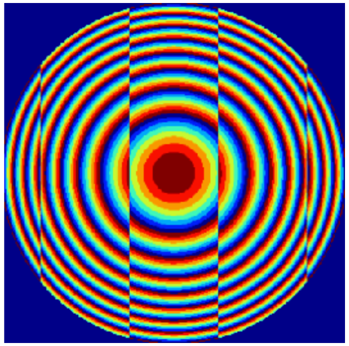

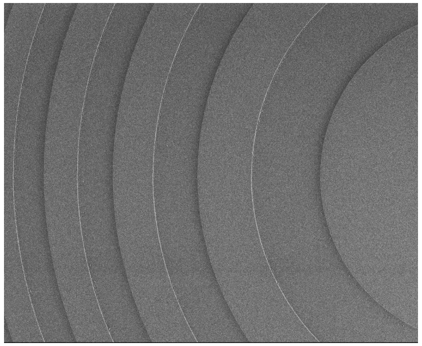

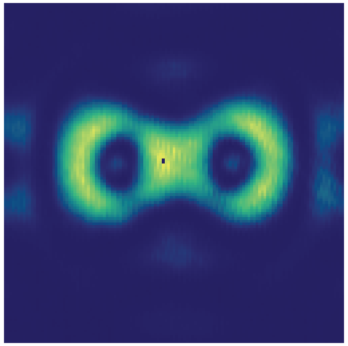

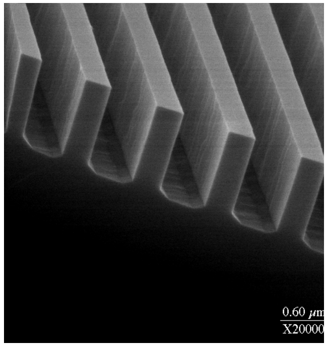

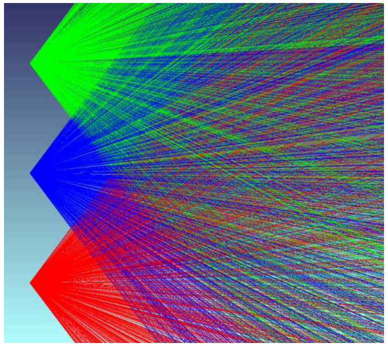

Diffractive Optical Elements for AQUARIUS

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Outline

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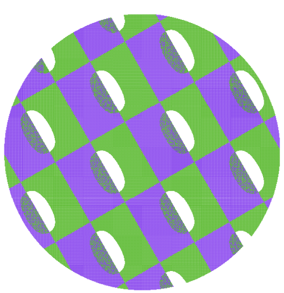
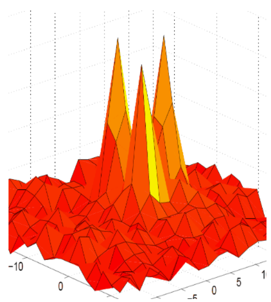
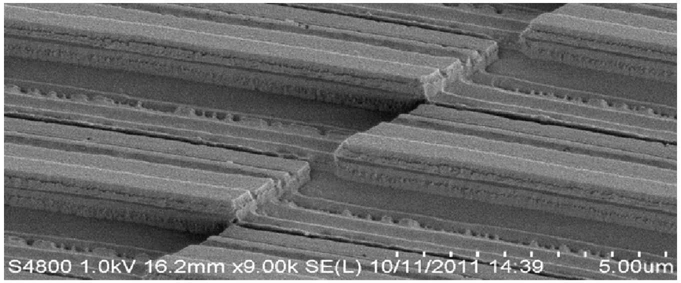
- Diffractive Optical Elements (DOEs)
- Update on Fabricated and Implemented Trapping DOEs
  - Bottle Beam DOE, Blue Detuned, Integrated Collection Lens
  - 3-Trap DOE, Red Detuned
  - 2-Trap DOE with Integrated Focus Function
- Collection Lens Design and Realization
- On going efforts
  - Experiments Exploring Pertinent Physics
  - DOE Technology Development, Multi-Function Integration







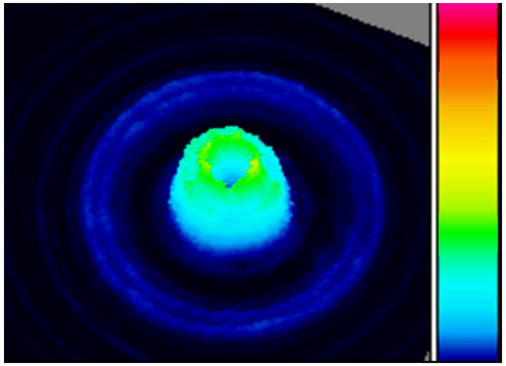
A CRITICAL ENABLING TECHNOLOGY

DIFFRACTIVE OPTICAL ELEMENTS (DOEs)

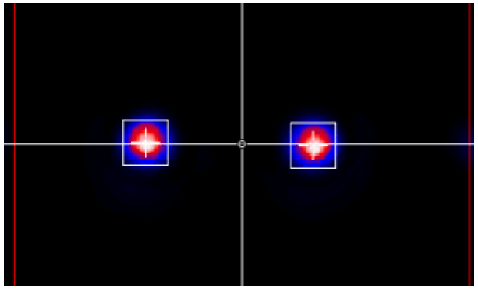
Diffractive Optical Elements (DOEs) as an Enabling Technology for AQUARIUS

Sandia National Laboratories

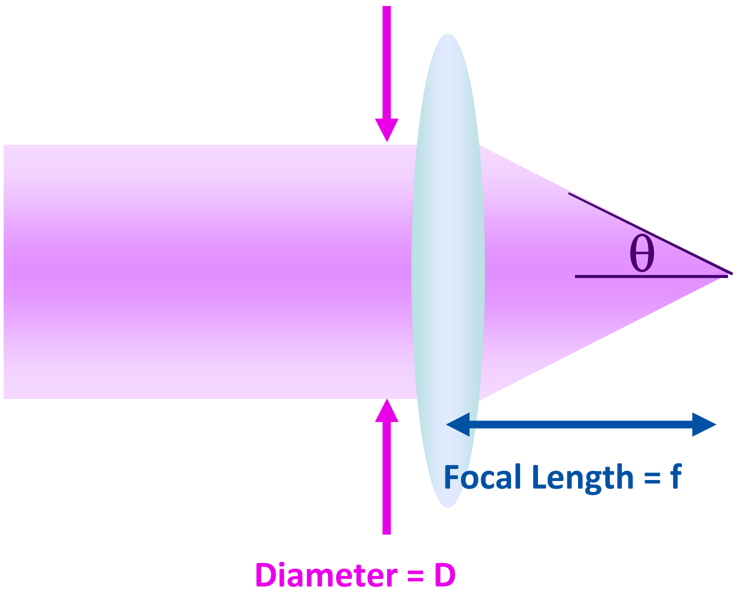
- Optics can perform multiple functions in quantum technologies:
  - Tailoring an optical trapping field
  - Manipulating light for optimal excitation
  - Efficient, in-vacuum signal collection
  - Propagating the signal long distances with low loss



- These tasks are sometimes considered a "packaging" or "engineering" function and may receive low priority
- Ultimately, in a determination of realizable quantum-technology configurations, the optical function is a critical enabling technology



Definitions



F/# = f / D

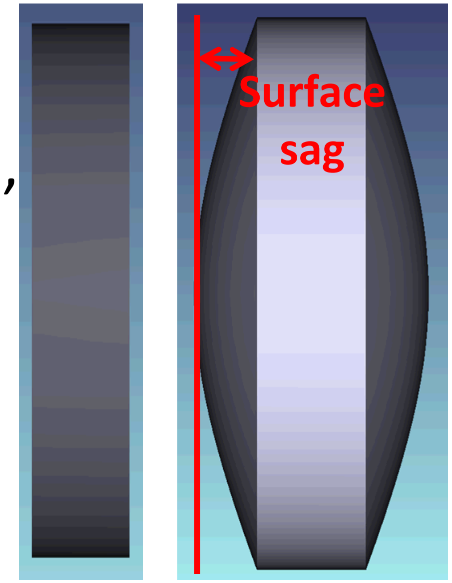
or

NA = sin (θ)

Small F/#s ≡ Large NAs ≡ Fast Optics ≡ Large Cone Angles → Small Spot Sizes

Diffractive Optics Enable Scaling

- A significant size advantage is conferred by the incorporation of DOEs as compared to refractive, bulk or even micro-optics
- 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
- An array of 100% fill-factor, mutually aligned DOEs is as easily accomplished as a single lens due to lithographic definition
- Enables scaling
  - Smaller system volume at small scale
  - Large scale will only be possible with DOEs in place of refractive lenses



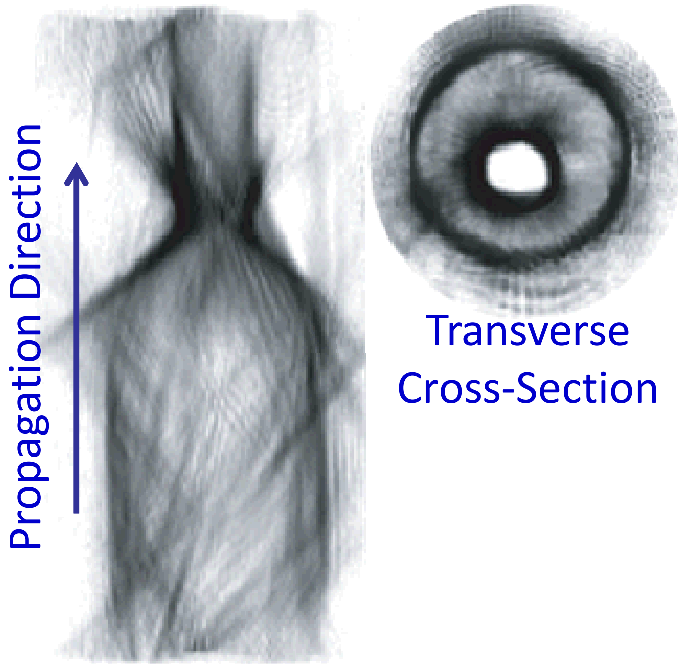
Addressing Previous EAB Feedback – Programmatic

- What is the road to scalability for the various approaches?
  - Local signal input and collection is primarily optical. This scalable and arrayable proposed DOE approach, implemented within the vacuum, is key
- What advantages does Sandia offer to a potential new sponsor?
  - SNL continues to successfully demonstrate state-of-the art DOE design to realization for AQUARIUS as well as other applications, such as ion trapping

Addressing Previous EAB Feedback – Technical Overview on DOEs for Neutral Atom Approach

- EAB was impressed by the DOE work, and views this as an opportunity for a high-impact paper, as well as for application to others areas such as microscopy
  - We presented and published the bottle-beam and high NA DOE work for Saffman's group at SPIE Photonics West 2012
  - We are preparing papers on the trapping successes with that component as well as with the 3-trap component
- EAB recommends that care be taken with the distance of the optical trap (BoB or otherwise) from the port to avoid stray electric fields
  - We (described later in talk) as well as Saffman's group are attempting to quantify this effect for red- and blue-detuned traps
- The team should consider how to scale up to larger arrays of qubits in the neutral atom system, for long term impact. Sandia needs to have a plausible description of how one might make a system large enough to solve a practical problem
  - The DOE implementation speaks to this issue

Bottle Beam Intensity Pattern



Whyte, G. & Courtial, J. Experimental demonstration of holographic three-dimensional light shaping using a Gerchberg-Saxton algorithm. *New J. of Phys.* **7**, 117 (2005).

BOTTLE BEAM DOE WITH COLLECTING LENS FOR BLUE DETUNED, SINGLE ATOM TRAPPING

1st Implementation of Bottle Beam Trap with DOE

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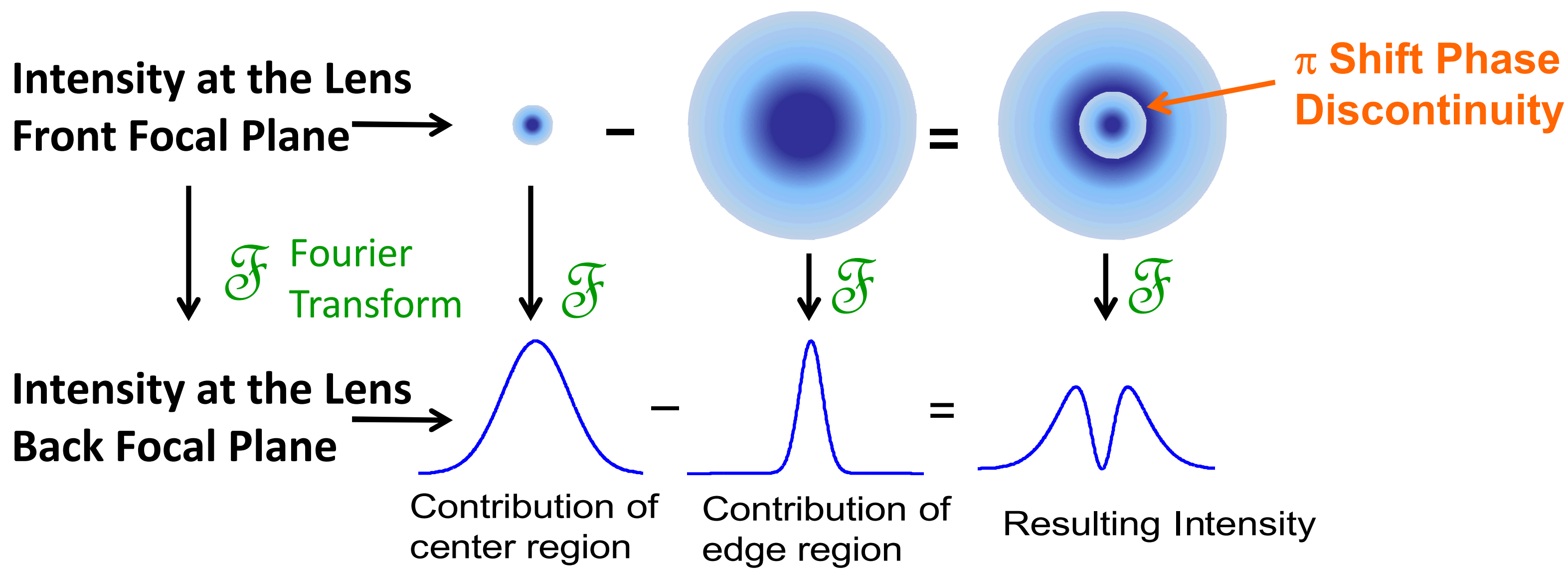
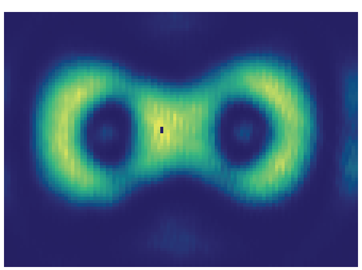
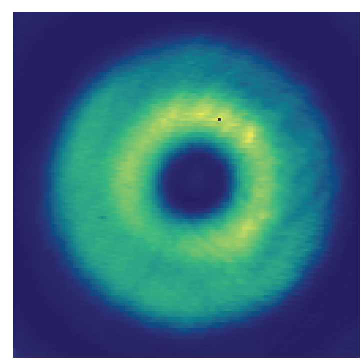
DOE Fourier Transforms Trapping Beam Intensity Pattern



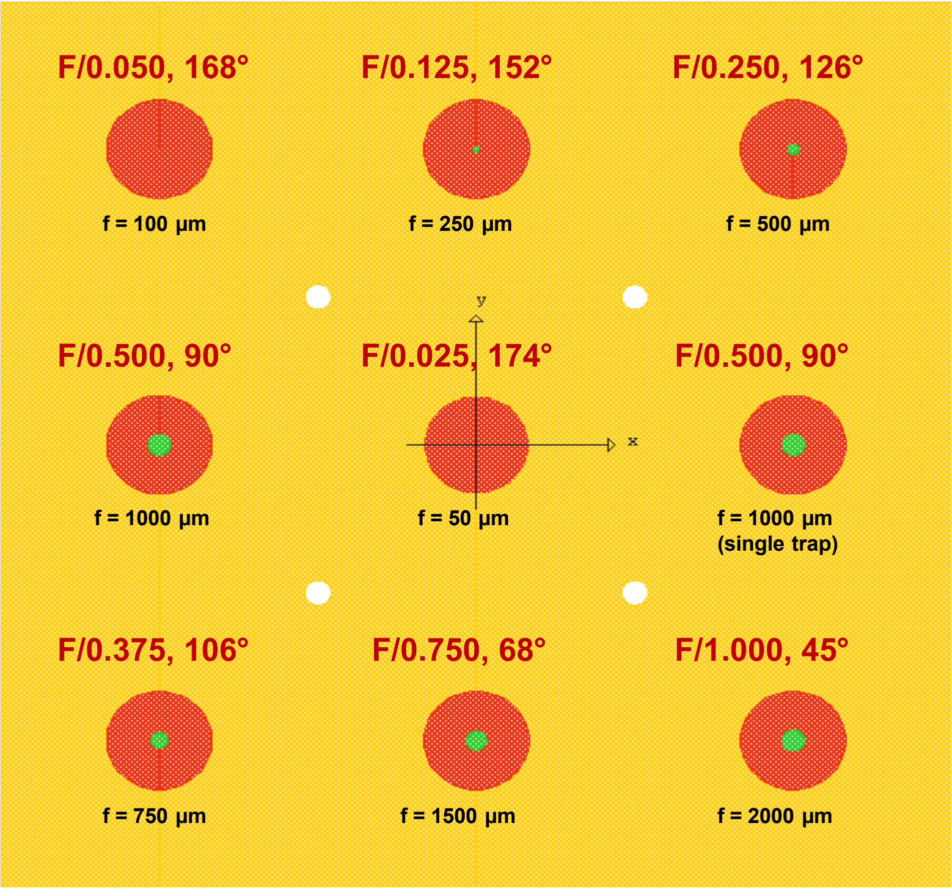


Measured intensity patterns

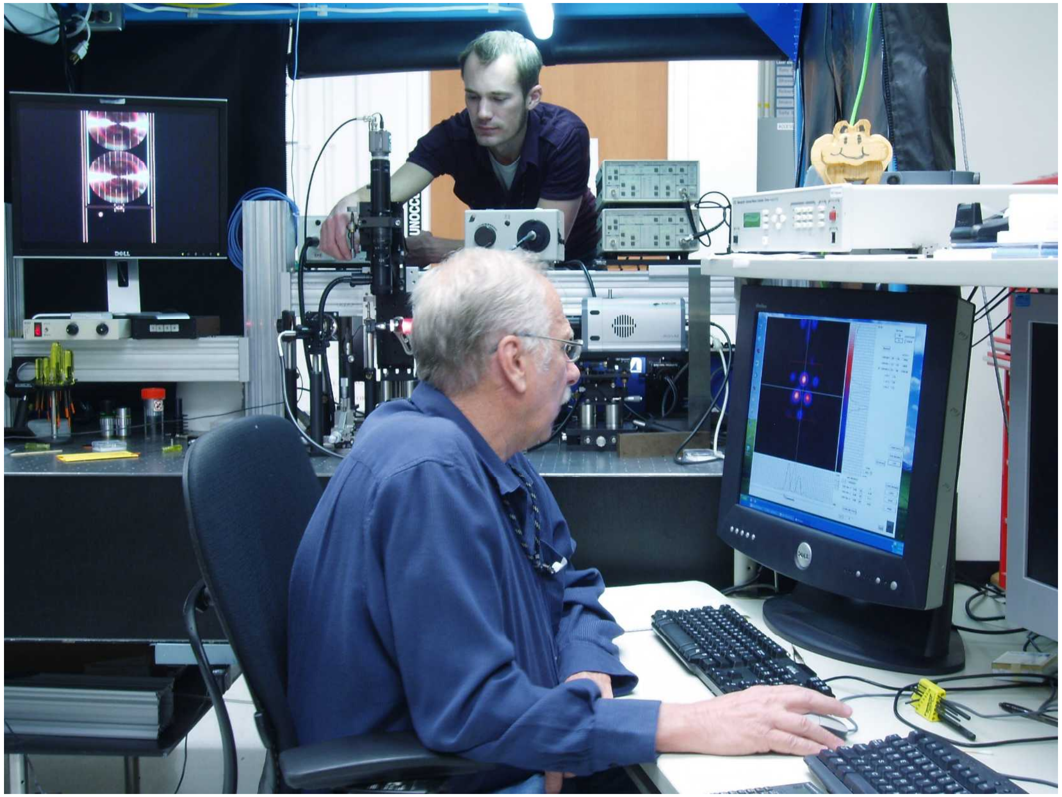


Fabricated Bottle Beam DOEs and Ultra-Aggressive Collection DOEs

Bottle Beam DOE Array



- Saffman group has successfully trapped using DOE-generated, blue detuned bottle beam!
- Paper in progress

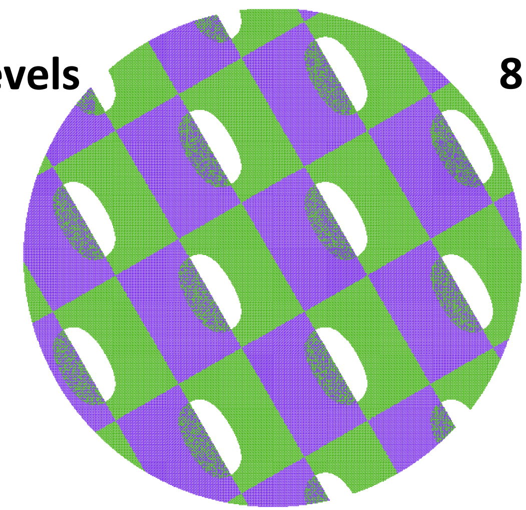


3-TRAP DOE FOR RED DETUNED, SINGLE ATOM TRAPPING

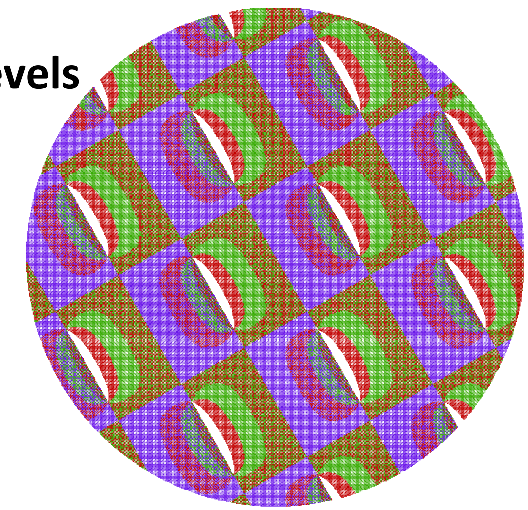
Design Choices for 3-Trap DOE

- Use Periodic, Pixelated Design (i.e., Computer-Generated Holography)
  - All features are same sized for simpler fabrication
  - Larger features allow for contact lithography instead of ebeam => large-area optics
  - Periodicity tends to be less efficient as intensity is a trade-off parameter for flexible patterns or uniform intensity requirements

4 levels

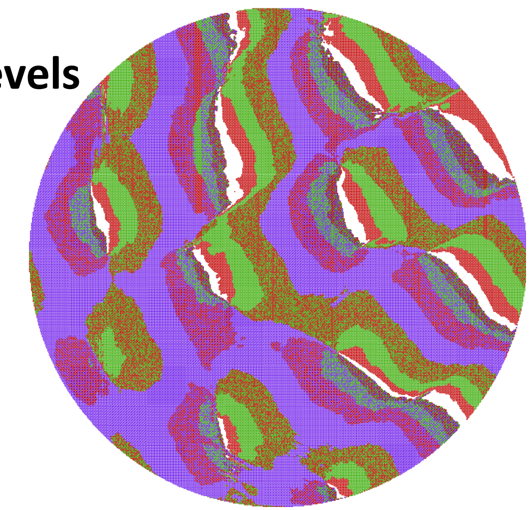


8 levels



Analytic Phase, 2 micron pixels

8 levels



Gerchberg-Saxton, 2 micron pixels

Zero-Order in 3-Trap DOE

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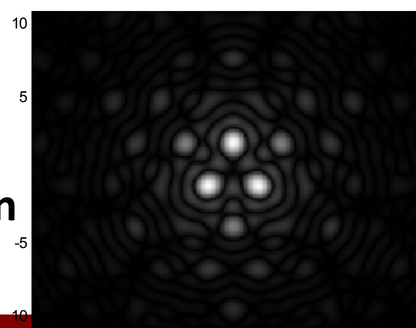
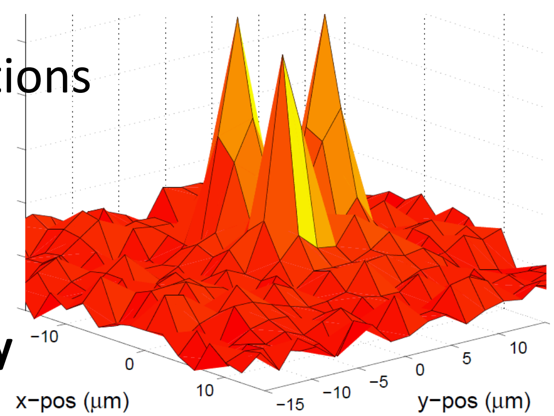
- Trade-offs in considering zero-order power as one of the 3 beams
  - Efficiency in each diffraction order is a function of DOE etch depth
  - Zero-order efficiency is VERY sensitive to etch depth
  - Utilizing, instead of suppressing, zero-order is overall most efficient
  - Any etch depth error makes that spot intensity different than the others
- Fabricated 3-trap DOE using zero-order
  - Successfully trapped using 4-level DOE
  - Used imaging to verify single atoms in all 3 traps simultaneously
  - Limitations due to anticipated non-uniformity in spot intensity
- Move to 2-trap system with integrated focus
- May choose to suppress the zero-order in future iterations

Predicted irradiance pattern



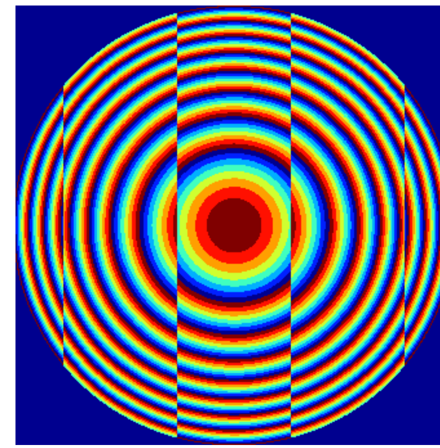
Emitted fluorescence from 3 single atoms trapped simultaneously

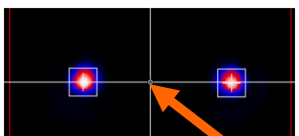


2-TRAP DOE WITH INTEGRATED FOCUS FUNCTION

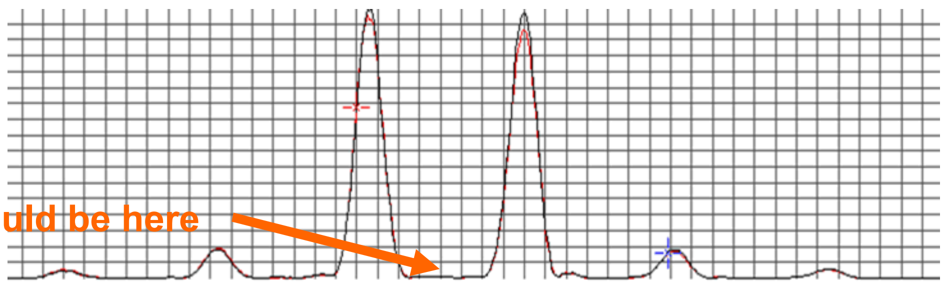
2-Trap DOE: Integration of Trapping and Lens Function

- In the design for 2-Trap DOE, combined a lens function with a grating to realize 2 focused spots of equal intensity, at a precise lateral spacing
- Now, lab implementation does not require a mutual alignment of DOE and fast refractive lens
- Suppressed the zero-order successfully!

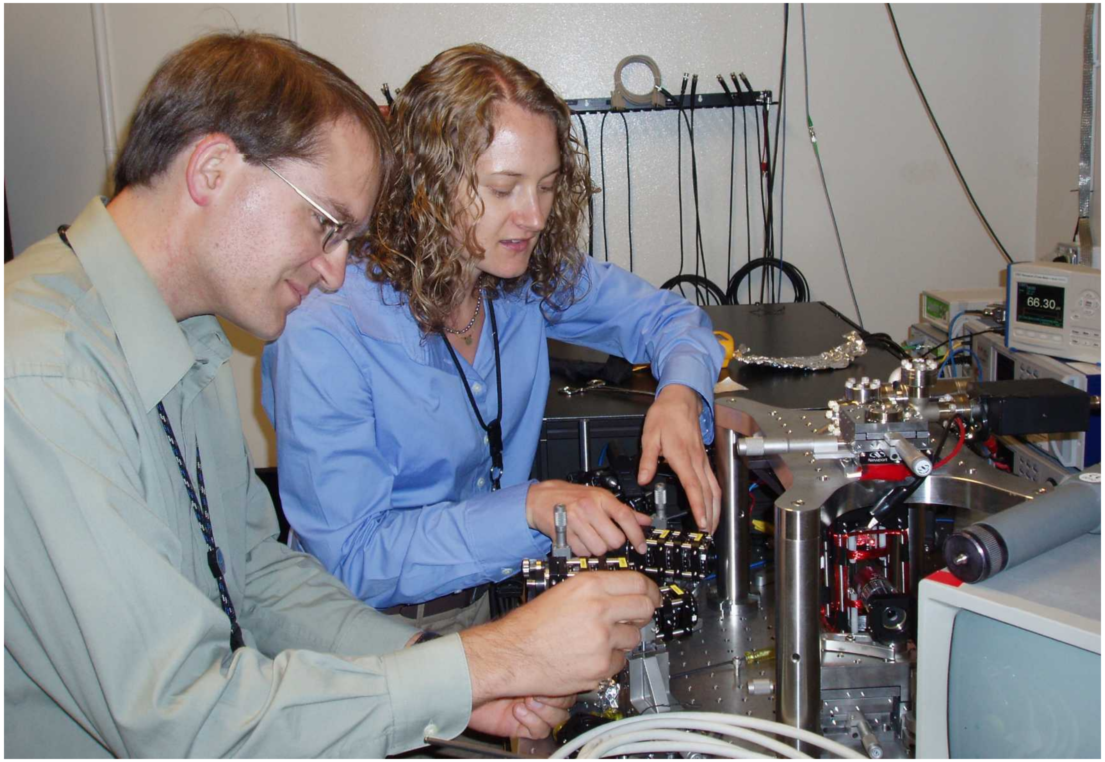




Zero-order would be here

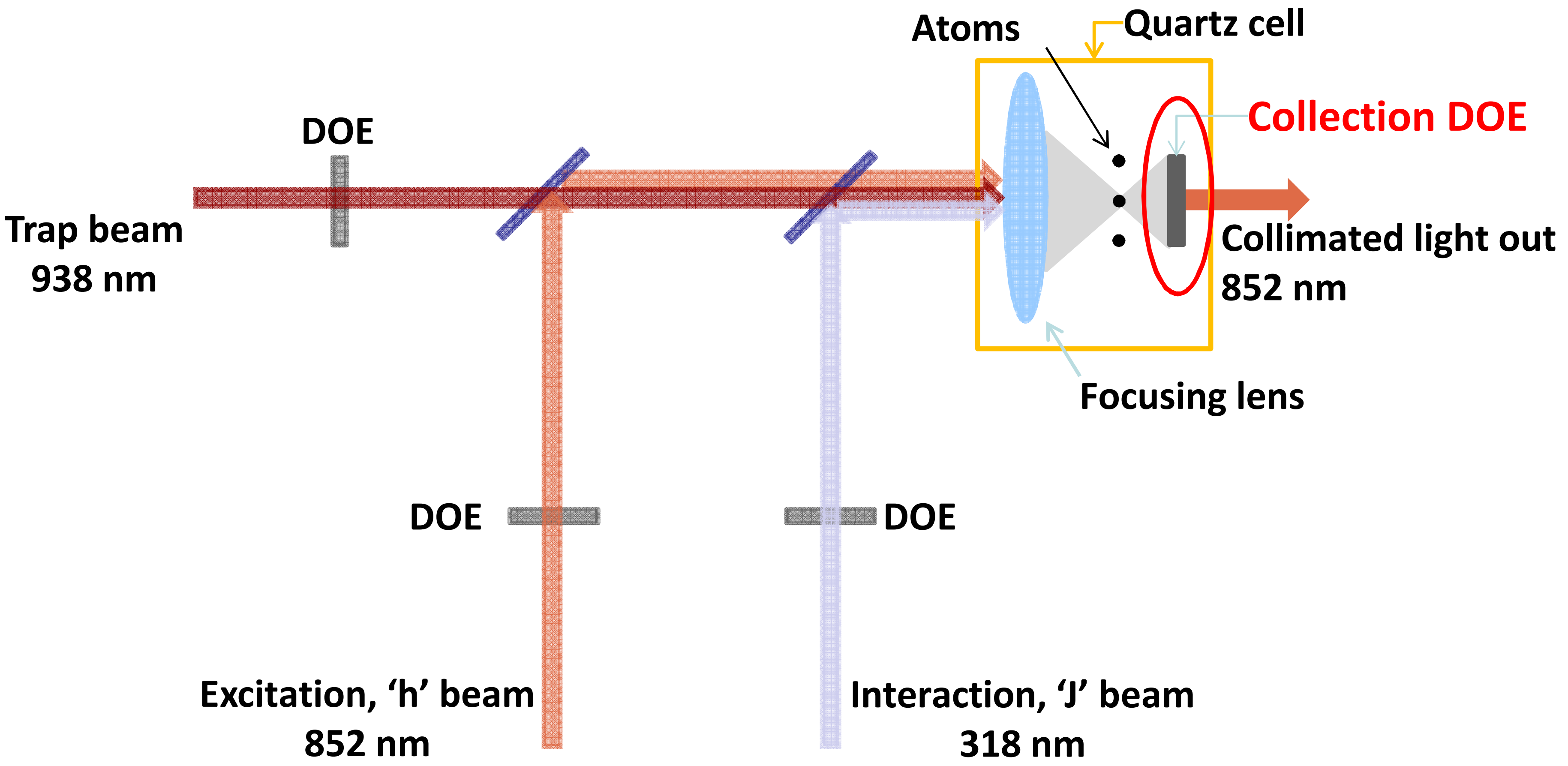


- Implemented 2-trap DOE with integrated focus
- Quartz cell cracked; gold suffered damage
- Develop parallel paths
  - Use AOMs to actively explore ideal lateral spacing
  - Focus DOE development on higher order traps to move toward a scalable architecture beginning with collection lens for linear 3-trap

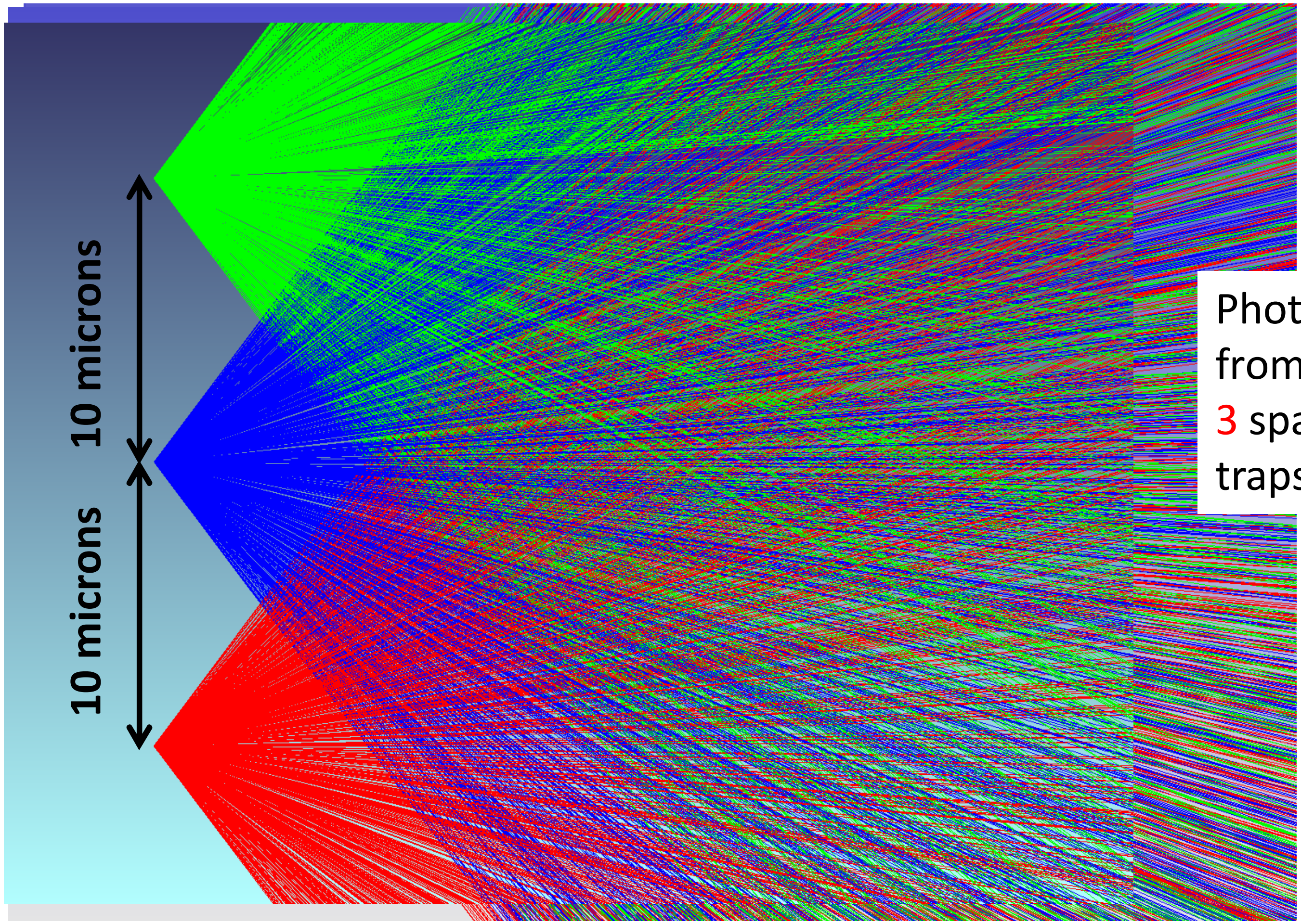


DOE HIGH NUMERICAL APERTURE (NA) COLLECTION LENS

Schematic Layout: Collection Lens

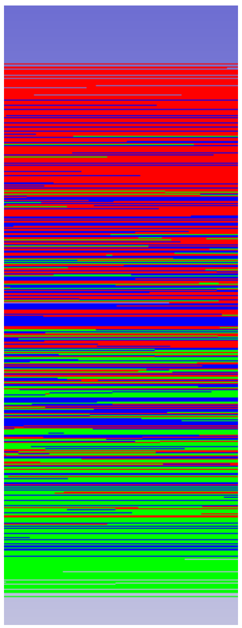


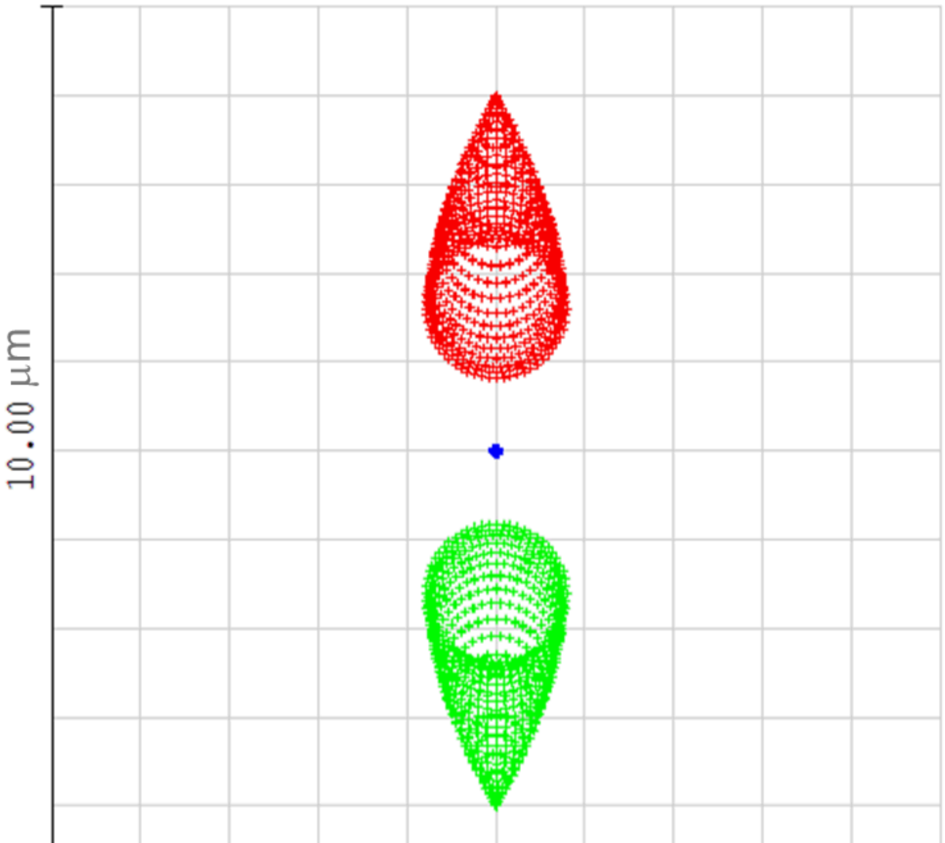
Photon Collection from Neutral Atoms: ZOOM

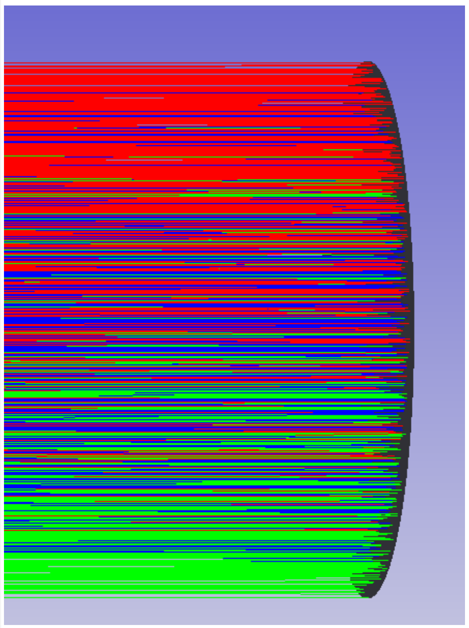


Photons are emitted from single atoms in 3 spatially separated traps

Photon Collection from Neutral Atoms







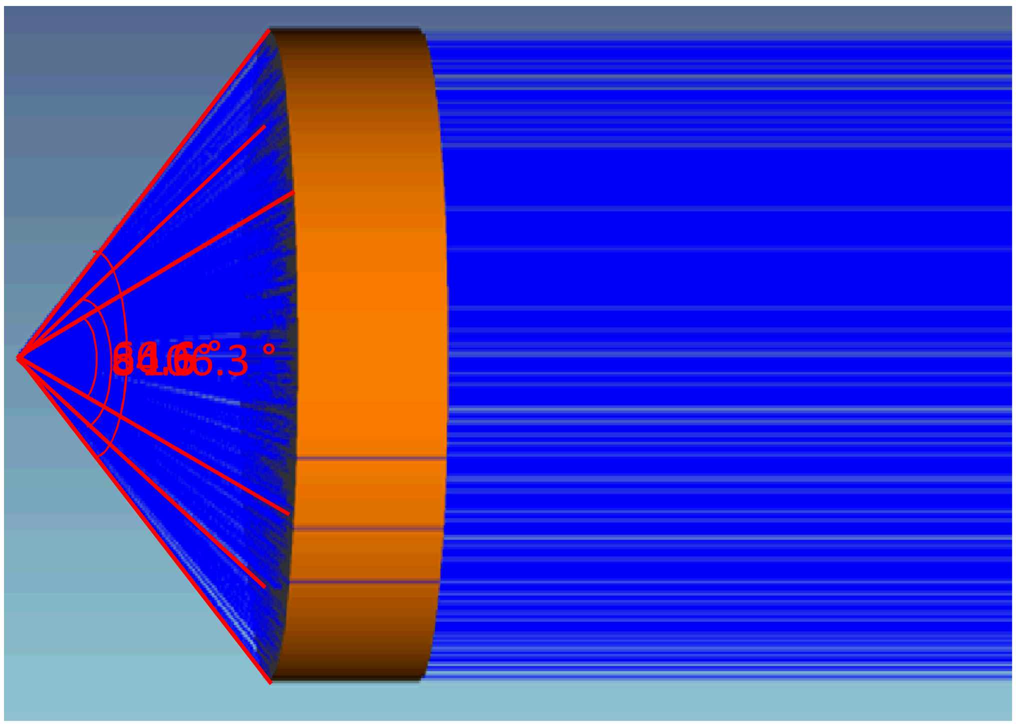
Refocus light to collect at fiber

3 spatially separated spots

(differences in spot size due to off-axis effects)

Diffractive Optic vs Refractive Optic for Collection

- Design for desired focal length and numerical aperture
- Can use full aperture of optic (no glass diameter vs clear aperture limitations)
- Smaller glass thickness (& no surface sag)
- Longer working distance (see discussion on Rydberg interaction with dielectrics)

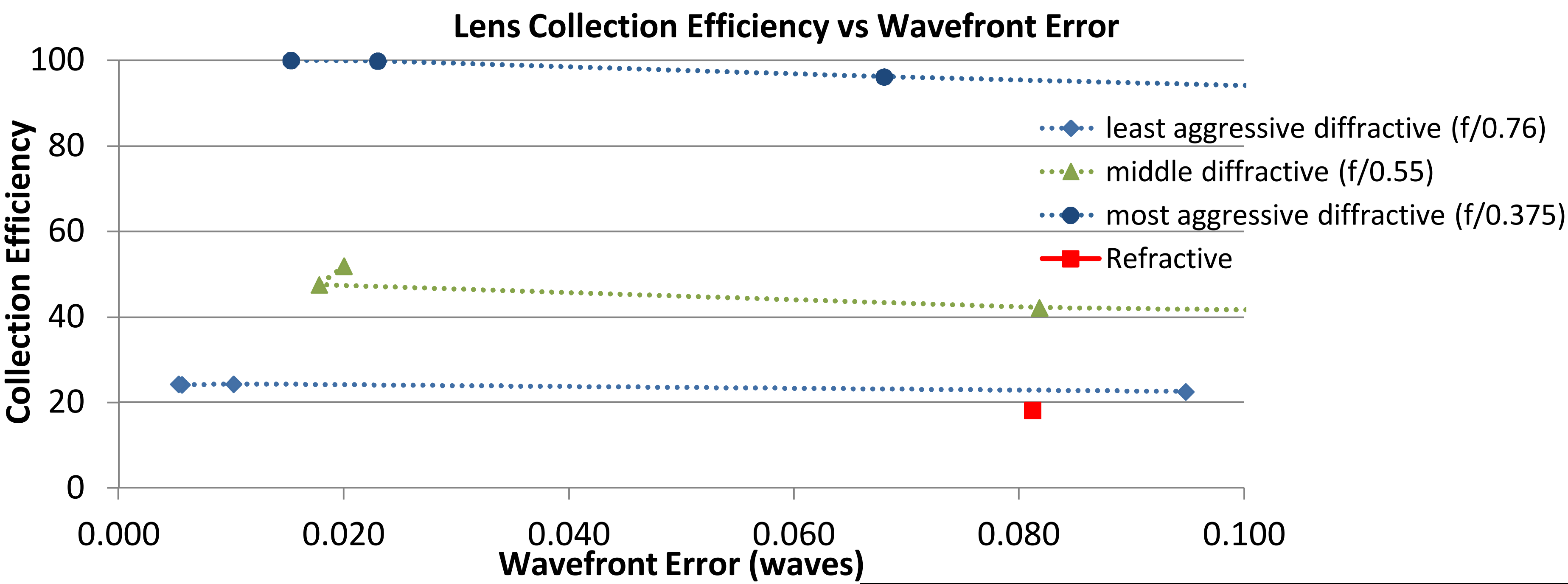


Diffractive that is twice as aggressive as current refractive: Numerical aperture: 0.8

Refractive/ Diffractive	Glass diameter (mm)	NA	f/#	% of sphere collected
R	4.5	0.55	0.76	8.23
D	3.3	0.55	0.76	8.23
D	4.5	0.67	0.55	13
D	6.7	0.88	0.38	20

Larger NA Enables Faster Data Rates

DOEs Access Larger Collection Fraction with Less Aberration



All 3 DOE options have less wavefront error and greater collection efficiency than the refractive comparison

f/#	NA	min OPD	max η	wavefront error at $0.9\eta_0$
		(waves)	%	(waves)
0.76	0.55	0.005	24.3	> .095
0.55	0.67	0.020	51.9	> .08
0.375	0.8	0.015	100	> .068
Refractive	0.55	0.081	18.2	--

Wafer Layout for Collection DOE with 9 mm Gold Wings to Reflect MOT Beam

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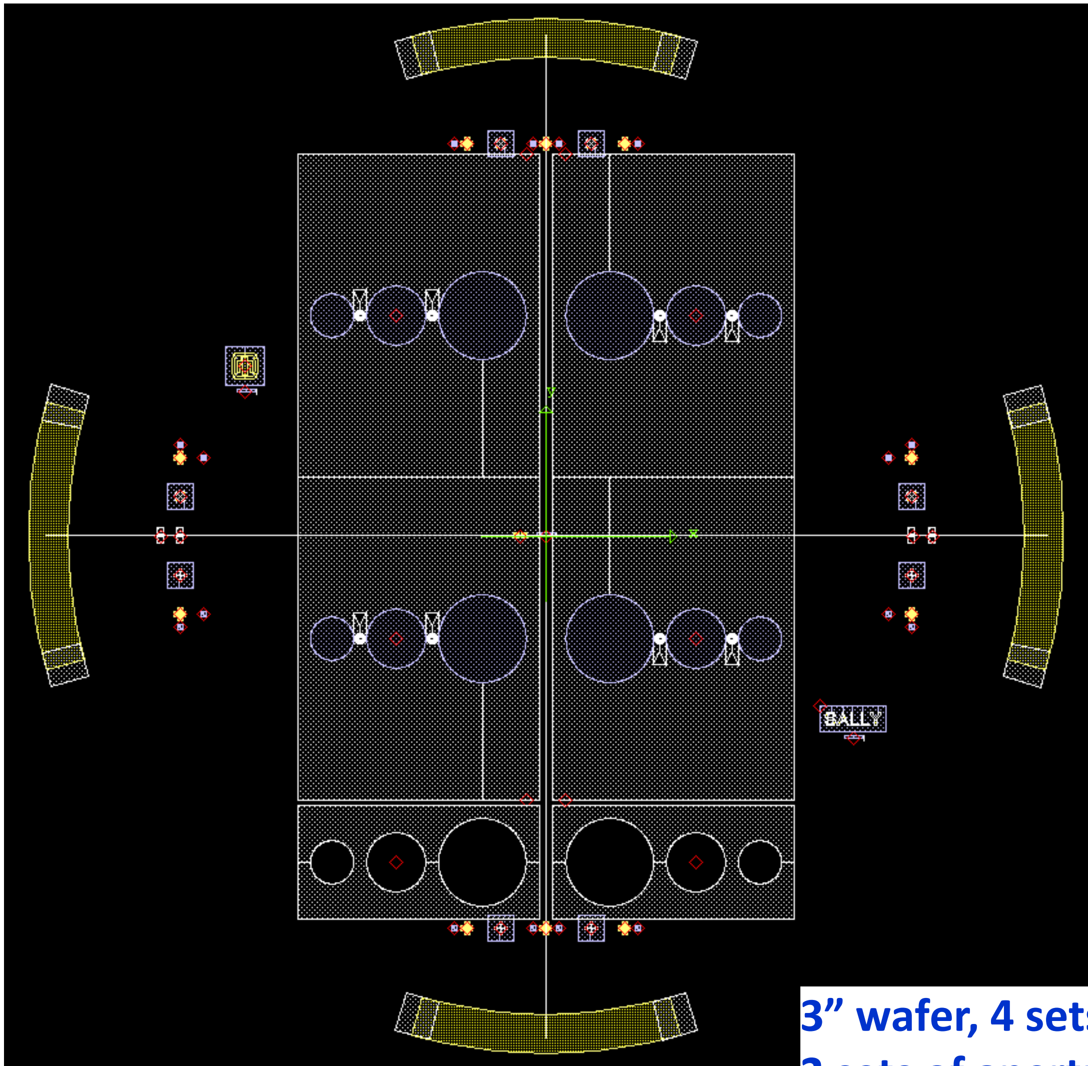
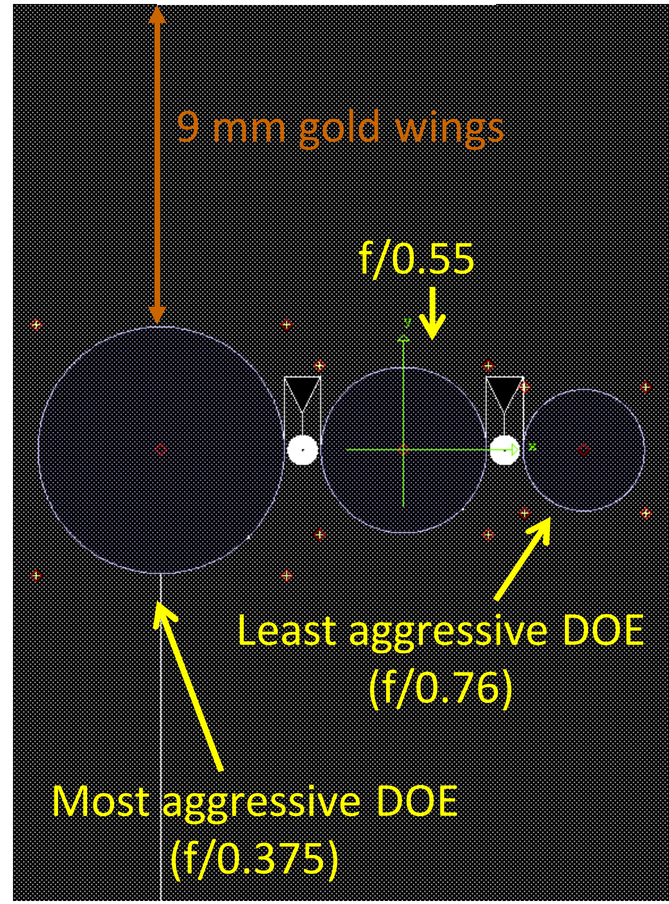


Single Device



3" wafer, 4 sets of 3 lenses

2 sets of apertures for characterization

Realized Collection DOE for linear trap

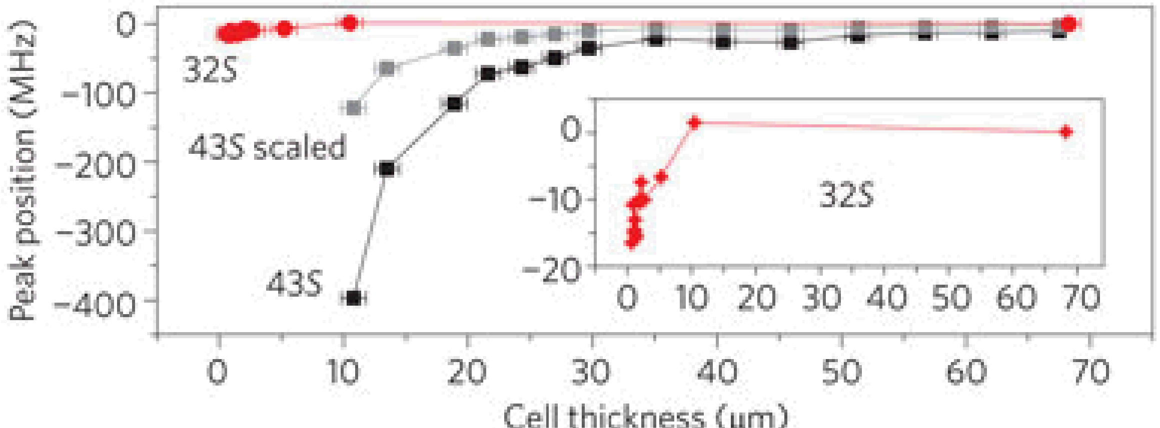
- Collection DOE is inside quartz vacuum cell
- Allows access for MOT beams
- Enables high collection efficiency
- DOEs occupy smaller volume than refractive options
- DOEs enables shorter distance to atoms
- The DOE matching the NA of the refractive is less sensitive to alignment than the refractive
  - The most aggressive DOE requires more careful attention to alignment
  - Alignment tools have been incorporated onto the wafer to aid with alignment
- Demonstration of 1 x 3 linear trap will establish pathway to a 3 x 3 array

Dielectric Proximity Effects

- Rydberg atoms likely to interact with dielectric material of DOE
  - May cause shift in peak position, peak width, both critical to atom-atom interactions
- Will conduct experiments to explore the effect and how close the atoms can be to the dielectric
- Current choice of 2.5 mm from lens is large and reduces the possibility of an interaction effect, decreasing this distance is important from a scaling perspective

Shift in Rydberg energy states in Rb observed below 35 μm for n = 32 and 43

Effect expected to scale with n, currently working at n = 70

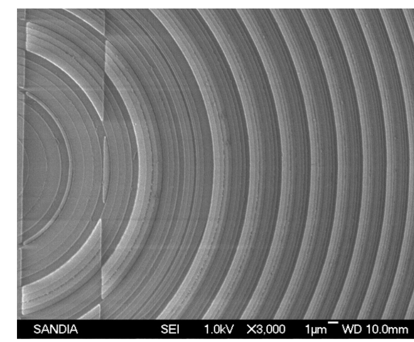


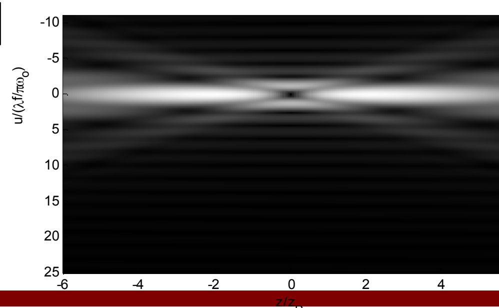
Kübler, H., Shaffer, J.P., Baluktsian, T., Löw, R., & Pfau, T. Coherent excitation of Rydberg atoms in micrometre-sized atomic vapour cells. *Nature Photon*. **4**, 112 - 116 (2010).

Notable

Sandia National Laboratories

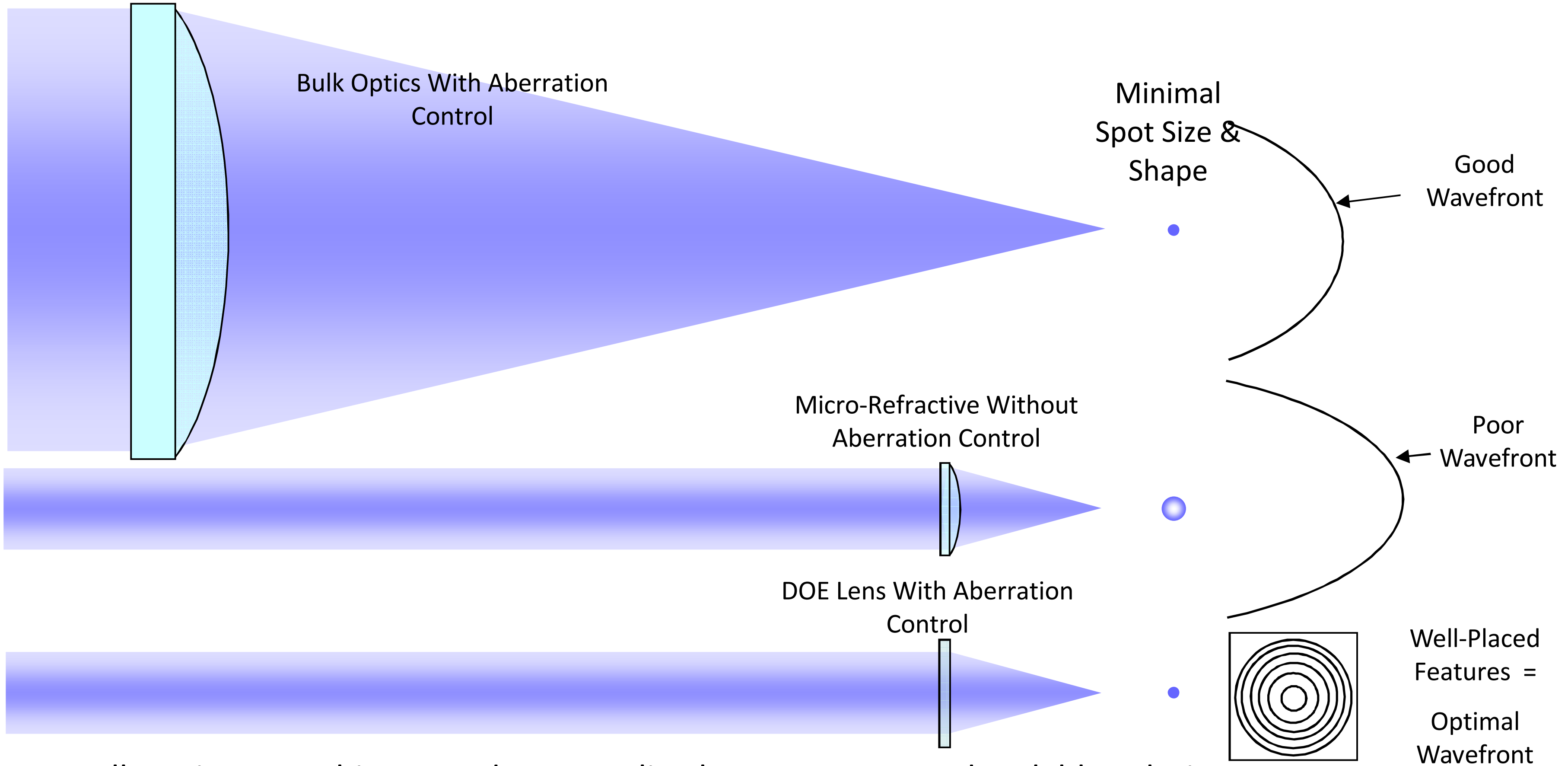
- Successfully trapped using DOE-generated, blue-detuned bottle beam
- Successfully trapped 3 single atoms simultaneously in 3-trap, 4-level DOE
- Smallest realized F/#s on integrated collection DOE of bottle beam trapping DOE
  - Presented at Photonics West, Jan 2012
- Implemented 2-trap DOE with integrated focus
- Pursuing parallel paths to simultaneously develop understanding of relevant physics and to advance DOE technology development toward higher order arrays





BACK-UP SLIDES

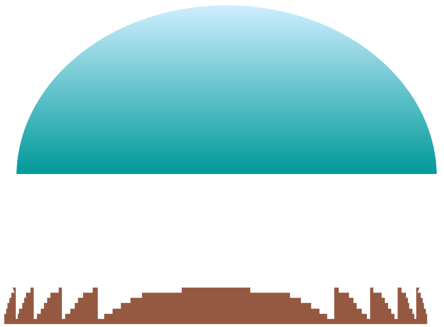
Aberration Control With Diffractive Optical Elements (DOEs)



- Bulk optics can achieve good spot quality, but are not a good scalable solution.
- Micro-refractive optics are fabrication limited and provide aberrated spots.
- Diffractive lenses ensure spot quality with precisely placed lithographic features.

DOEs and Gray Scale Lenses

- Can realize transmissive and/or reflective integrated optics
- Because of off-axis capability, can pack lenses densely and with 100% fill factor
- Lens focus need not be a point, can be a volume to accommodate ion motion or integration tolerance
- Realize high-efficiency, low-scatter integrated optics – gray scale optics
- Prototype integrated optics with diffractive optical elements (DOEs)



3-Trap Predicted Pattern at Focus

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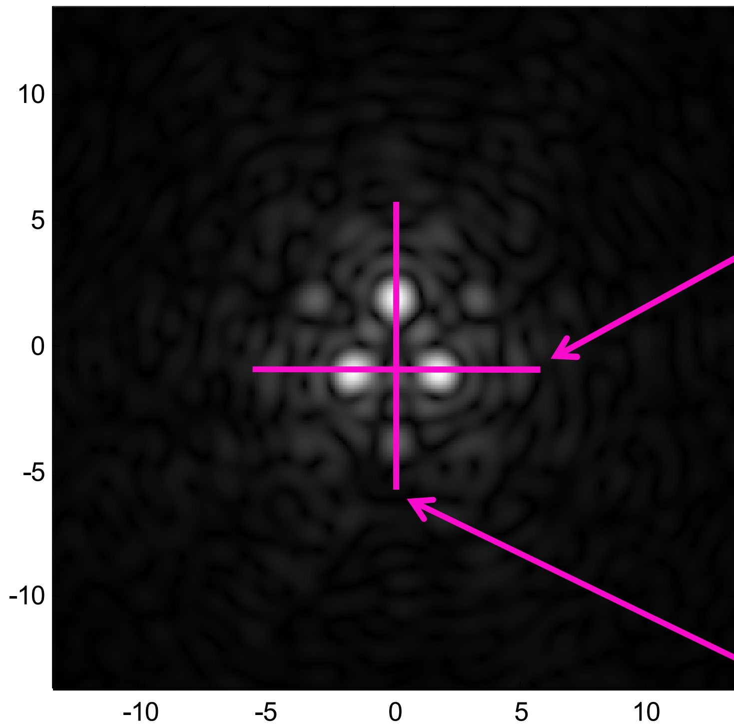
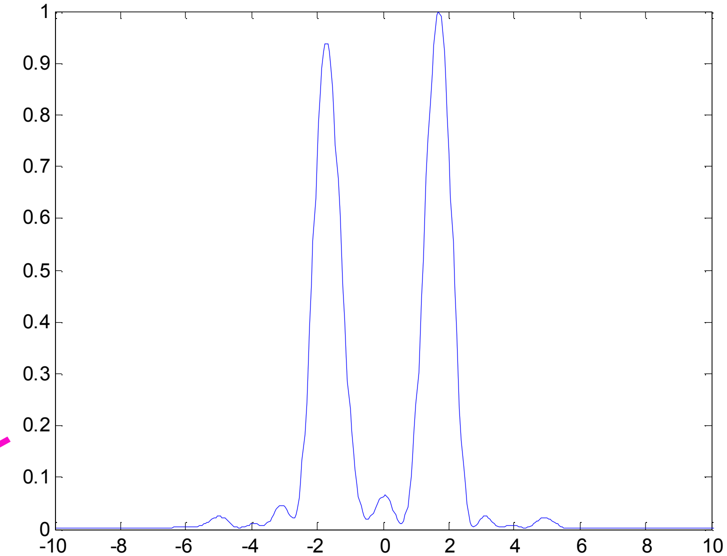
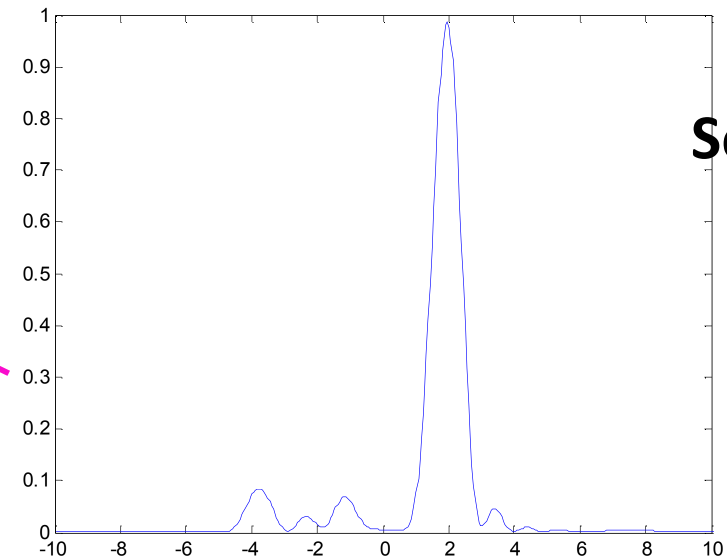
Irradiance Pattern



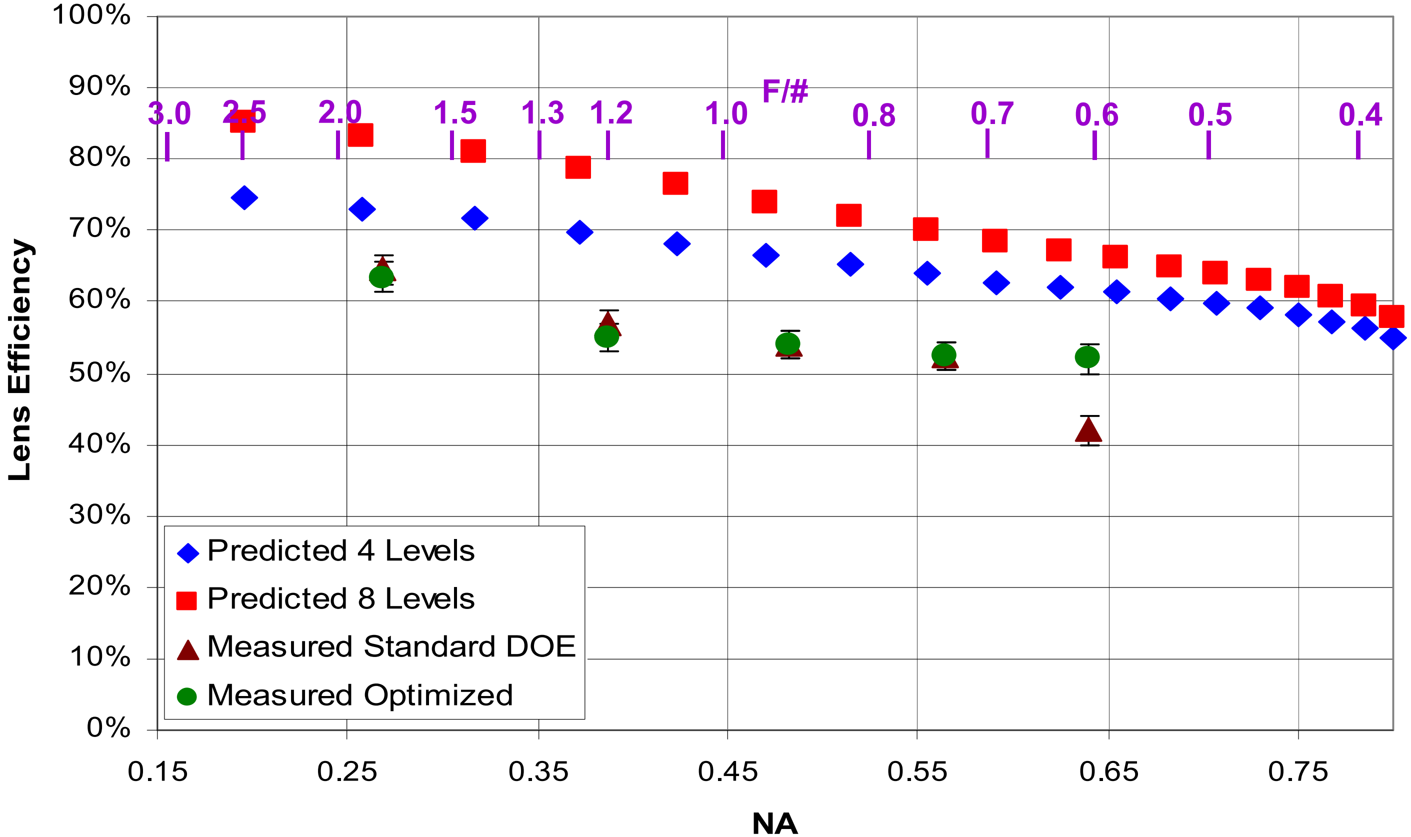
Scaling intensity as $I^{0.4}$
to enhance small artifacts





Cross Sections

Predicted and Measured Efficiencies



Theoretical diffraction efficiency as a function of numerical aperture (NA) for four-level (diamonds) and eight-level (squares) optimized DOEs at 370 nm design wavelength.

Measured efficiencies for Sandia optimized DOEs at 850 nm (circles and triangles).

Collection Lens Alignment Sensitivity

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Shift at which Coupling Efficiency Drops to 90% of peak efficiency

	lens			$\eta_{initial}$ %	Decenter X 90% $\eta_{initial}$ (microns)	Decenter Y 90% $\eta_{initial}$ (microns)	Tilt About X 90% $\eta_{initial}$ (deg)	Tilt About Y 90% $\eta_{initial}$ (deg)
Diffractive Optics	f/0.375	NA 0.8	on-axis	99.5	328	336	1.17	1.512
			+10 microns	99.5	326	344	1.12	1.476
			-10 microns	99.5	330	312	1.2	1.512
	f/0.55	NA 0.67	on-axis	45.0	441	444	1.4	3.64
			+10 microns	44.9	498	460	1.34	4.04
			-10 microns	44.2	448	464	1.74	4.44
	f/0.76	NA 0.55	on-axis	24.4	1250	1240	1.84	>8
			+10 microns	24.2	1280	1260	1.88	>8
			-10 microns	24.3	1260	1220	1.92	>8
Geltech	f/0.76	NA 0.55	on-axis	18.0	840	840	2.46	>8
			+10 microns	17.9	810	850	2.43	>8
			-10 microns	18.1	840	790	2.37	>8

Figure of merit to compare functions: collection efficiency into fiber

Reference aspheric Geltech, previous experience with alignment

- Matching DOE will be easier to align, with a slightly great sensitivity in tilt about X
- More aggressive DOEs will be more challenging to align, but alignment tools have been incorporated onto the wafer