SAND2013-3051P

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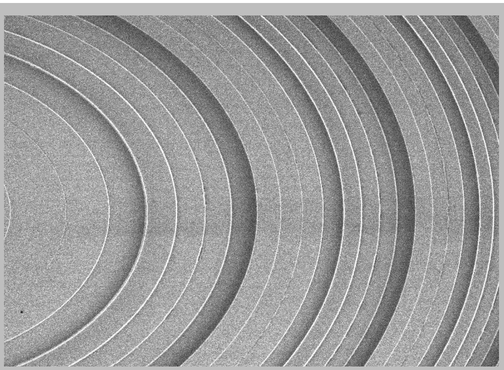

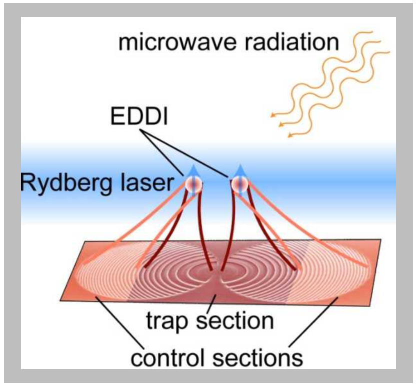

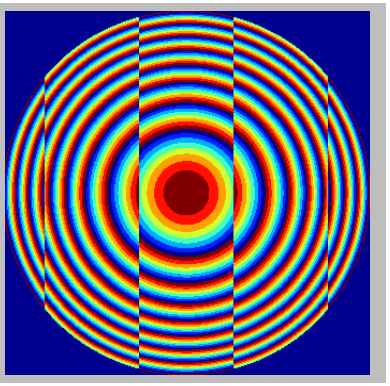

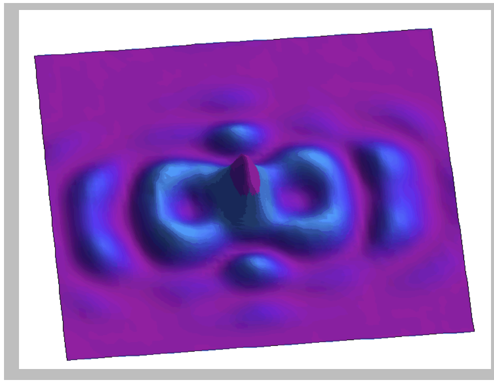

Micro-Optics for AQUARIUS

Shanalyn A. Kemme

- A. R. Ellis, A. L. Young, D. A. Scrymgeour, , J. R. Wendt, T. R. Carter, S. Samora
- Collaborators: Mark Saffman (U. Wisconsin)

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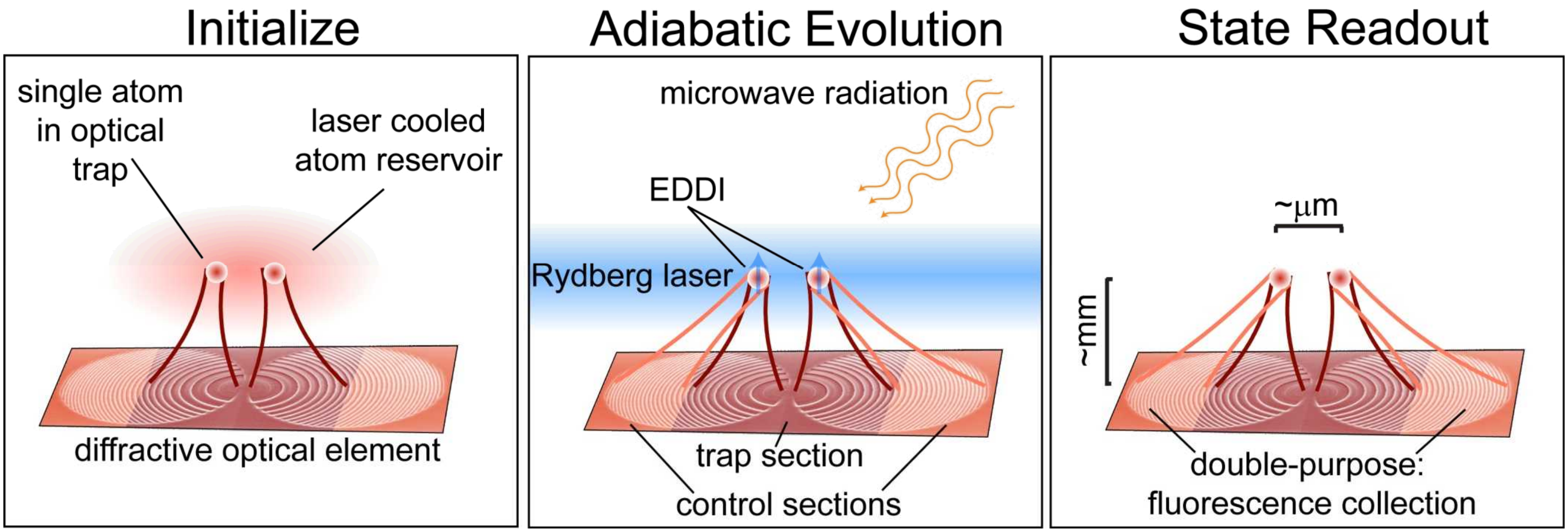
Outline

- How to scale – micro-optics near the atoms
- Quantifying scaling issues that impact packaging and performance
    - Dielectric and metal proximity effects
    - Grayscale development for reduced scatter from surfaces
    - High NA diffractive optical elements (DOEs)
    - Optical tasks and priorities for an optimized optical layout
- Fabricated and delivered bottle beam trap DOE to Saffman lab
    - Utilized in experiment and paper submitted soon
- Designed 4X4 DOE bottle beam array
- Notables

Scaling: a near surface approach

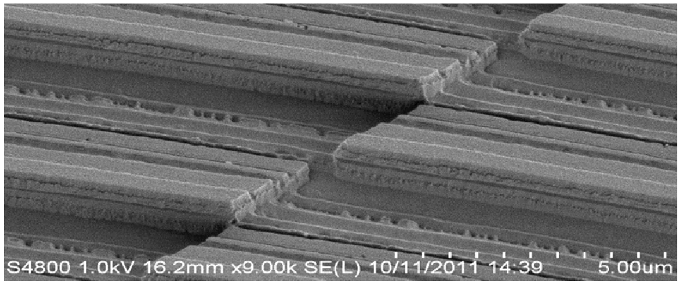


Microfabricated diffractive optical elements

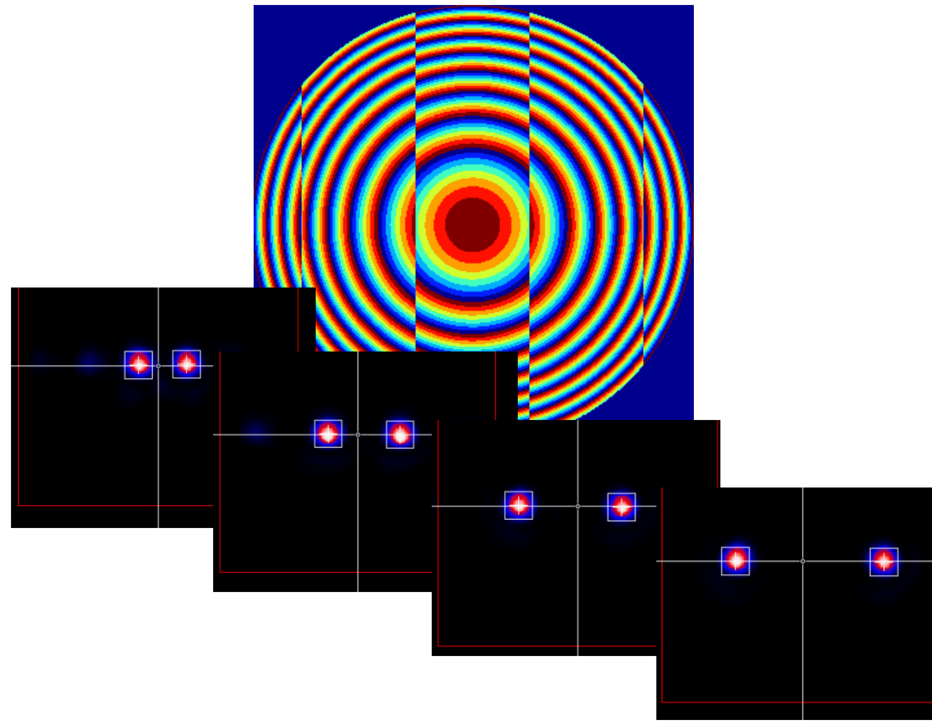
- Multiple functions juxtaposed
- Advantageous for near surface imaging
- Reduces Numerical Aperture requirements for external optics
- Multiple wavelengths juxtaposed

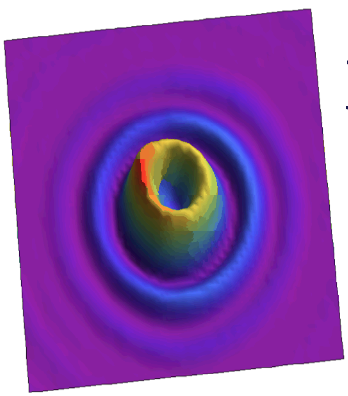
Diffractive optics

SEM tilt view of lens



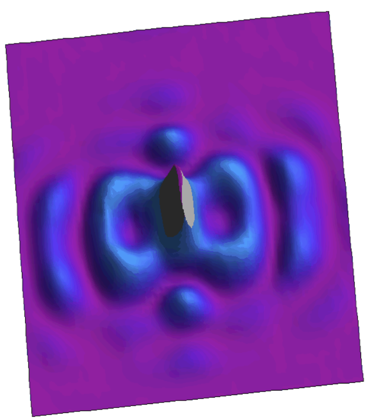
2-trap





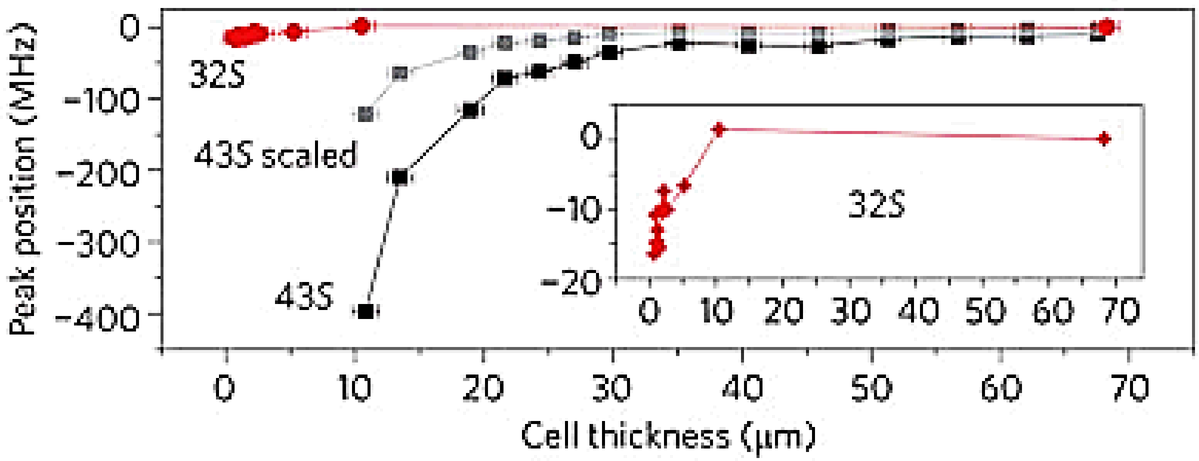
Single trap

Double trap



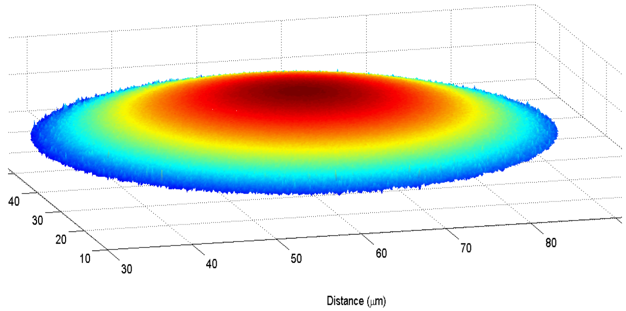
Dielectric Proximity Effect

- Rydberg atoms likely to interact with dielectric material of DOE
  - May cause shift in peak position, peak width, both critical to atom-atom interactions
- Current choice of 2.5 mm from lens is large and eliminates the possibility of an interaction effect, decreasing this distance is important from a scaling perspective
- Characterizing this now with EIT experiment

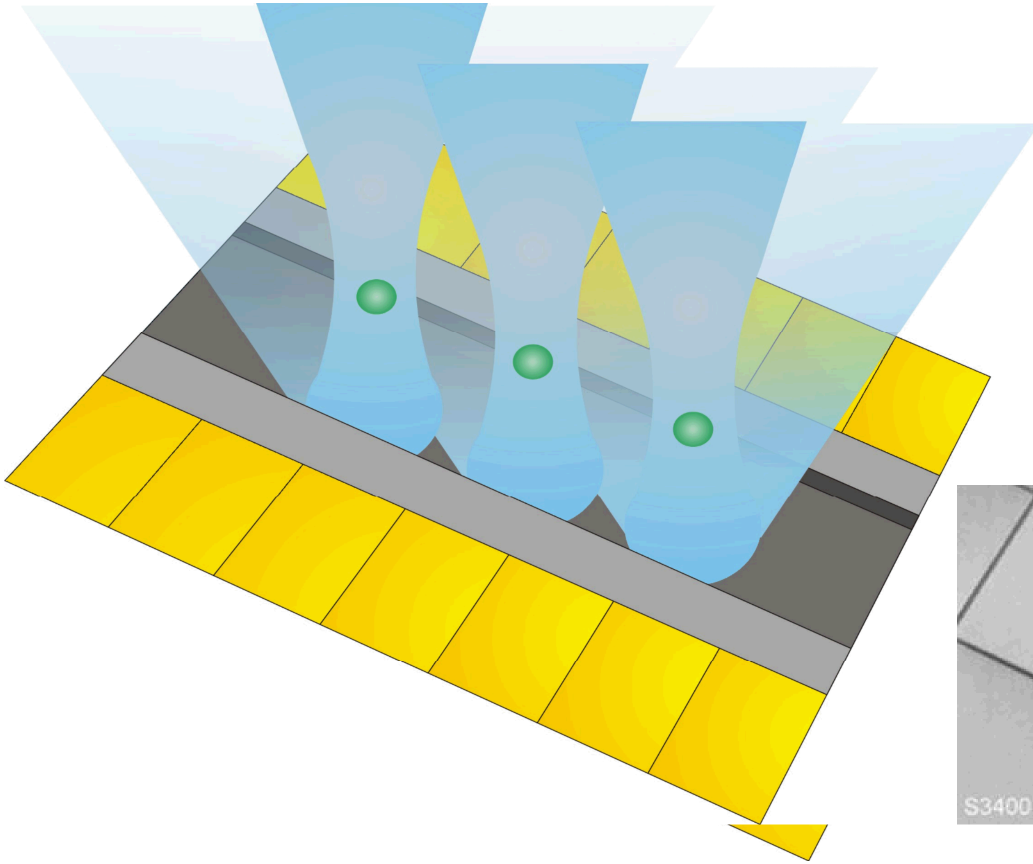


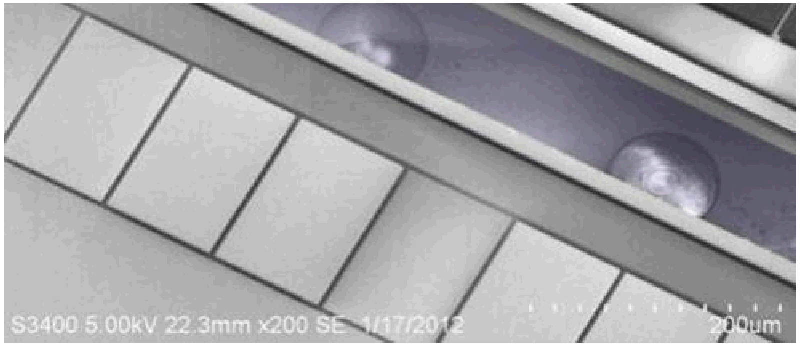
Kübler, H., Shaffer, J.P., Baluktsian, T., Löw, R., & Pfau, T. Coherent excitation of Rydberg atoms in micrometre-sized atomic vapour cells. *Nature Photon*. **4**, 112 - 116 (2010).

Grayscale for reduced scatter



Concern that diffractive excitation optic would detrimentally scatter light

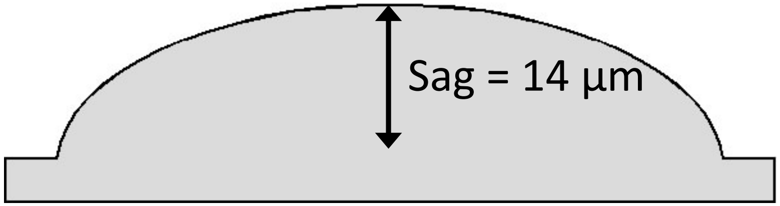




- Atoms sensitive to scattered light/field
- Impacts how close interfaces can be
- Should we develop grayscale to reduce diffracted-order “scatter”

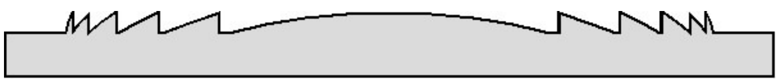
Refractive grayscale optics offer higher efficiency & lower scatter

Grayscale Transmissive Lens



Cross Section, bulk patterning

Diffractive Lens

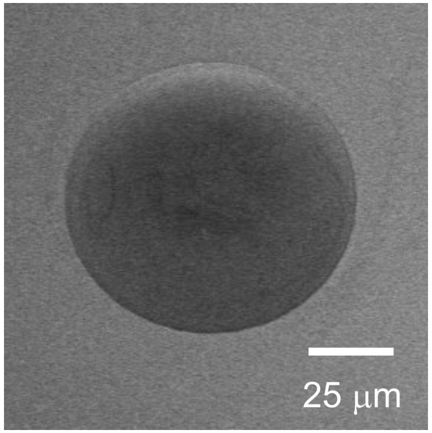


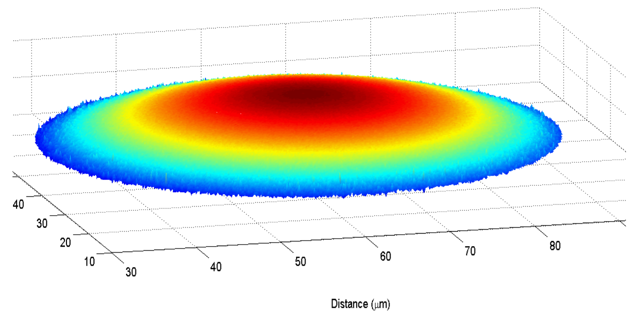
Cross Section, Surface patterning

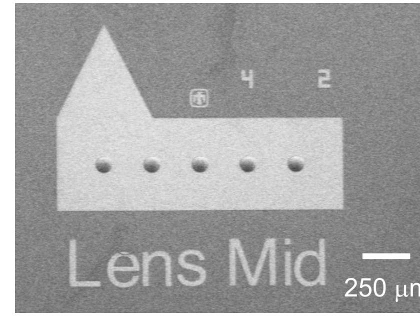
Grayscale also offers (unlike reflow):

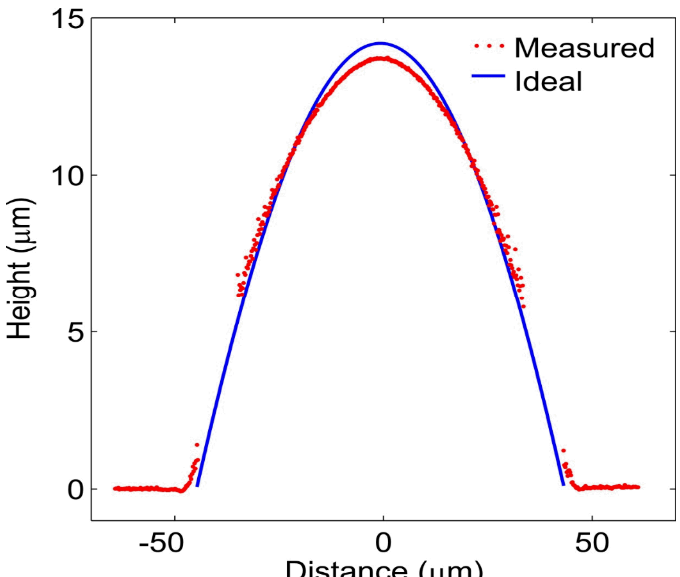
- Aspherical and off-axis capabilities
- 100% fill factor
- Concave shapes (divots)

Successful lens transfer into silica

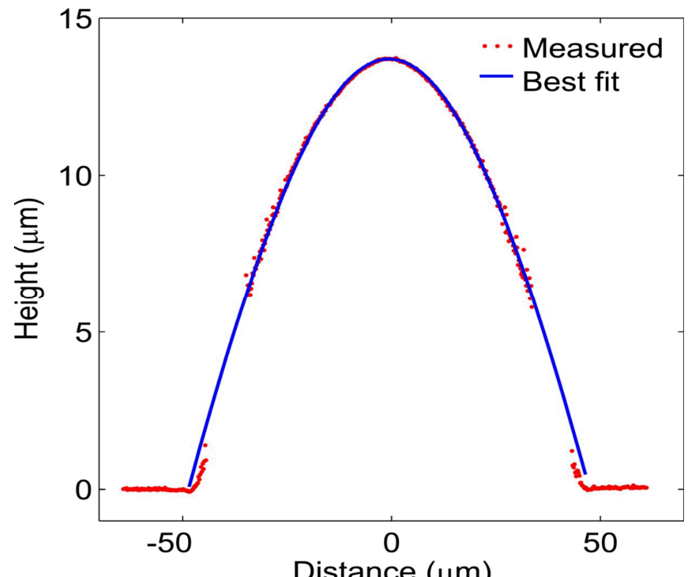






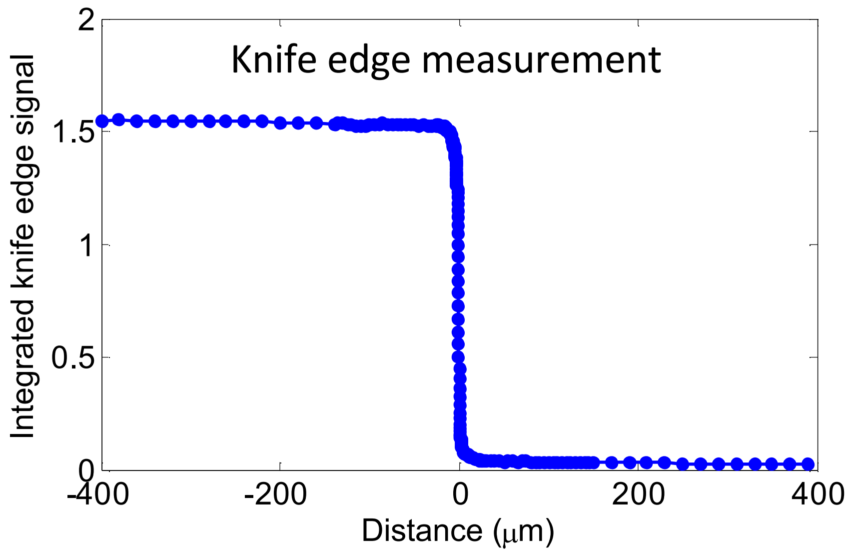


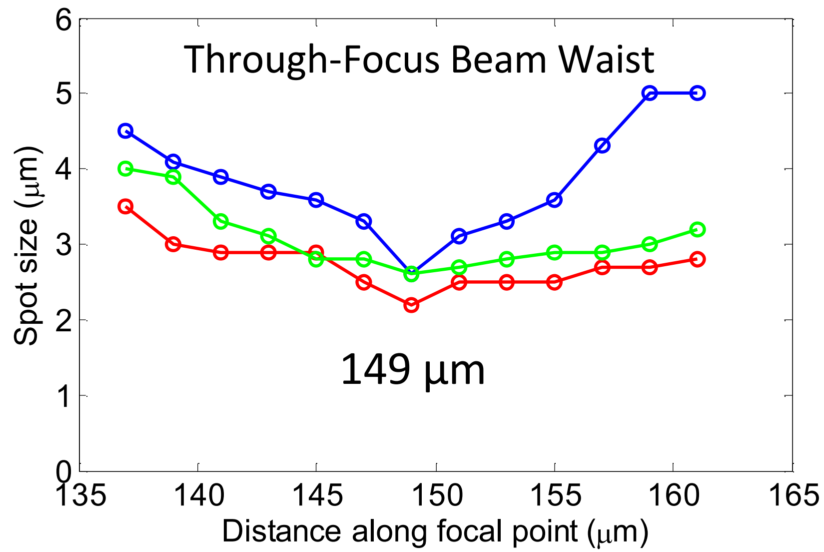
Radius of curvature	62.3 µm
Conic constant	-1.851



Radius of curvature	69.8 µm
Conic constant	-3.082

Grayscale lens performance was exactly as designed





- Knife-edge measurements of spot size through focus => 2.6 microns diameter
- At-spec focus position => 149 microns
- Theoretical grayscale lens efficiency is 92%
- Knife-edge measurement of efficiency => 79% (86% of theoretical, loss due to some rms roughness?)

Scaling Means High NA Optics Close to Atoms, DOEs are a Packaging Answer for Scaling

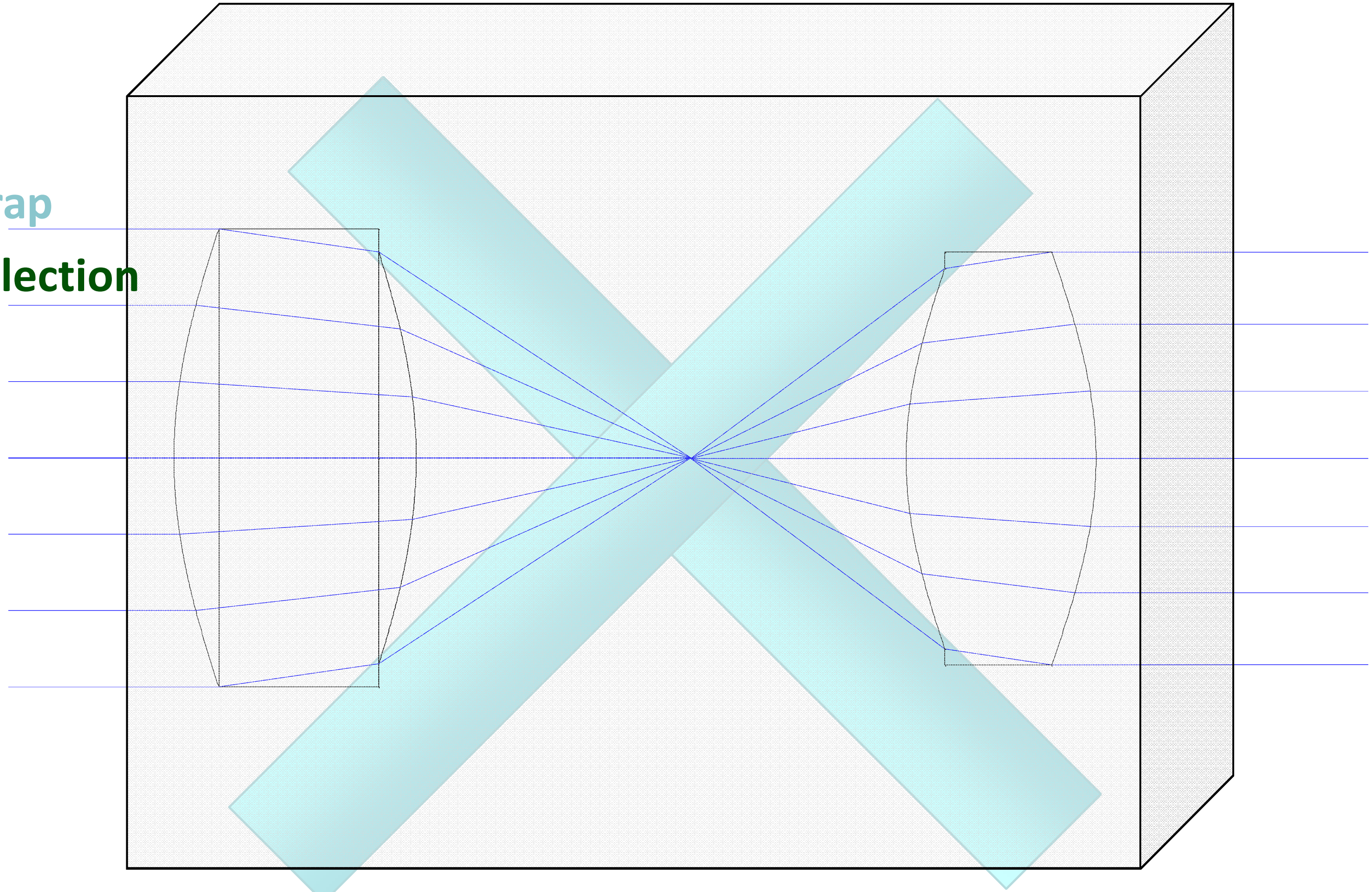
Limited Optical Access

MOT beams

Optical Dipole Trap

Fluorescence collection

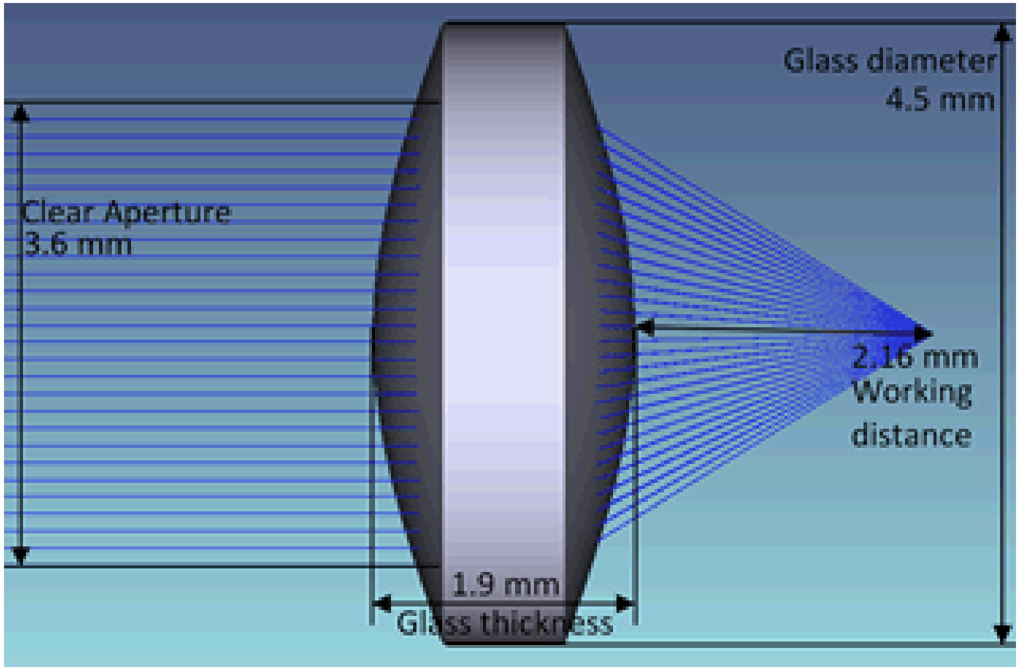
Vacuum cell



- Small space, in vacuum
- Multiple laser lines spread over broad spectral range
- Maximize fluorescence collection

Small-Refractive Lenses are still Bulky

Lens diameter = 4.5 mm
Clear aperture = 3.6 mm
Lens thickness = 1.9 mm
Focal length = 2.75 mm
Working distance = 2.15 mm
Numerical aperture = 0.55



- Large numerical aperture refractive lenses have significant surface sag
- The working distance of the lens is substantially shorter than the focal length

DOEs Occupy a Small Volume and are Best Suited for Use in Vacuum

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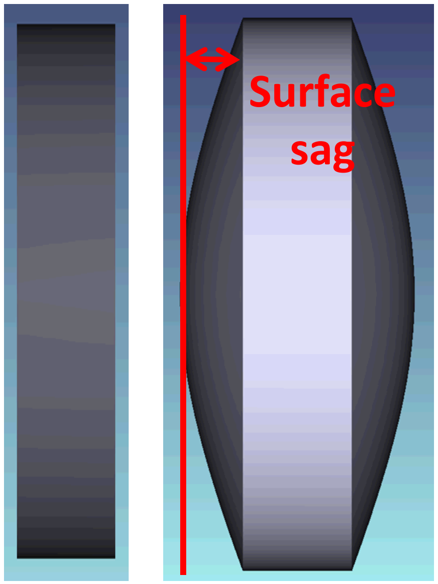
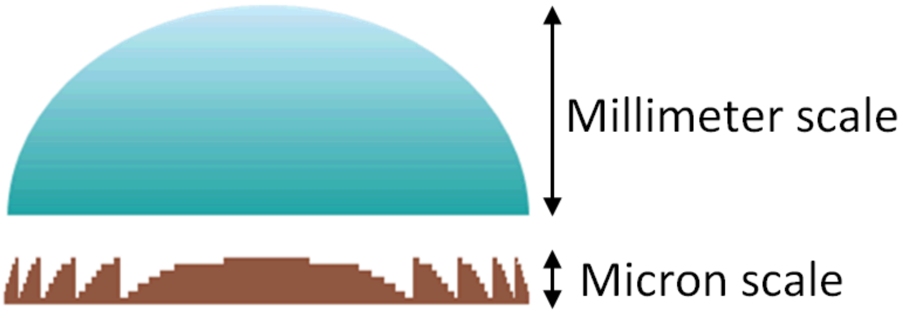
- A significant size advantage is conferred by the incorporation of DOEs
- DOE does not have surface sag
  - Occupies a smaller volume for the same NA
  - A smaller thickness can be used in a DOE, limited only by need for structural rigidity

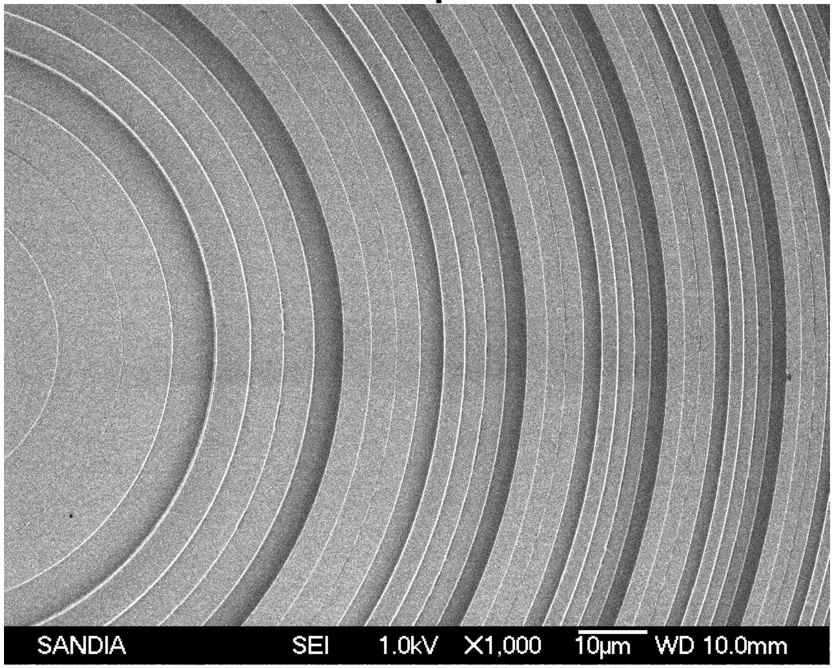


- 100% fill-factor
- Ideal for small spaces, vacuum and working at a single wavelength



Diffractive Optics Enable Scaling

- Diffractive Optics are an enabling technology in the scalability to large numbers of qubits in neutral atom based quantum computing
- Vacuum compatible
- Small physical profiles
  - High optical access
  - Enables shorter distance to atoms
- Specifically tailored to the optical field
- High collection efficiency
  - An NA of 0.55 represents photon collection from 8.2% of the sphere whereas at an NA of 0.8, photons from 20.3% of the atom's radiating sphere are collected



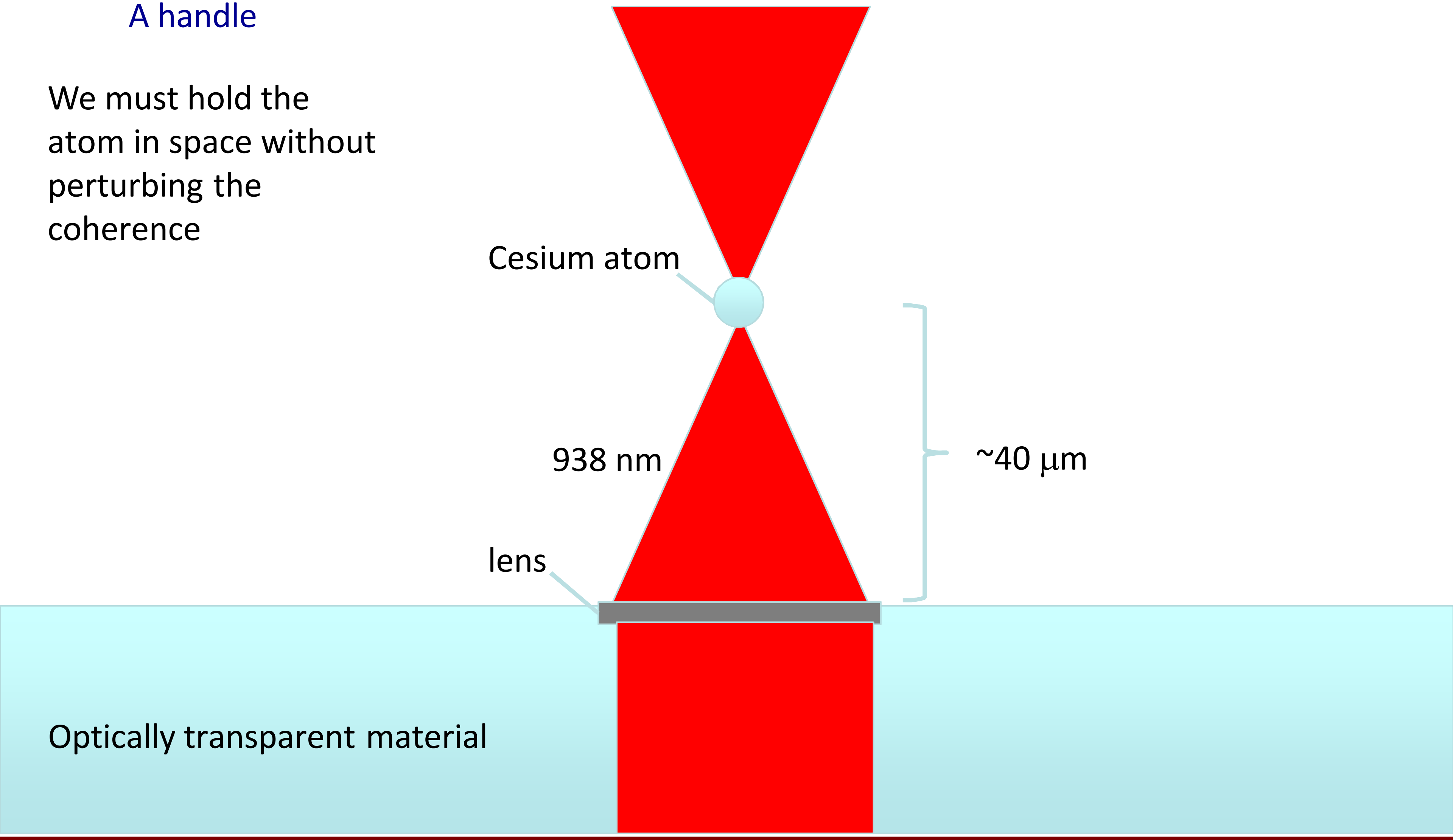
Path Forward

- Realization of quantum computers: must be able to scale up to many-qubits
- DOEs allow custom design of the optical fields and efficient packaging
- Arrays of DOEs can create optical traps, collect fluorescence, …
  - Larger NA
  - Smaller package
  - Better uniformity than refractive optics
- Wafer level fabrication facilitates ease of optical alignment and integration

What does a useful qubit require?

A handle

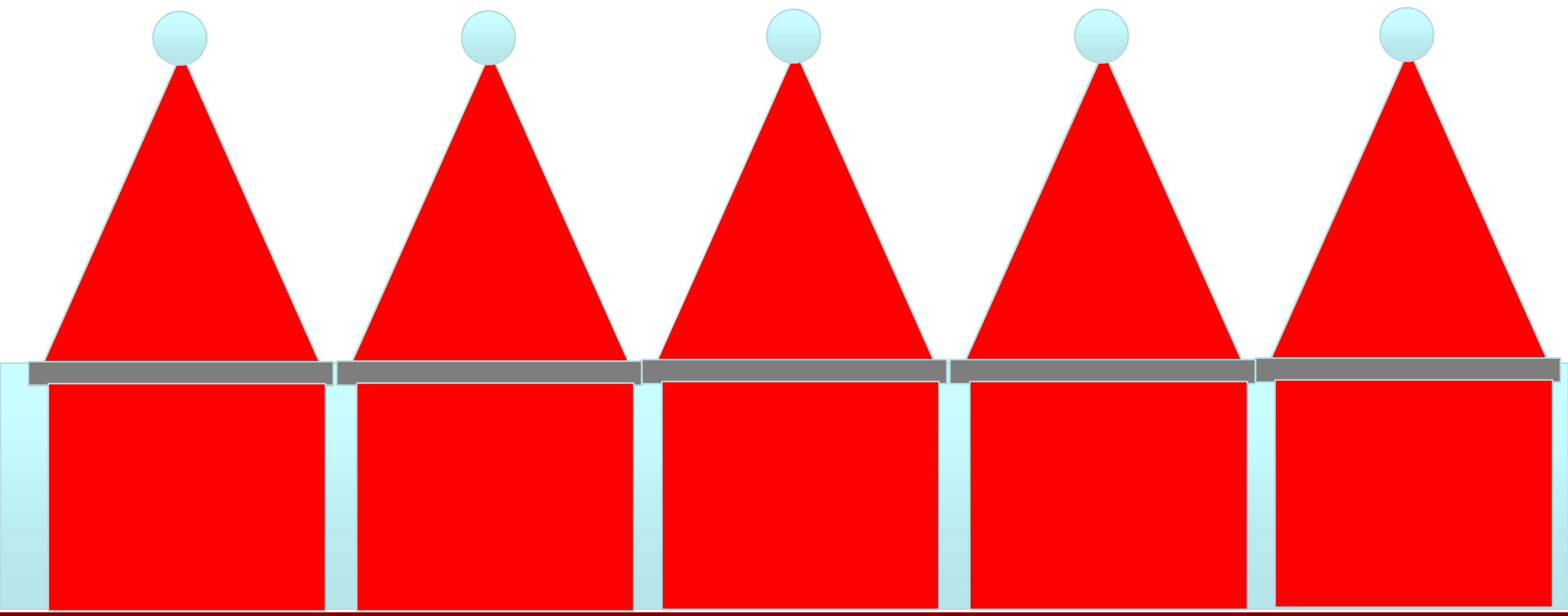
We must hold the atom in space without perturbing the coherence



What does a useful qubit require?

Lots of them

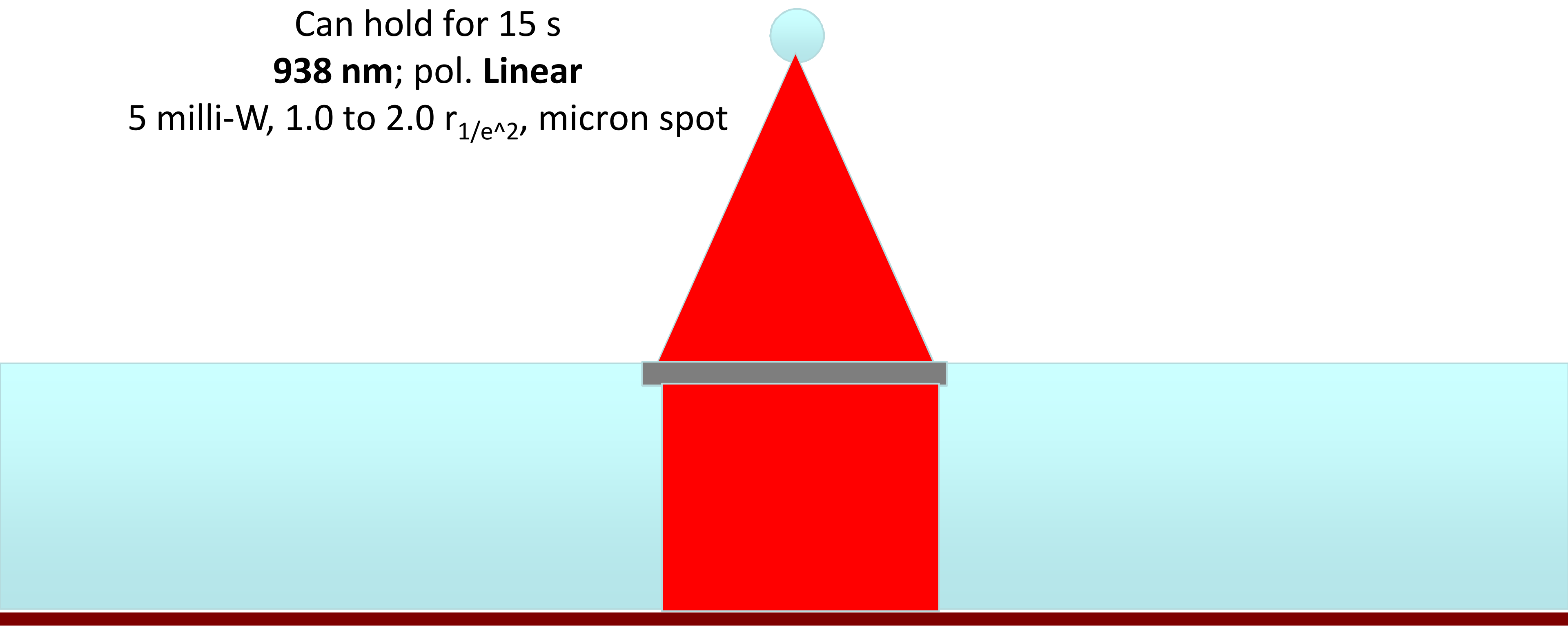
Need a large number to make a useful computer



How can we do this?

The sequence for each atom

Trap an atom:
Can hold for 15 s
938 nm; pol. **Linear**
5 milli-W, 1.0 to 2.0 r_{1/e^2}, micron spot



How can we do this?

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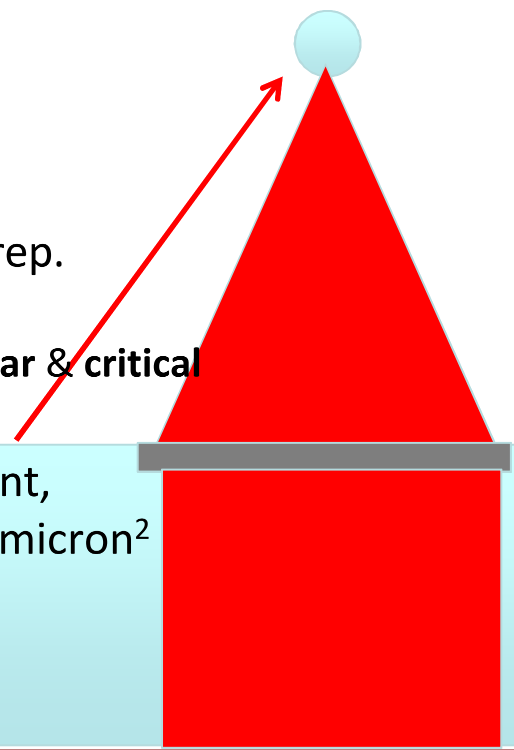
The sequence for each atom

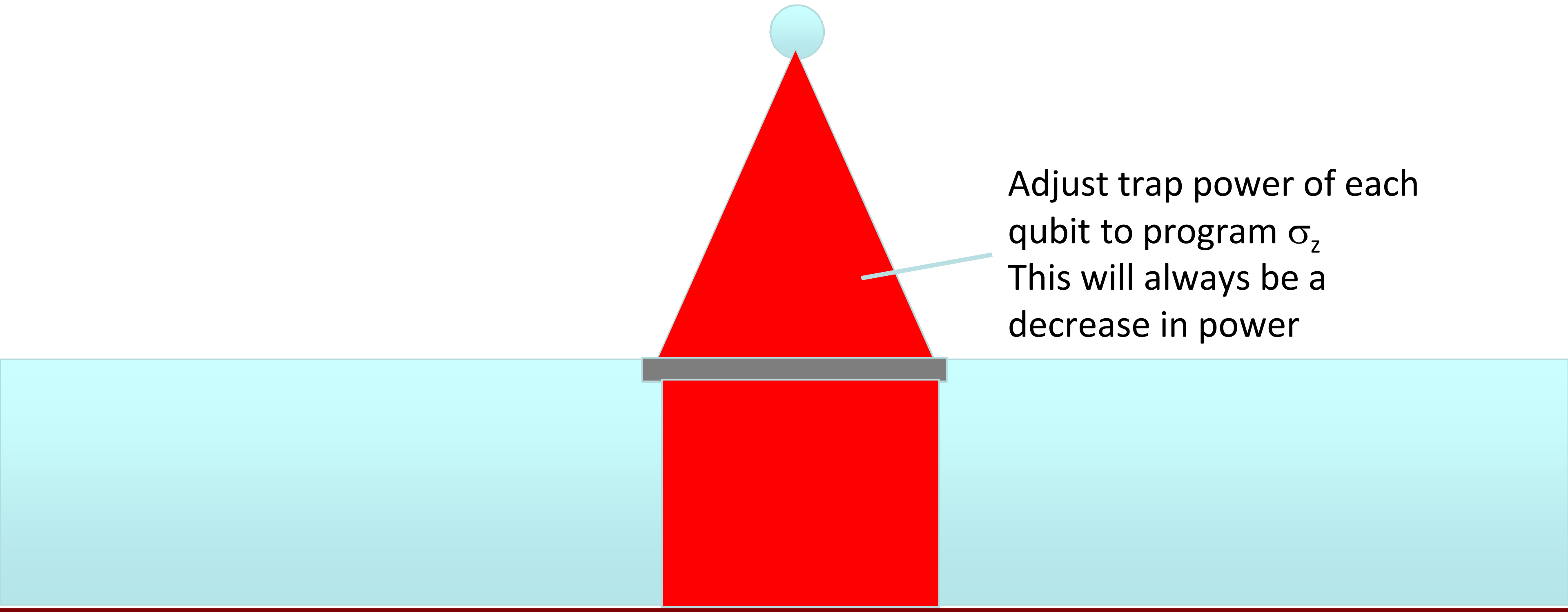


State prep.
895 nm
Pol. **Linear** & **critical**

No size requirement,
intensity is 10 pico-W/micron^2

How can we do this?

The sequence for each atom



How can we do this?

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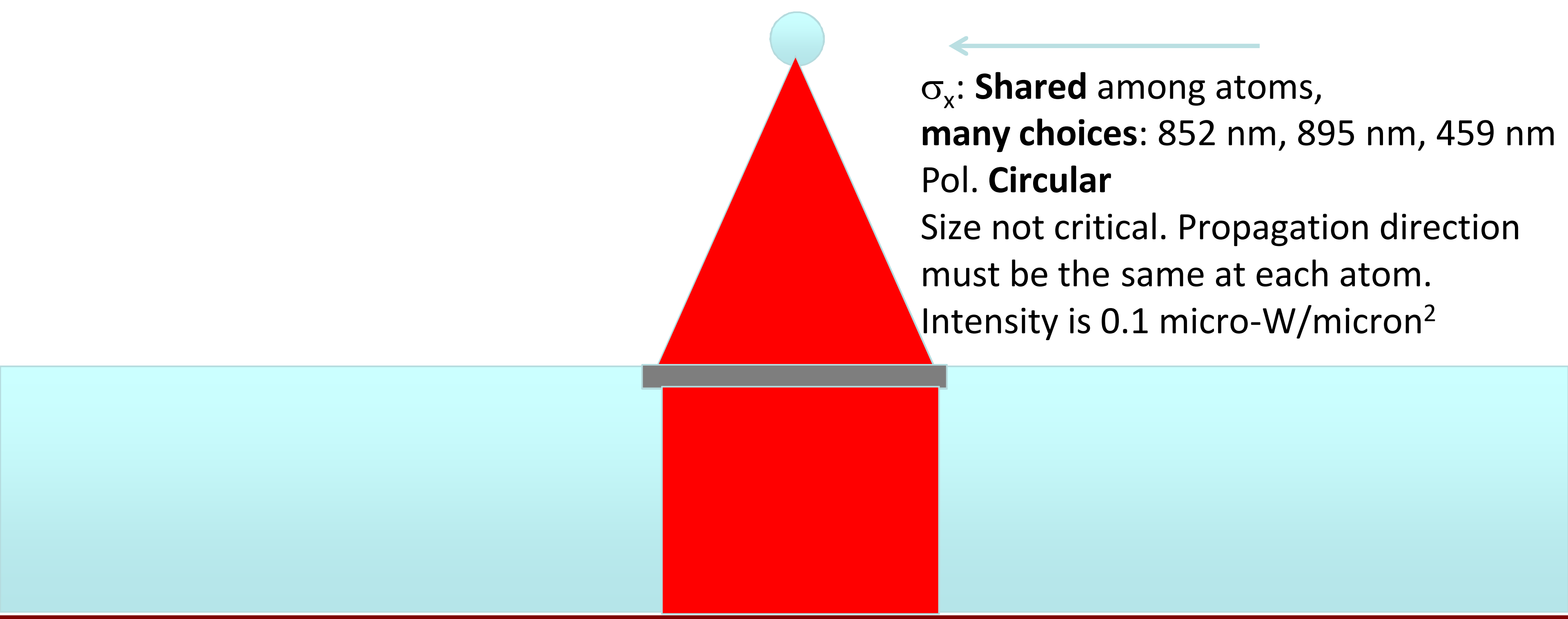
The sequence for each atom

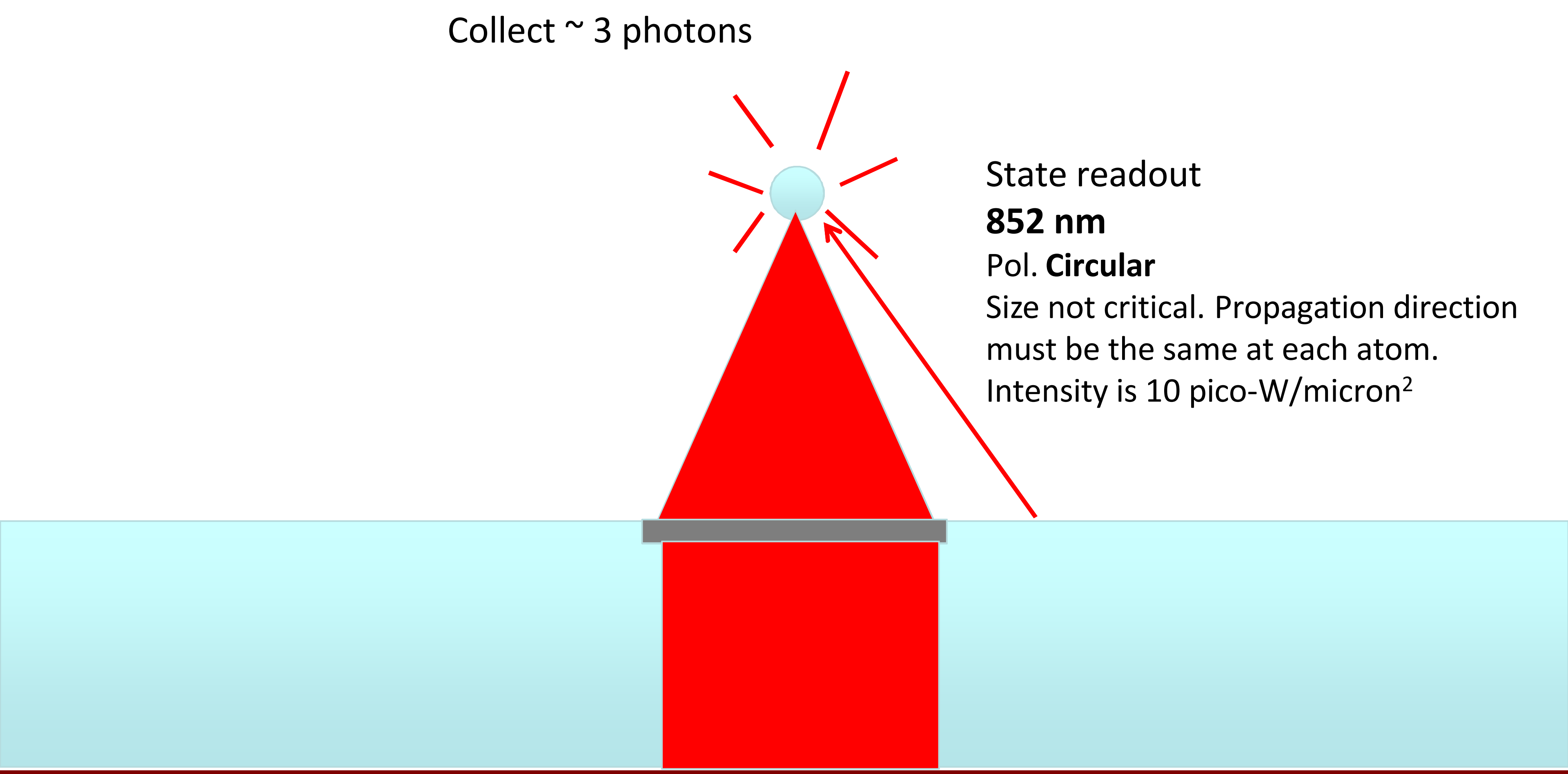
J (Rydberg interaction): **shared**
318 nm
Pol. **Linear**
Size not critical. Propagation direction must be the same at each atom.
Intensity is 1.0 milli-W/micron^2



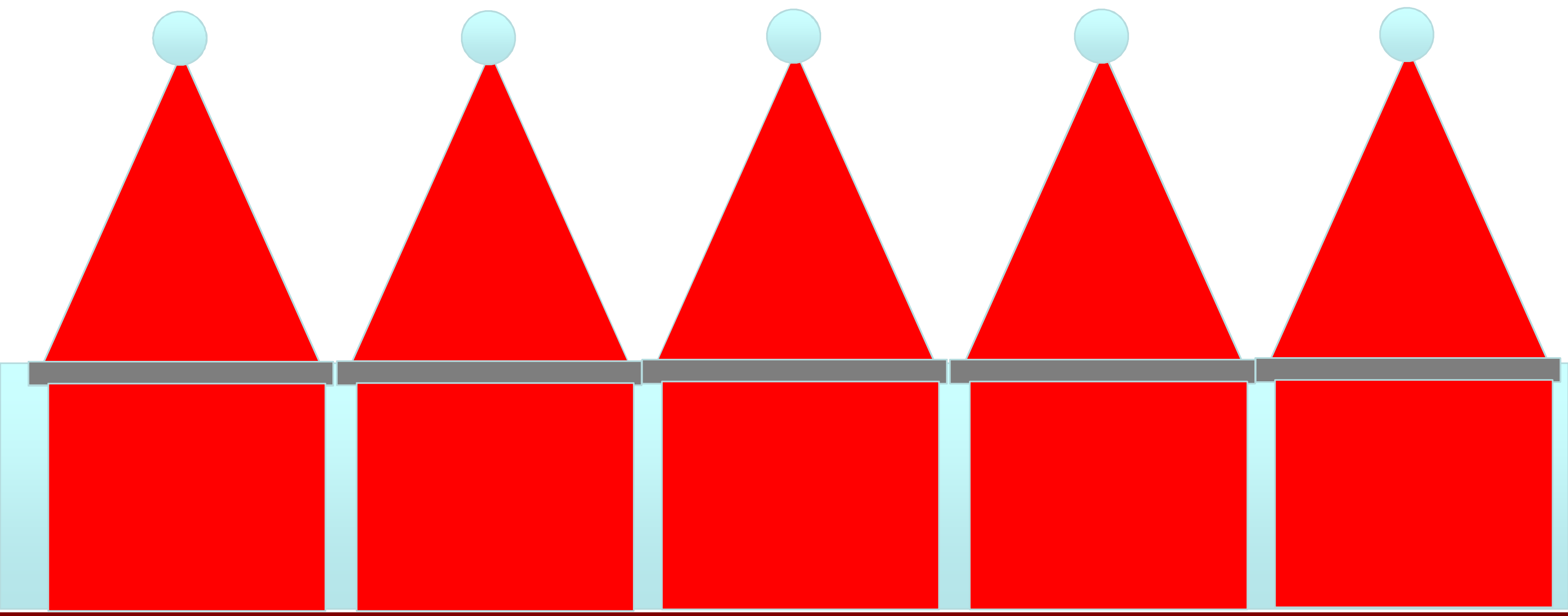
σ_x: **Shared** among atoms,
many choices: 852 nm, 895 nm, 459 nm
Pol. **Circular**
Size not critical. Propagation direction must be the same at each atom.
Intensity is 0.1 micro-W/micron^2

How can we do this?

The sequence for each atom



Just remember we have a bunch



Optical Tasks

A DOE is an encoded phase plate for each point in x and y for an on-axis lens:

Priority	Task	Impact	Wavelength (nm)	Polarization	Power (nW)	Spot Size (microns)	Irradiance (nW/micron^2)
1	Trap	holds for ~15sec, posn important	938	linear	5000	2-4	300 - 1300
6	State Prep	no size rqmt => flood, orientation important	895	linear			0.01
1'	σ_z	Adjust (decrease) trap power to set	938	linear			
2	J	Rydberg, **k** same direction for all atoms	318	linear		30	1000
4	σ_x	**k** same direction for all atoms	852 or 895 or 459	circular			100
5	Readout		852	circular			0.01
3	Collection	efficiency impacts speed => **hi NA**	852				

Controlling Spot Size and Spacing for Traps

Atomic layout necessary

1. spot size ~ 2-4 microns
2. ~ 10 micron +/- 1micron

Individual trapping lens speed ($F^{\#}$) determined by required spot size:

$$D_{trap\ spot\ diameter} \sim 2.44\,\lambda\, F^{\#} = 2.44\,\lambda \left(\frac{f}{D_{lens}}\right)$$

$\Rightarrow$ For trap size of 2-4 microns at λ = 938nm, then **$F^{\#}$ = 0.9-1.7**

For periodic atomic spacing of D_{lens} = 10 microns =>

9 ≤ f ≤ 17 microns (close proximity to dielectric DOE substrate)

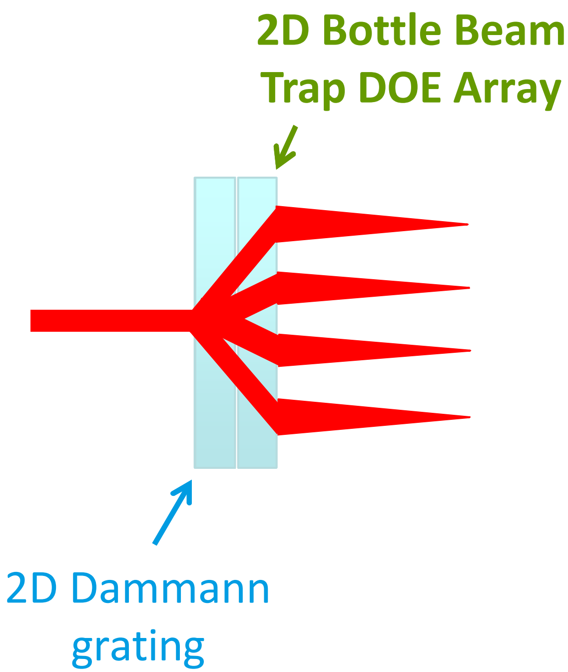
Annular Coaxial Trap with Inner Rydberg

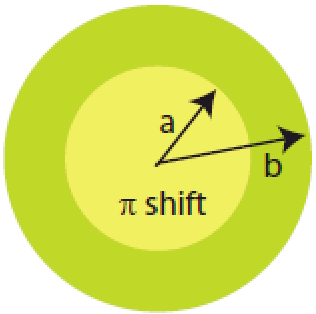
Setting priorities based upon irradiance, spot size, and efficiency:

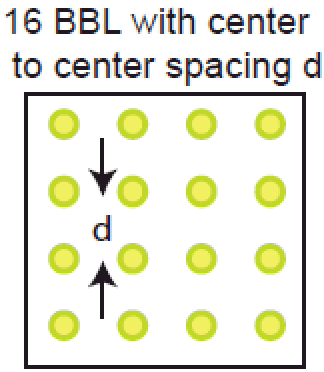
1. Annular, coaxial trap for power (area) and small spot size
2. Inner Rydberg/Collection for efficiency (larger DOE features)

Saffman 4X4 DOE Array

Saffman 4X4 DOE Design







How to design the DOEs in the 4X4?

A DOE is an encoded phase plate for each point in x and y for an on-axis lens:

$$\varphi(x, y) = m(a_1 r^2 + a_2 r^4 + a_3\, r^6 + a_4\, r^8 \dots)$$

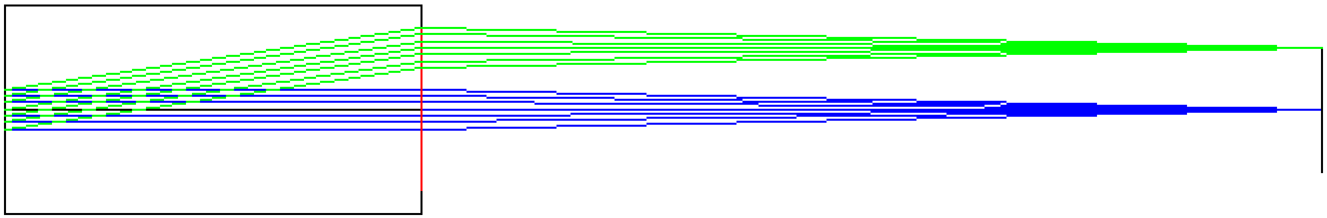
For the off-axis lens, we add a linear phase term (like a wedge):

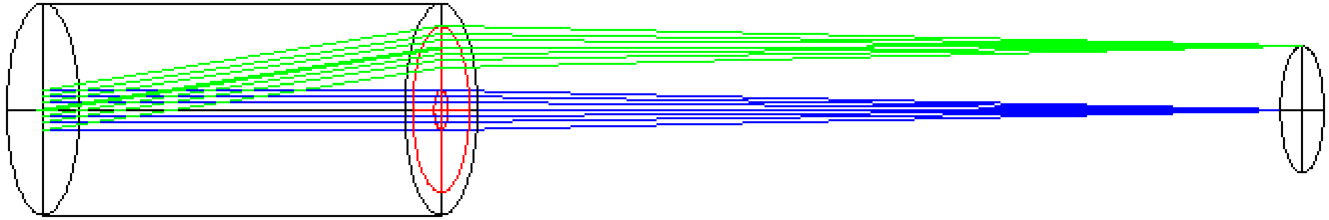
$$\varphi(x, y) = m(c_1 y + a_1 r^2 + a_2 r^4 + a_3\, r^6 + a_4\, r^8 \dots)$$

Note: there are three different lens designs in the 4X4 array, with various rotations

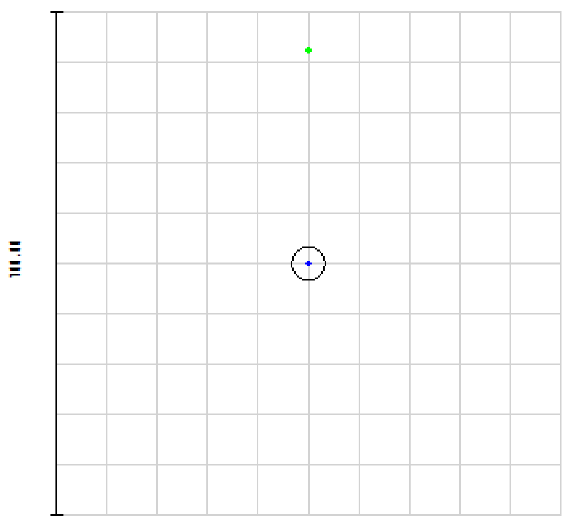
1) Identify the optimal coefficients for the phase terms
2) Map these phase contours to depth contours for a etch process in fused silica
3) Impart the pi phase shift aperture for the desired bottle beam intensity pattern
4) Place these DOEs on the substrate so that they match positions for the Dammann grating incident beams

On-axis DOE and Off-axis DOE Performance





On-Axis DOE and Off-Axis DOE Performance



Surface: IMA

IMA: 0.000, 0.000 mm

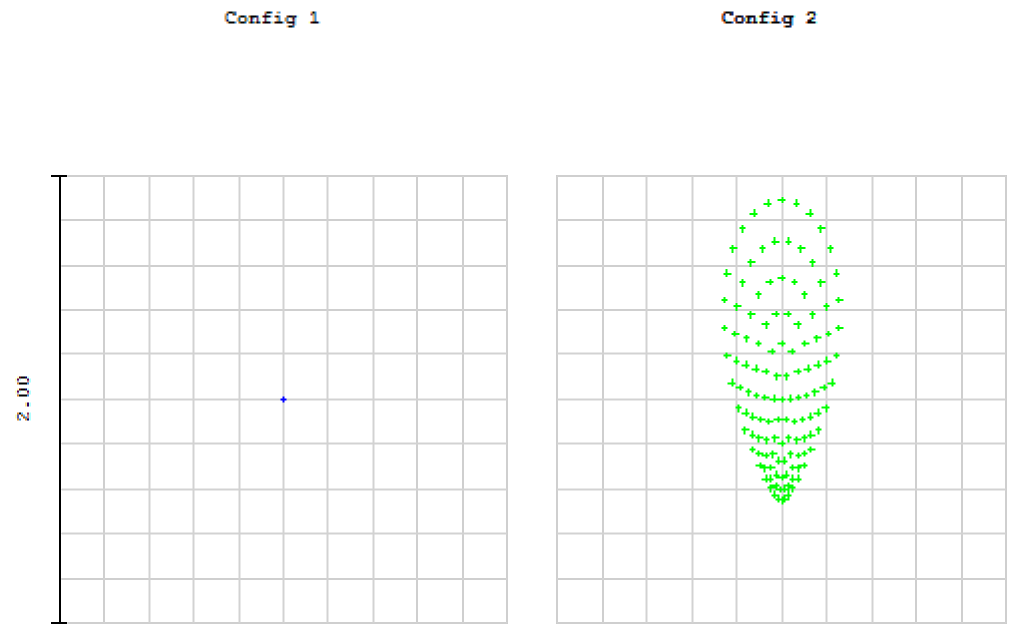
Spot Diagram

4/9/2013 Units are µm.
Field : 1
RMS radius : 210.428
GEO radius : 298.394
Scale bar : 700

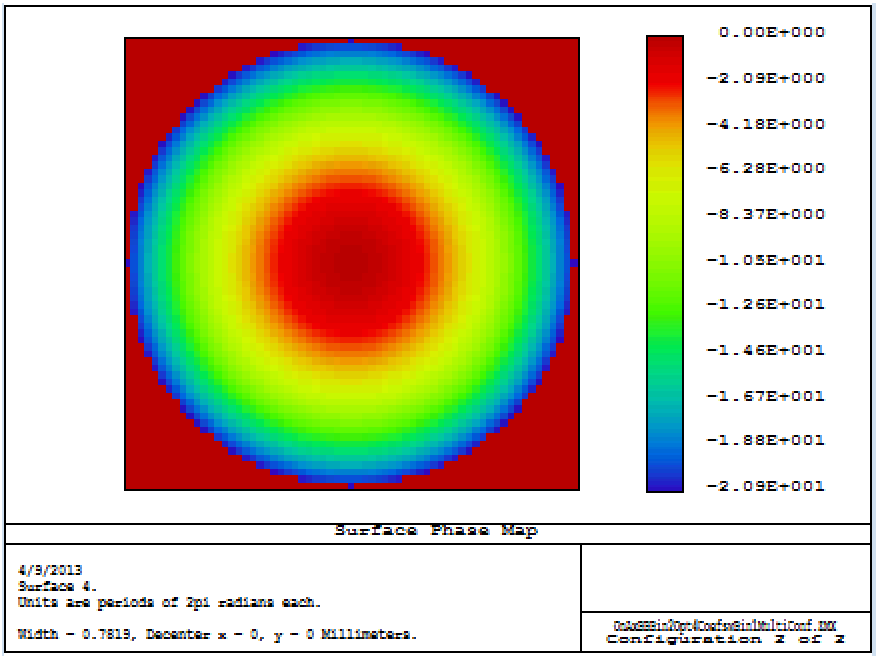
Airy Radius: 23.17 µm

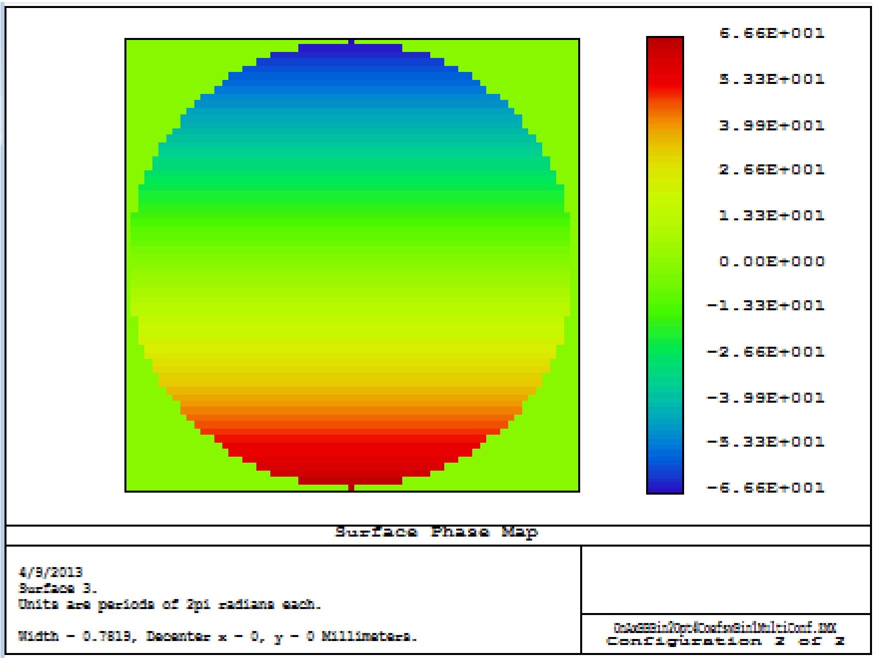
Reference : Chief Ray

OnAxBBBin2Opt4CoefswBin1MultiConf.ZMX
Configuration: All 2



Separate Phase Plots for an Off-Axis DOE





Notables

- **Fabricated and delivered bottle beam trap DOE to Saffman lab**
- **Utilized in experiment and paper submitted soon:**

V. V. Ivanov, J. A. Isaacs, M. Saffman, S.A. Kemme, A.R. Ellis, G.R. Brady, J.R. Wendt, G. Biederman, S. Samora, "Atom trapping in a bottle beam created by a diffractive optical element," submitted to App. Phys. Lett. B, 2013.

- **Fabricated large NA collection DOE (in addition to trapping DOEs)**

- **Quantified scaling issues that impact packaging and performance**

- **Designed 4X4 DOE bottle beam array**

- **Presented and published for SPIE Photonics West:**

S. A. Kemme; G. R. Brady; A. R. Ellis; J. R. Wendt; D. W. Peters; G. W. Biedermann; T. R. Carter; S. Samora; J. A. Isaacs; V. V. Ivanov; M. Saffman, "Ultrafast diffractive optical micro-trap arrays for neutral atom quantum computing," Proc. of the SPIE – The International Society for Optical Engineering, San Francisco, CA, vol. 8249, Jan 2012.

A.L. Young, S. A. Kemme, J. R. Wendt, T. R. Carter, S. Samora, "High numerical aperture diffractive optical elements for neutral atom quantum computing," Proc. Of the SPIE– The International Society for Optical Engineering, San Francisco, CA, vol. 8249, Feb 2013.

D. A. Scrymgeour, S. A. Kemme, R. R. Boye, A. R. Ellis, T. R. Carter, J. D. Hunker, "Micro-optical grayscale collection lenses for atom and ion trapping," Proc. Of the SPIE– The International Society for Optical Engineering, San Francisco, CA, vol. 8249, Feb 2013.