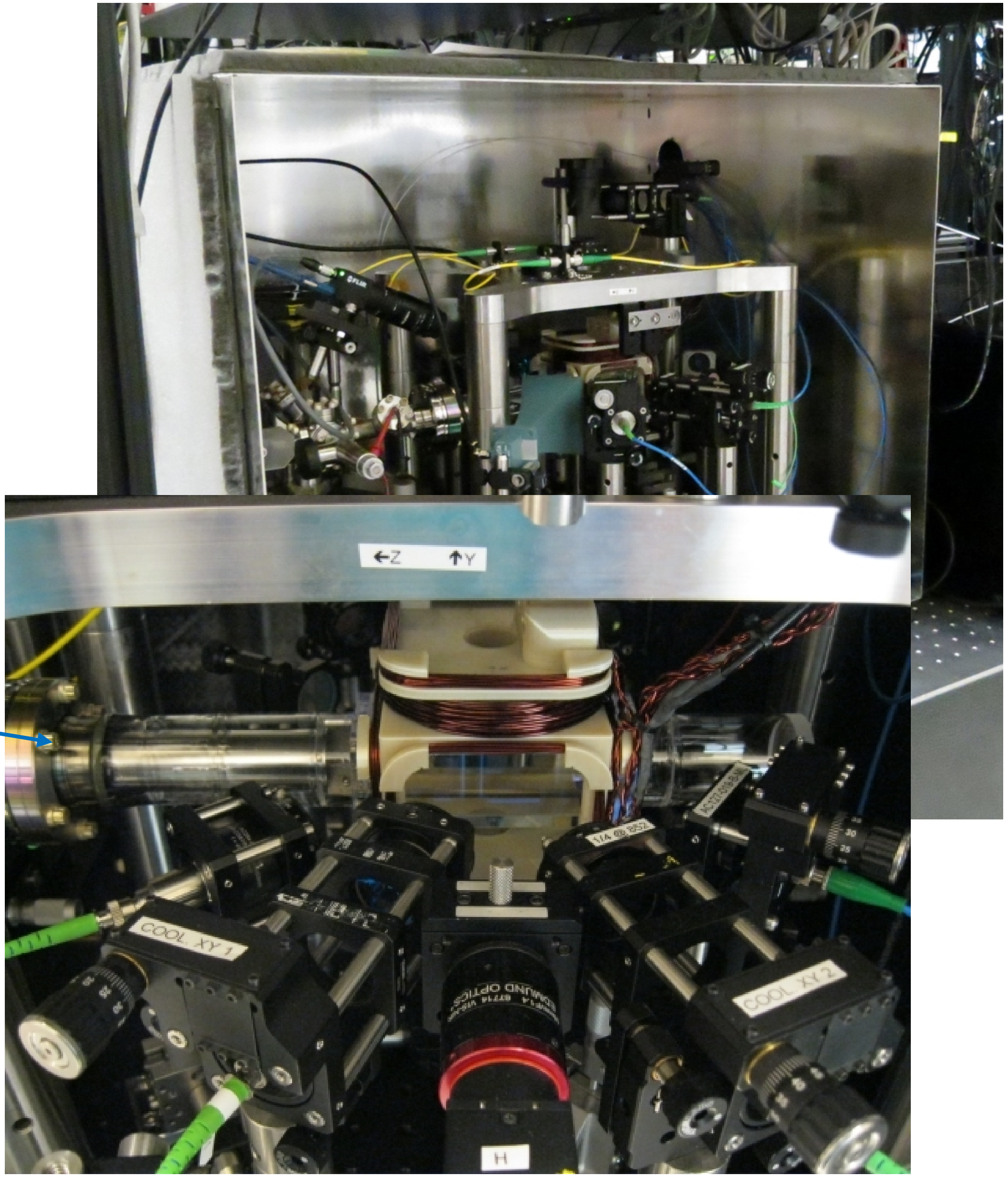
PRA **70**, 063403 (2004), PRL **104**, 203603 (2010)

Experimental Apparatus

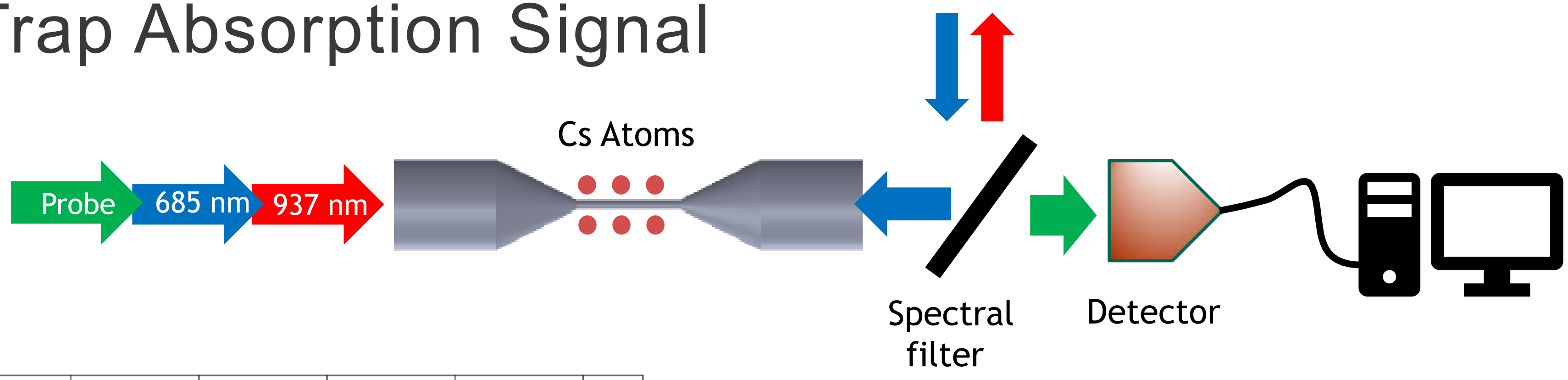
- 5 L/s ion pump maintains ultra-high vacuum pressure (~10^{-9} Torr)
- Retroreflected cooling beams produce a magneto-optical trap (MOT) with ~10^6 atoms
- Mu-metal magnetic shield reduces environmental magnetic field noise
- Vacuum cell and MOT optics are inside the 2 ft^3 enclosure
- Also, included are CCD cameras with polarizers used for setting trap beam polarization

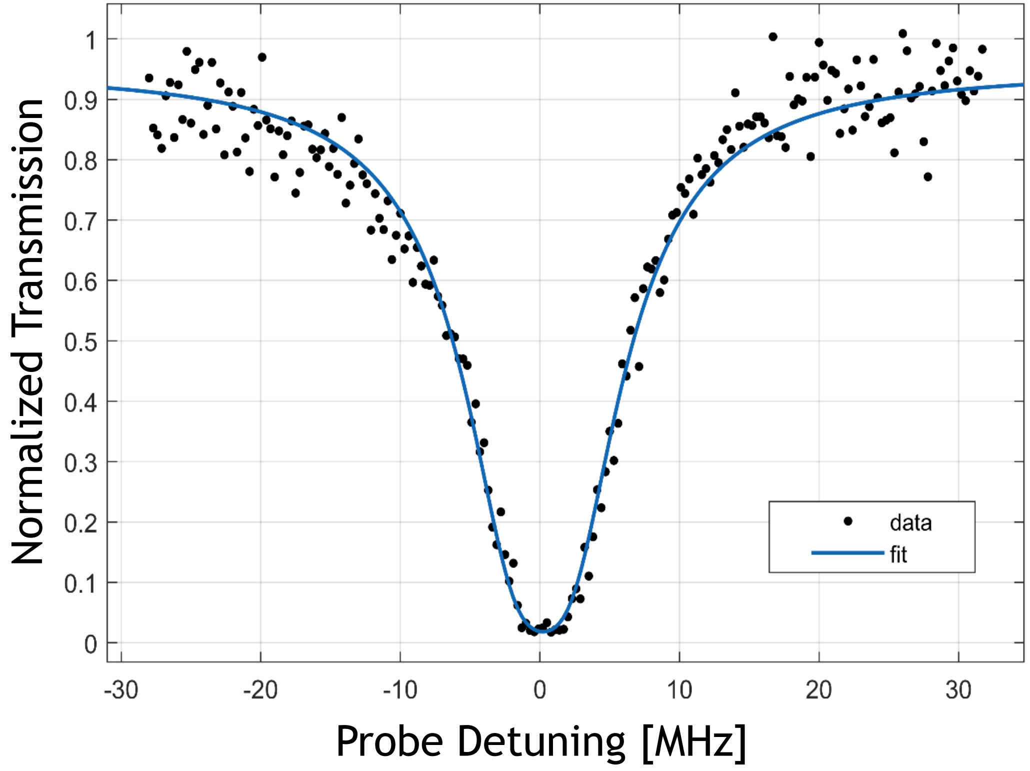


Inside Glass cell

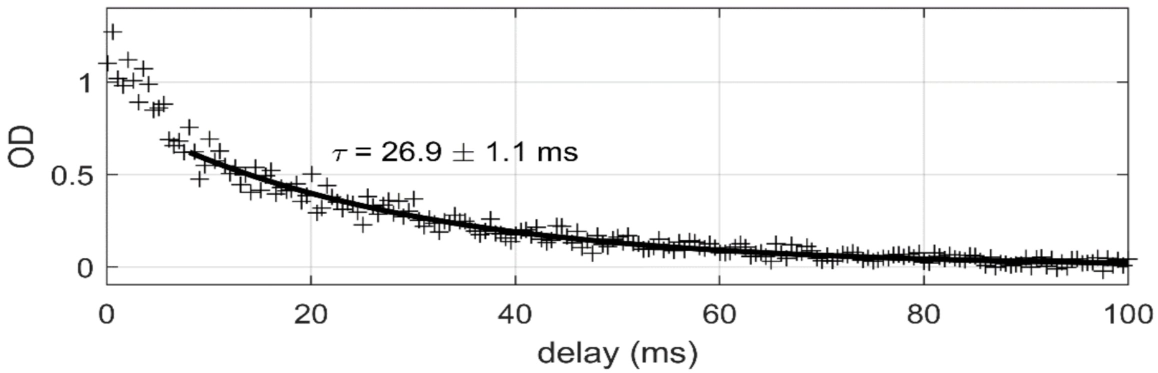


Atom Trap Absorption Signal

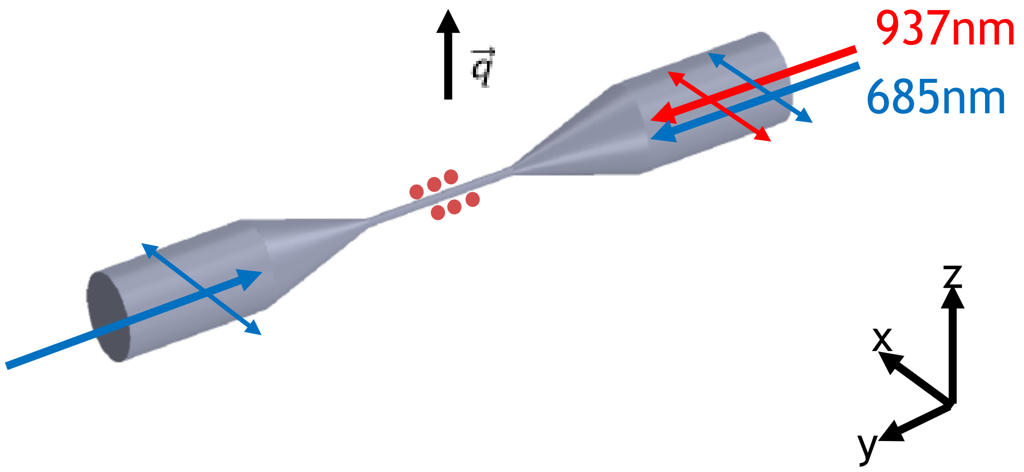


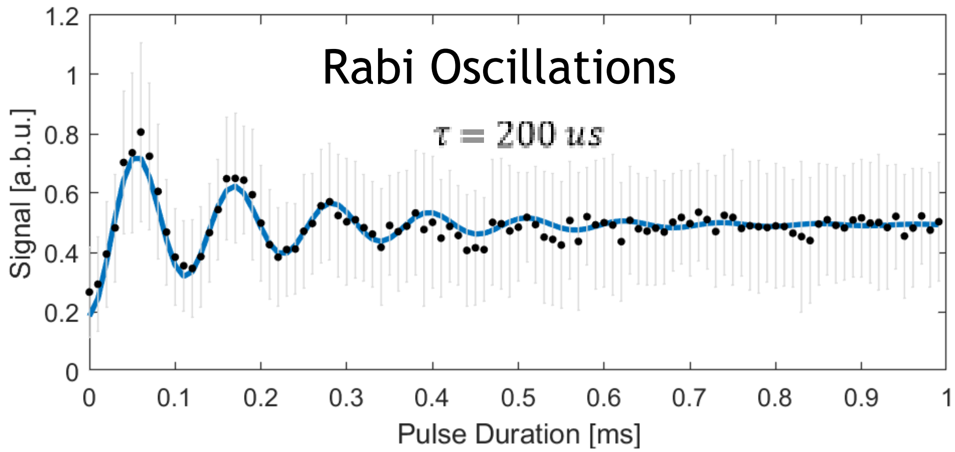


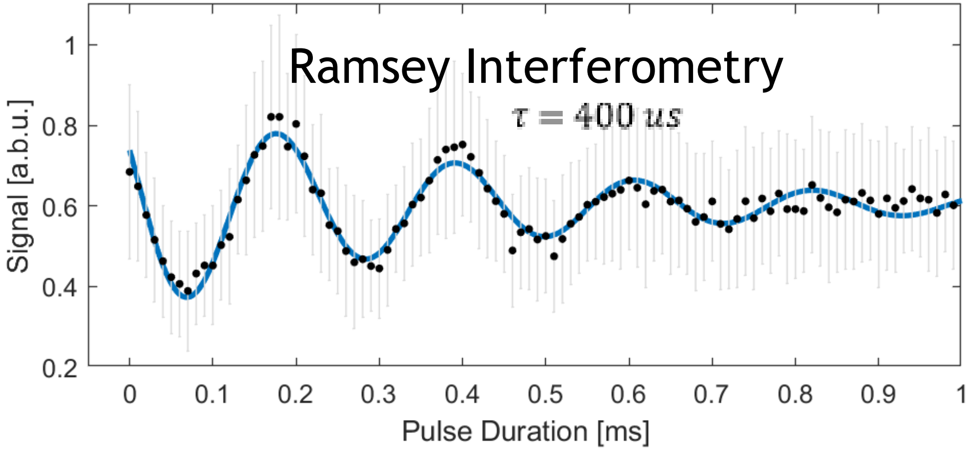
- Estimated MOT atom number ~ $5x10^6$ and its temperature = 28μK
- OD = 3.95, OD1 = 0.078
- Trapped atom number = 50
- Trap depth = -435uK, P_{Probe}; 852nm = 30pW (Cs atoms)



Microwave transitions show a short coherence time



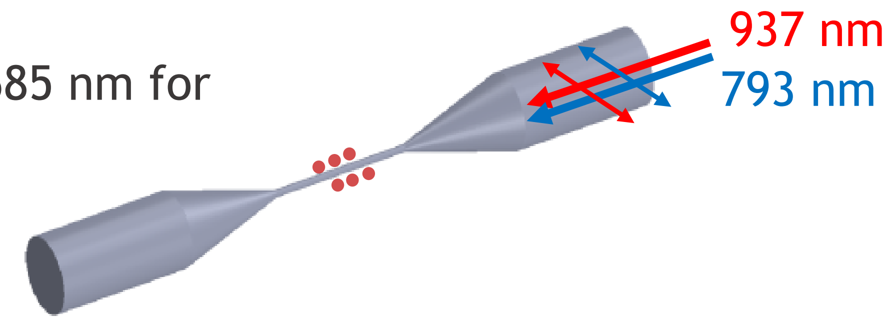


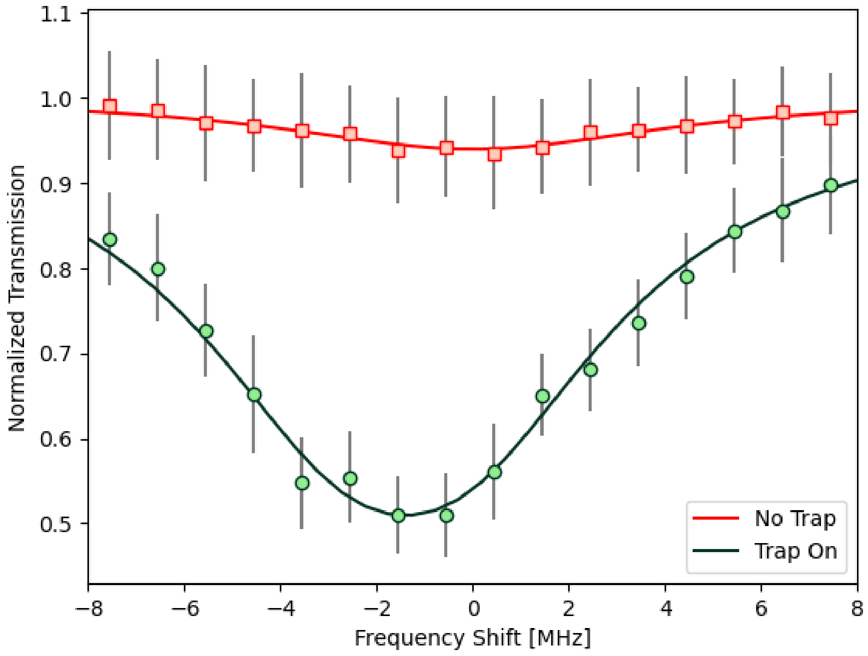


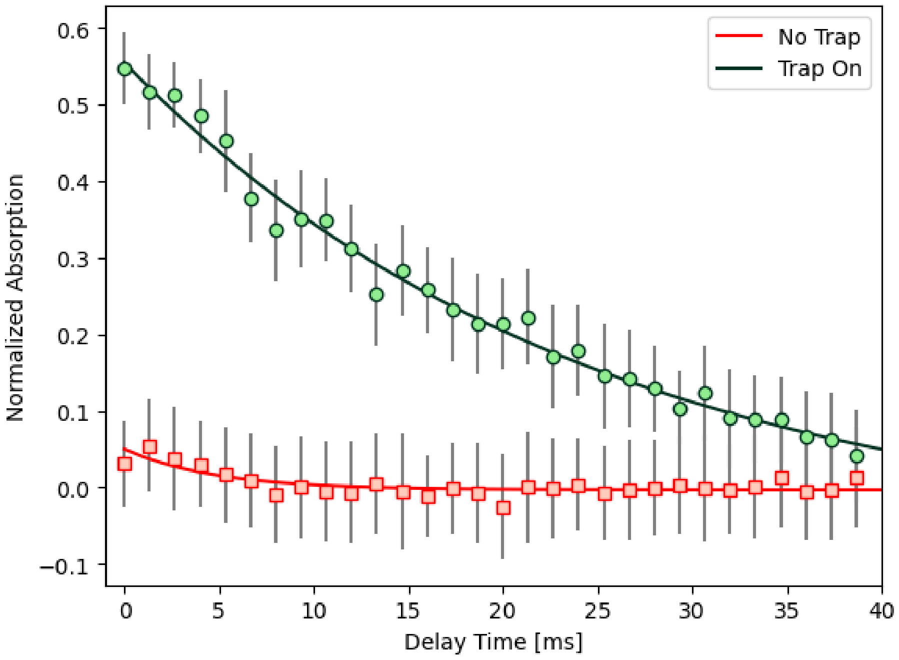
- Using Cs atoms trapped on a nanofiber, we drive transitions between the $6S_{1/2}$ hyperfine ground states using a microwave horn
- The coherent evolution is damped due to trap decoherence (reversible + irreversible)
- Seeing several oscillations indicates we have enough coherent time to perform atom interferometry.

Trapping with 793 nm light reduces total power

- Proof-of-principle experiment – changed out the 685 nm for a 793 nm laser
- Trap powers: P_{937} = 1.6 mW, P_{793} = 3.2 mW
- Total trap power of 4.8 mW!



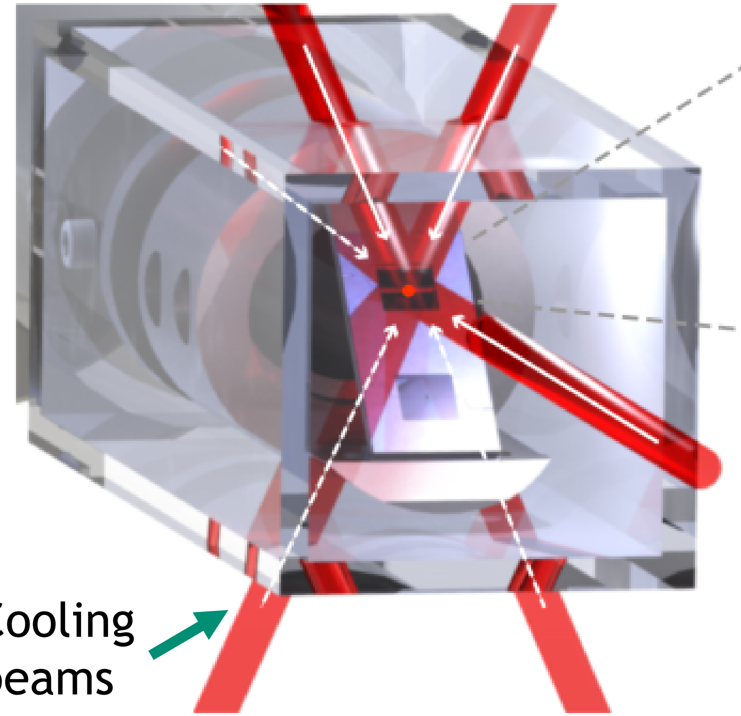




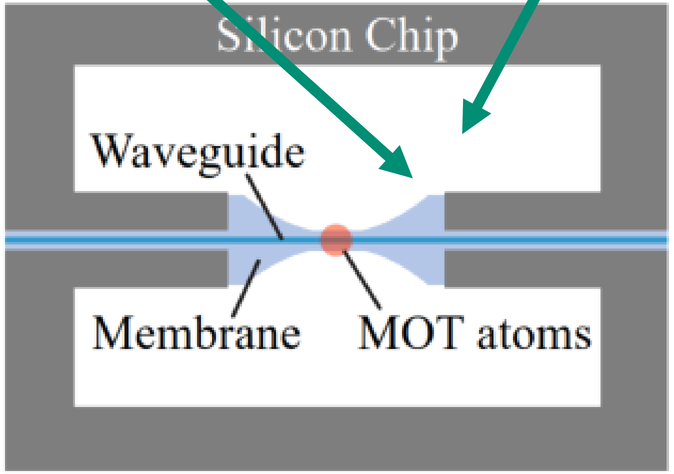
Optical Waveguide Design

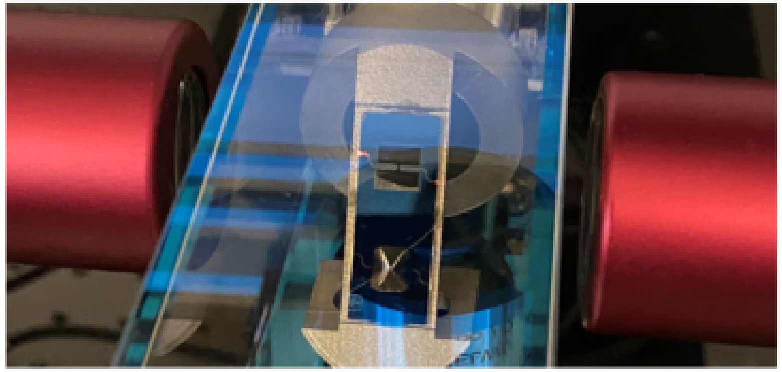
Membrane helps dissipate heat

Large space for cooling beams



Cooling beams





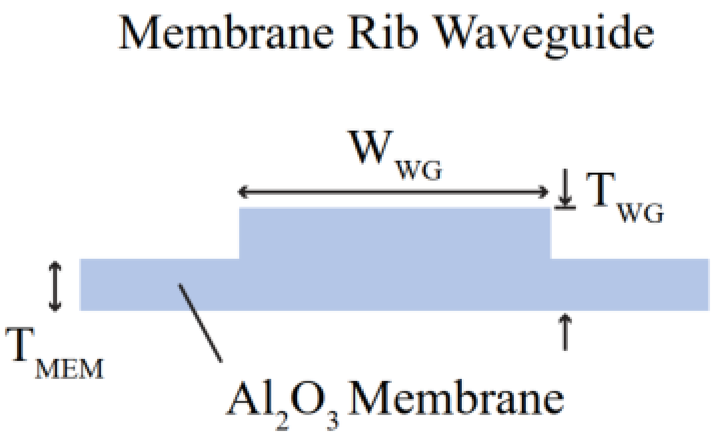
Large NA objectives used to couple to WG

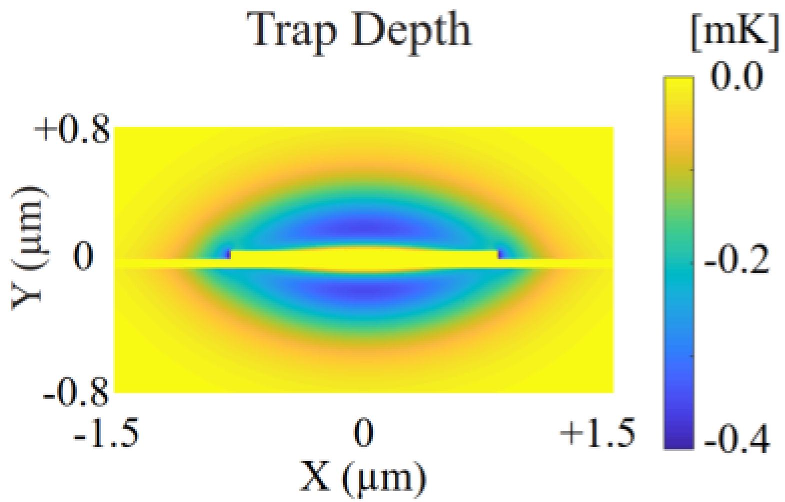
Experiment image

M. Gehl, Optics Express, Vol. 29, 9 (2021)

Trapping potential using Rib Waveguide

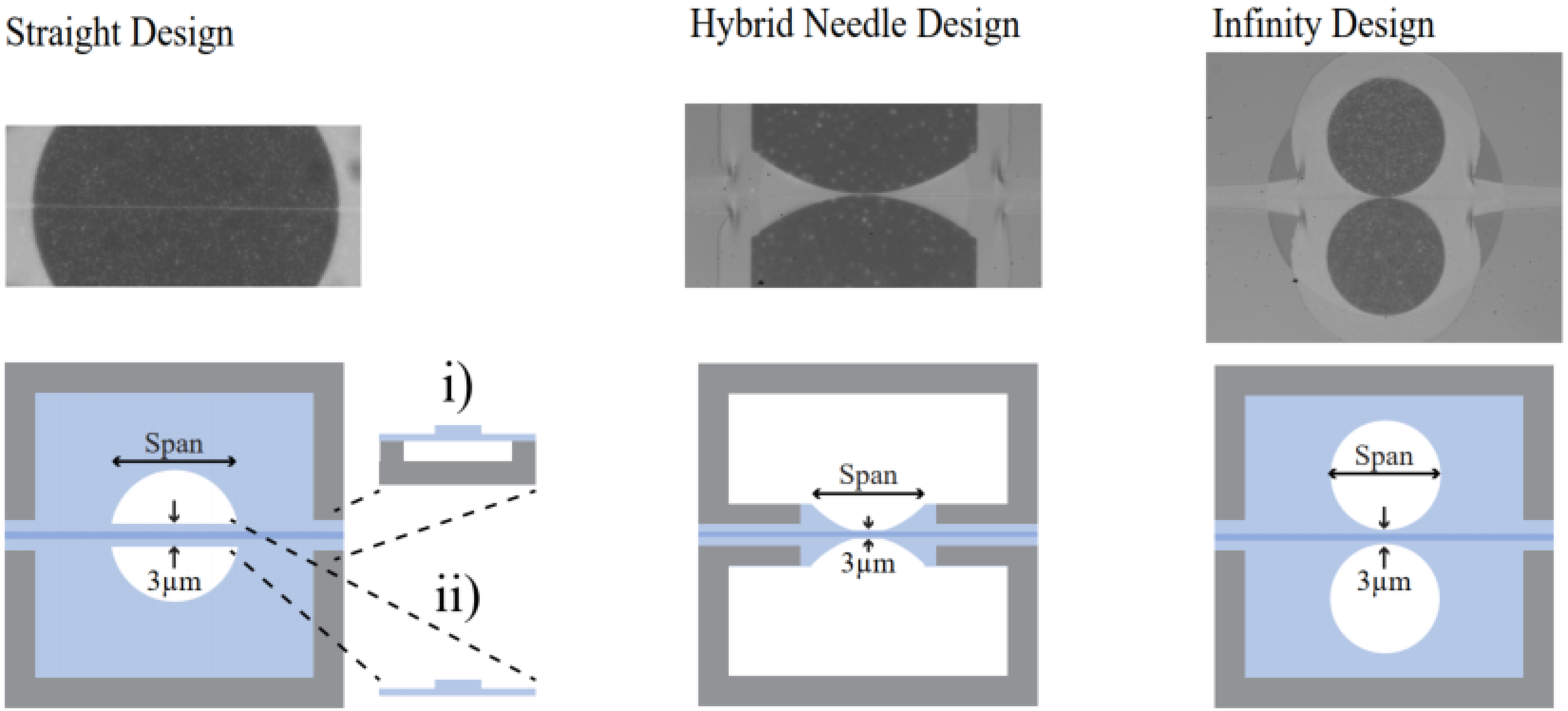
- Rib waveguide consists of the same material for the substrate and the waveguide made from aluminum oxide
- The waveguide is assumed to surrounded by vacuum
- The dimensions of the waveguide are W_{WG} = 1.6 μm, T_{WG} = 100 nm, and T_{MEM} = 50 nm
- Trapping potential calculated using 937 nm (2.73 mW) and 793 nm (3.27 mW)
- Maximum trap depth is 350 μK





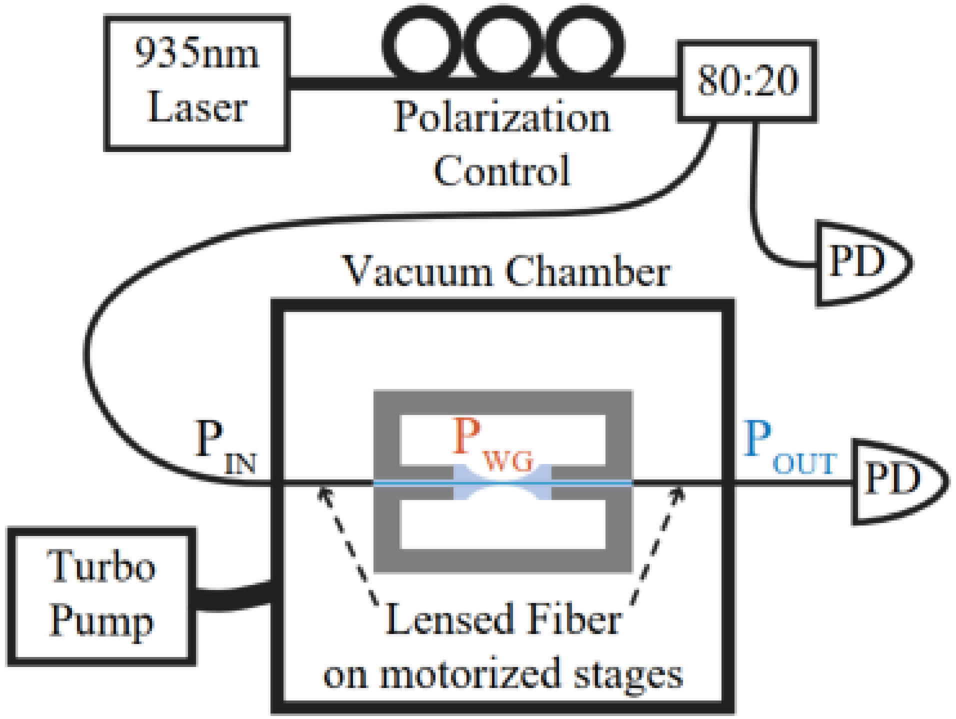
Different Geometries

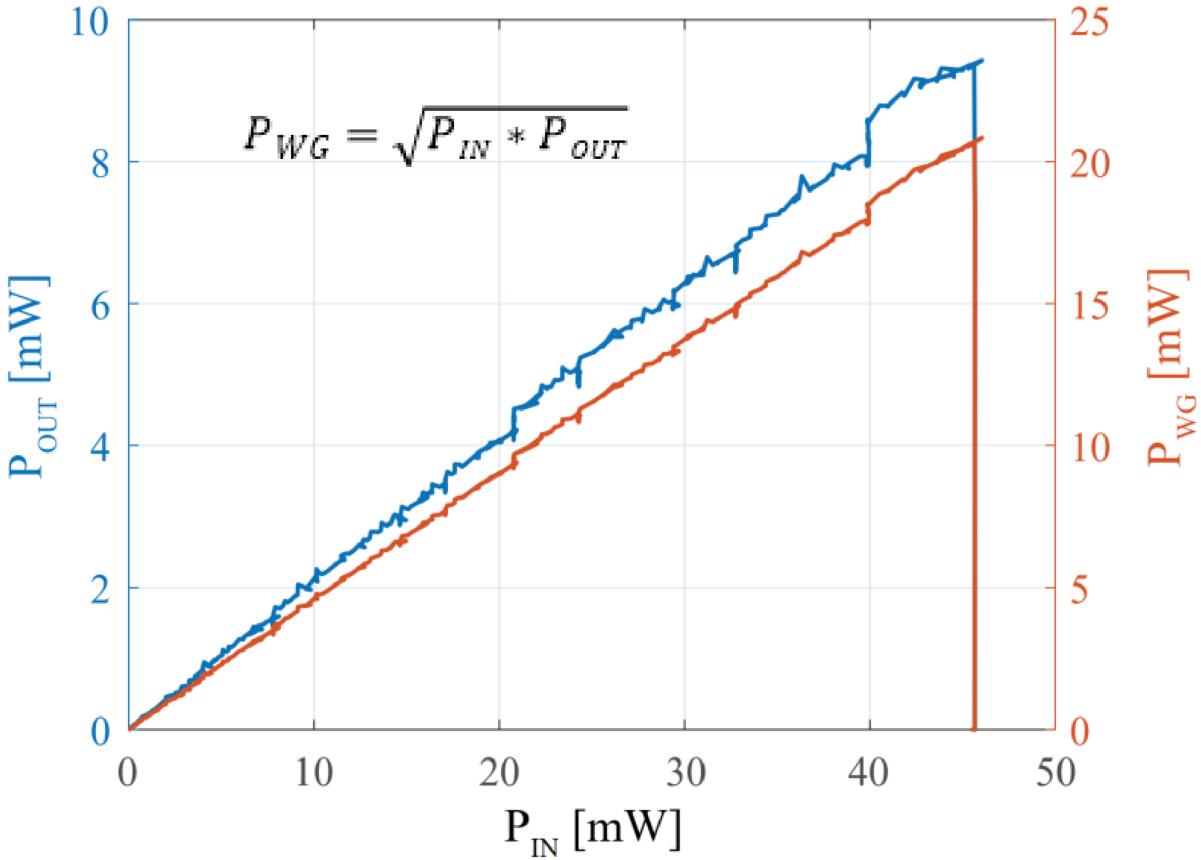
- Different designs→ change open area and membrane size
- Increasing open are increases MOT beam size but reduces power handling capabilities



Power Handling Measurements

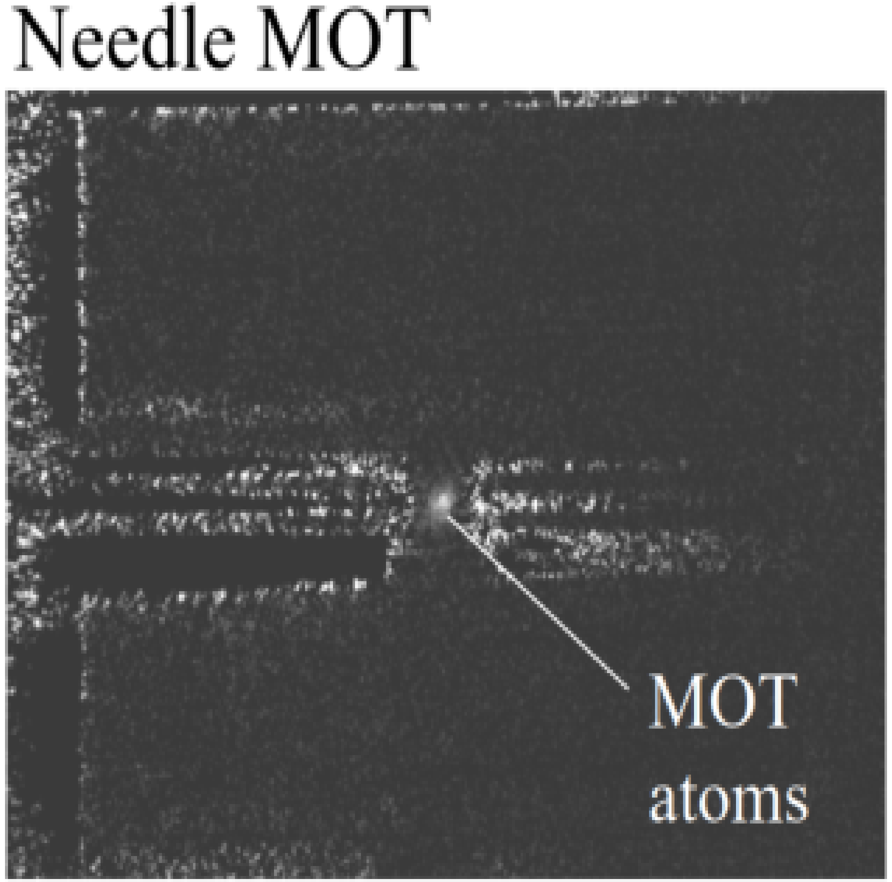
- Experiment under vacuum 10^{-6} Torr
- Power transmitted is increased until WG fails/breaks





Atom Cloud and WG Overlap

- The MOT atom cloud was overlapped with the waveguide
- The needle structure casted shadows on the MOT cooling beams
- Atom number was measured with a CCD camera
- When the atom cloud was overlapped with the waveguide the atom number reduced my an order of magnitude
- N_{atom} ~1000 (cloud and WG overlapped)



Conclusion

- Trapped Cs atoms around a nanofiber using magic wavelengths in a 1D Dual-color nanofiber atom trap without axial confinement
- Probed atomic coherence of nanofiber trapped atoms with microwave transitions between clock states
- Used nanofiber platform to test trapping with blue detuned wavelength 793 nm to further reduce power requirements in atom chip waveguides
- Developed atom-chip designs and tested power handling capabilities for atom trapping on chip

Future Work

- Drive Doppler sensitive Raman transitions to nanofiber trapped atom using fiber guided or free space laser beams
- Measure gravity and rotation using nanofiber atom interferometer platform

Acknowledgements

Experiment



Adrian Orozco[1,2] William Kindel[1] Jongmin Lee[1]

Advisor

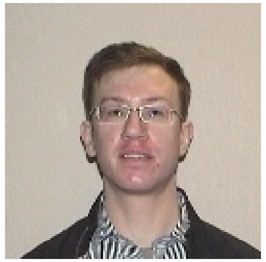
Grant Biedermann[3]

Theory


Weng Chow[1] Jonathan Sterk[1]

Other Contributors



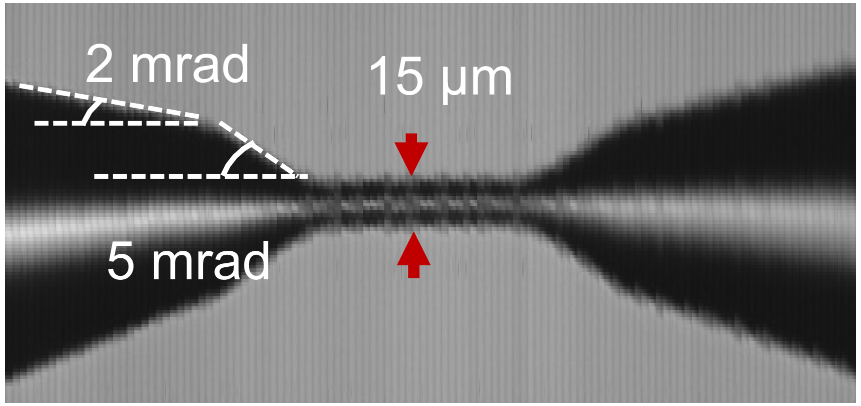
Yuan-Yu Jau[1] Michael Gehl[1] Ivan Deutsch[2] Nicholas Karl[1]

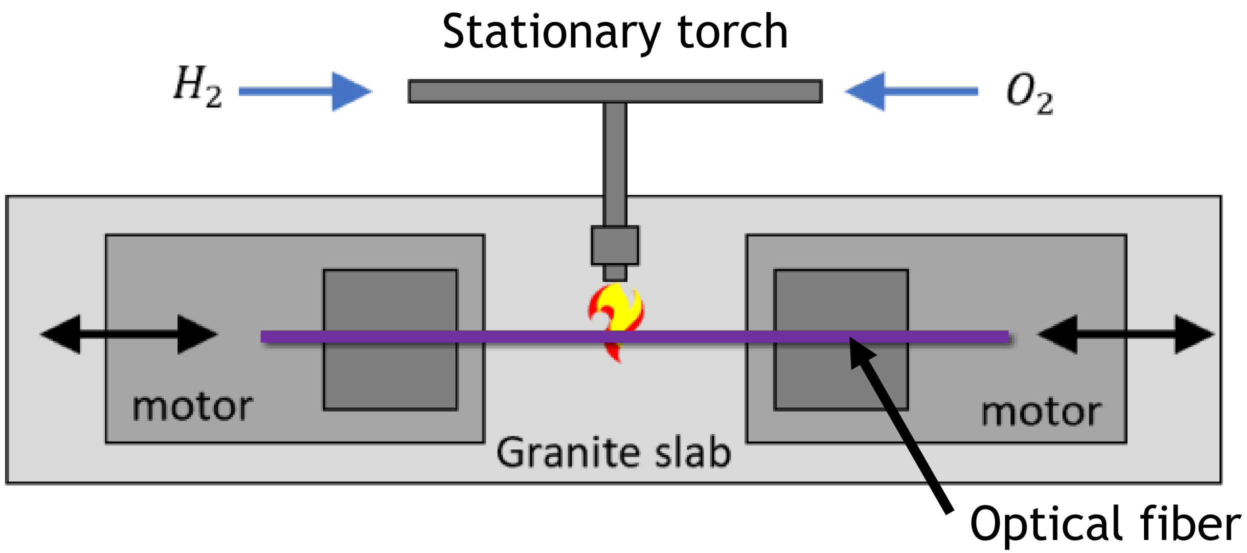
1. Sandia National Laboratories
2. Center for Quantum Information and Control, University of New Mexico
3. Center for Quantum Research and Technology, University of Oklahoma

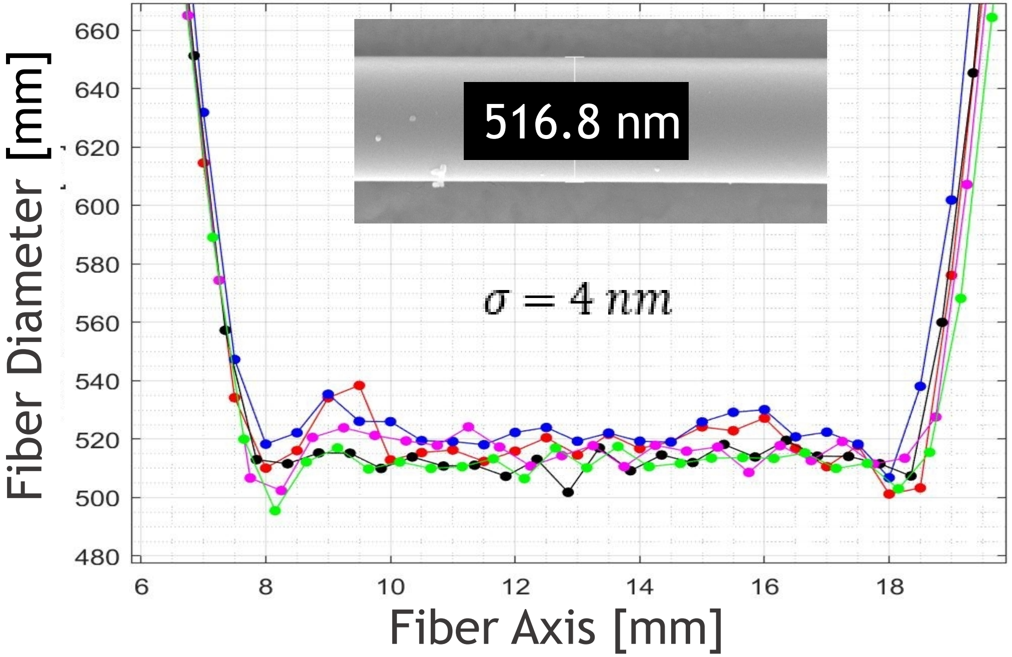
Nanofiber fabrication at Sandia

- Flame-brushing technique with stationary oxyhydrogen torch using computer controlled motors
- Algorithmic pulling allows for precise design of fiber profile* (linear, linear, exponential taper slope)
- Highly consistent production of optical fibers with sub-micron diameters
- Shallow fiber tapers increase transmission efficiency >99%

Algorithmic Pulling

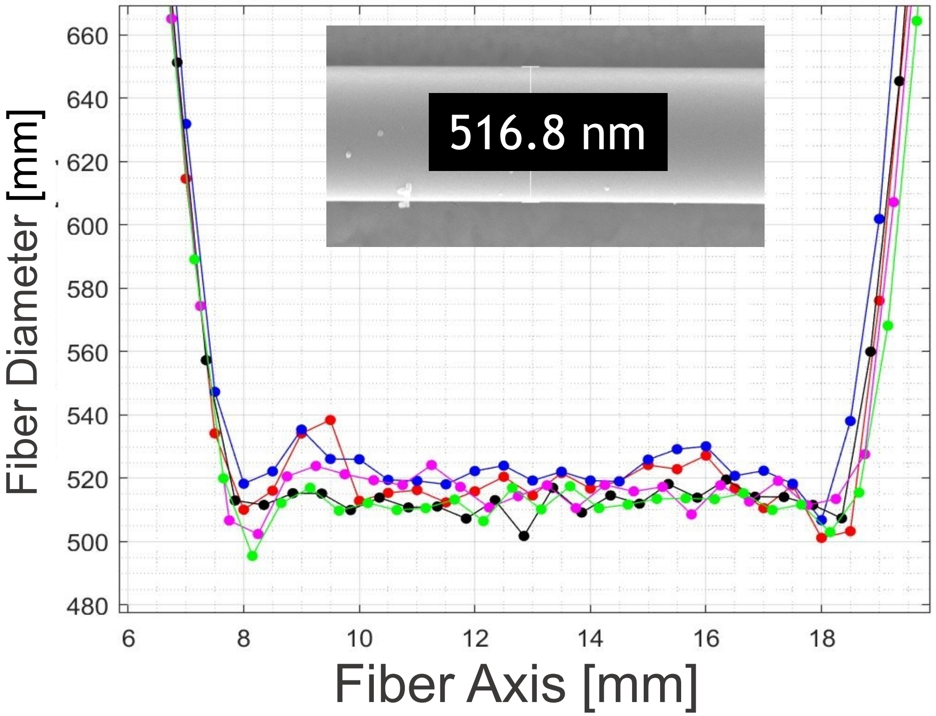






*Fiber Pulling Rig based on: AIP Advances 4, 067124 (2014)

Fabricated nanofibers' diameters have a std ~ 4 nm



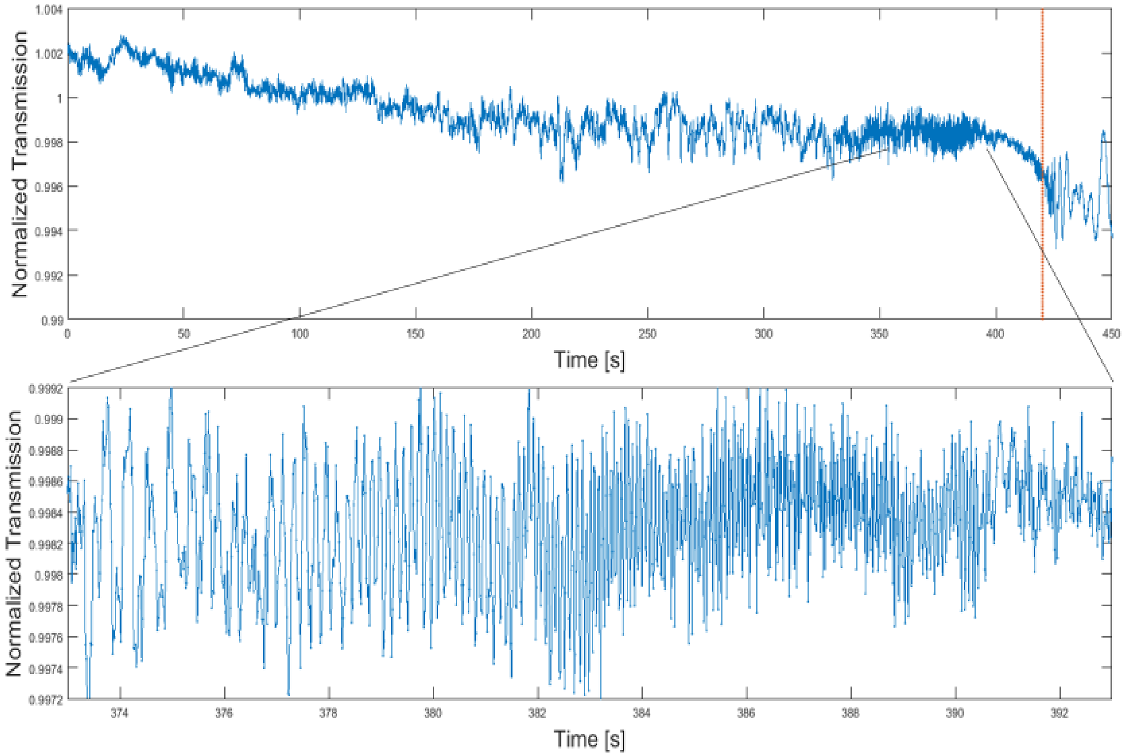
Fiber diameter uniformity

Fiber	Mean [nm]	STD [nm]
1	518	9
2	522	6
3	512	4
4	516	6
5	512	5

Comparing fiber mean diameters $\sigma = 4\ nm$.

Transmission During Fabrication

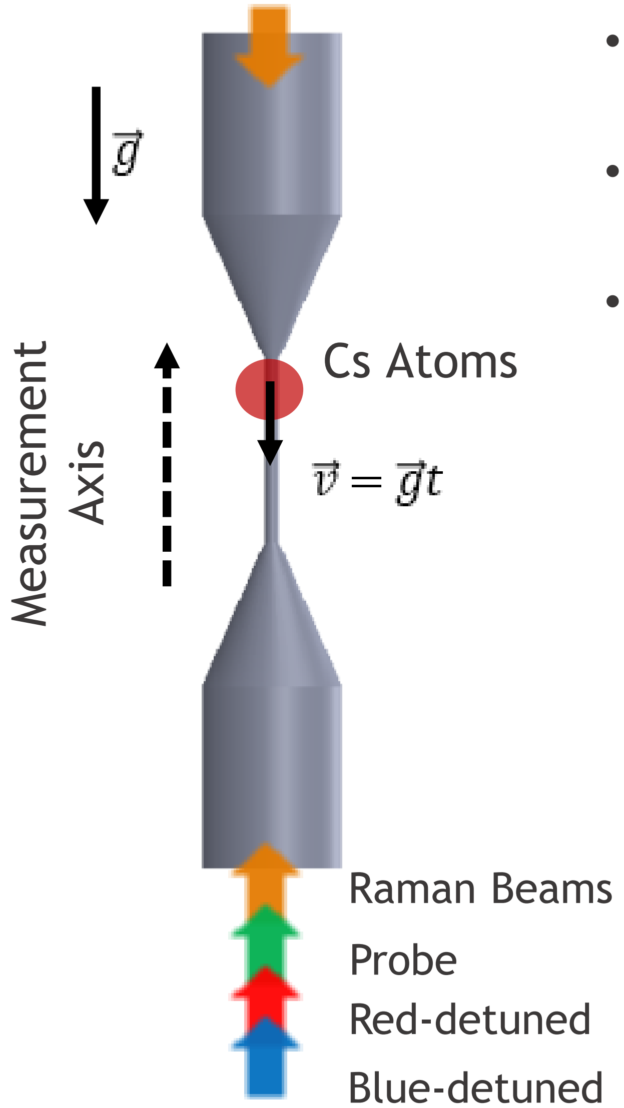
Fiber pulling stops



- Rapid oscillations indicate mode beating
- Damping of oscillations indicate single mode regime
- Transmission is greater than 99 % after pull

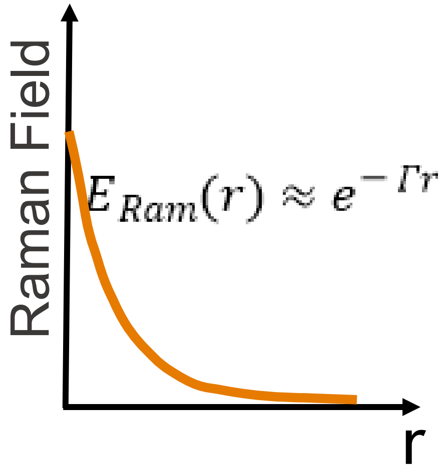
Graph borrowed from Vetsch PhD Thesis (2010)

Conceptual implementation of atom Interferometry on a nanofiber

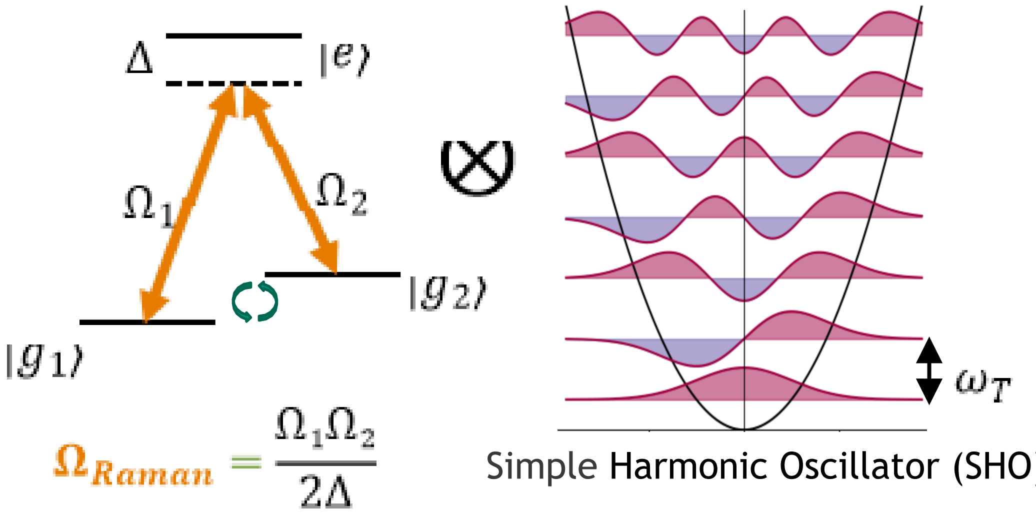


- All beams are guided in the nanofiber
- Trapped atoms are tightly confined along radial direction (~11nm) and free to move along z
- Doppler sensitive Raman transitions are guided through the nanofiber resulting in the sensing axis is along the fiber axis
- Radial intensity decay of Raman beams couples atom states to phononic degrees of freedom

Radial Field Amplitude



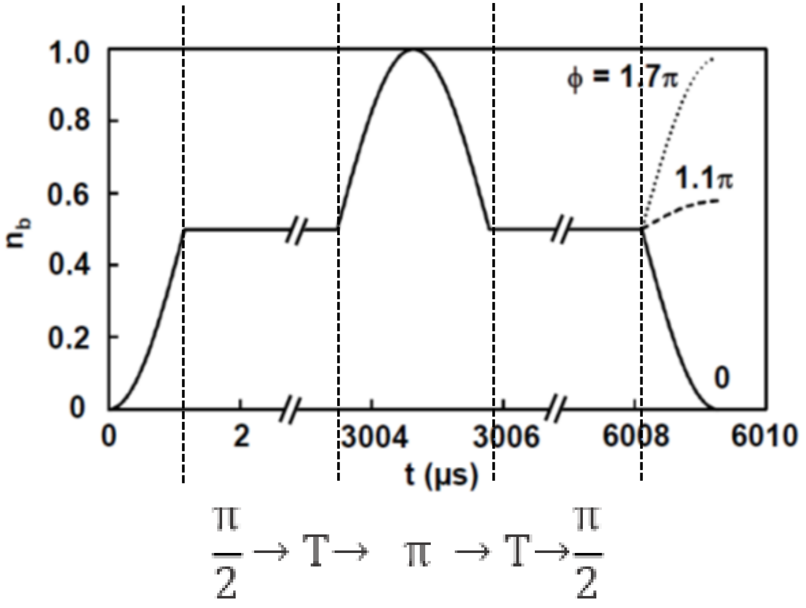
Coupled Degrees of Freedom



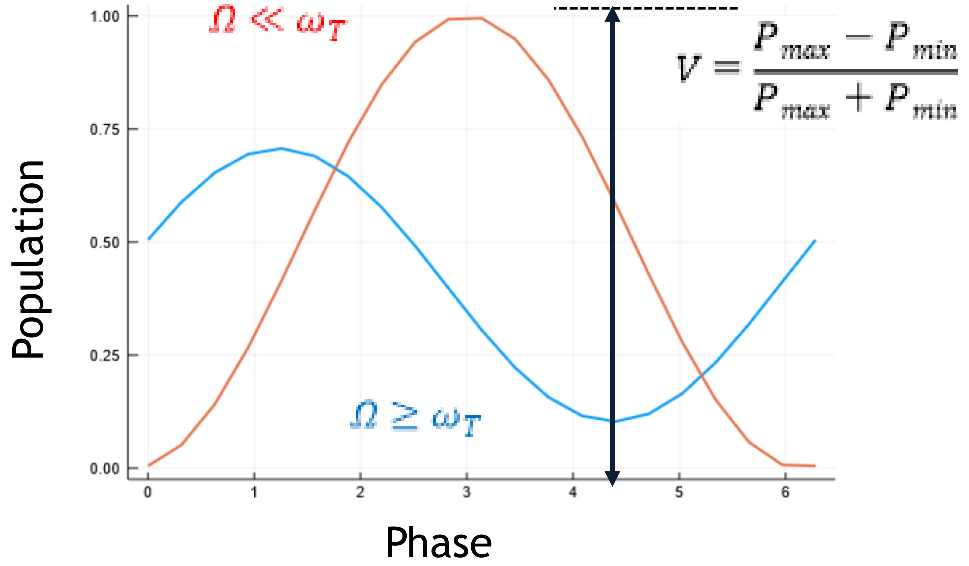
Simple Harmonic Oscillator (SHO)

AI Pulse Sequence Simulation: Fringe Visibility

Population evolution during pulse sequence



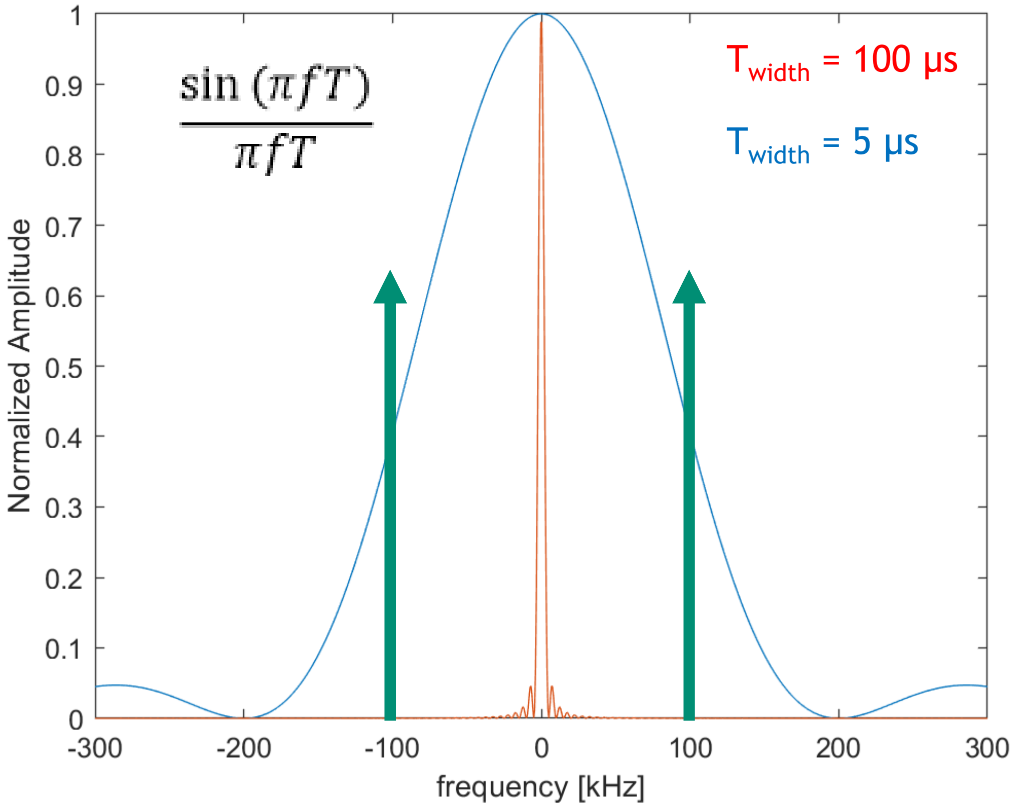
Fringe Visibility



- (Left) Atom interferometry pulse sequence $\frac{\pi}{2} \to T \to \pi \to T \to \frac{\pi}{2}$ where T is interrogation time.
  - The laser phase is swept during the last pulse to obtain interferometric signal
- (Right) The fringe visibility decreases in the unresolved case due to driving multiple motional states in the trap when

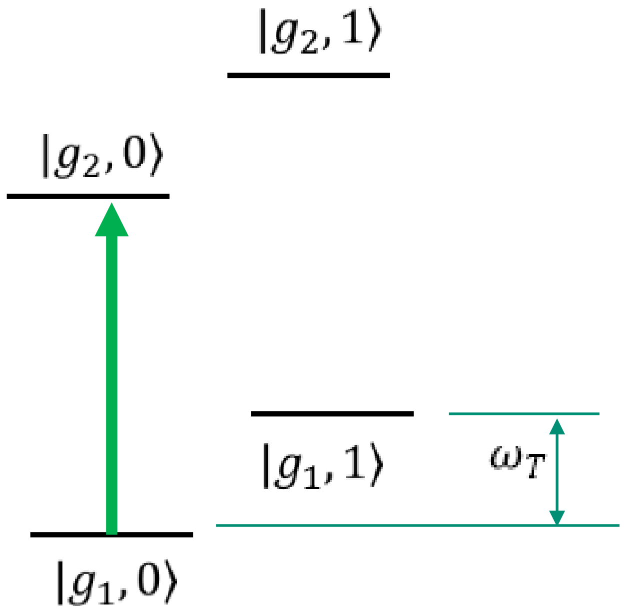
Transform of square pulse

- Raman linewidth is kHz
- Square pulses used with pulse duration T
- Short pulses lead to transform limited pulses
  $$\Delta f = 2\pi/T$$
- Nanofiber trap frequencies are typically in the 100 kHz's regime

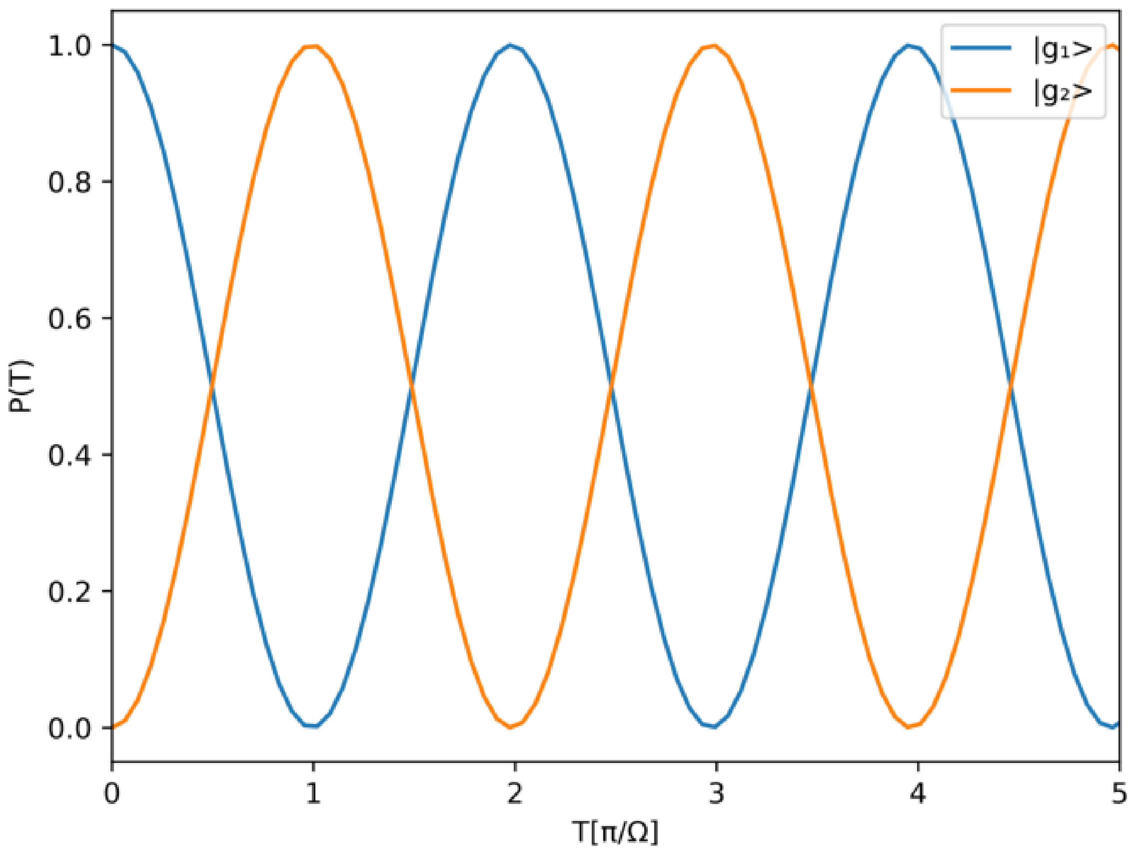


Simulations: Resolved Regime

- Two level atom in a harmonic well
- Resolved regime $\Omega_{Raman} \ll \omega_T$
- Driving carrier transition
- Initially state $|g_1, n = 0\rangle$

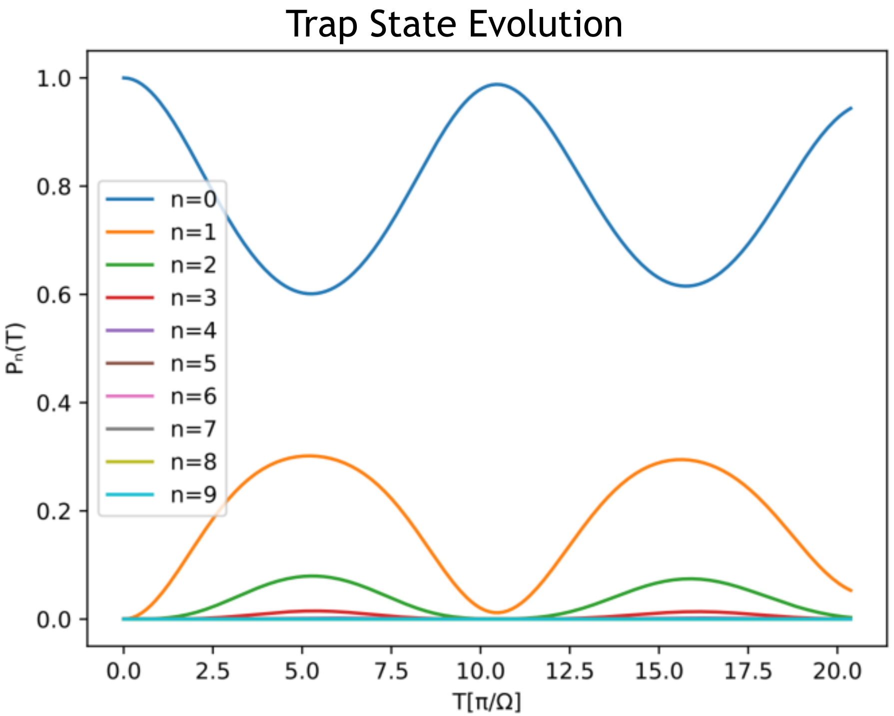


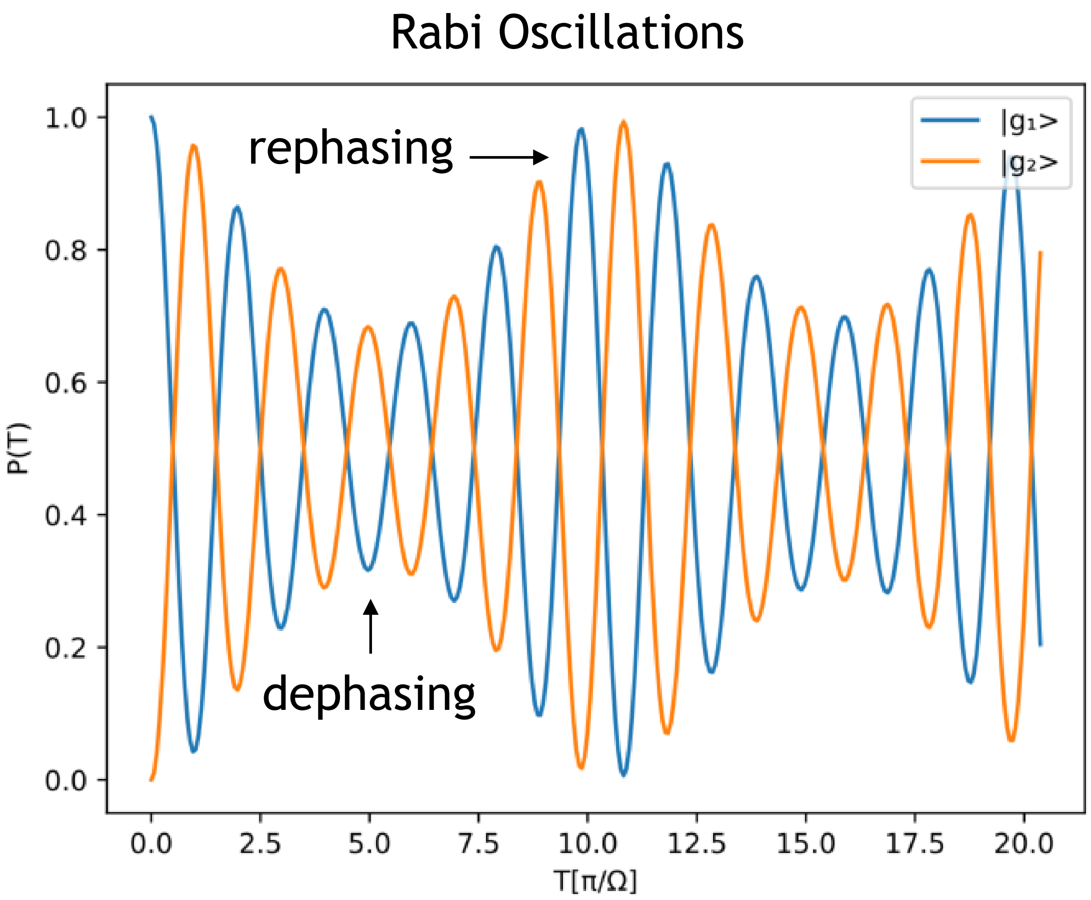
Rabi Oscillations



Simulations: Unresolved Regime

- Two level atom in a harmonic well
- Unresolved regime $\Omega_{Raman} \geq \omega_T$
- Driving carrier transition
- Initially state $|g_1, n = 0\rangle$
- Dephasing due to multiple trap states populated

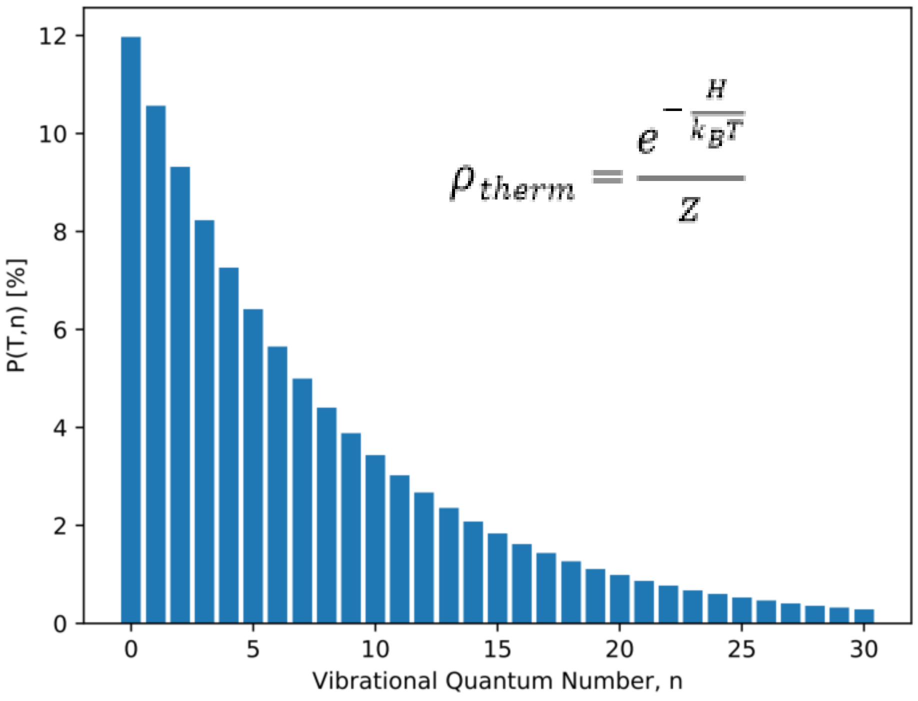




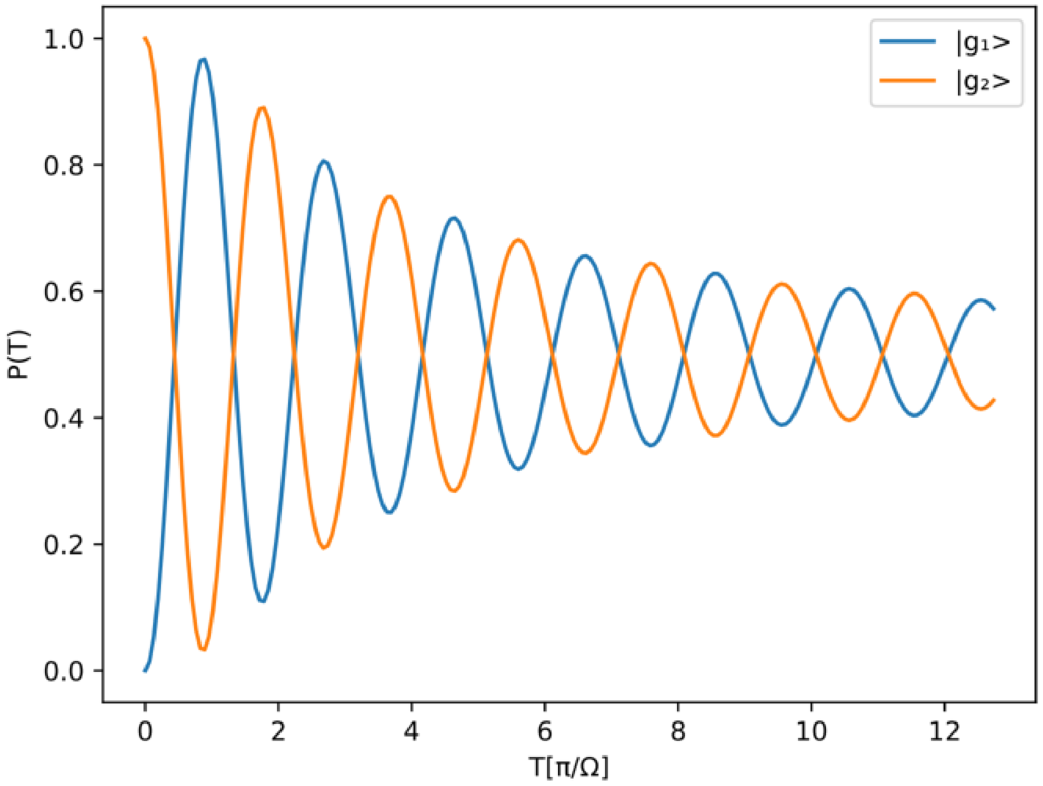
Simulations

- Two level atom in a harmonic well
- Resolved regime $\Omega_{Raman} \ll \omega_T$
- Driving carrier transition
- Initially in a thermal state for harmonic trap

Thermal state: 38 μK



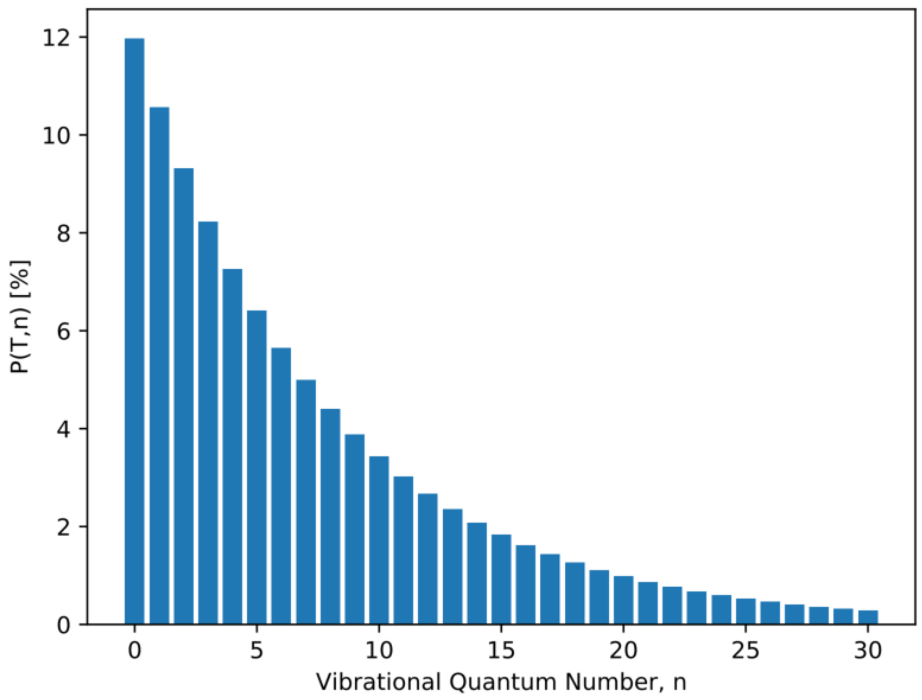
$$\rho_{therm} = \frac{e^{-\frac{H}{k_B T}}}{Z}$$

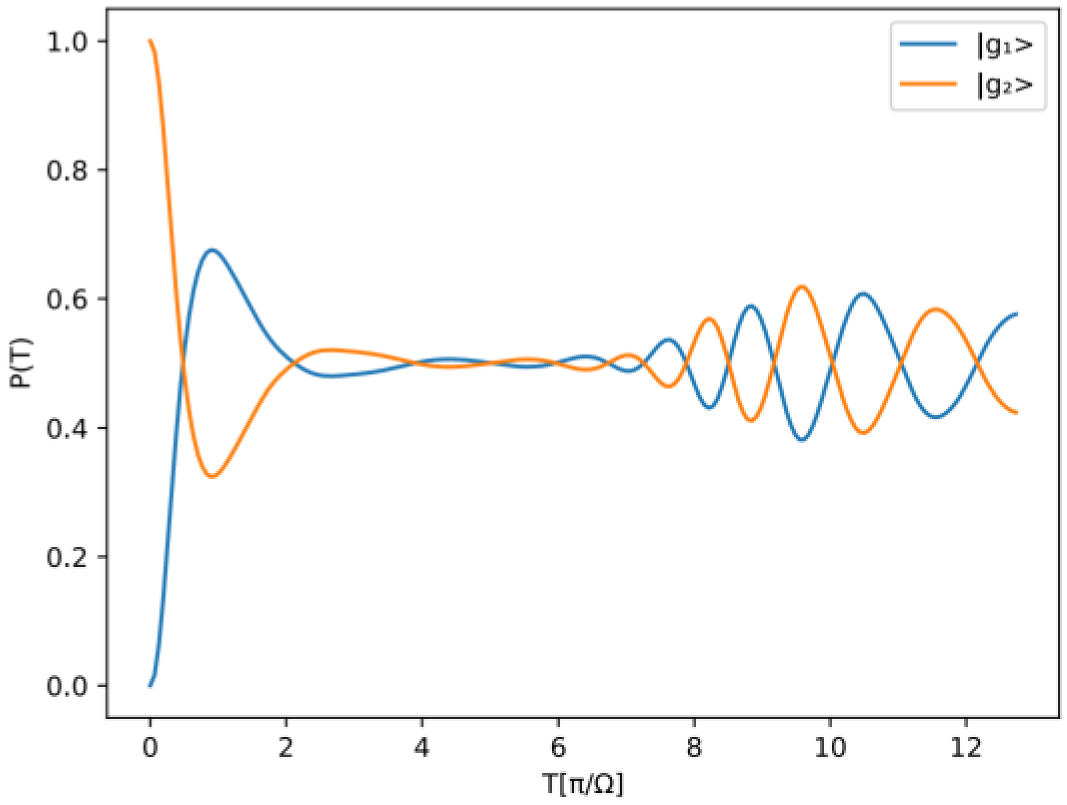


Simulations: Add temperature

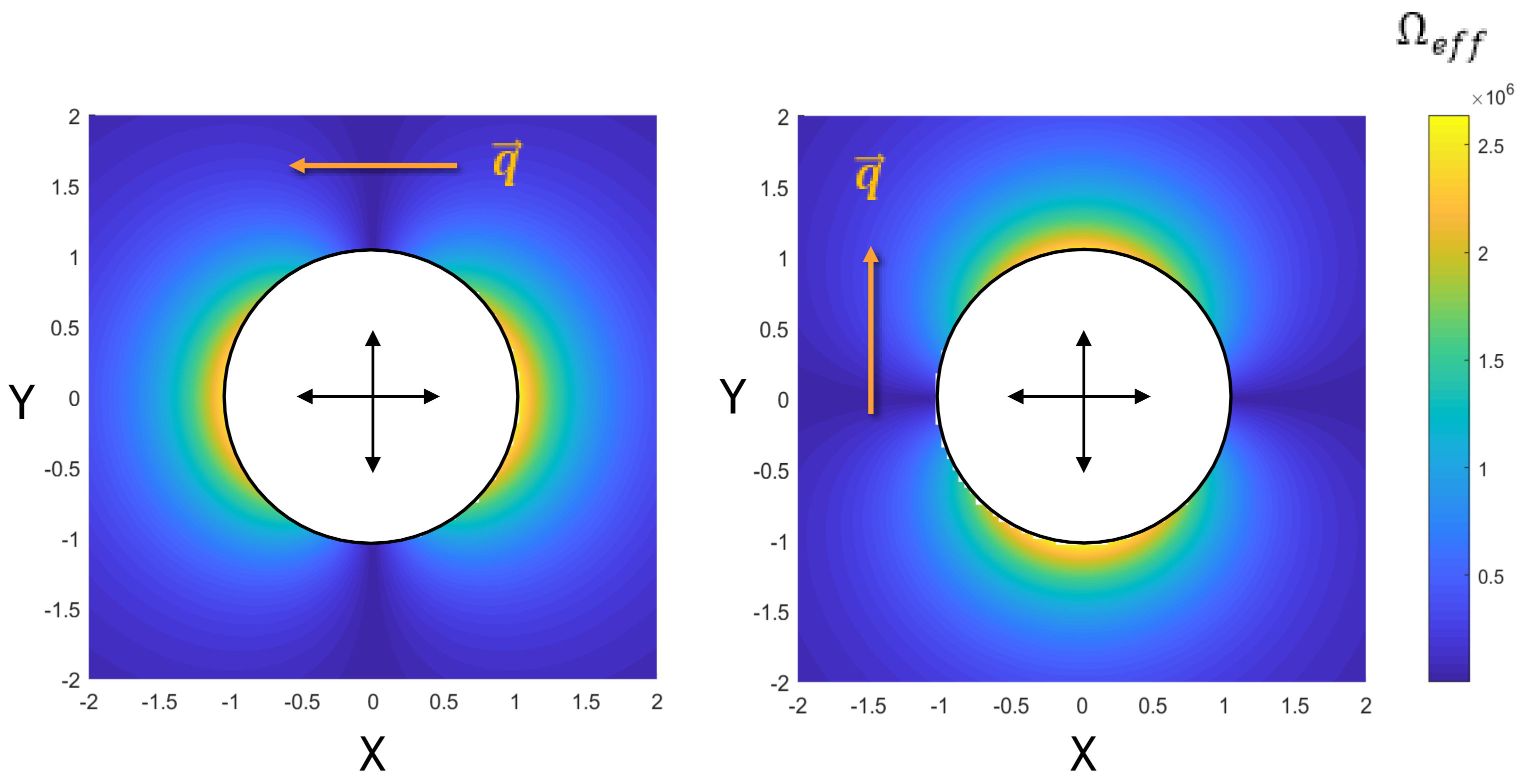
- Two level atom in a harmonic well
- Unresolved regime $\Omega_{Raman} \geq \omega_T$
- Driving carrier transition
- Initially in a thermal state for harmonic trap

Thermal state: 38 μK



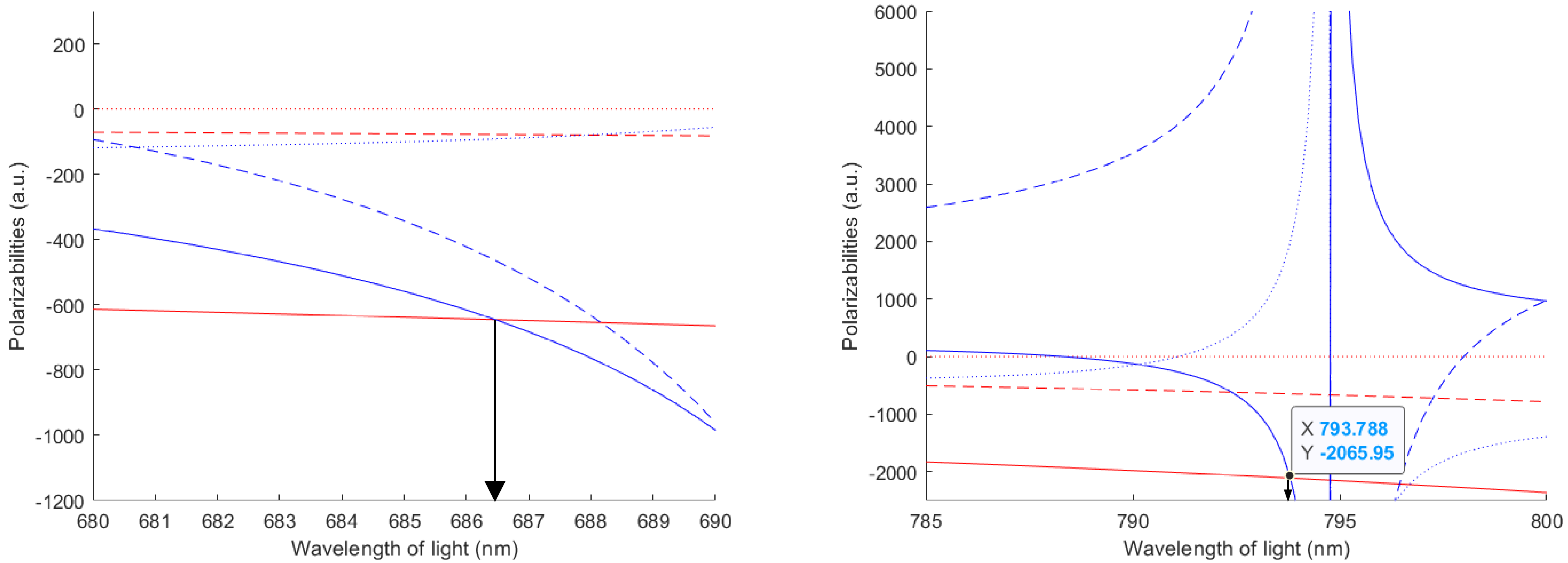


Guided Raman beam polarization



- Fields are guided in nanofiber (HE_{11} mode)
- Lin-perp-lin polarization
- Quantization axis can be used to direct maximum Rabi frequency

Cesium polarizability near 685 nm and 793 nm



- Solid: scalar component, Dashed: vector component, Dotted: tensor component
- Red: $6S_{1/2}$, Blue: $6P_{3/2}$