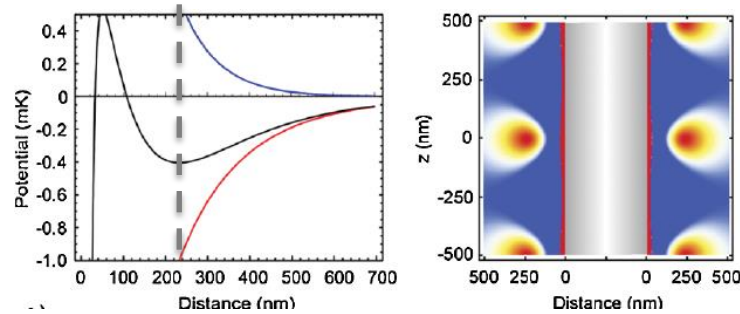


Microfabricated Waveguide Atom Traps

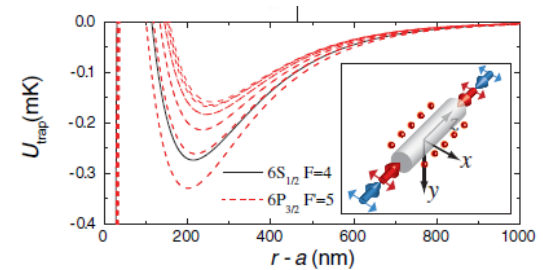
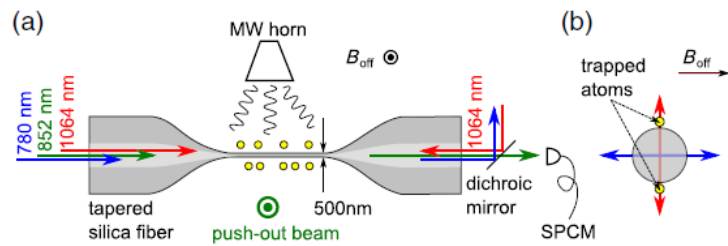
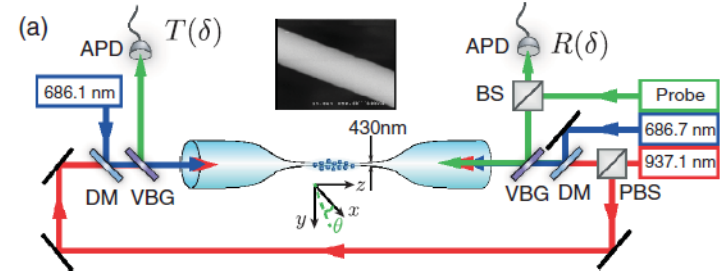
Yuan-Yu Jau

Evanescent-Fields Atom Traps

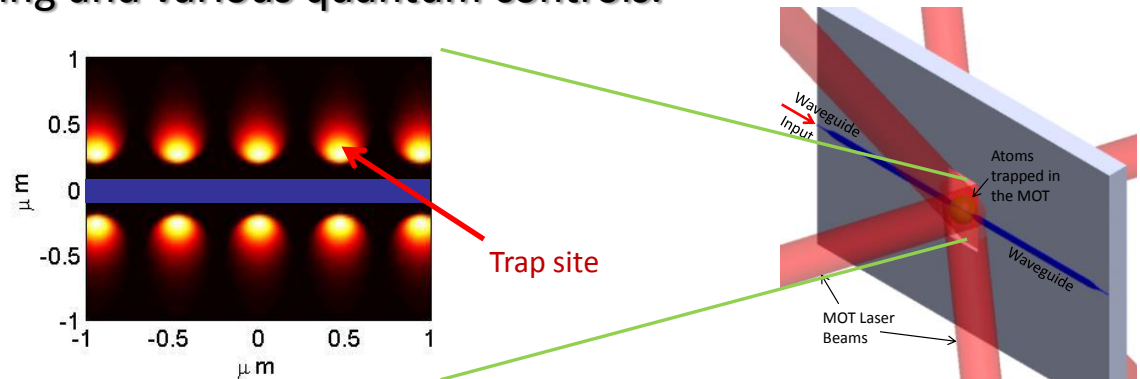
Rauschenbeutel's group uses 780 nm & 1064 nm



Kimble's group uses 686 nm & 937 nm



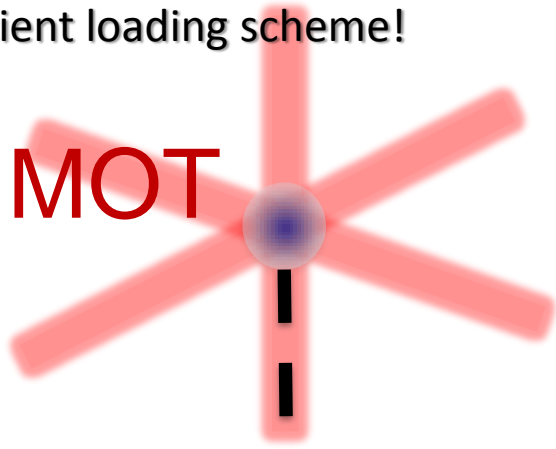
Our ultimate goal is to use the same principle to trap atoms with microfabricated waveguide devices to make a robust platform and achieve strong, uniform interactions to enable spin squeezing and various quantum controls.



Loading Atoms to the Waveguide Traps

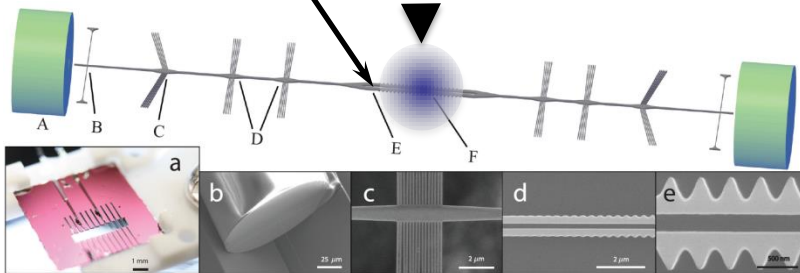
Inefficient loading scheme!

MOT



Drop the MOT cloud

Turns on the waveguide trap when the cloud arrives



The waveguide device from Kimble's group @ Caltech

Research groups in Caltech, Harvard, and JQI have been working on realizing waveguide atom traps for years but failed to load atoms into their waveguide devices. Their loading scheme is illustrated on the left. We can easily argue why it fails.

MOT cloud density: $10^{10} - 10^{11} \text{ cm}^{-3}$

Trap site volume $\sim 10^{-15} \text{ cm}^3$

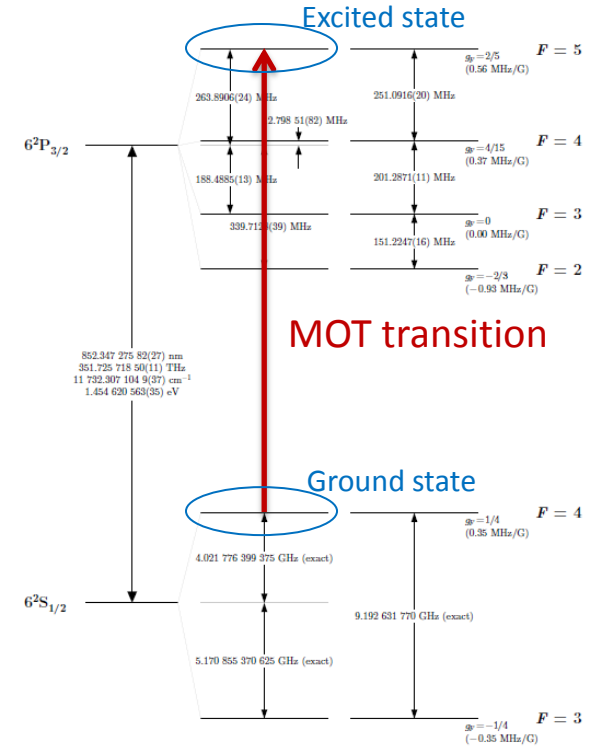
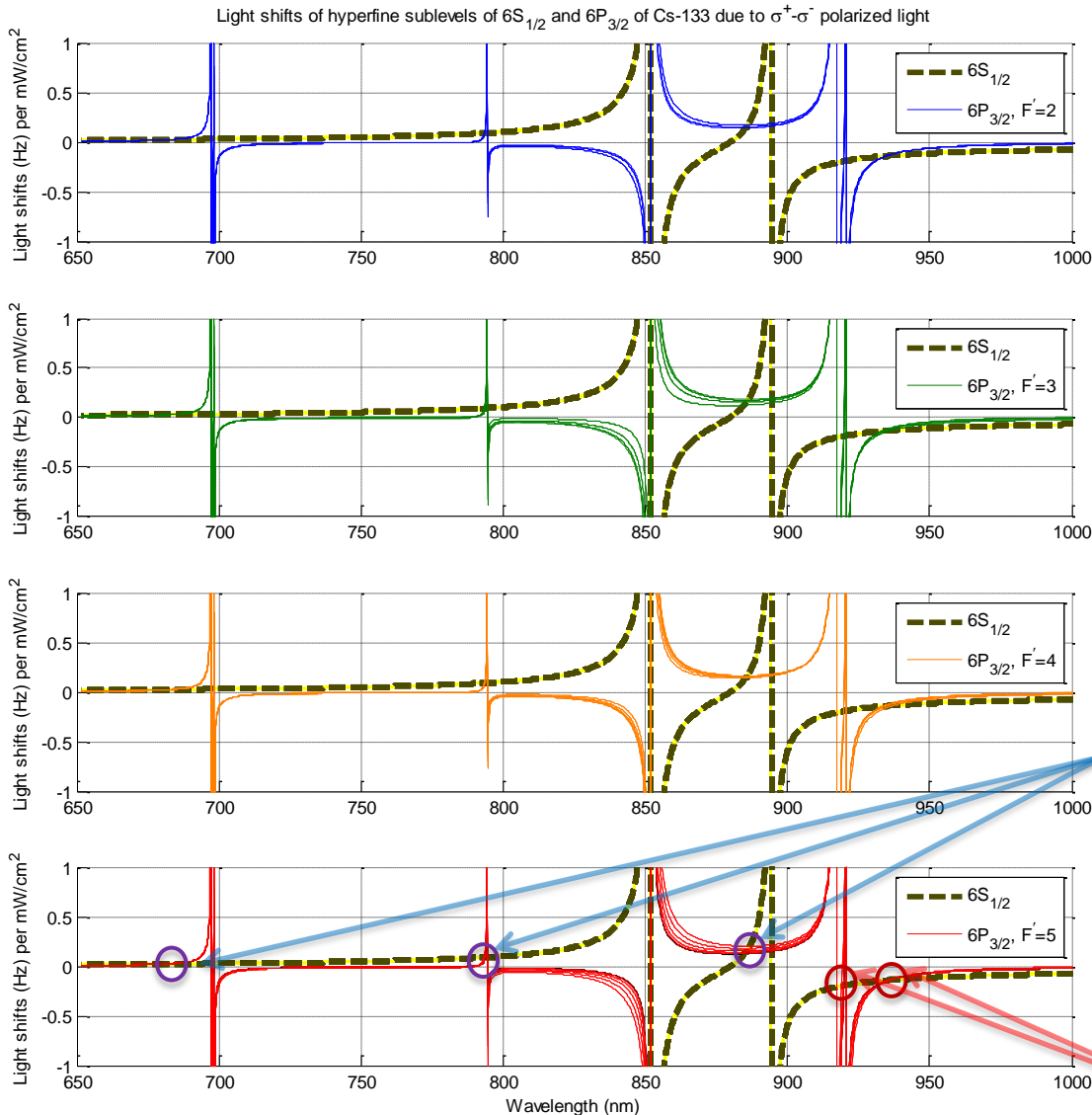
Hence, trapping probability is $10^{-5} - 10^{-4}$.

To efficiently load atoms into the trap sites, we believe that constant cooling forces and cold-atom source at the trap sites are demanded (i.e. need to have the MOT overlapped with the waveguide.).

Objectives and Milestones for FY15

- Atomic Physics Modeling
- Waveguide design
- Experimental studies of the atomic physics and waveguide design ideas
- Microfabrication of waveguide devices
- Demonstration of MOT at waveguide traps
- Demonstration of using the evanescent fields from waveguide devices to probe the atom signals

Cs Magic Wavelengths



Blue detuned magic wavelengths
 ..., 686 nm, 793 nm, 886 nm

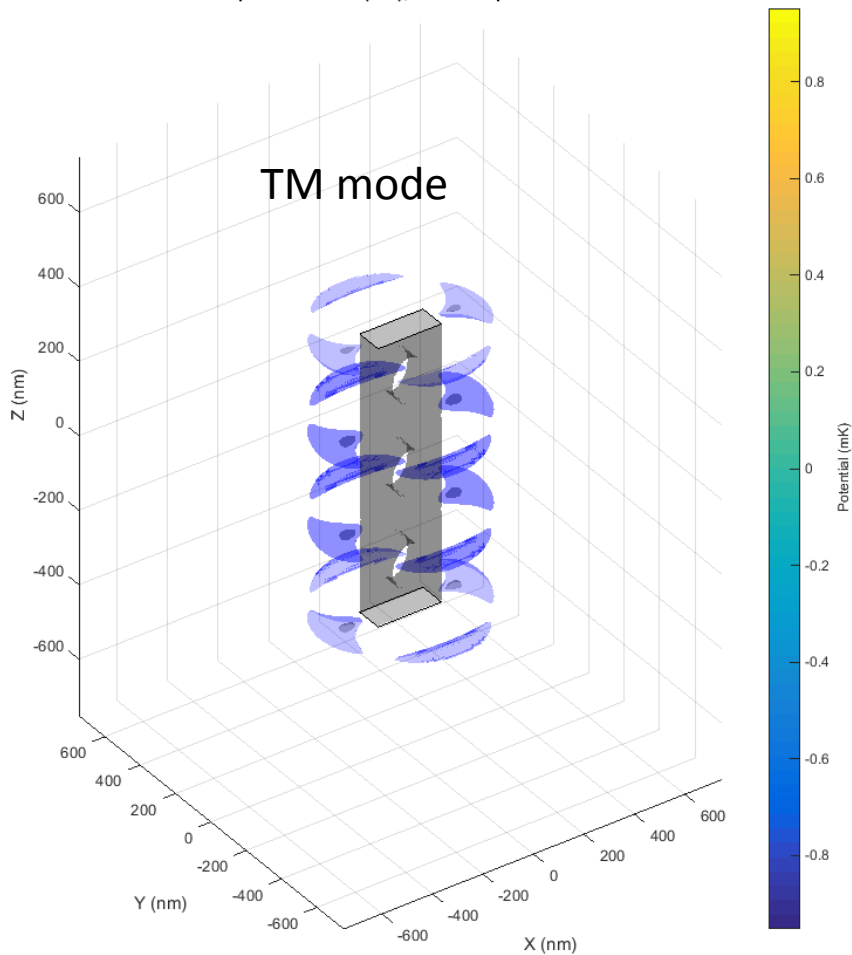
The magic wavelength produces
 the same AC Stark shifts to both
 ground state and excited state!

Red detuned magic wavelengths
 921 nm, 937 nm, ...

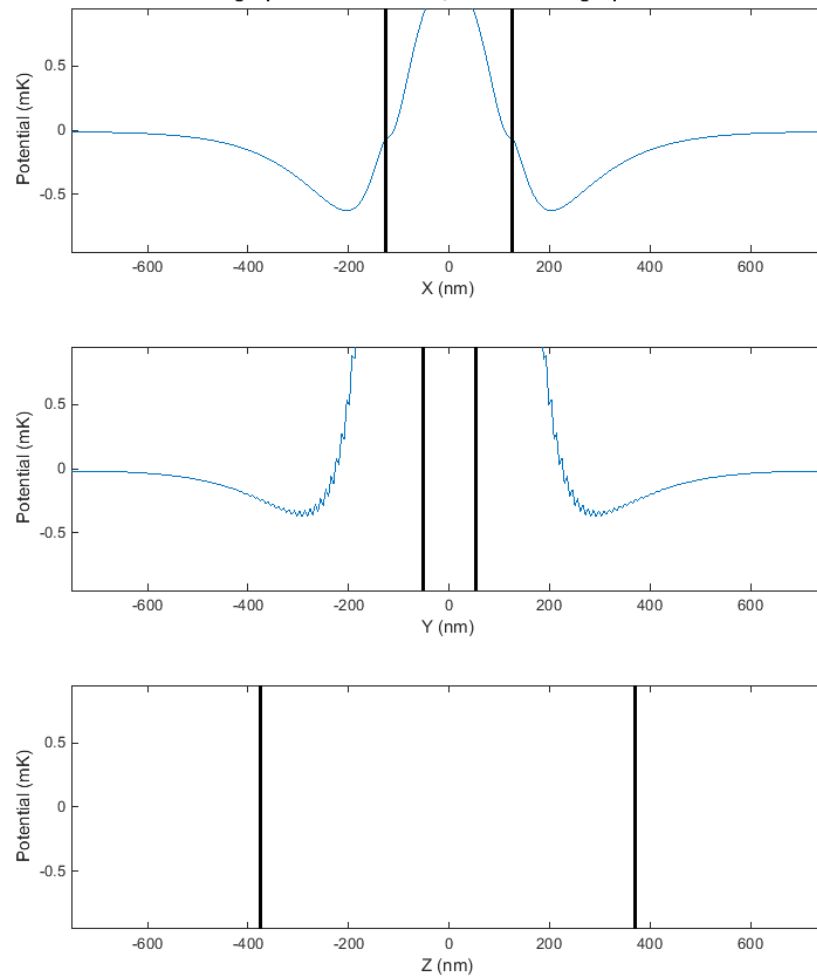
Modeling of Atom Traps with Different Waveguide Devices

Sliced Colormaps of Potential (mK); Minimum potential = -0.62947 mK

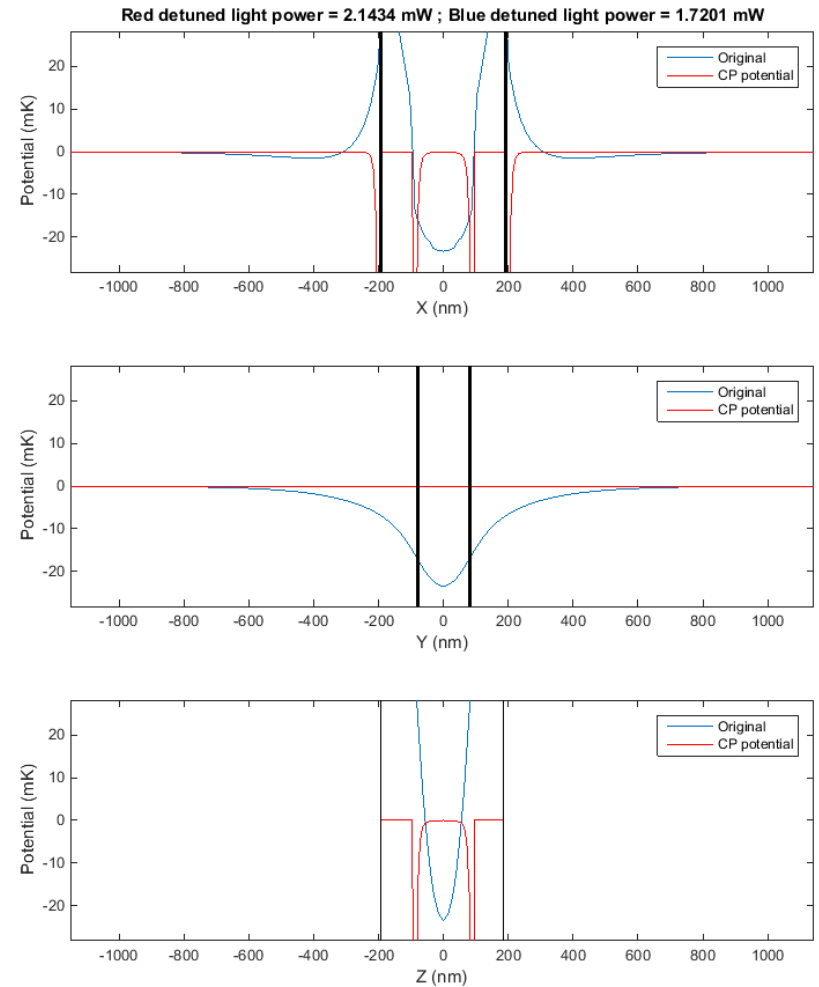
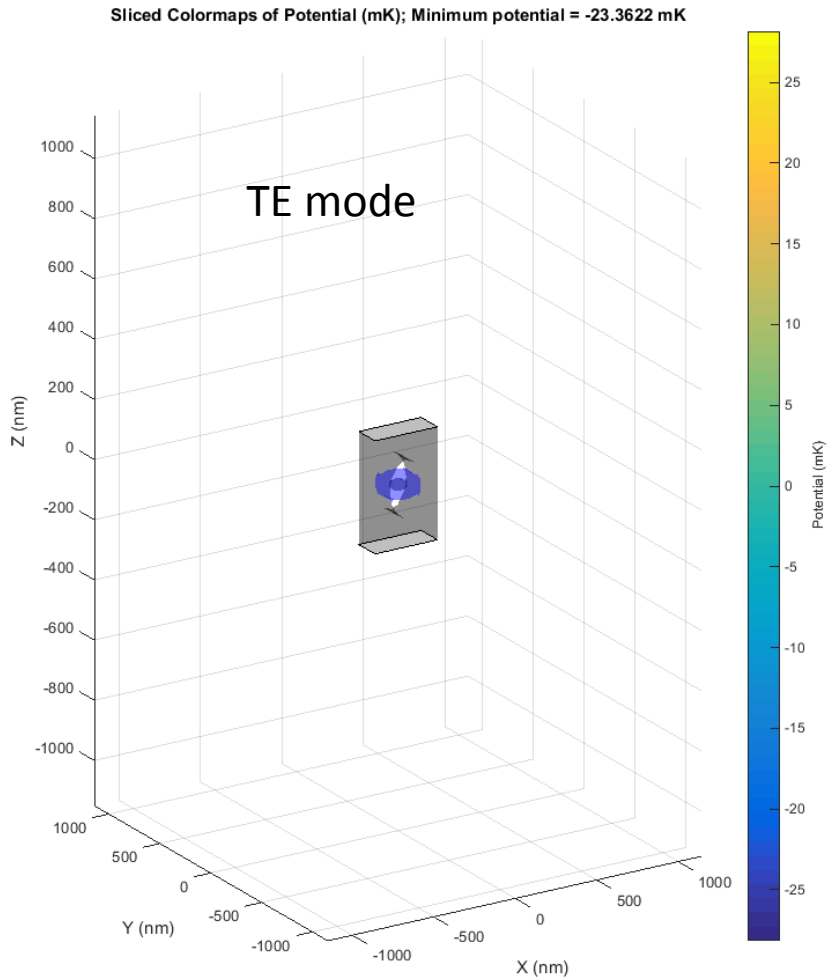
TM mode



Red detuned light power = 0.82386 mW ; Blue detuned light power = 0.78129 mW

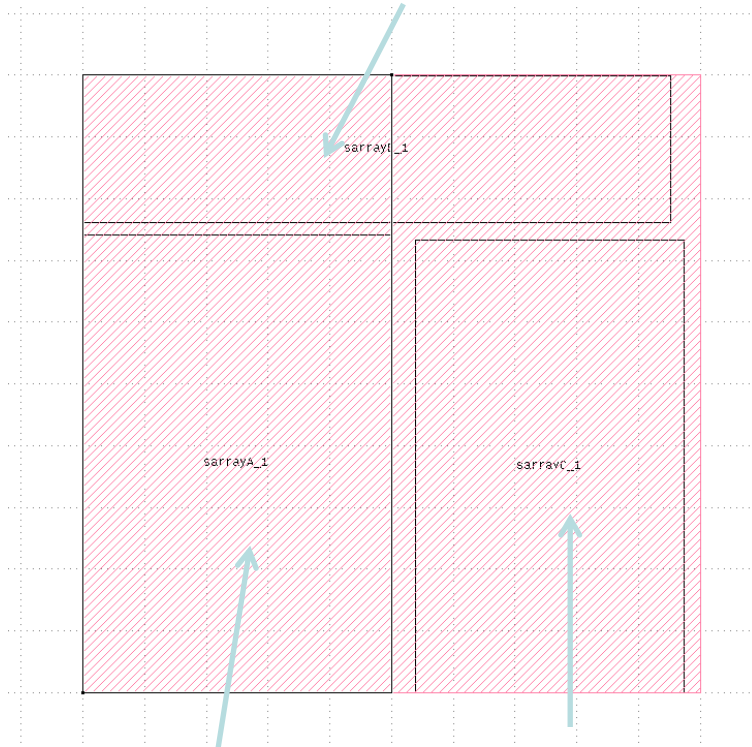


Modeling of Casimir-Polder Potentials

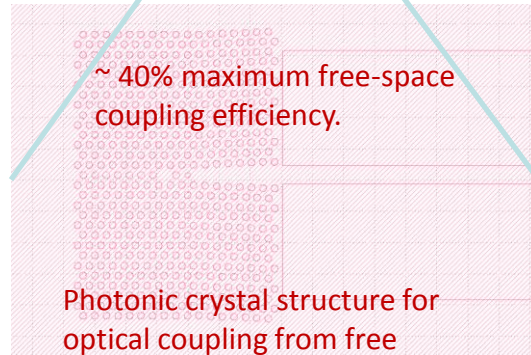
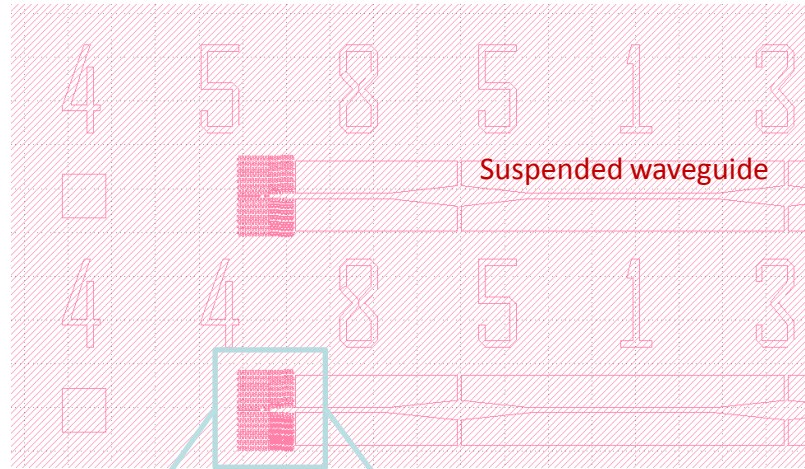


Waveguide Mask Designs

Transmission Suspended waveguide devices

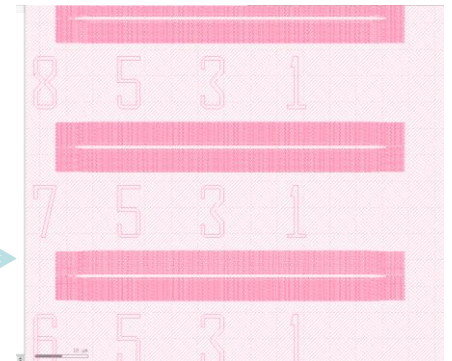


Reflection photonic crystal devices

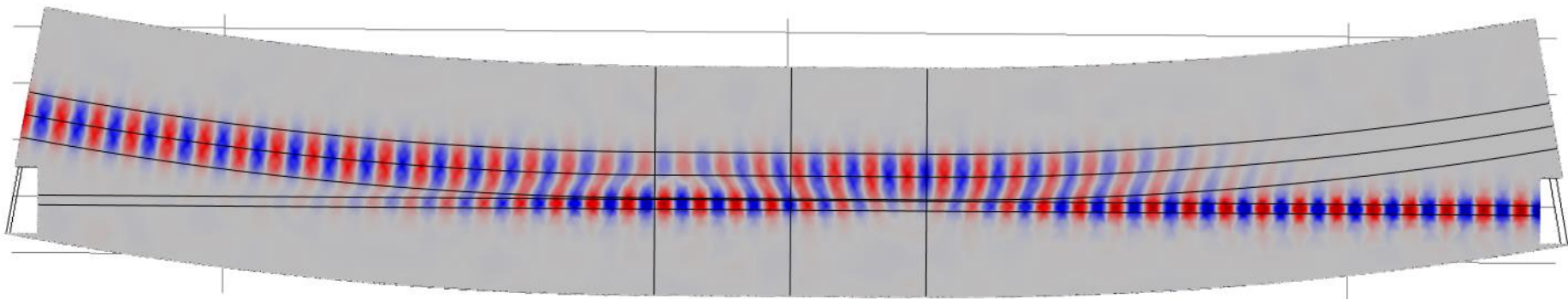
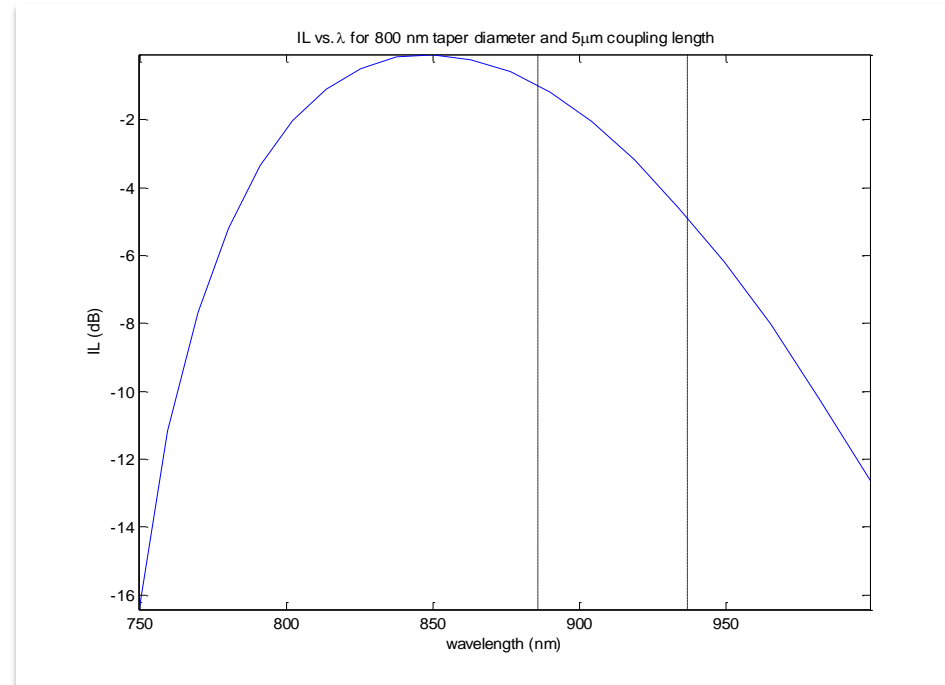
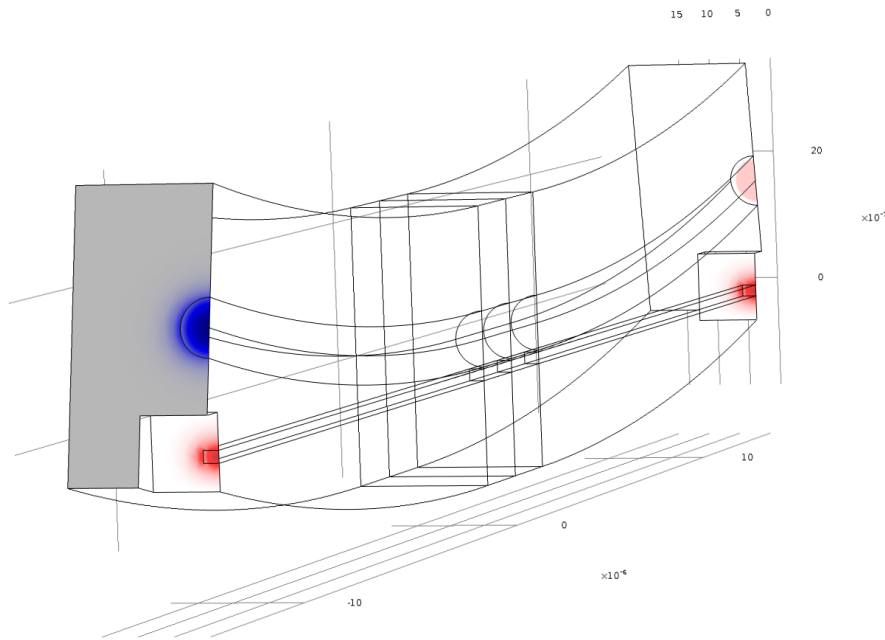


Photonic crystal structure for optical coupling from free space

The waveguide devices will be made with SiN and "AIN."



Tapered Fiber to Waveguide Coupling

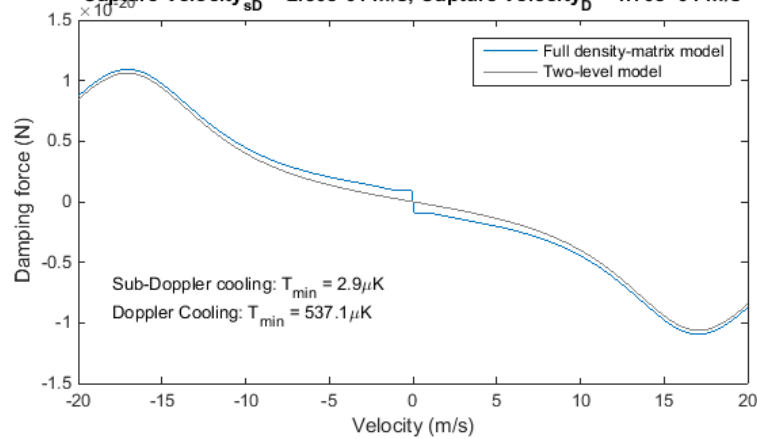


Detailed Modeling of MOT

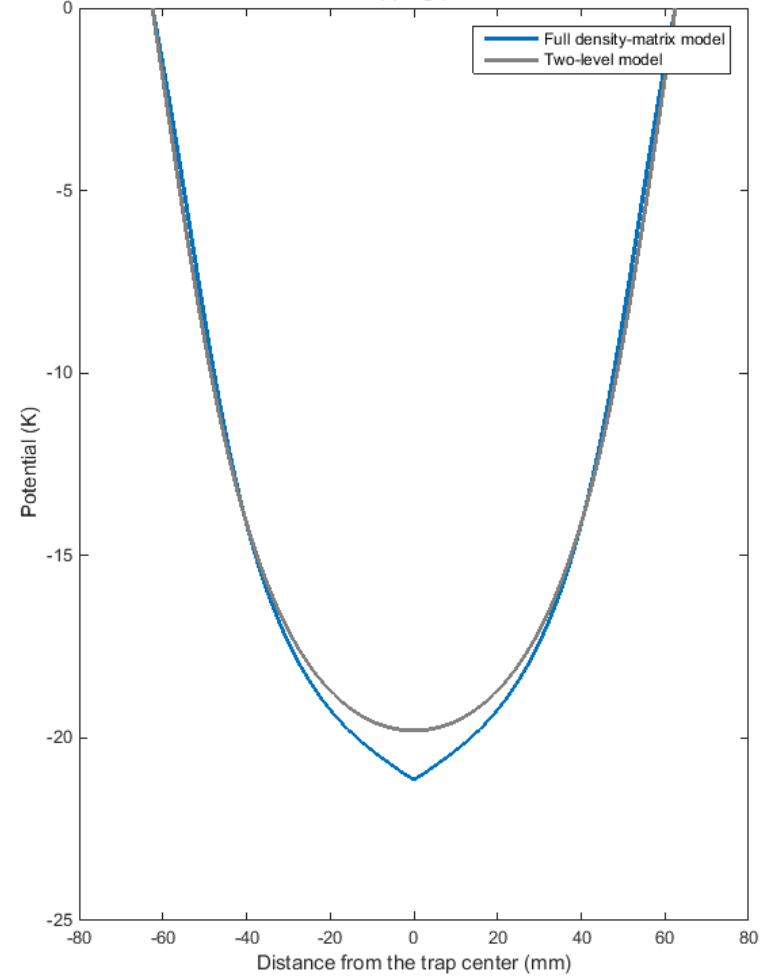
Atomic mass = 133; MOT beam I = 6.6 mW/cm² (0% imbalance); Optical detuning = 20.00 MHz; B-field gradient = 2.4 G/cm

DampRate_{SD} = 1.07e+05 sec⁻¹; DampRate_D = 1.11e+03 sec⁻¹

Capture Velocity_{SD} = 2.50e-01 m/s; Capture Velocity_D = 1.70e+01 m/s

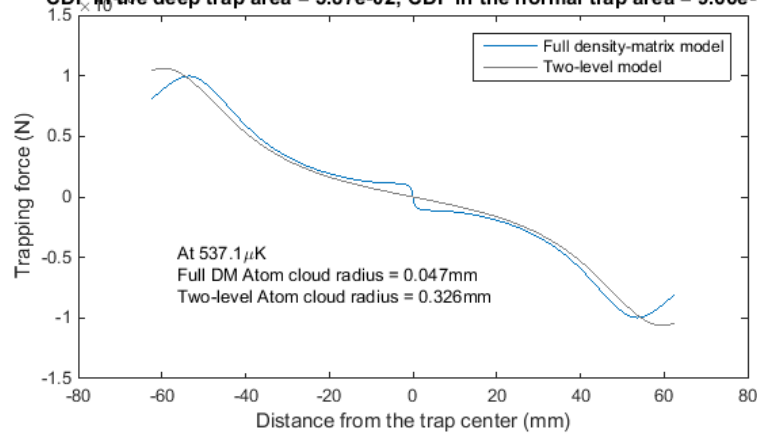


MOT trapping potential

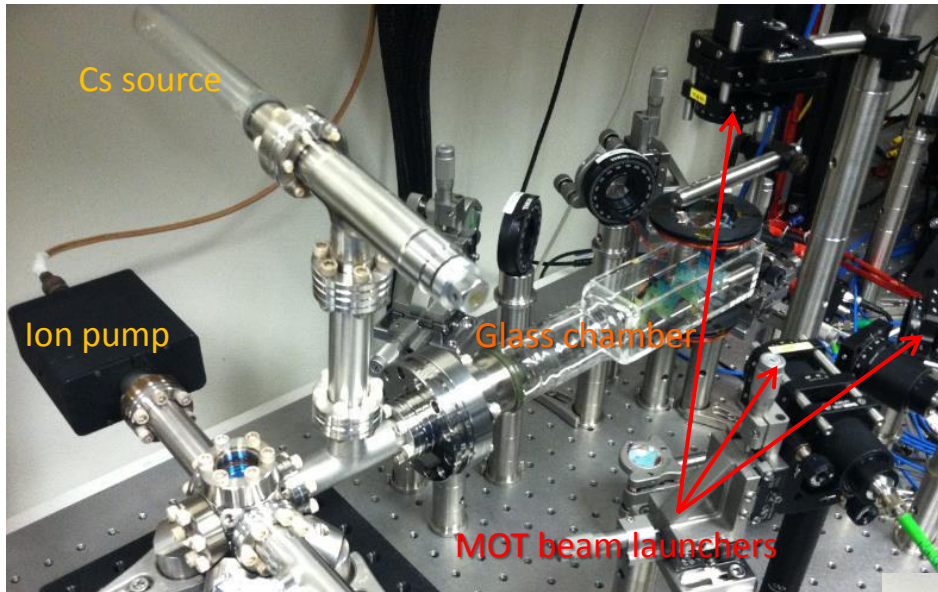


$\epsilon_{DM} = 2.81e+03/s$; Deep trap radius = 0.2 mm; $\omega_{TL} = 5.63e+02/s$; Broad trap radius = 59.5 mm

CDF in the deep trap area = 3.87e-02; CDF in the normal trap area = 9.66e-01

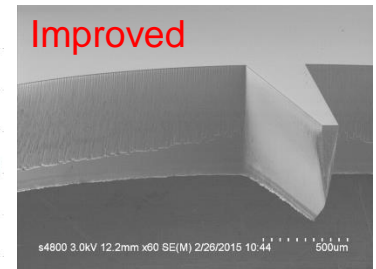
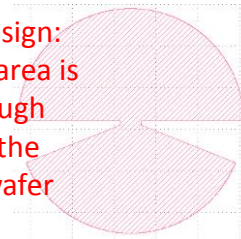


Atomic-Physics Experimental Apparatus



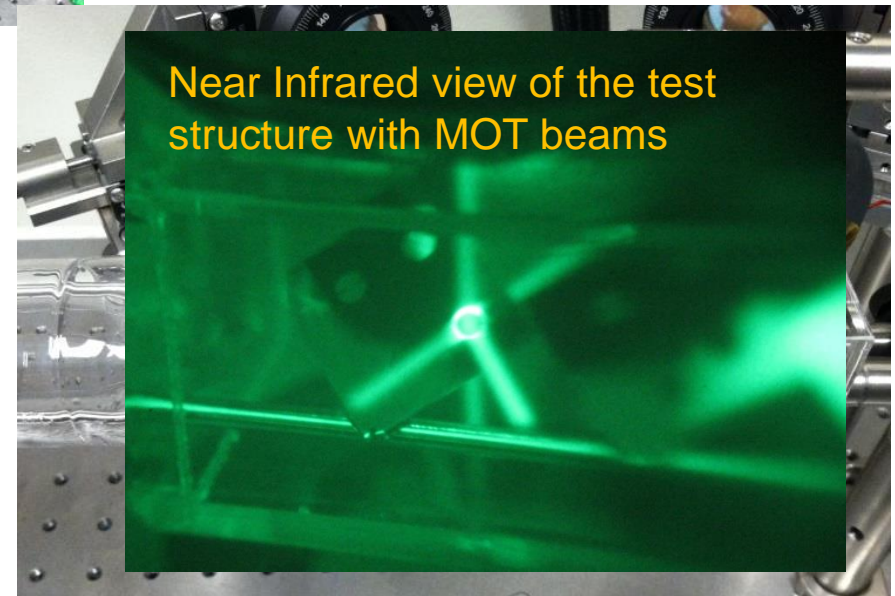
The glass vacuum chamber is mounted on a 3-axis translation stage. This allows us to move the test samples without affecting the MOT alignment.

Mask design: Shaded area is the through hole on the silicon wafer



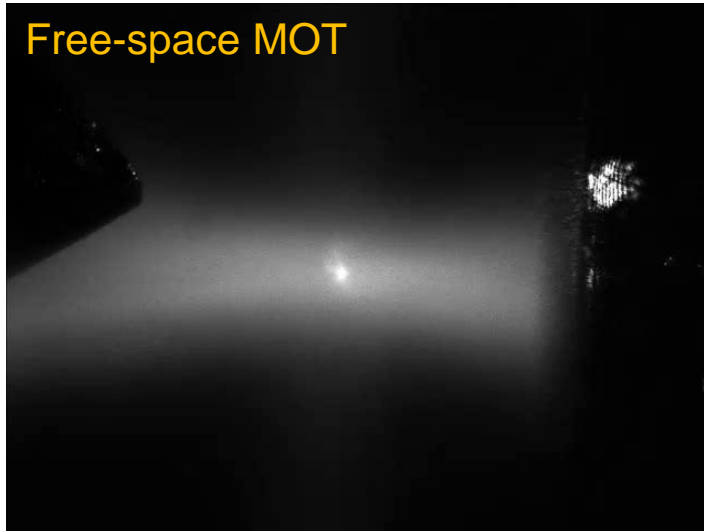
The original MOT was set up with 3 beam launchers and 3 retroreflectors. We have recently modified it to 6 beam launchers.

Our vacuum chamber was suffering from high Cs vapor pressure. We have changed to use a Cs getter source and incorporate graphite Cs absorber into the chamber.

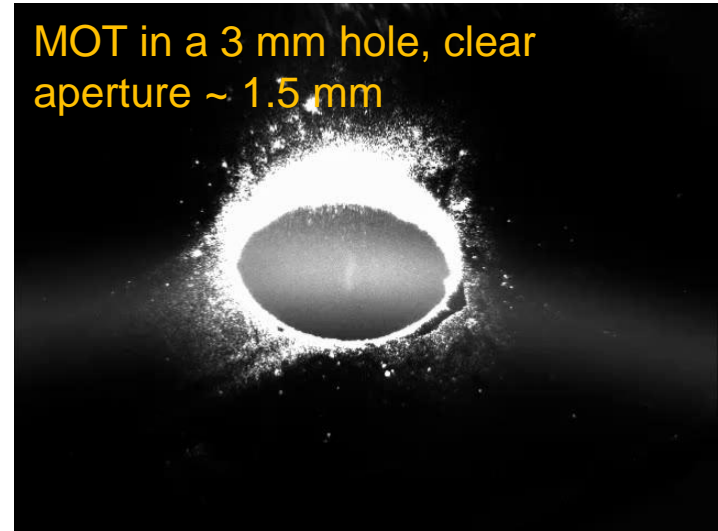


Six-Beam MOTs at different locations

Free-space MOT



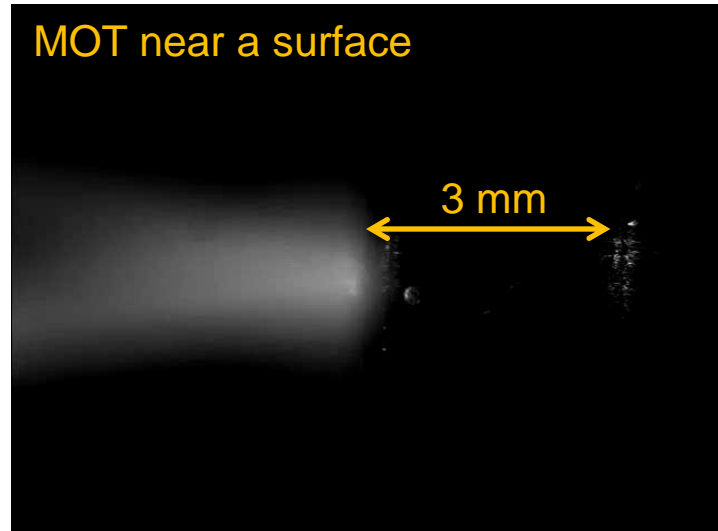
MOT in a 3 mm hole, clear aperture ~ 1.5 mm



Free-space MOT moving toward the glass chamber wall

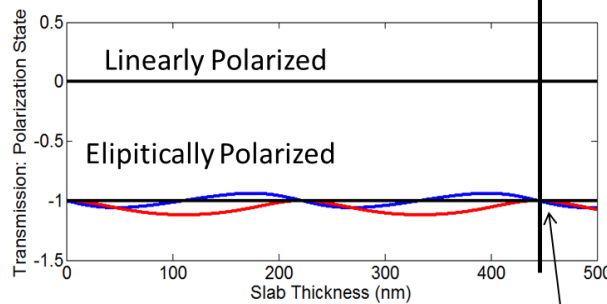
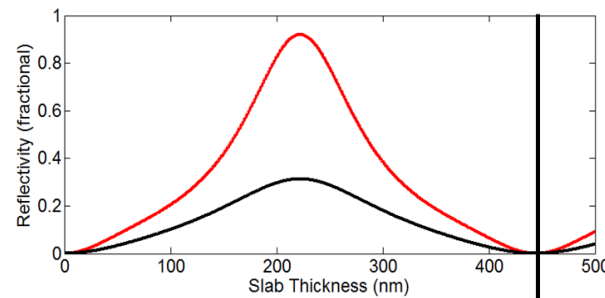


MOT near a surface

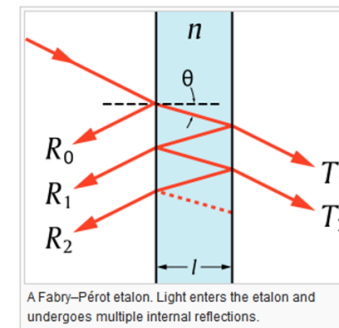
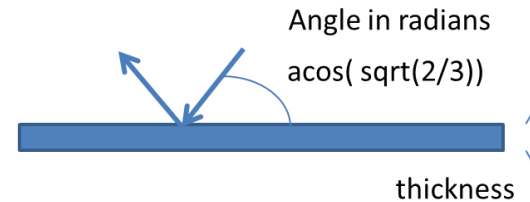


Membrane Idea

- Our original proposal describes of using small MOT laser beams passing through a small aperture on the silicon substrate limit by the length of the suspended waveguide. This limits the cooling capability and the maximum atom number in the MOT cloud.
- We can in-principle use a transparent membrane to support a short suspended waveguide and allows us to use larger MOT laser beams.



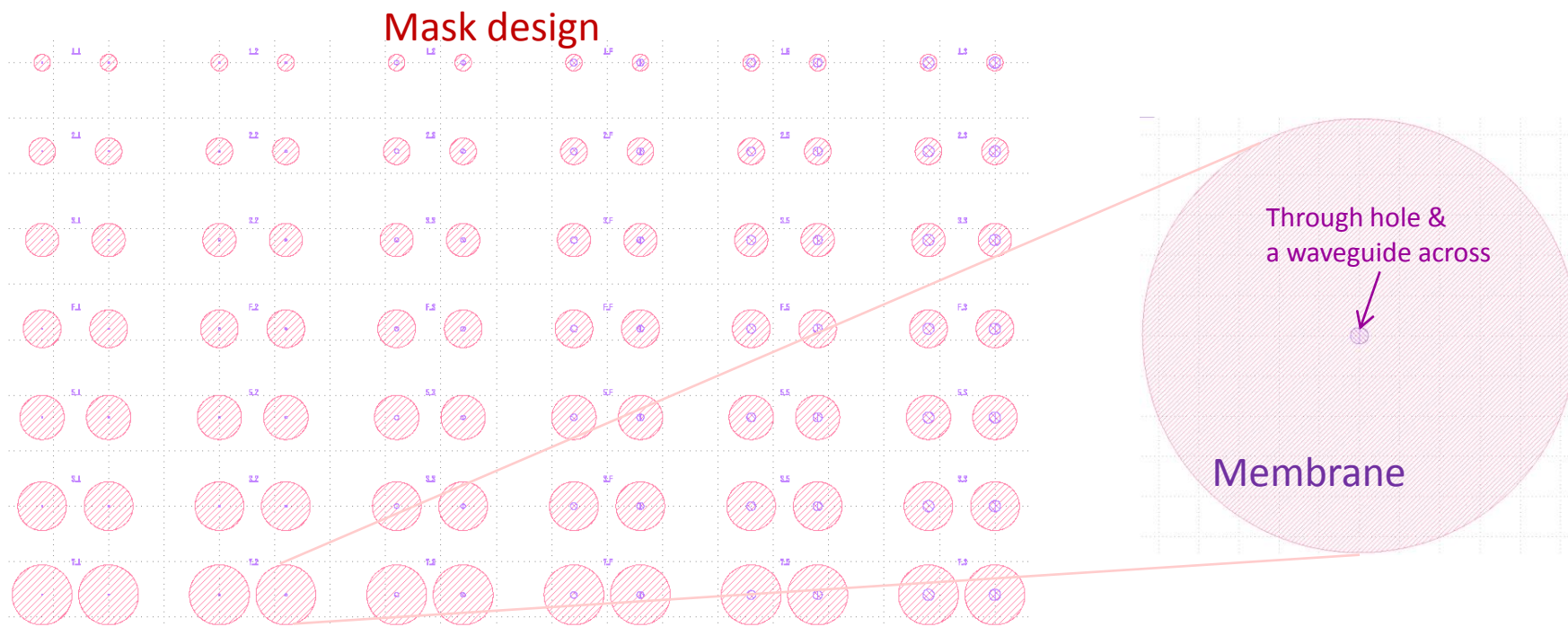
Circularly Polarized



Thickness can be adjusted to be on resonance

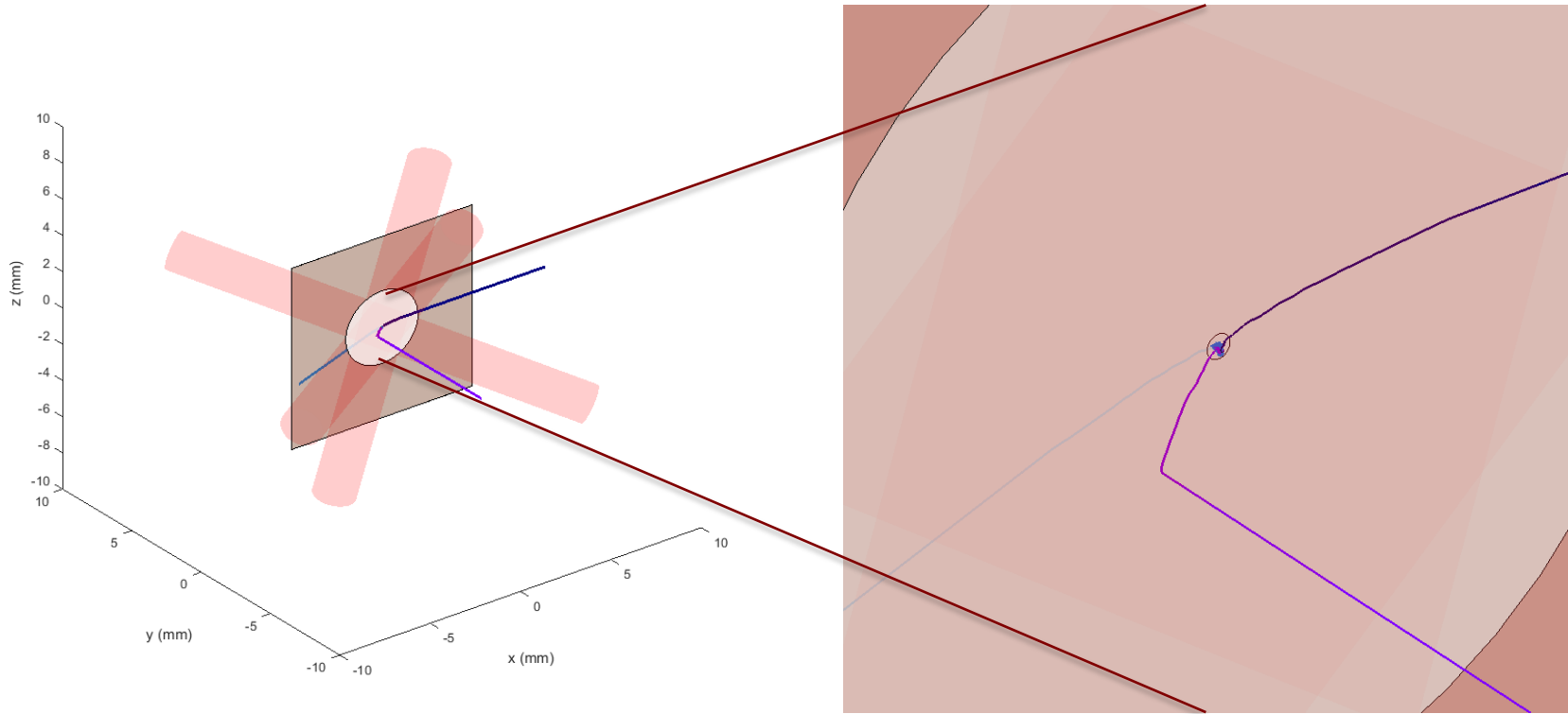
Design of the Test Membrane Structures

- Use appropriate thickness of SiNx membrane bonded with a silicon substrate of a large optical clear aperture.
- A through hole at the center of the membrane will allow to collect a cold MOT atom cloud and a suspended waveguide will run across the hole.
- Large MOT laser beams can therefore be used to have a larger capture volume.



Computer Simulations

Cs-133, MOT beam intensity = 8 mW/cm², Optical detuning = 8 MHz, B-field gradient = 1.5 G/cm



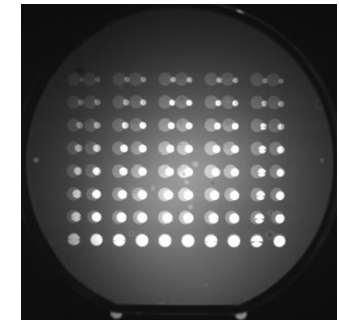
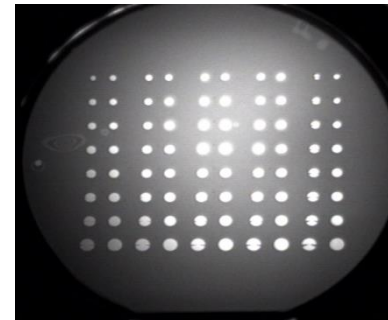
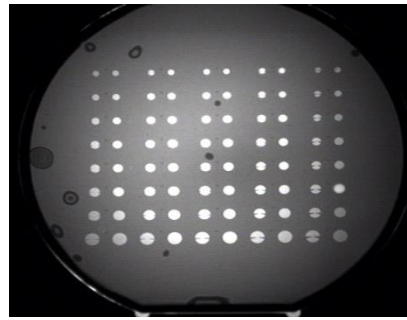
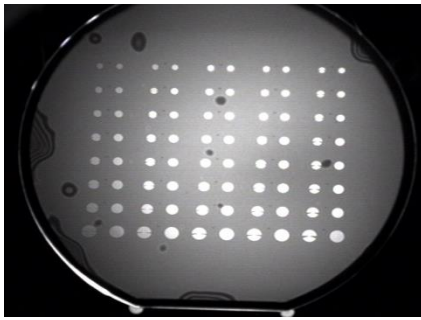
Under the condition of a perfectly transparent membrane, computer simulations show that the membrane idea will help the MOT formation and increase the atom density!

The only unknown is the possible local optical-field distortion due to the presence of the through hole on the membrane.

Test Membrane Bonding

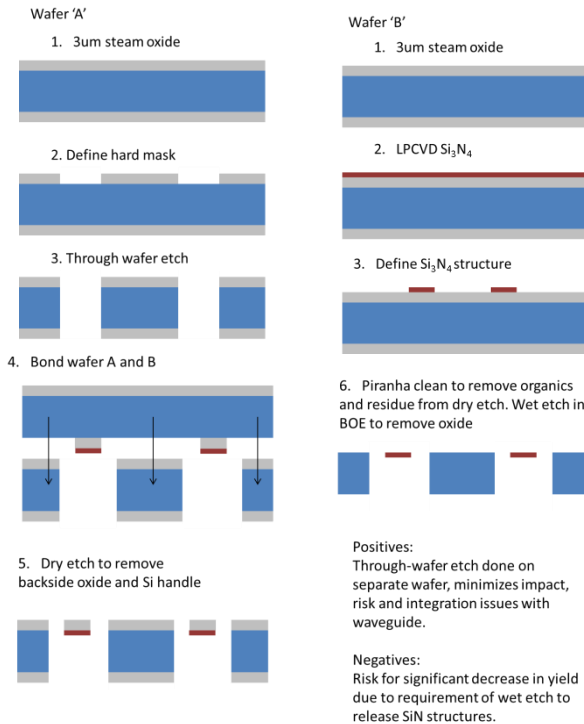
Early results: Lots of voids present between layers

New results: very few voids present between layers



Plasma Bonded

After 4 hour anneal at 200C

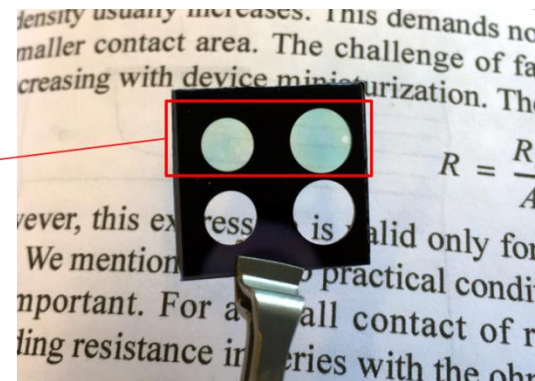


Si₃N₄ membranes have shown extreme robustness to processing.

Perforations of membrane combined with wet processing decreases rigidity, resulting in some loss to yield (~25%).

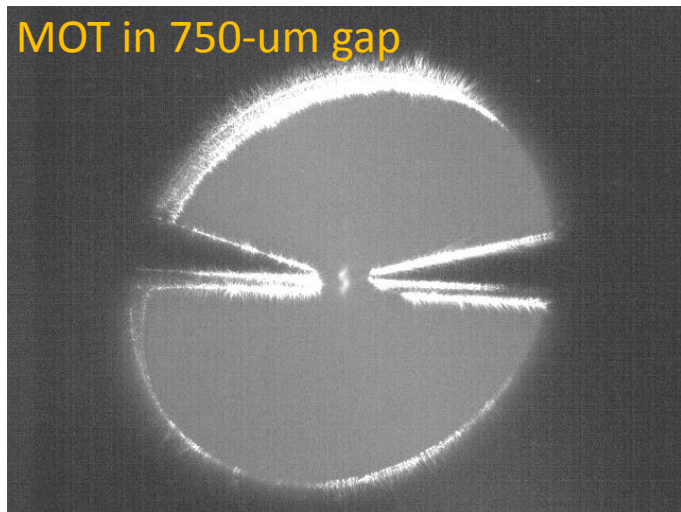
Currently pursuing AlN membranes in parallel for risk mitigation since this will not require a wet etch to release the structures.

Suspended Si₃N₄ membranes. Far right is hole through membrane. Bottom two membranes did not survive wet processing.

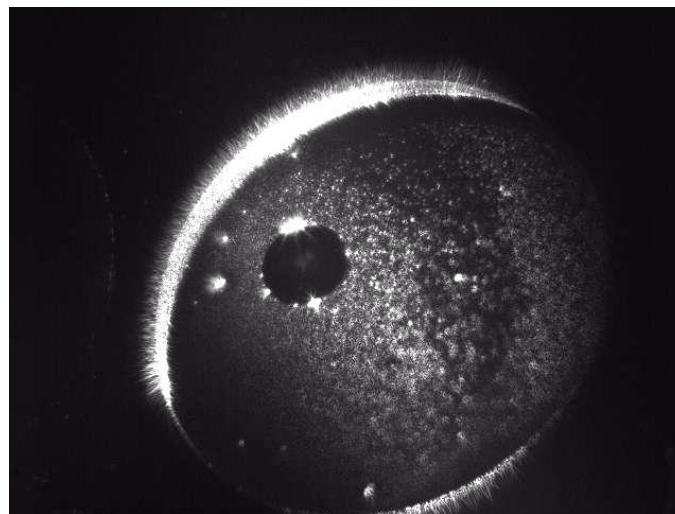
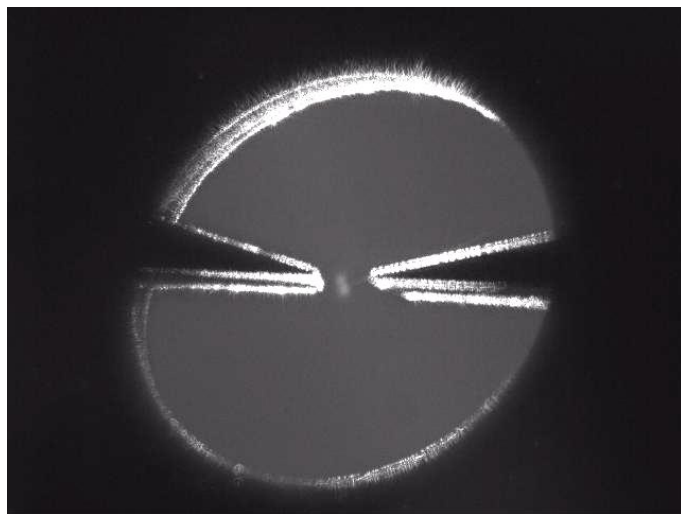
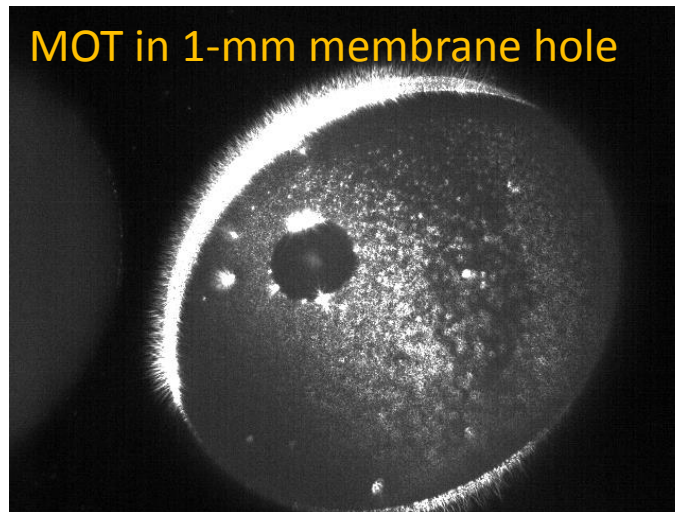


MOTs in Silicon & Membrane Structures

MOT in 750-um gap



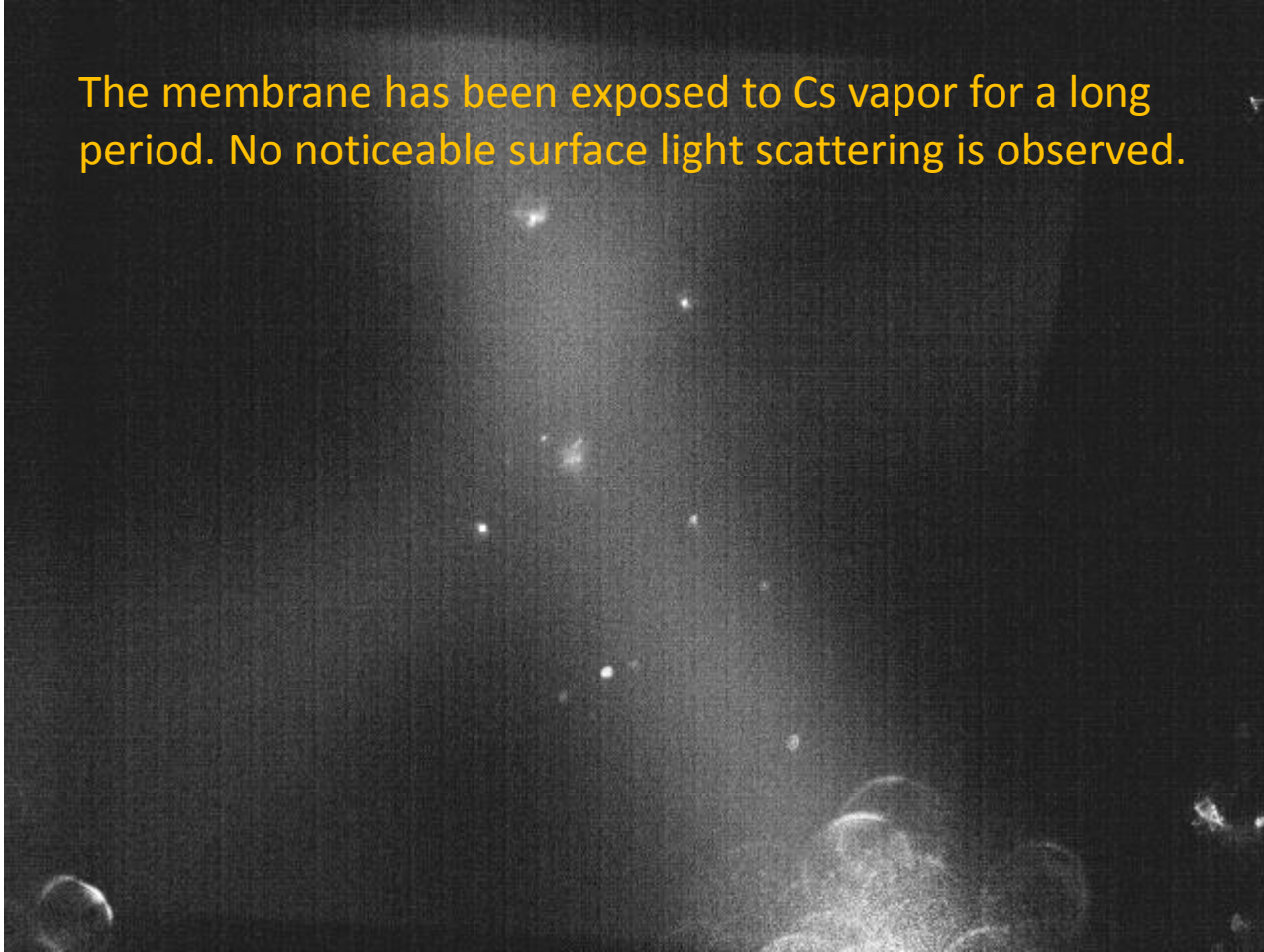
MOT in 1-mm membrane hole



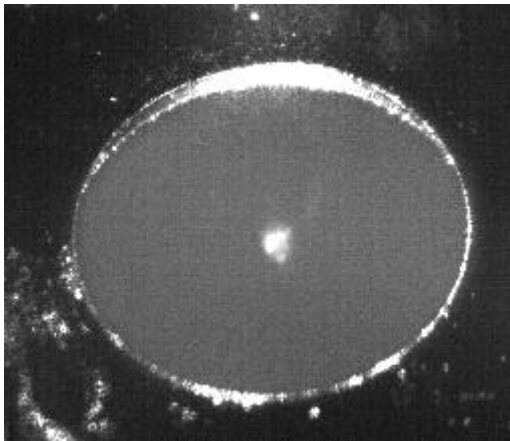
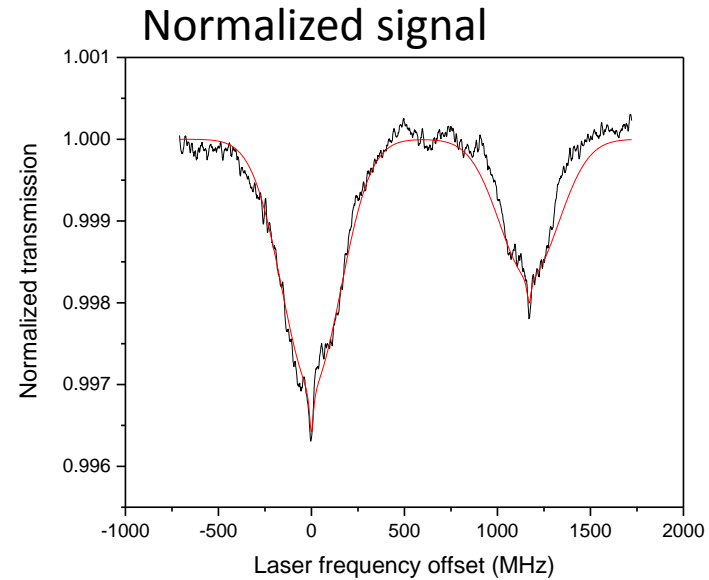
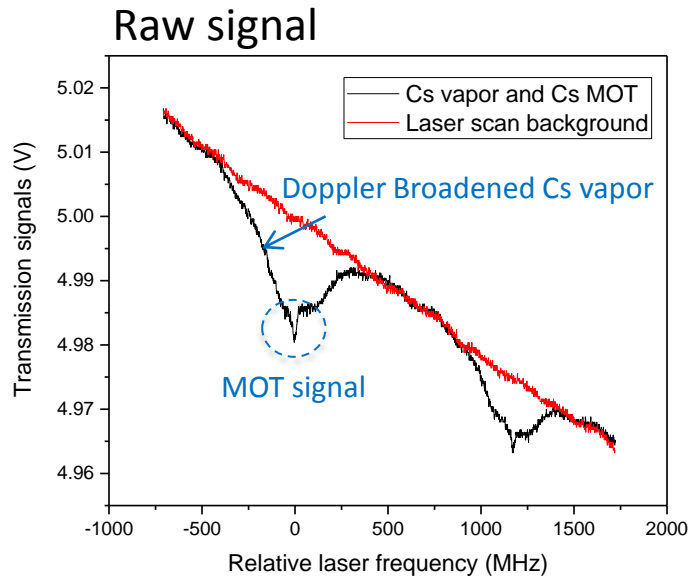
MOT signals in these structures are strong. They can be seen directly with an IR viewer. The positions of MOTs are confirmed to be inside the structure with different viewing angles.

MOT at surface of a 500-nm Commercial SiN Membrane

The membrane has been exposed to Cs vapor for a long period. No noticeable surface light scattering is observed.



Atom Number in a MOT Cloud

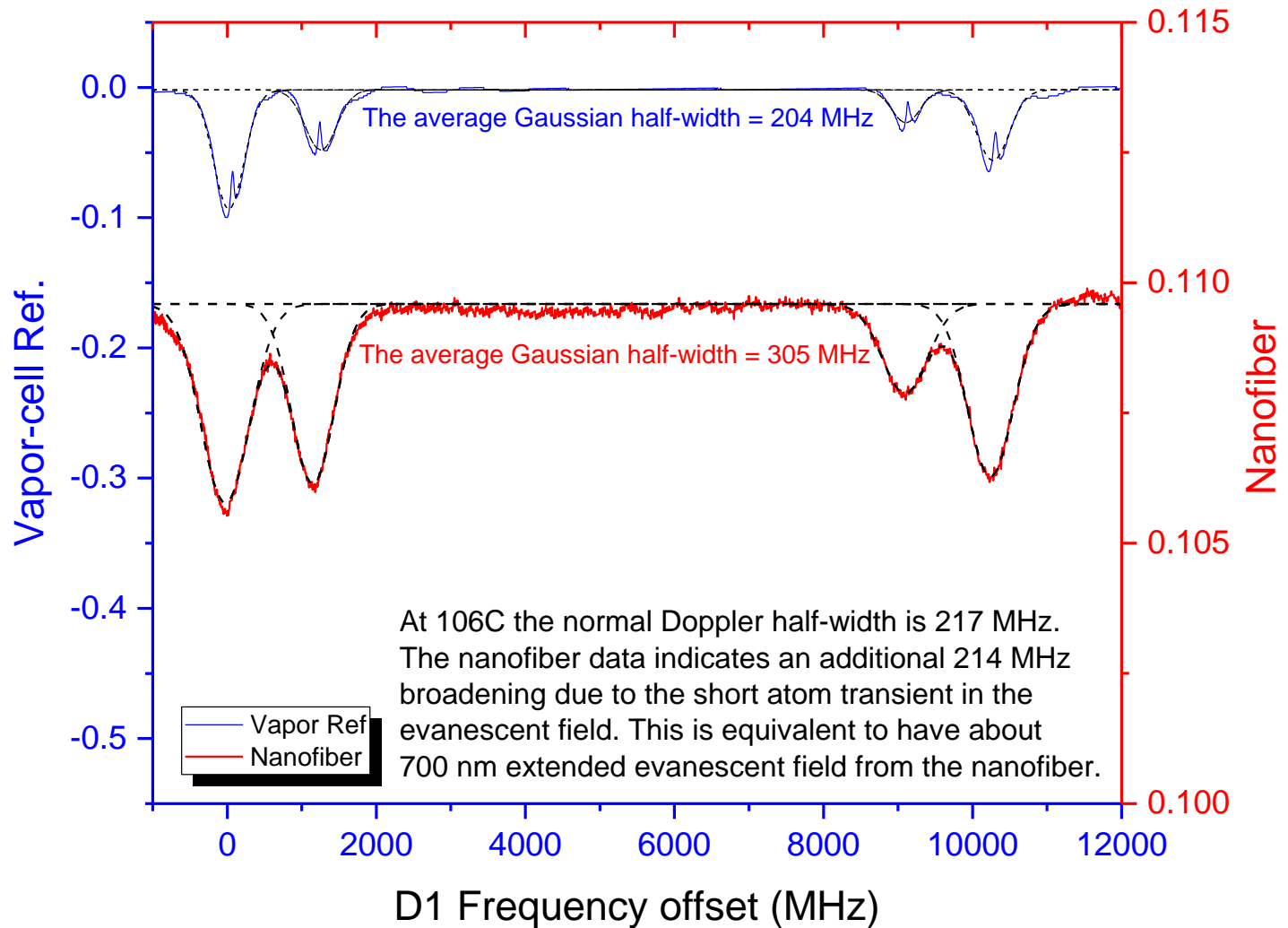


$$\text{Atom number} = \text{absorption} \times \frac{\pi \omega_0^2}{2\sigma_0}$$

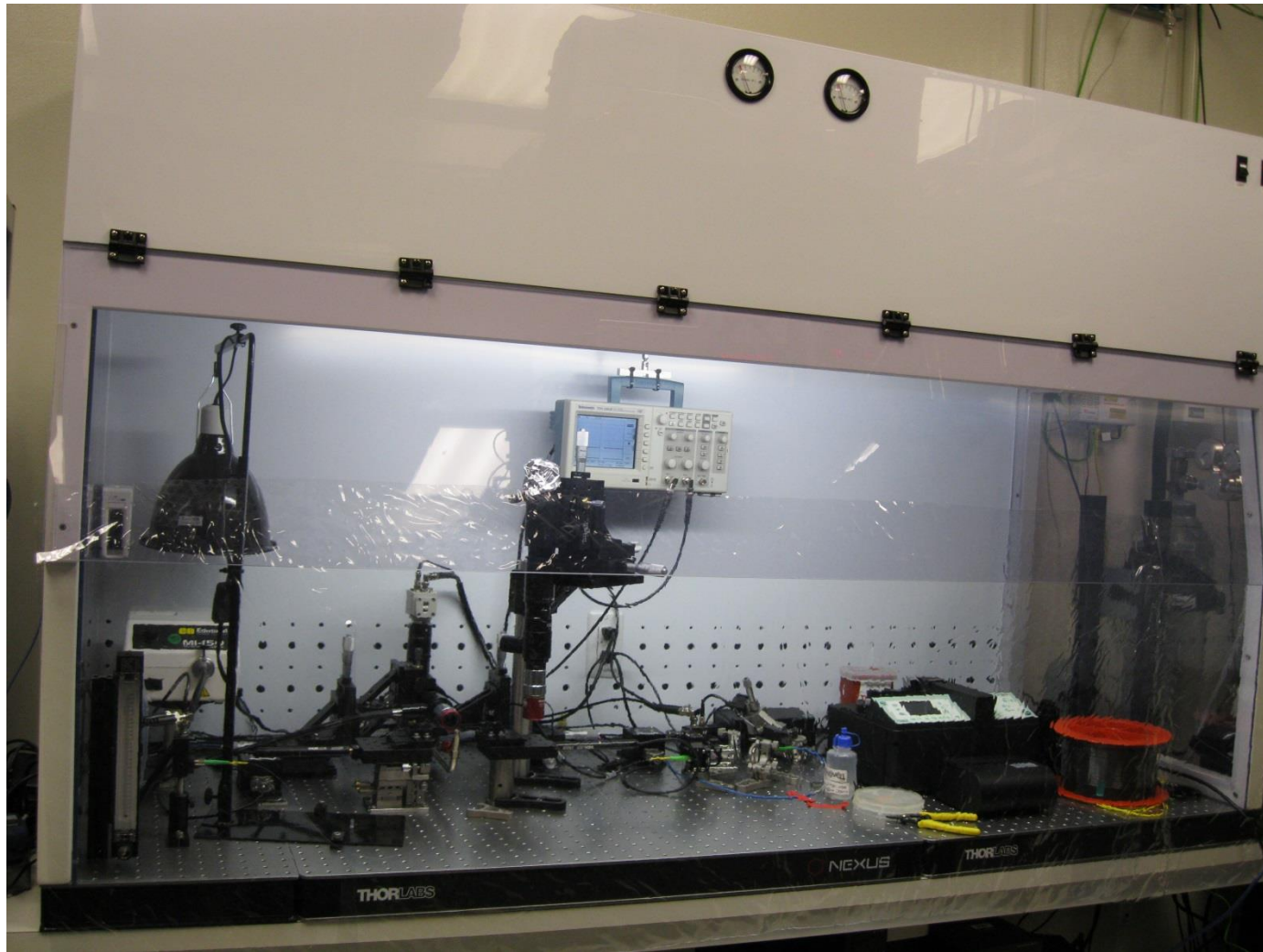
Here, ω_0 is the beam waist radius and σ_0 is the absorption cross section.

We find about 10^5 atoms in the MOT.

Atom Signal from the 2nd Pulled Nanofiber Sandia National Laboratories



Fiber Pulling System in AMO Lab



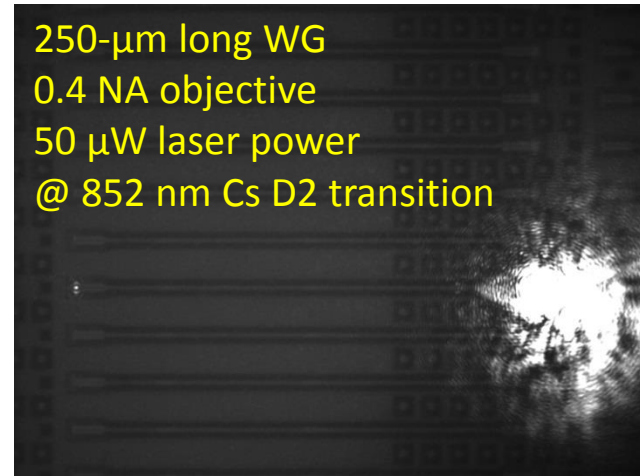
Free-space light coupling to waveguides inside a vacuum chamber



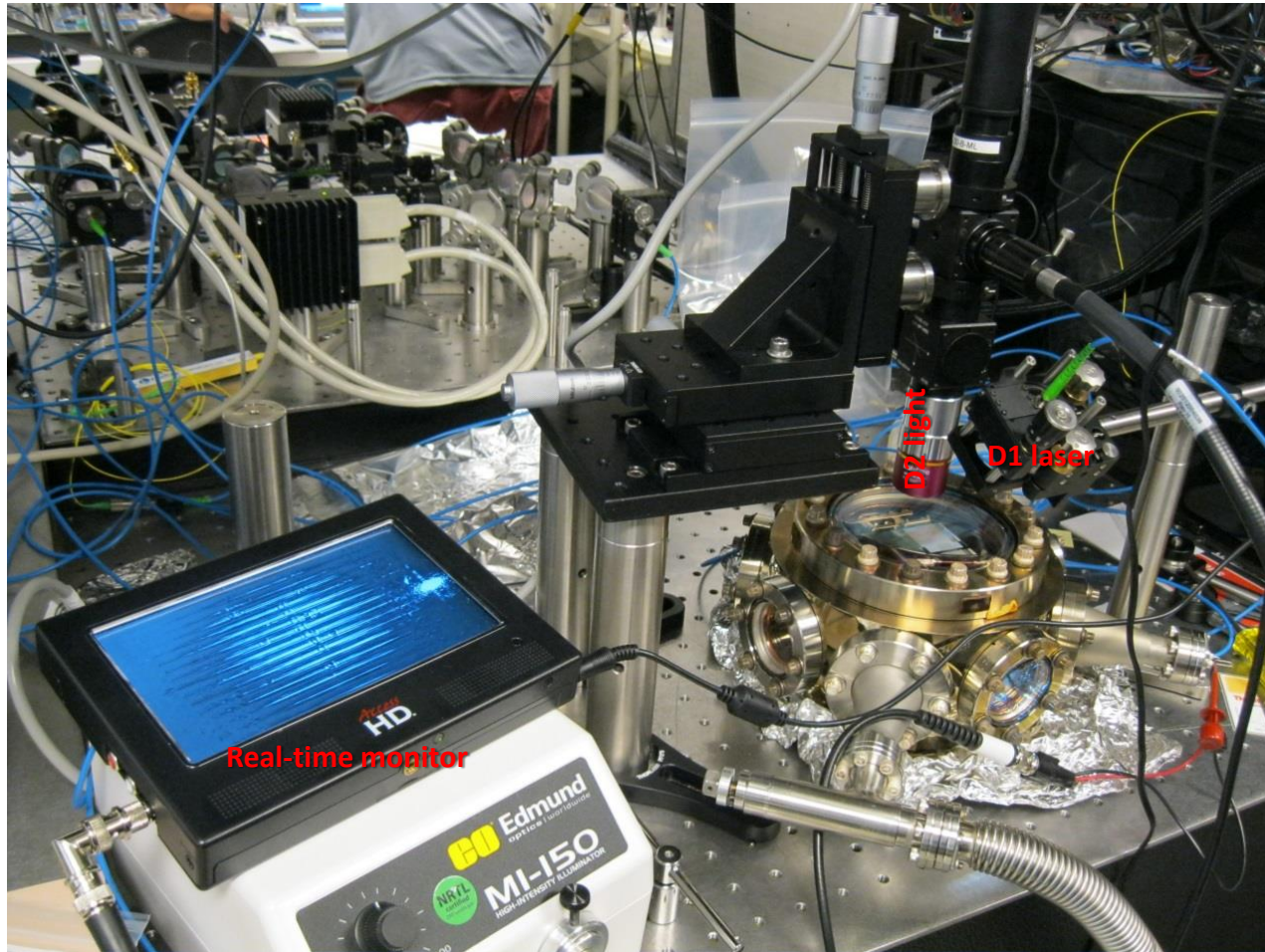
125- μm long WG
0.4 NA objective
50 μW laser power
@ 852 nm Cs D2 transition


Incoming laser spot
Light leaks out from the
other end of the WG

250- μm long WG
0.4 NA objective
50 μW laser power
@ 852 nm Cs D2 transition

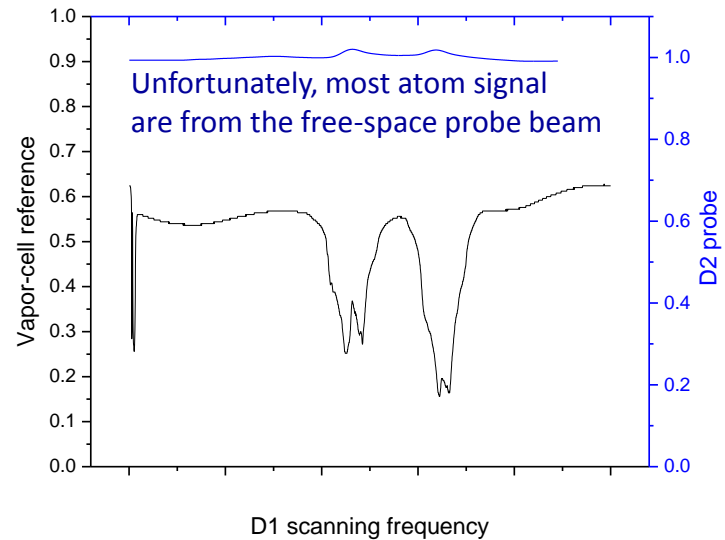
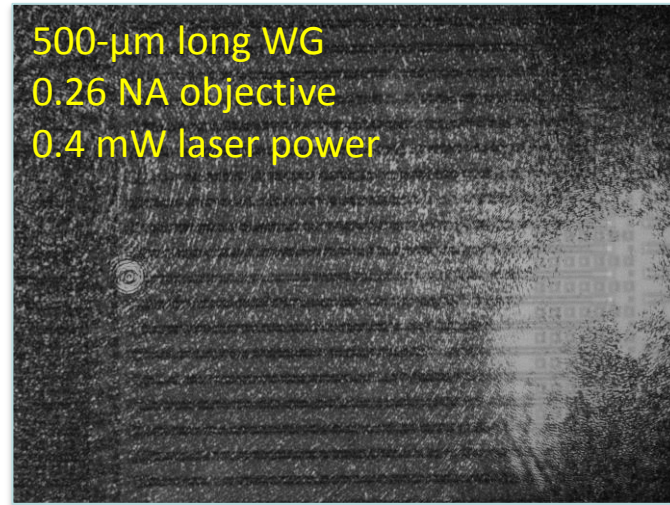
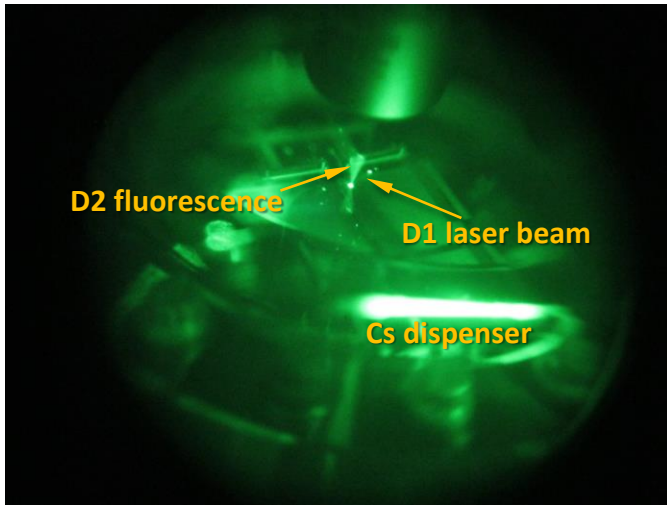


Setup for probing atom signals

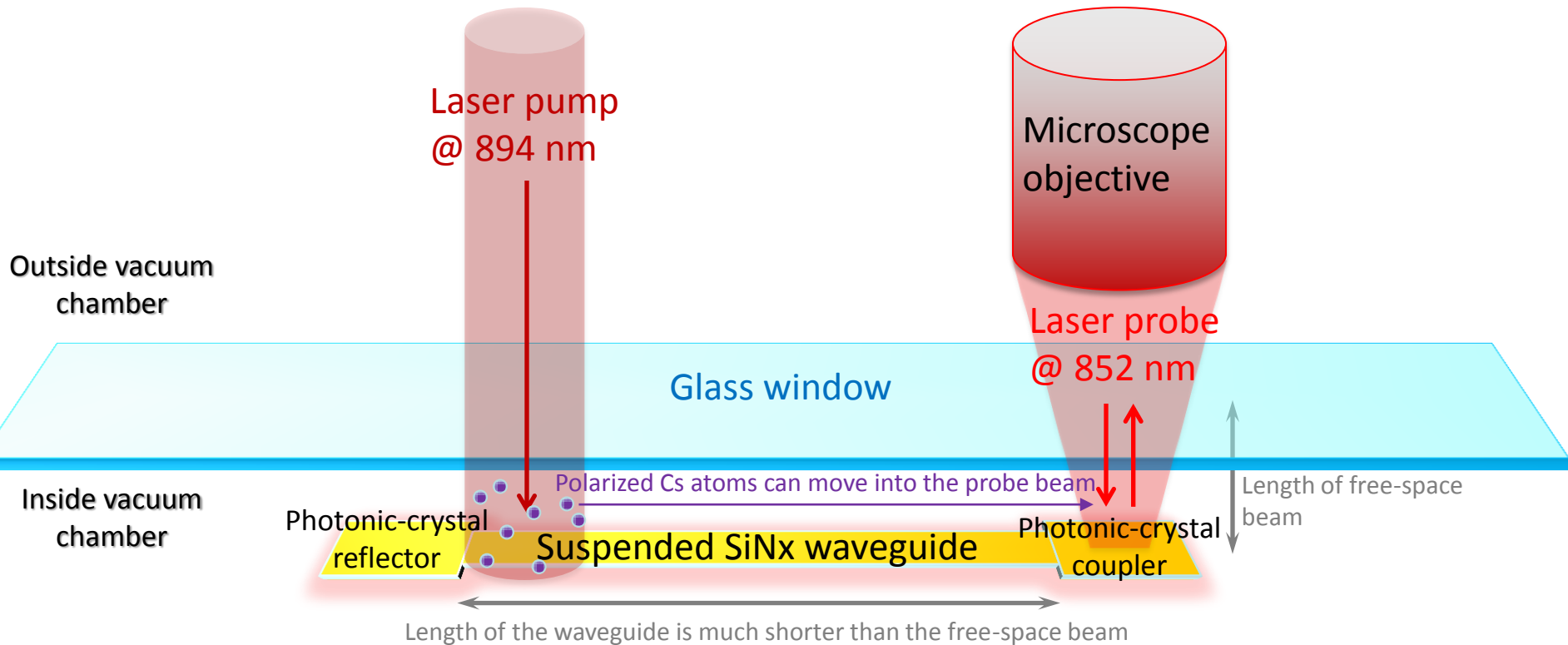


- Switch to NA=0.26 objective for larger field of view to use 500-nm WG
- Introduce a scanning D1 laser to illuminate the waveguide

Probing atom signals

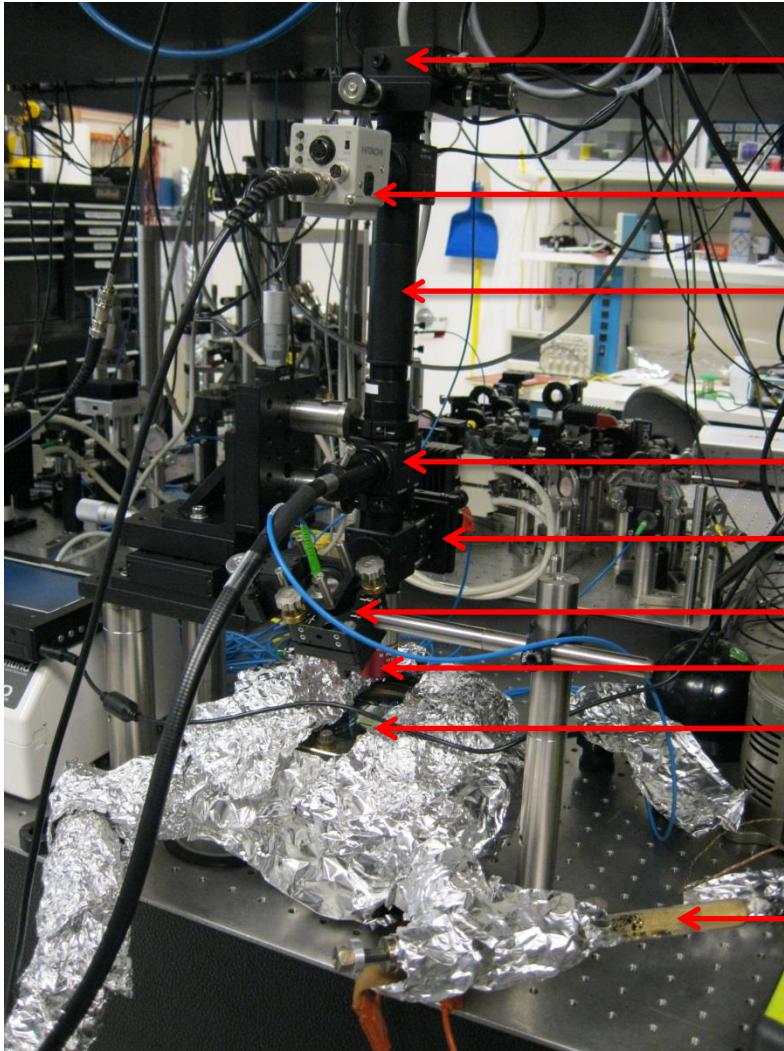


Probe, Pump Lasers and the Waveguide



The probe beam is tuned on a Cs resonance. The pump laser is used to polarize Cs atoms by doing hyperfine optical pumping. The polarized atoms do not attenuate the probe light. Ideally, the probe laser is guided by the waveguide and its evanescent field can be used to detect the polarized atoms. **However, both the waveguide evanescent field and the probe beam propagating through free space can see polarized atoms.**

Experimental Setup



Preamplified Photodetector

This direct detection of the reflection on the photodiode has better SNR compared to the previous method of using back-coupled light into the fiber with a fiber splitter.

CCD camera

Tube of microscope assembly

Beam splitter for illumination light

852-nm laser from optical fiber

894-nm D1 pump laser from fiber

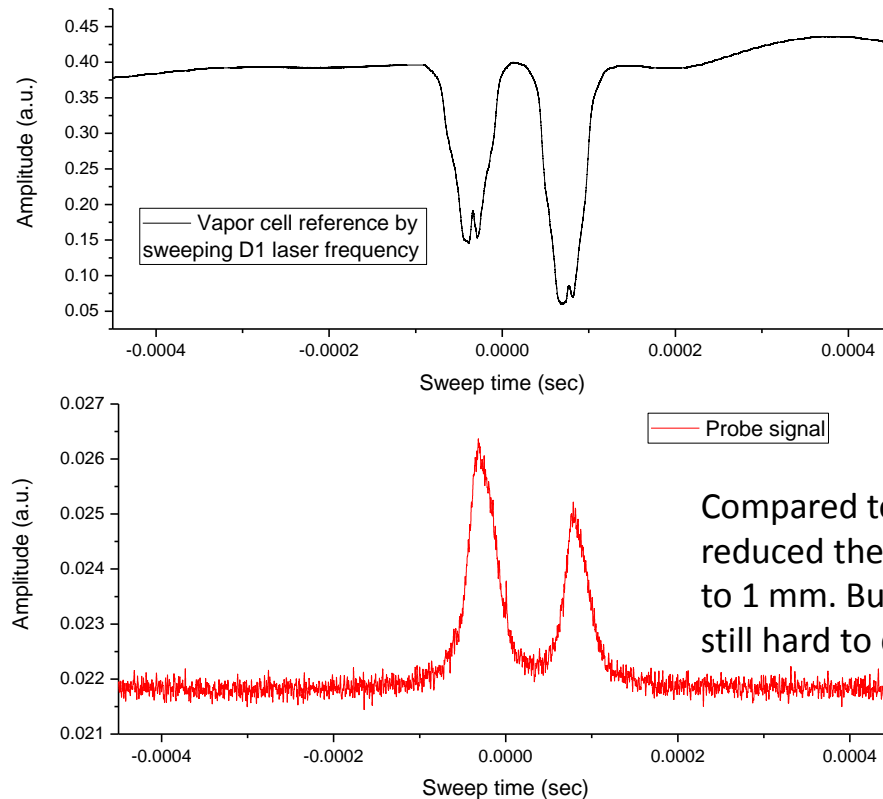
Microscope objective NA=0.26

Waveguide chip inside the chamber

Cs ampoule

Atom Signal as Transparent Peaks

By sweeping the D1 laser frequency in time, the atoms are polarized when it hits the resonances, which reduces the attenuation to the probe beam.



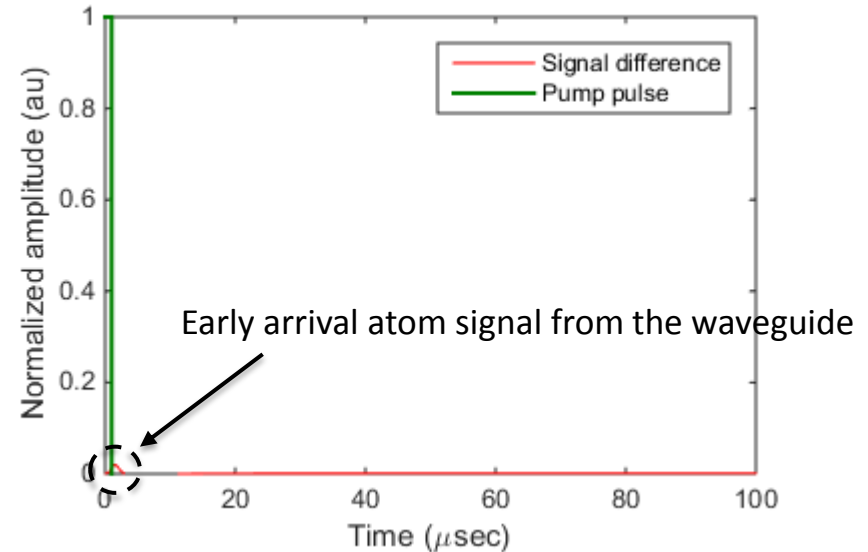
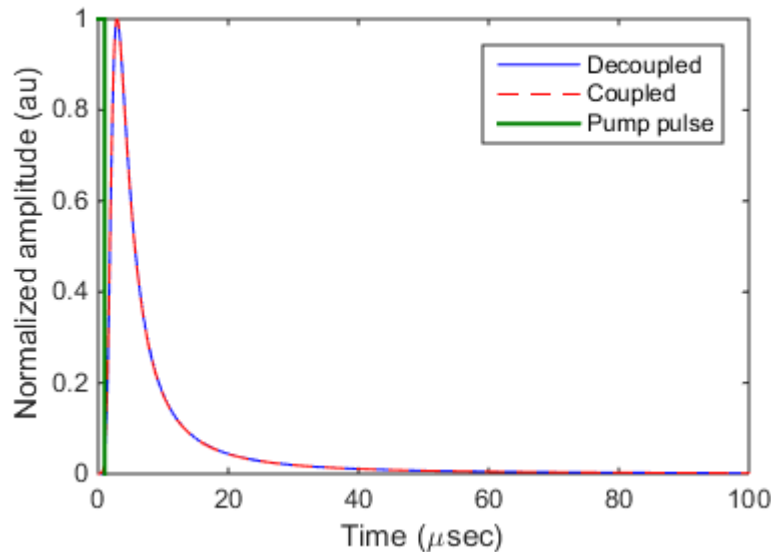
Compared to the earlier data, we have reduced the free-space distance from 1 cm to 1 mm. But the waveguide atom signal is still hard to detect.

Unfortunately, most polarized atom signal is detected by the focused probe beam in the free space inside the vacuum chamber, because of the much longer free-space path length compare to the waveguide length. In addition, the low waveguide coupling efficiency and detection ratio also reduce the atom signal from the waveguide.

Distinguish Free-Space & Waveguide Atom Signals in Time

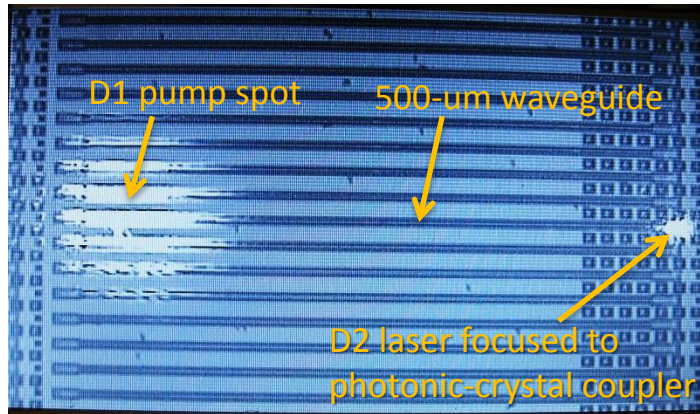
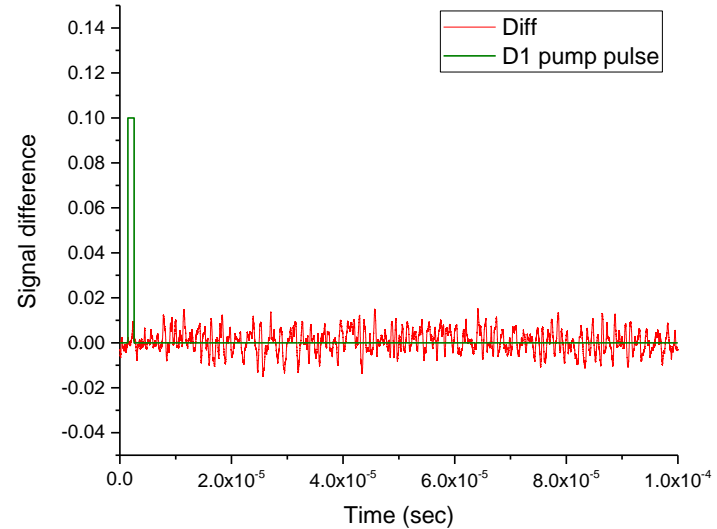
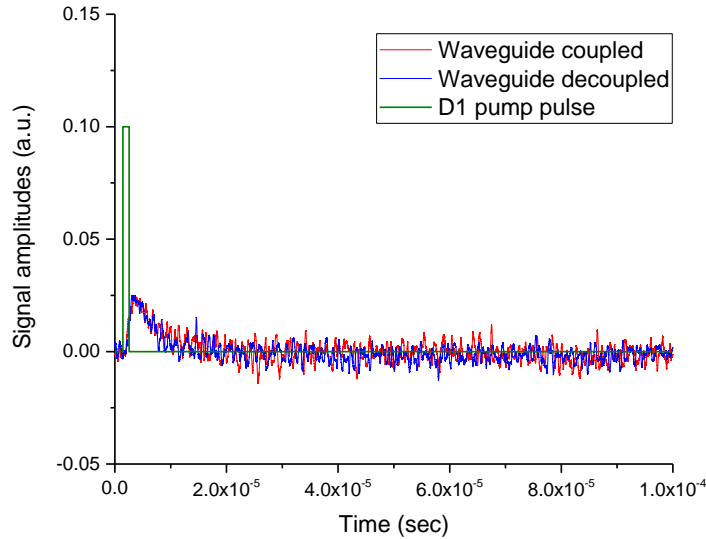
- Make a short, strong D1 pump pulse near the end of the waveguide
- Look at the time-dependent atom signal from the probe
- Compare cases of waveguide coupled and decoupled signals

Simulation Results



These plots are the **simulation results** using parameters of 1- μs pump pulse with 100- μm spot size, 1-mm free-space path length, 500- μm waveguide length, 20% coupling efficiency (measured), 18% waveguide detection ratio (calculated).

Initial Results



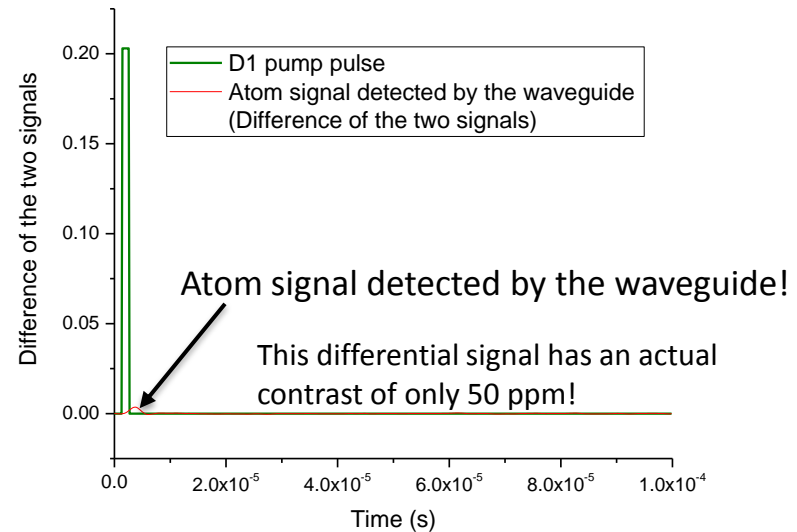
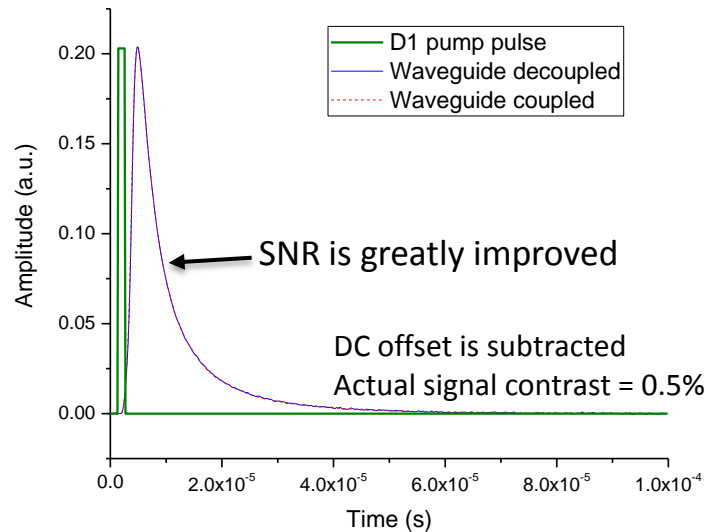
Microscope image

We need to improve the SNR!

The data presented here is with room-temperature Cs ampule and 512 times average, which is limited by the oscilloscope.

Atom Signal from the Waveguide

We improve the SNR by increasing the Cs ampule temperature to 60C and increasing the number of average to 1024k.



The SNR is improved by about a factor of 450, and we can clearly see the early atom signal detected by the waveguide!

World-Wide Progress in Waveguide Atom Traps

Research groups:

Caltech (leading in the field), Harvard (ongoing), NRL-JQI-UMD (ongoing), Penn-State U (just started), Imperial College (in London, demonstrated some related work 6 years ago).

Recent progress:

Group led by Jeff Kimble at Caltech borrowed the idea from Harvard to trap about 2-3 atoms near their photonic-crystal waveguide by introducing an external laser beam to the surface of the waveguide. The interference fringes near the surface provide optical trapping potential to trap atoms.

➤ Still, no one is able to trap atoms using the evanescent fields from the waveguide.

Overall challenges:

- Overlapping of the waveguide with the cold-atom cloud
- Capability of handling the optical power in the waveguide
- Adsorption of alkali-metal atoms to SiNx material, especially Cs is the worst
- Surface smoothness of the microfabricated waveguide
- Optical nonlinear effect from the SiNx waveguide
- Caltech makes a too complicated design before they can demonstrate atom trapping

Objectives in FY16

Trapping atoms with suspended waveguide:

- Design and fabrication
- Alignment with silicon structure
- Coupling between the optical fibers and the waveguide: evanescent coupling, bulk coupling with inverse tapers? (we need efficient coupling at 937 nm, 852 nm, and 686 nm)
- E-beam or photolithography with stepper?
- Optical power handling tests
- Alternative ideas of using non-suspended waveguide
- If transferring UMD-JQI device to Sandia, what are we going to do with it?
- If successfully trapping atoms with a waveguide, results will be published in a high-profile journal

Improving SiNx membrane optical quality:

- Producing large SiNx membrane with optical quality similar to the commercial membrane
- Demonstrating high-density MOT inside the hole (This result can be published and patented.)
- Possible optical coupling through the waveguide implemented on the membrane structure

Trapping atoms with optical nanofiber:

- Establishing a procedure to make nanofibers with required diameters
- Placing the nanofiber on the silicon substrate across the gap of the needle structure
- Trapping atoms with nanofiber at the silicon gap (This result can be published.)