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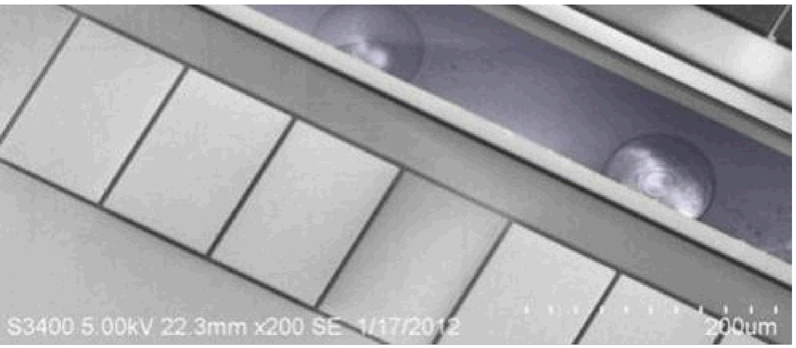

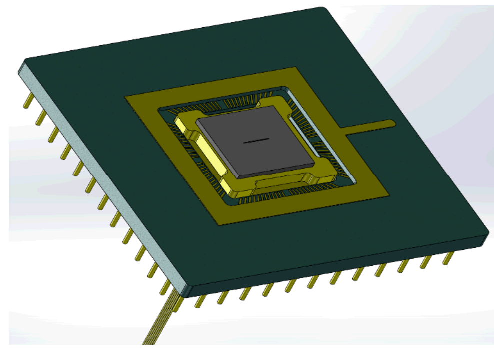

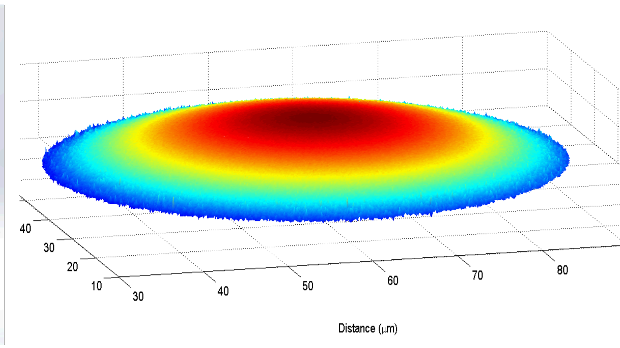

Micro-optical grayscale excitation lens for atom and ion trapping

D.A. Scrymgeour, S.A. Kemme, R.R. Boye, A.R.Ellis, T.R. Carter, S. Samora, J.D. Hunker

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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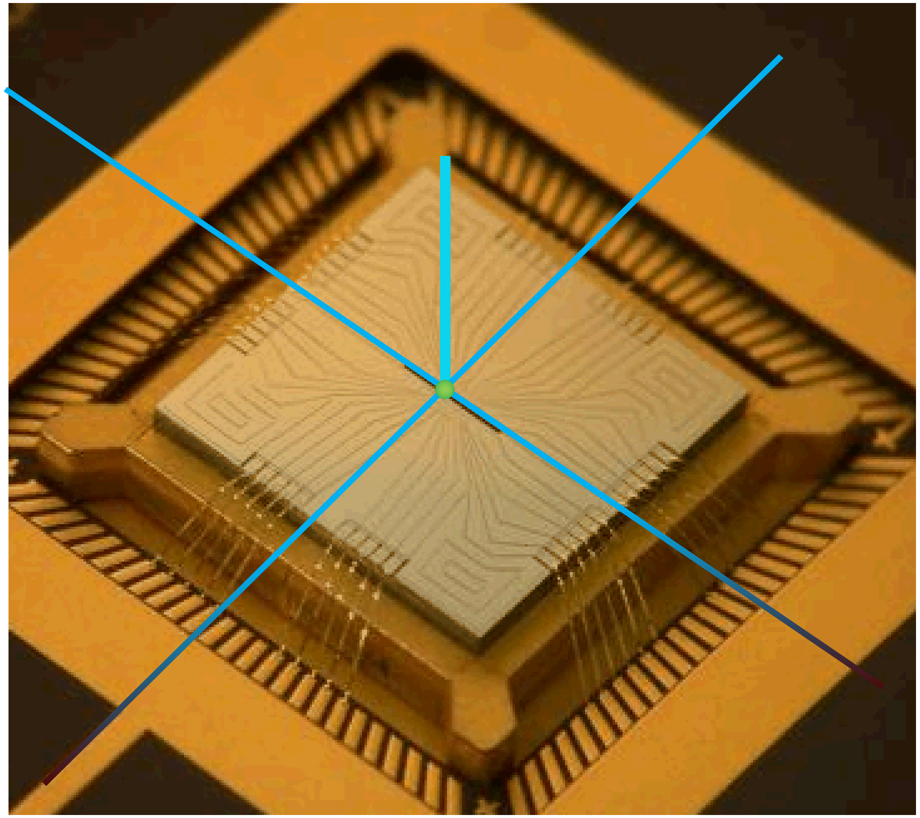
Using integrated optics to deliver light to surface trapped ions



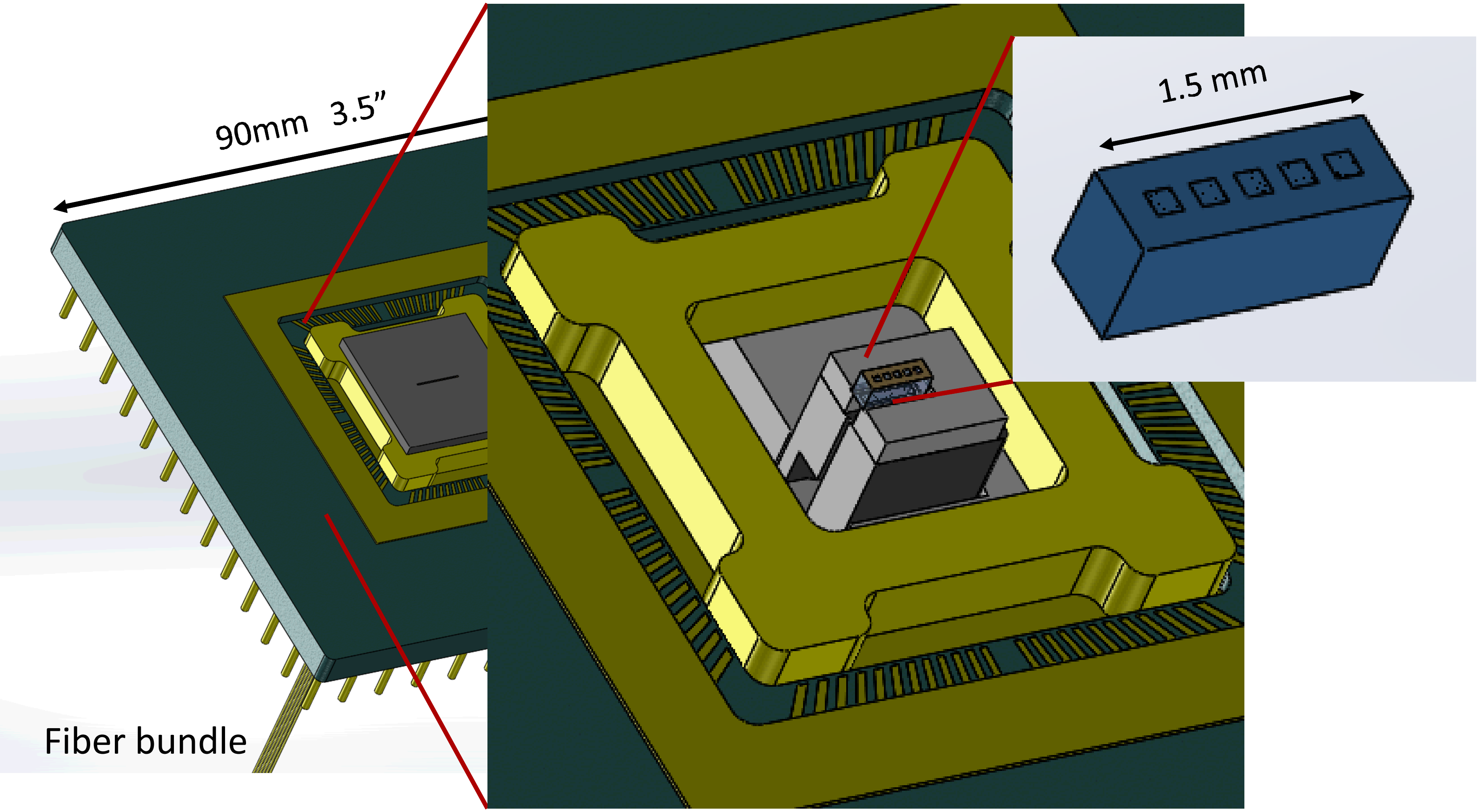
- Increase NA of lenses
- More light delivered / collected
- Increase speed of computation
- Miniaturization of system

Optical system requirements:

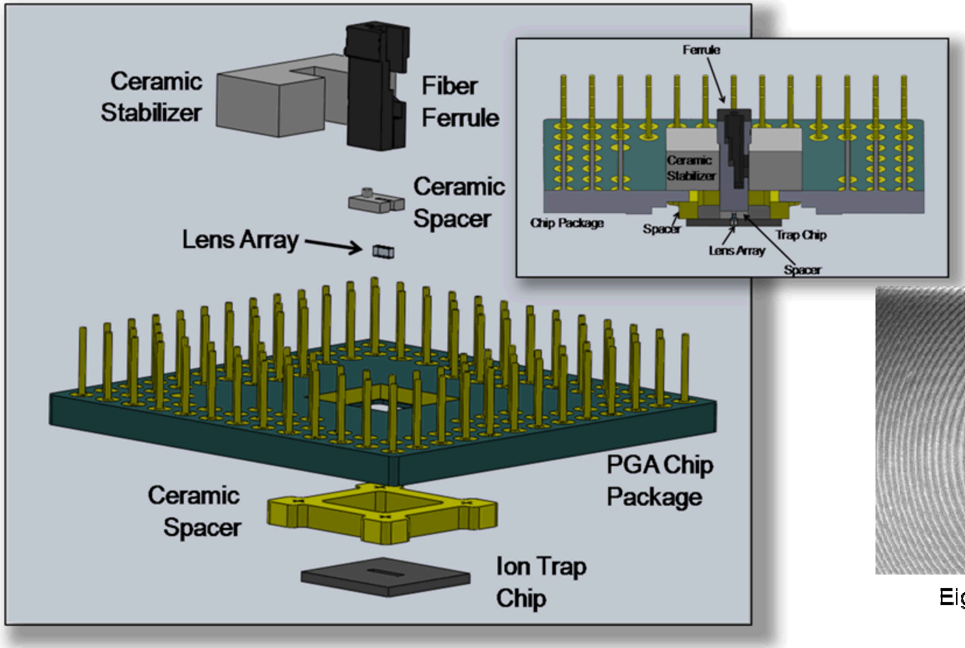
- Wavelength 397 nm
- Bake-out at 200-250°C
- UHV operation

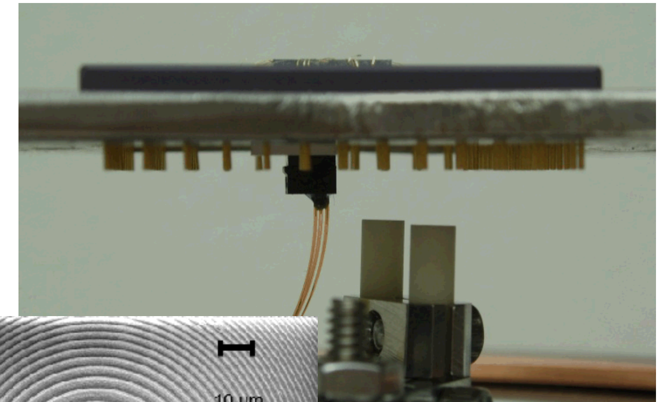
Fused silica

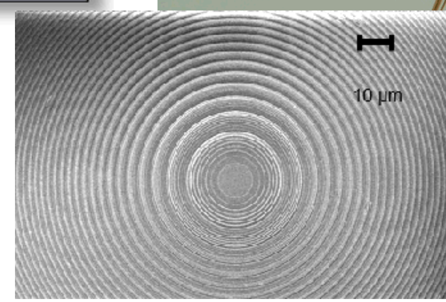
Micro-optics layout



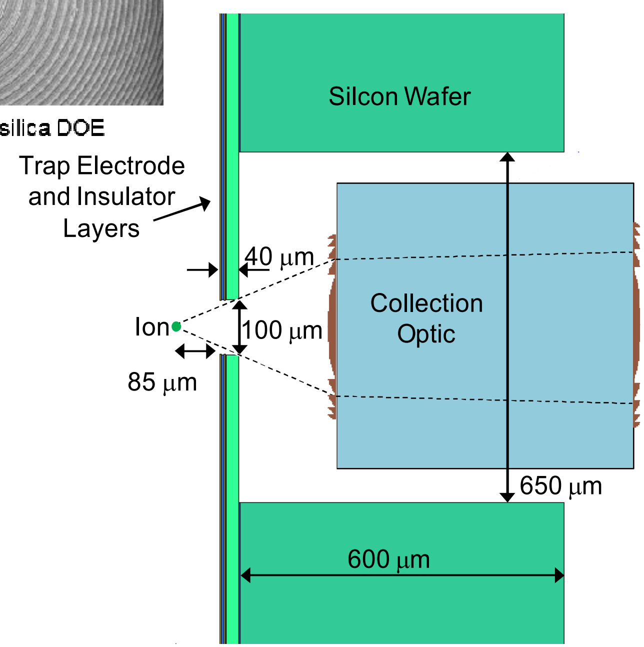
Previously demonstrated diffractive collection & excitation lenses







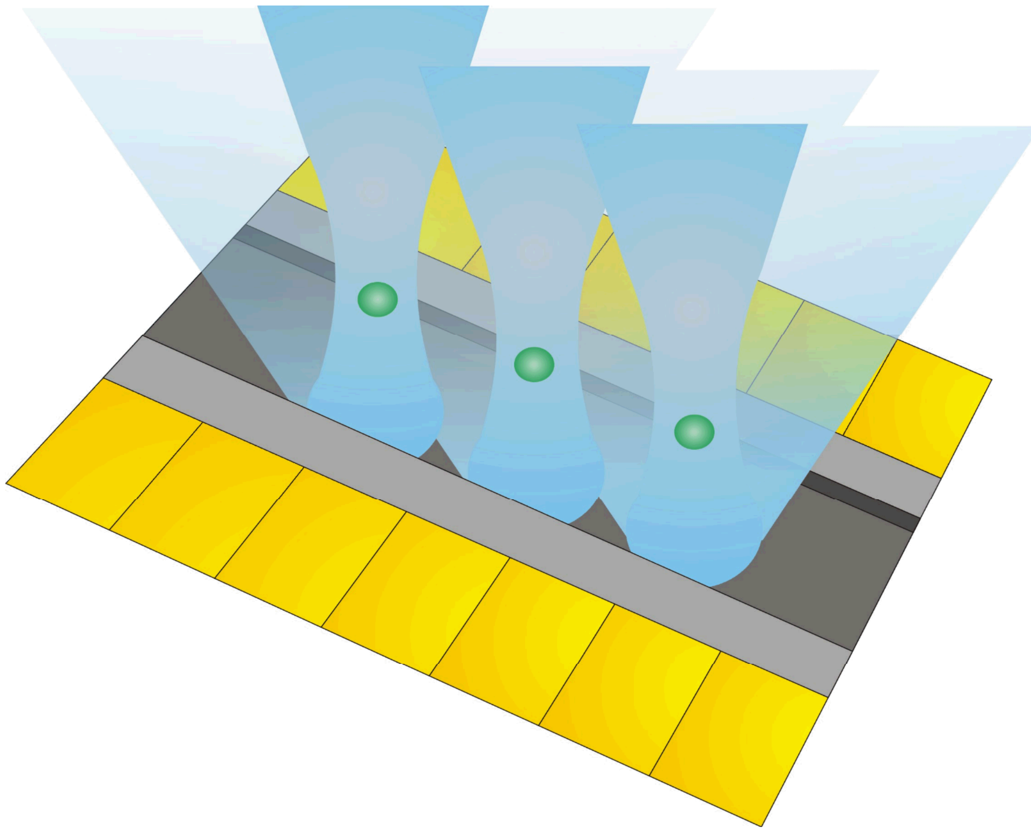
Eight level F/1 fused silica DOE



- Optics have been integrated into linear ion trap.
- No detrimental effects to ultra-high vacuum.
- Dielectric lenses ~150 microns away from ion.

G. R. Brady, *et al.* Appl. Phys. B: Lasers and Optics 103, 801-808 (2011).

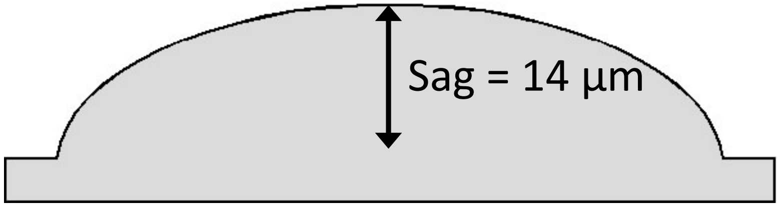
Concern that diffractive excitation optic would detrimentally scatter light



- Excitation – lots of light
- Ions inherently sensitive to scattered light
- Impact ultimate density of trapped ions

Refractive grayscale optics offer higher efficiency & lower scatter

Grayscale Transmissive Lens



Cross Section, bulk patterning

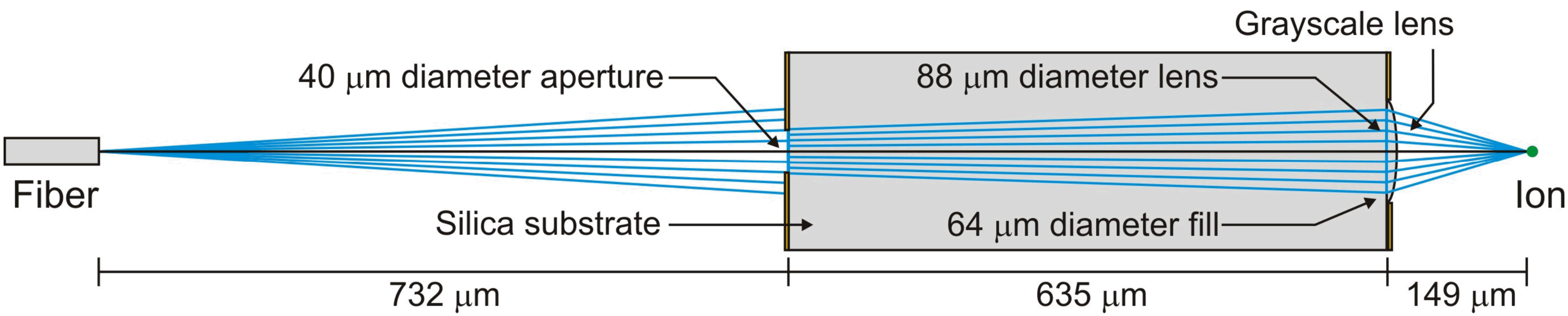
Diffractive Lens

Cross Section, Surface patterning

Grayscale also offers (unlike reflow):

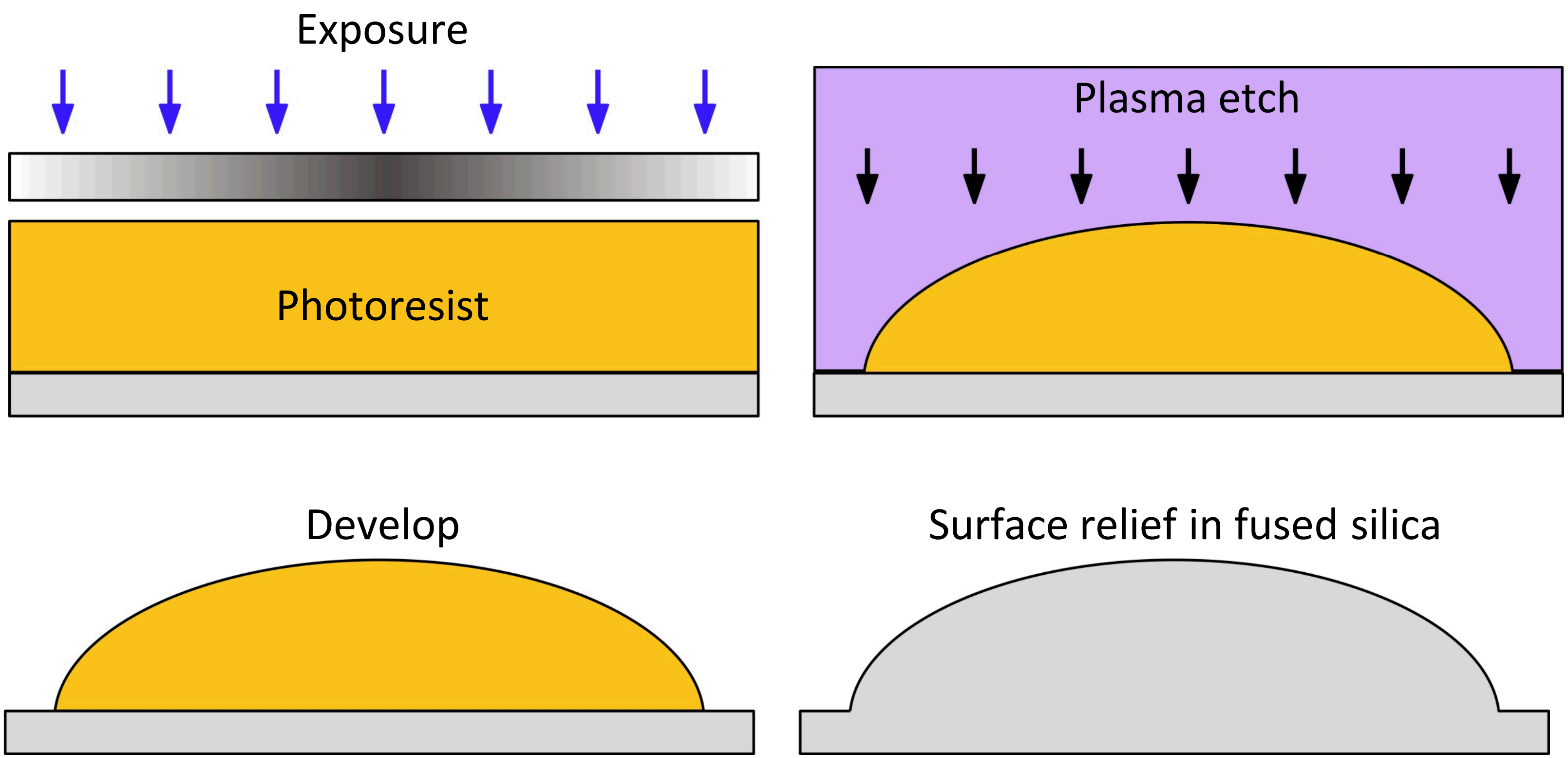
- Aspherical and off-axis capabilities
- 100% fill factor
- Concave shapes (divots)

Design equivalent refractive lens to match performance of diffractive lens



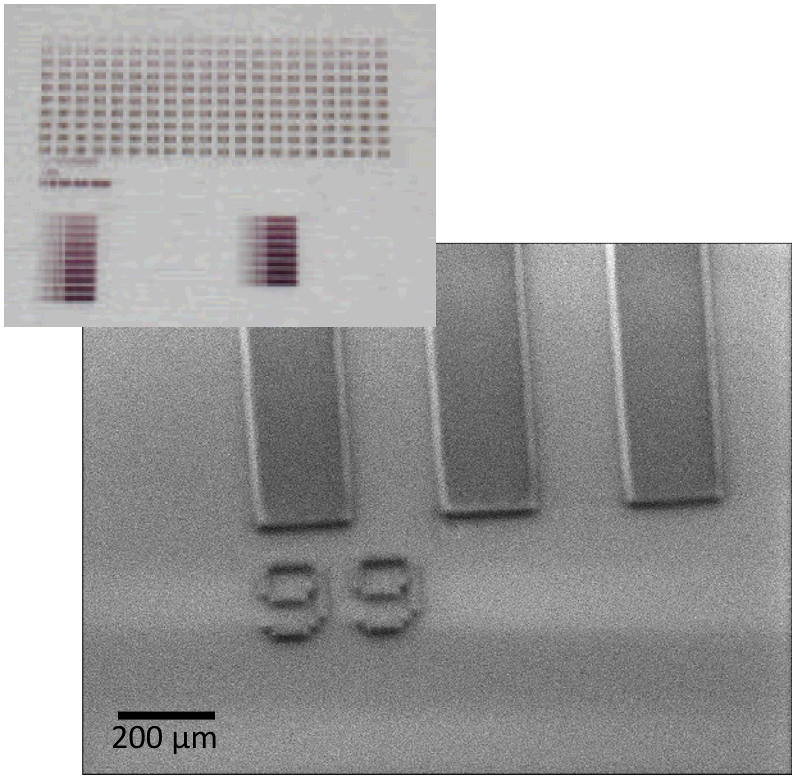
- High efficiency, precision ion illumination with lowest signal outside of focal position – lowest "scatter" over ion field
- Single surface optic, diffraction limited over a 5 micron field
- Surface Sag = 14.2 μm

Grayscale processing creates surface relief in one exposure step

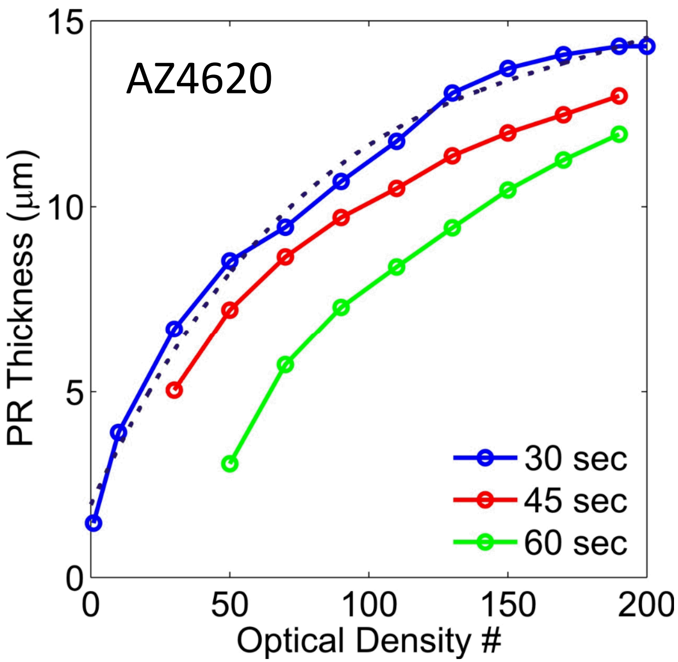


Iterative process to relate developing conditions to final PR thickness

Calibrated test structures



PR Spin Thickness
Exposure Conditions
Development time

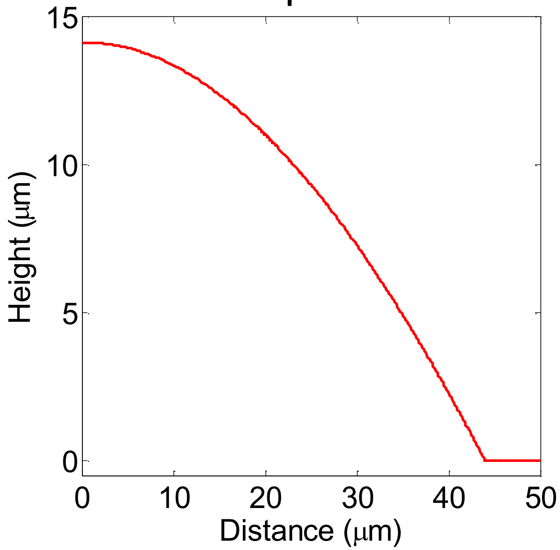


Mask design and fabrication once calibration process is complete

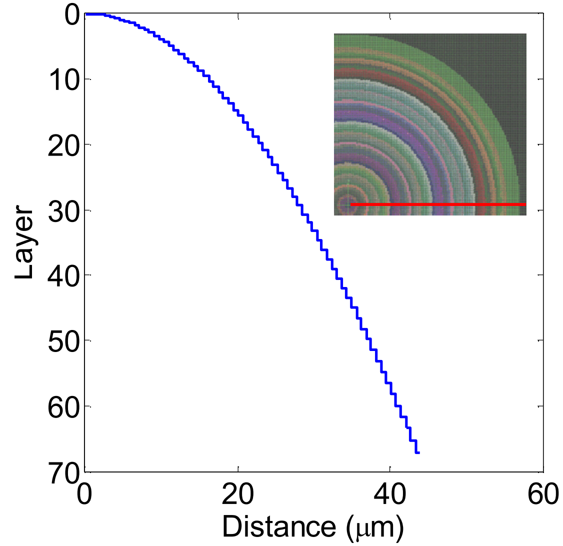
88 optical density levels
Pixel size of 500 nm

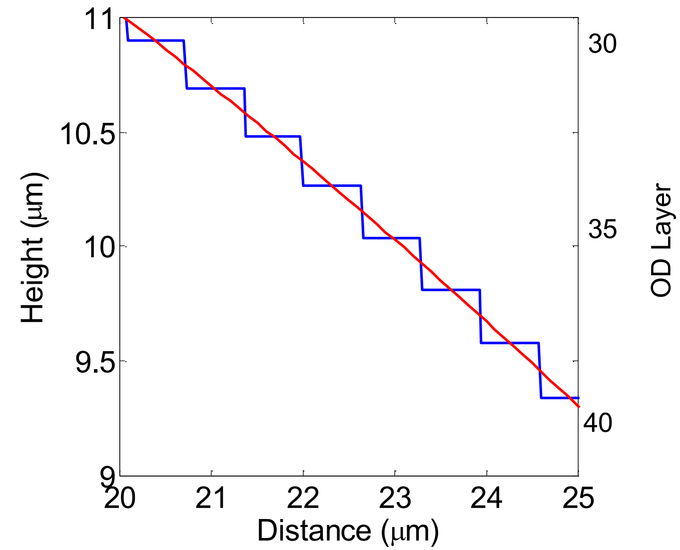
Fracture in constant horizontal steps of varying heights

Ideal profile



OD layer





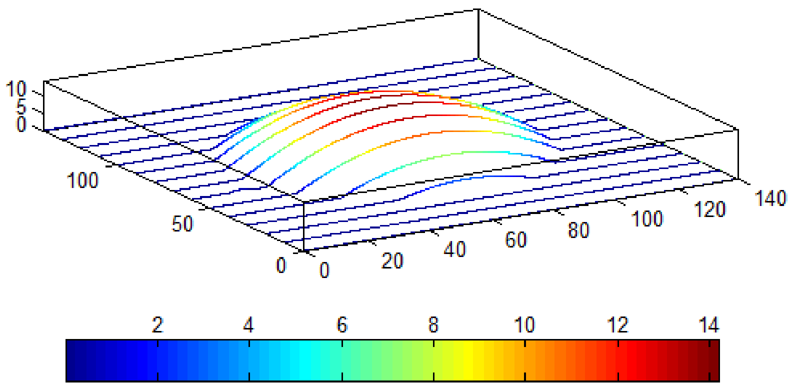
Conic aspherical microlens

Sag	14.16 μm
Lens Diameter	88 μm
Radius of curvature	62.3 μm
Conic constant	-1.851

Masks fabricated by both
Canyon Materials & University of Delaware

RIE used to transfer smooth PR features to fused silica substrate

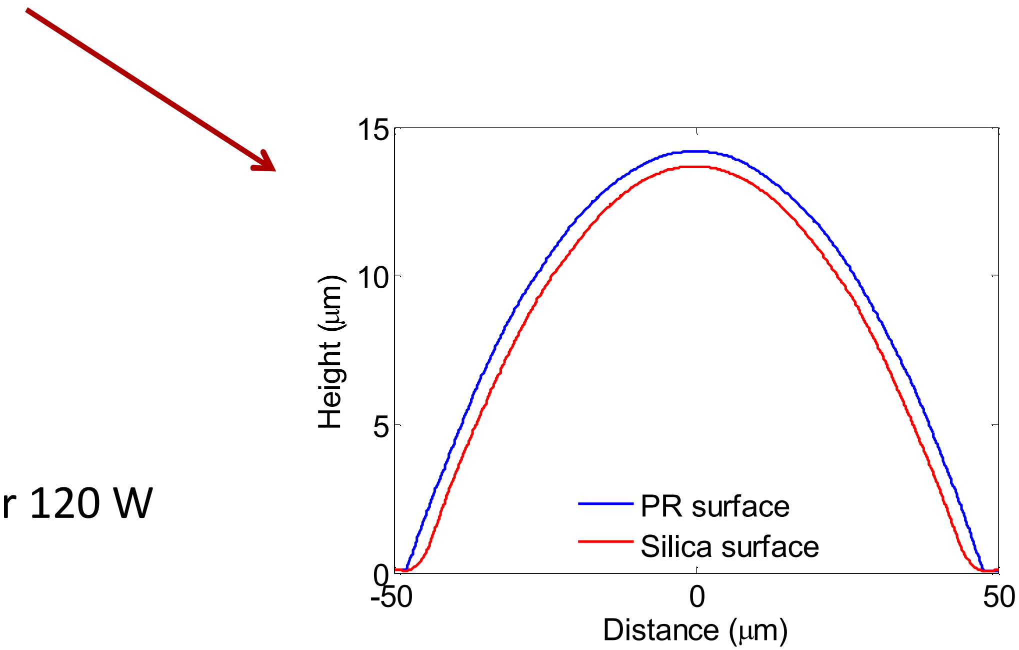
Stylus profilometry of PR surface



Etch depth 14.2 µm

Etch rate ~2.5 nm/sec (90 min etch)

Selectivity (Silica/PR) 1.05:1 – 1.2:1



Plasma-Therm Versaline ICP

ICP conditions: CHF_3:CF_4:Ar (3:4:4)

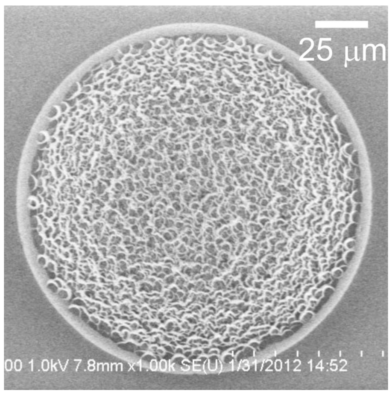
ICP power 810 W Bias Forward power 120 W

Backside He cooling

Temperature control of substrate vital for proper etching

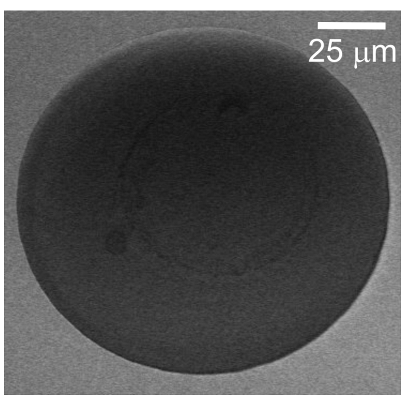
Fused silica wafer mounted to a cooled silicon wafer submount

Improper temperature control



Non uniform etching
Pitting and PR damage

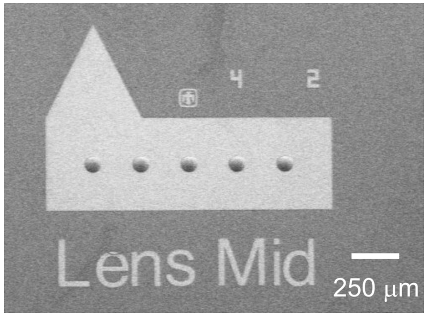
Successful temperature control

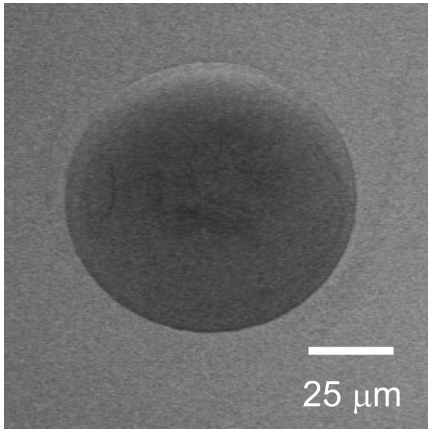


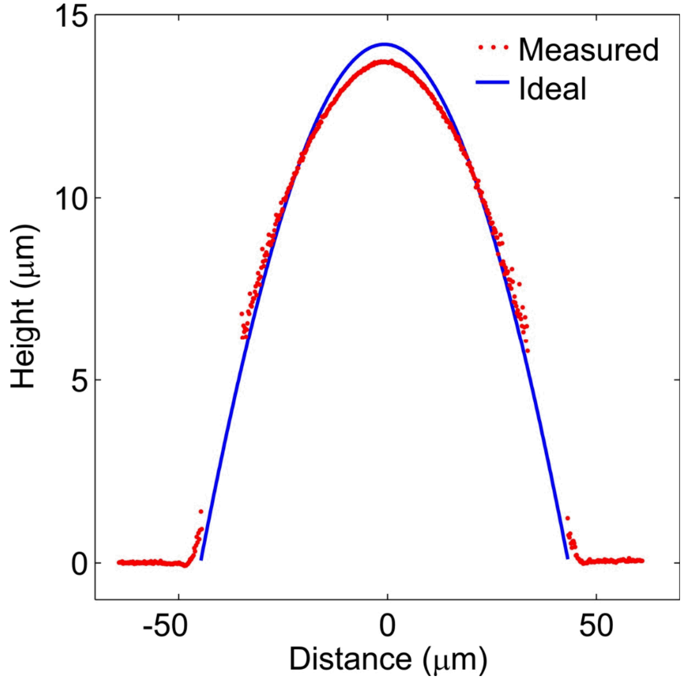
Best T control we could achieve:

Etch selectivity (Silica/PR) 1.05-1.2 : 1
Variable surface roughness (5 – 50 nm RMS)

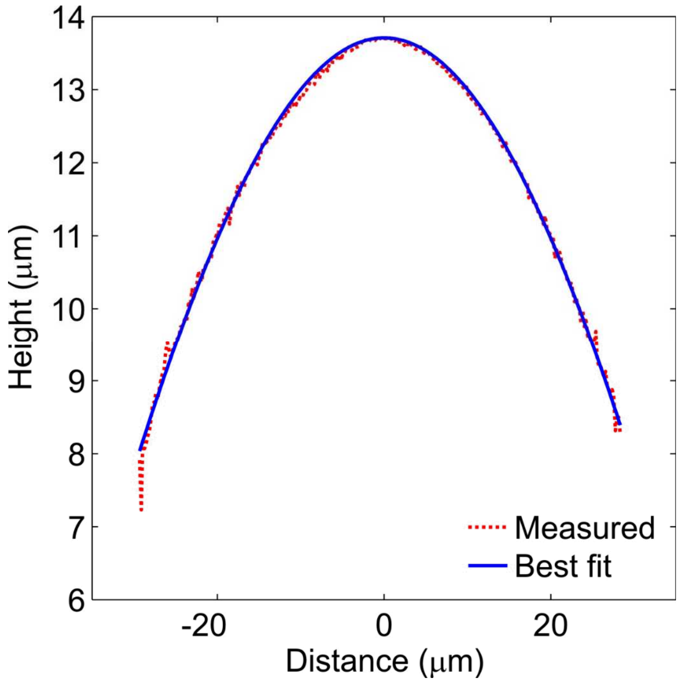
Successful lens transfer into silica







Radius of curvature	62.3 µm
Conic constant	-1.851



Radius of curvature	69.8 µm
Conic constant	-3.082

Focal distance and focus size was determined by knife edge measurements

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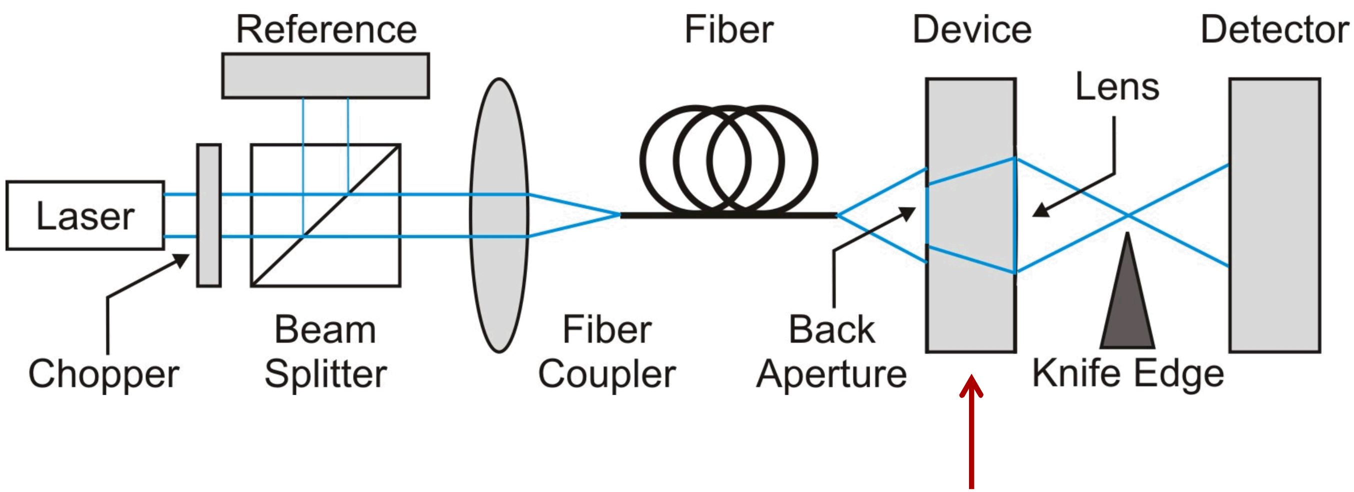
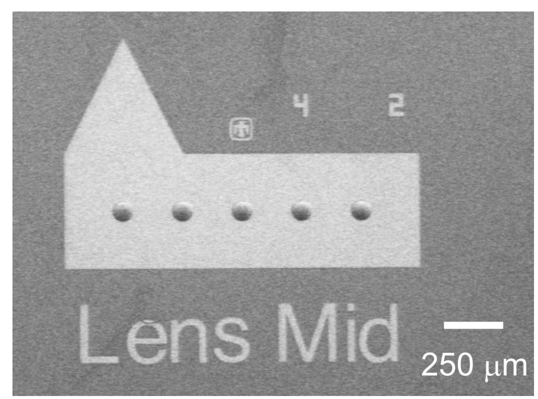
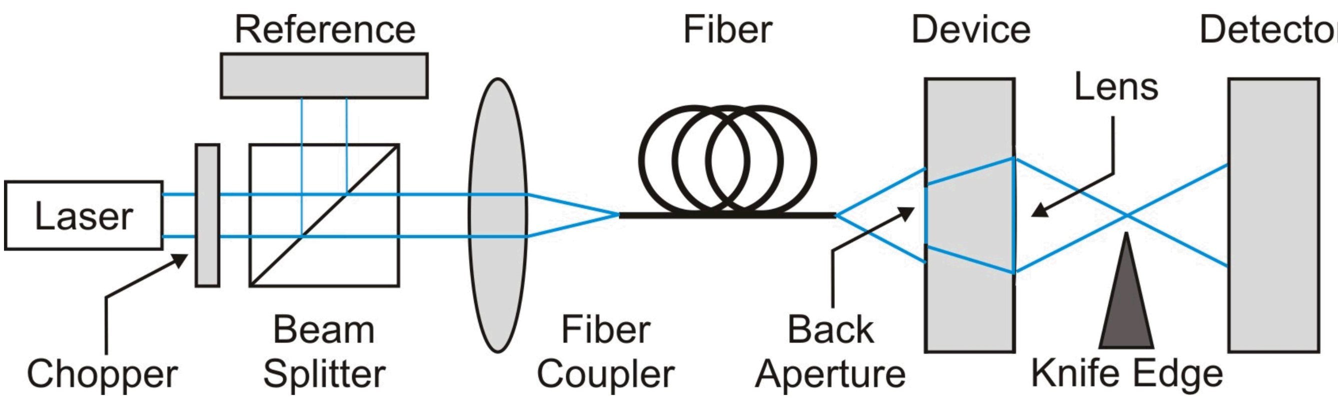


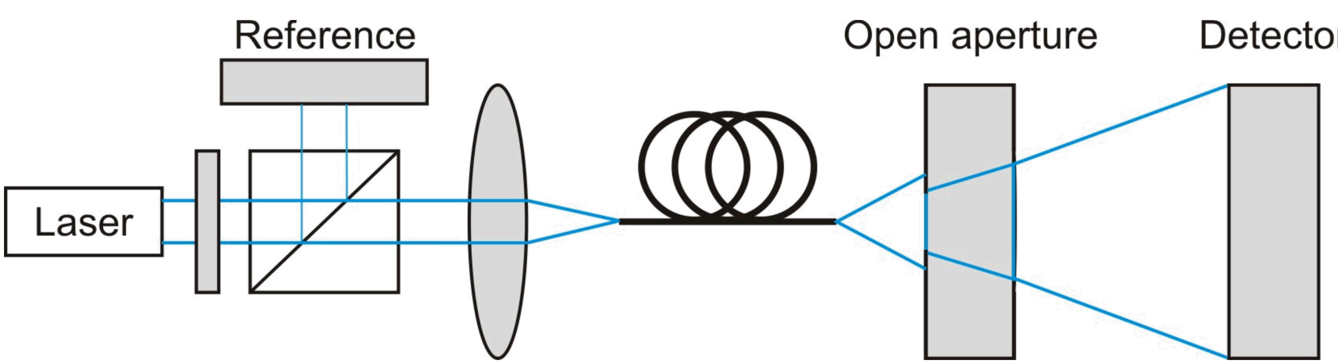


Efficiency estimated by comparing lens to open aperture



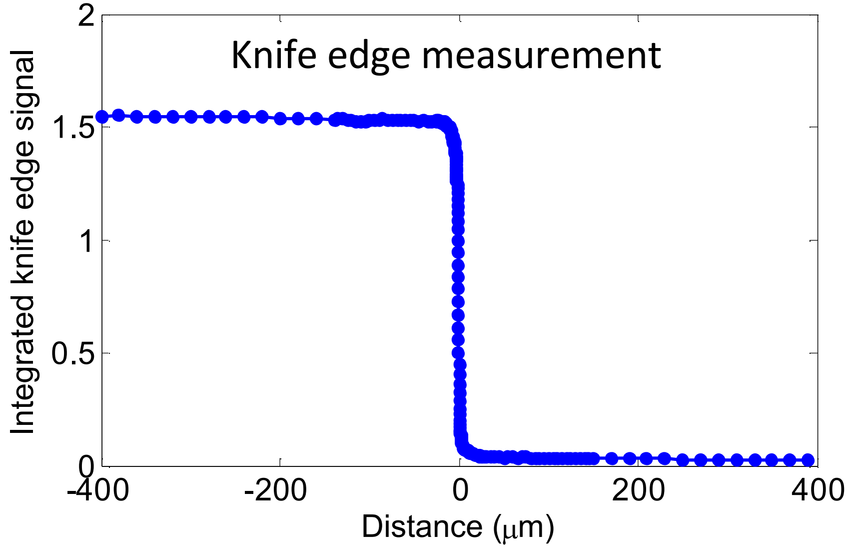
Intensity at focus

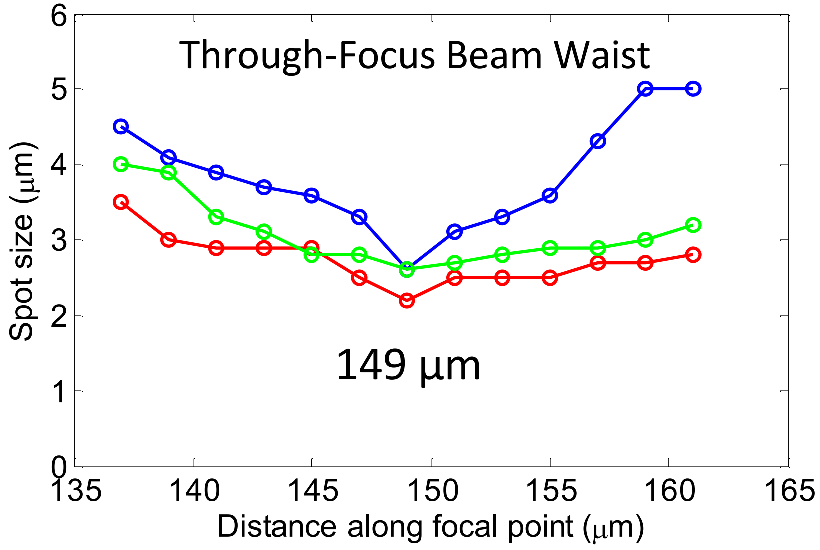
Vs.



Intensity going into lens

Grayscale lens performance was exactly as designed

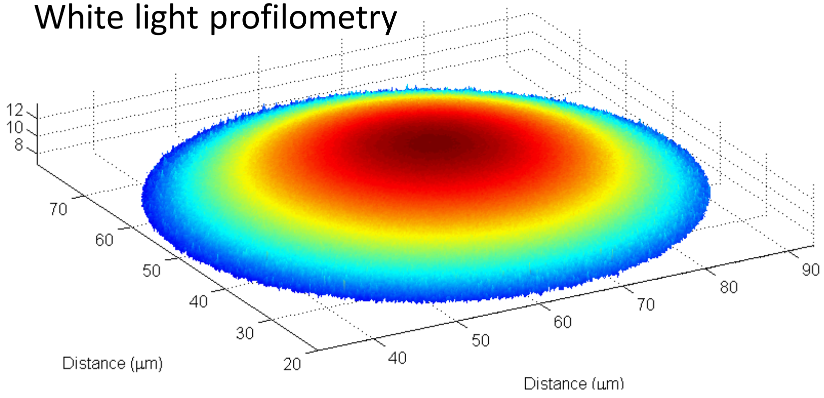




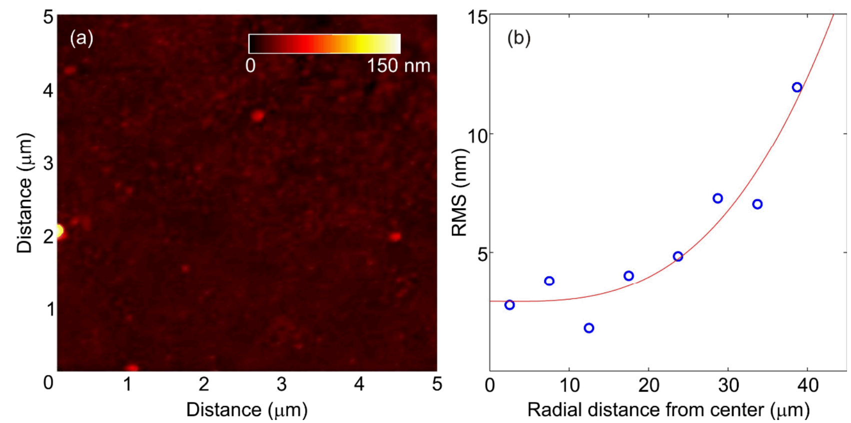
- Knife-edge measurements of spot size through focus => 2.6 microns diameter
- At-spec focus position => 149 microns
- Theoretical grayscale lens efficiency is 92%
- Knife-edge measurement of efficiency => 79% (86% of theoretical, loss due to some rms roughness?)

Roughness of lens surface critical to low scatter performance

White light profilometry



Noncontact AFM measures



As tested lens:

Roughness (RMS): ~36 nm
Diffuse scatter losses of ~7%

Best lens surface:

Roughness (RMS): ~5 nm
Diffuse scatter losses of <0.1%

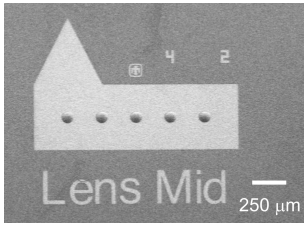
→ Need to hit these values for optimal performance

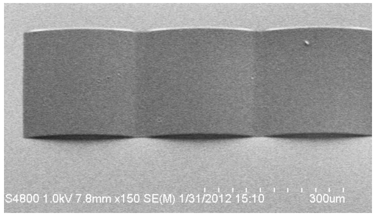
Conclusions

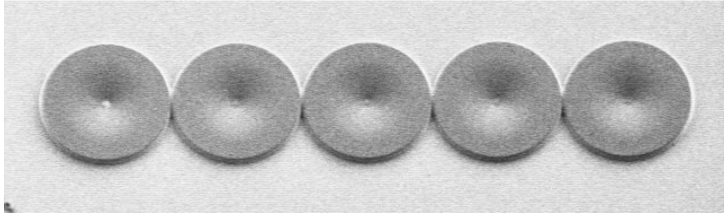
- Designed and fabricated grayscale equivalent excitation optic for single mode fiber coupling with low scatter and high efficiency for trapped ion

- Successfully developed process to realize grayscale micro-optics in fused silica with off-axis capabilities and precision aberration control for 100% full-filled lens arrays

- Characterized grayscale excitation micro-lens arrays that produce:
    - high-efficiency (~79%),
    - as-designed focal position (149 microns)
    - near-diffraction limited focused spots (2.6 microns)
    - Surface roughness critical for ion trapping applications

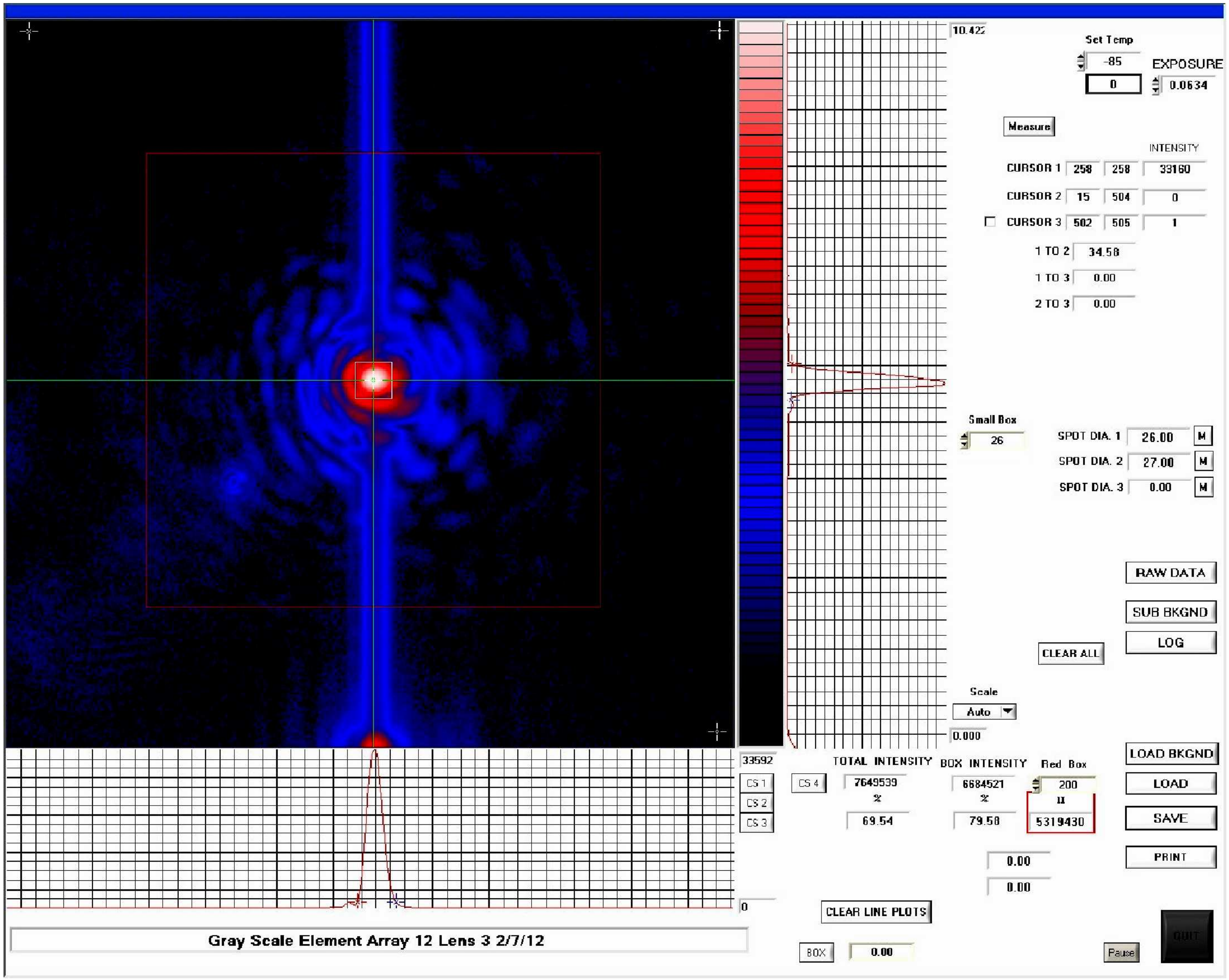






The End

Grayscale Excitation Lens Focused Spot Showing Airy Rings (Log-scale to enhance low-light detail)



Simulations