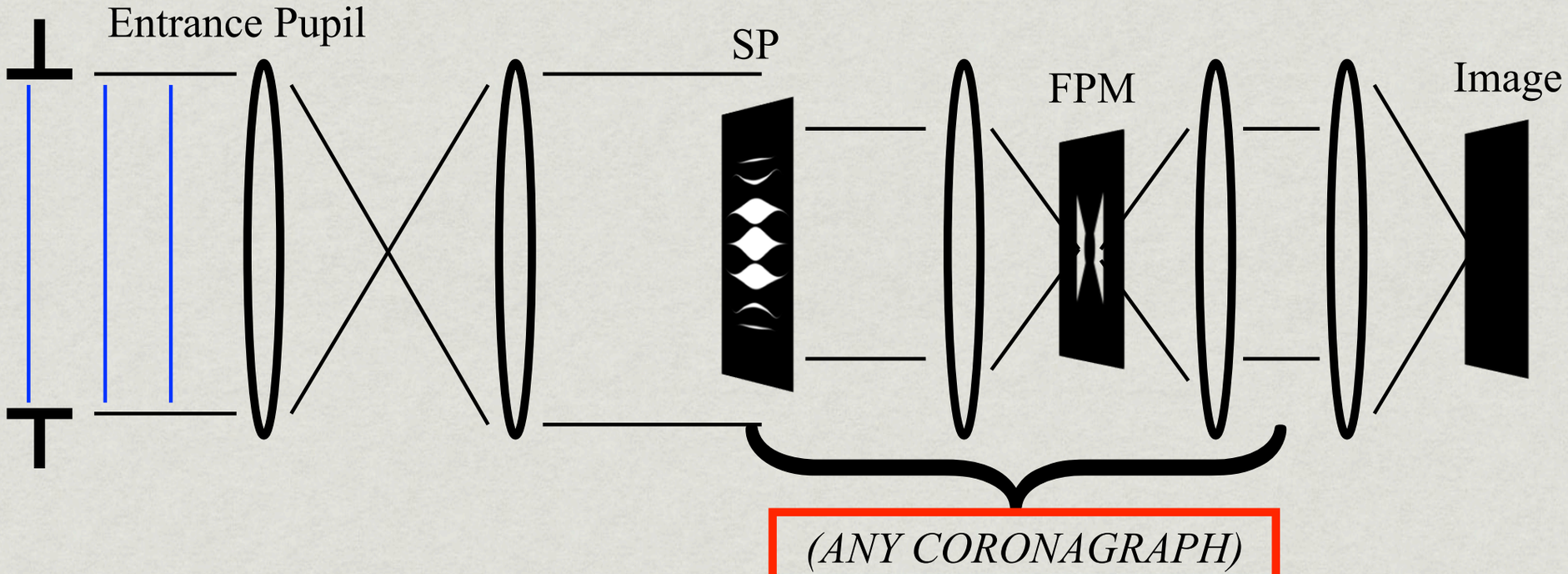
Shaped Pupils Technology Plan

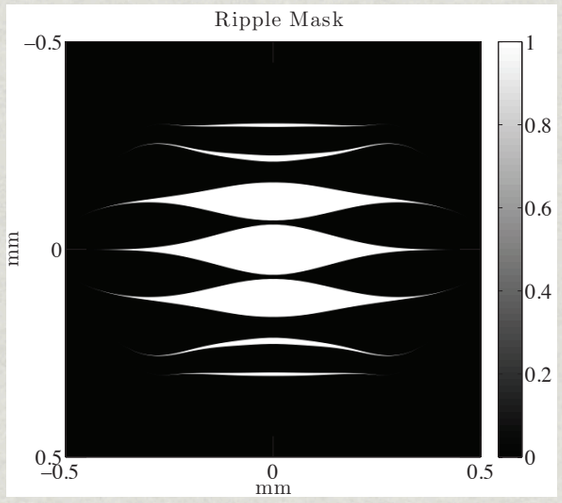
N. Jeremy Kasdin
A J Riggs, Robert Vanderbei, Tyler Groff

ACWG 2.5
October 24-25, 2013

Reminder - Shaped Pupils for High-Contrast

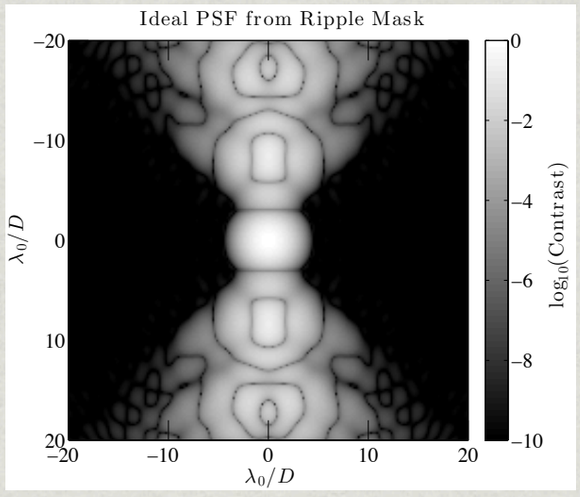


Shaped Pupil Coronagraph



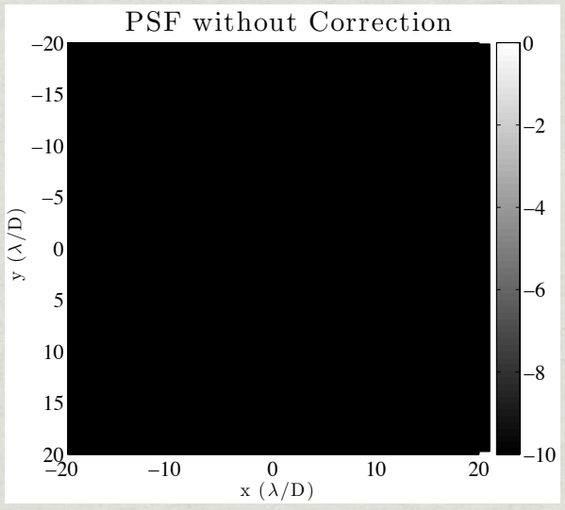
Transmission: 15%

Ideal Image (Log Scale)



IWA = 4.5 λ/D, OWA = 56 λ/D
$1x10^{-10}$ average contrast

Image after Focal Plane Mask (FPM)



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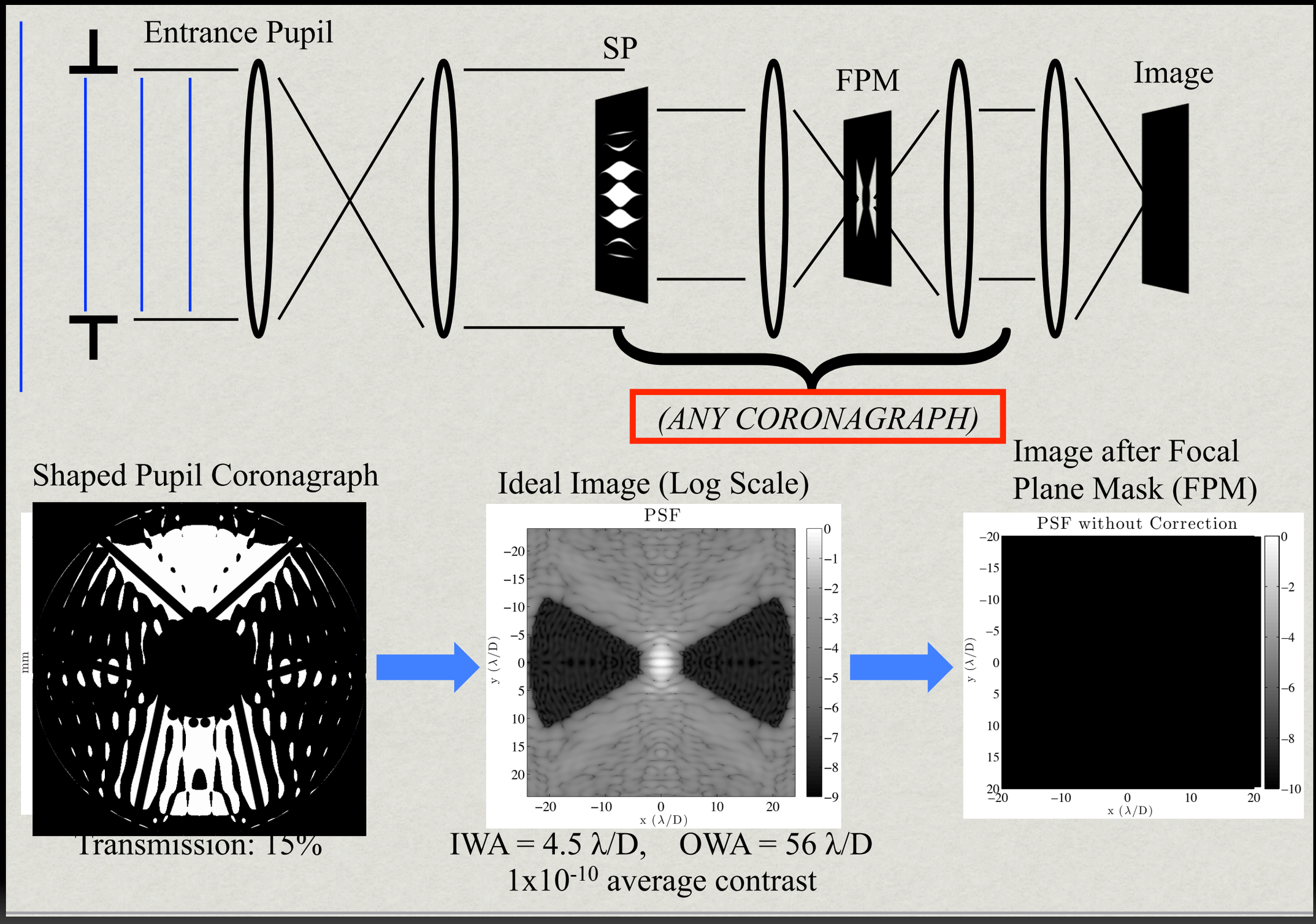

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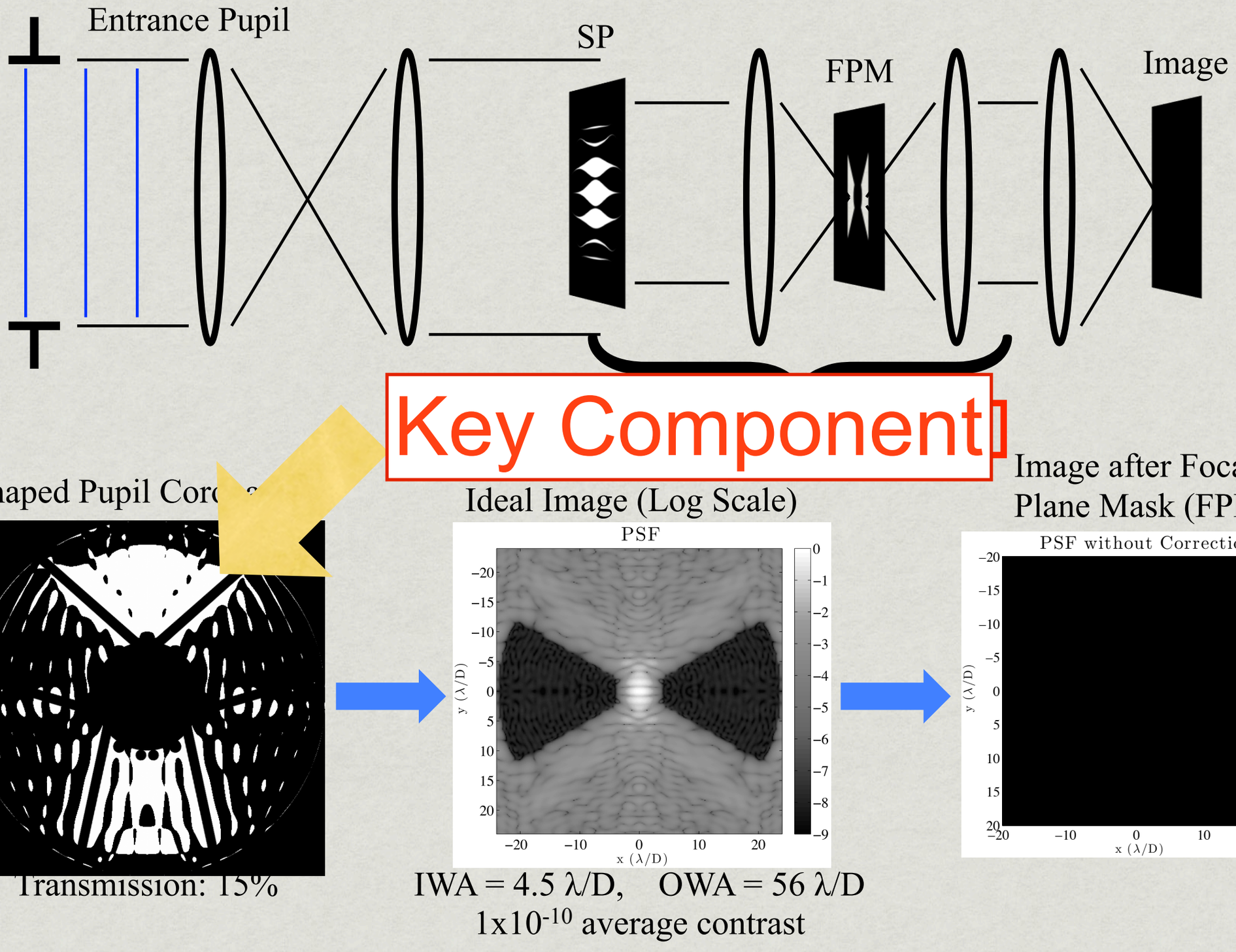
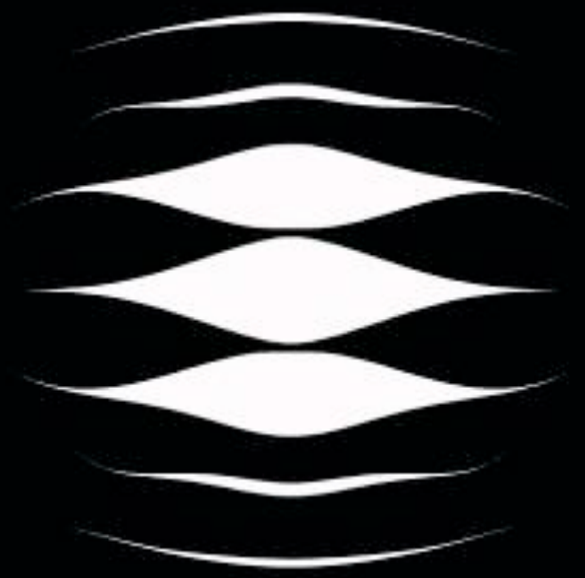
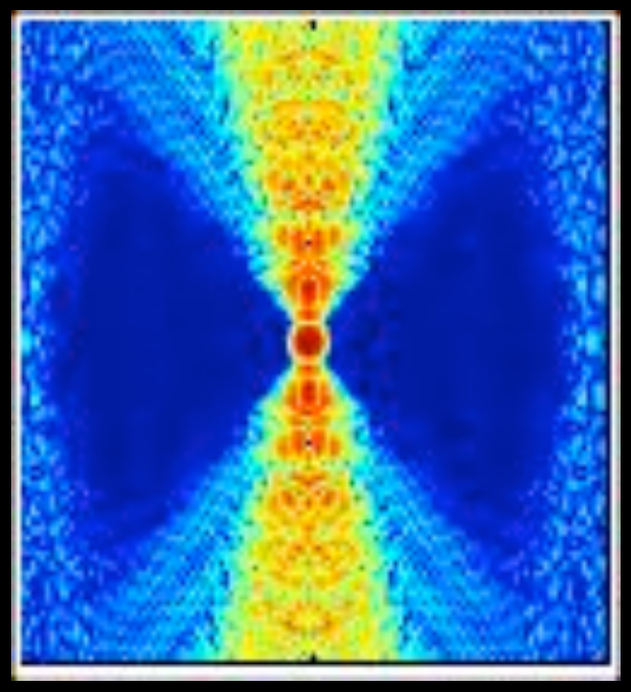


Current mask manufacturing approach

Ripple 3 mask





Mask is etched from Si on Insulator (SOI) using Deep Reactive Ion Etching (DRIE) with ~ 1 micron resolution.

Minimum openings of 10-20 μm, dashing used to approximate thin slits to avoid waveguiding effects.

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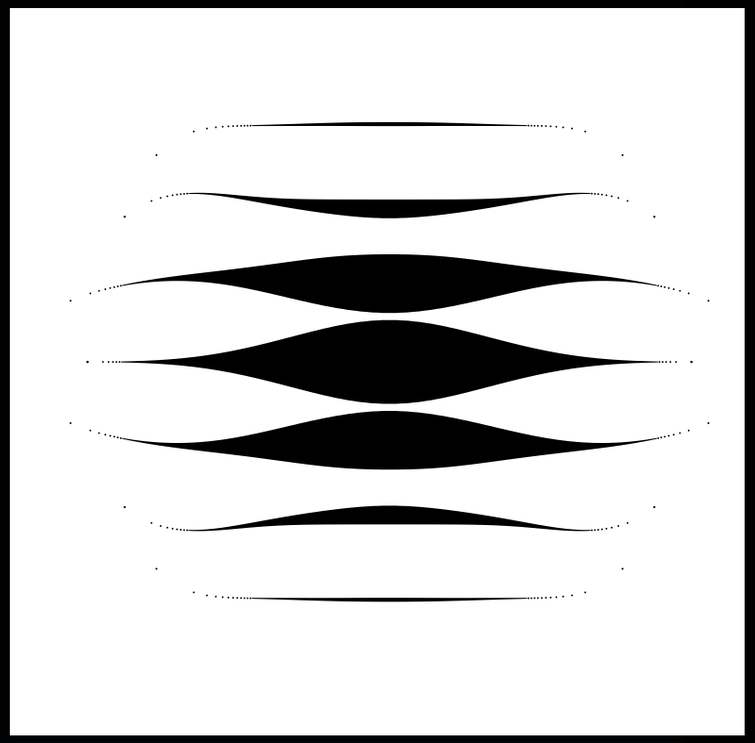

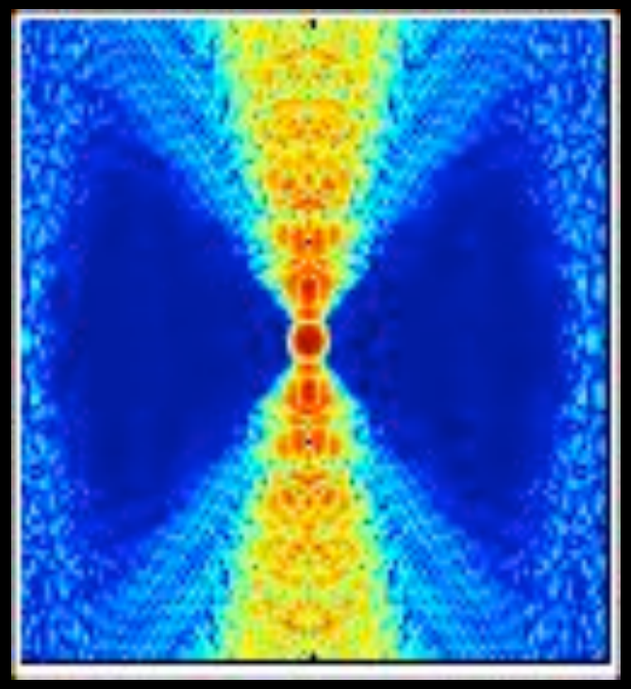

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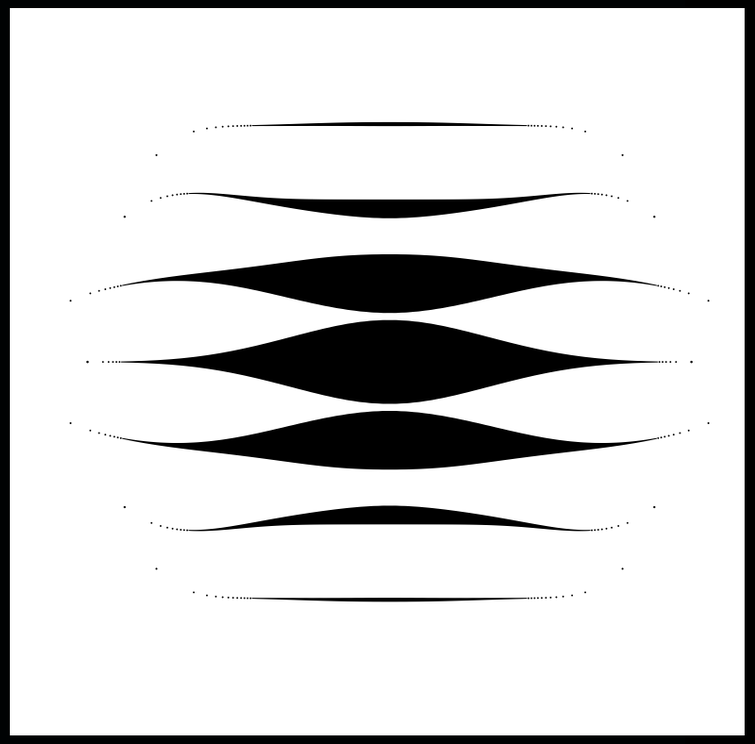

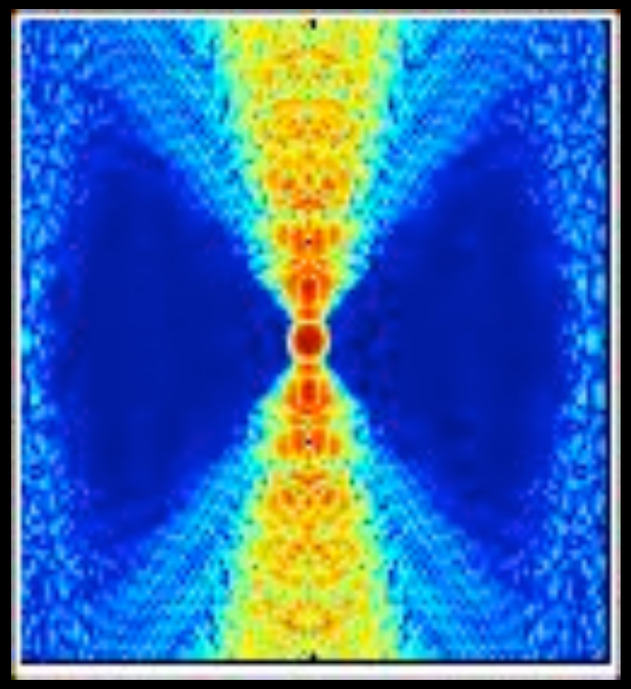

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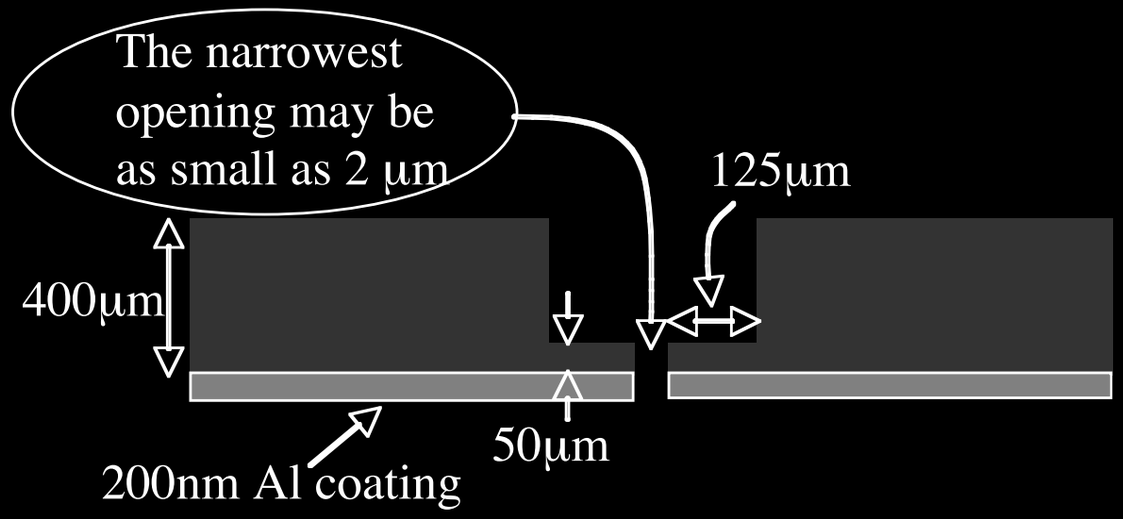
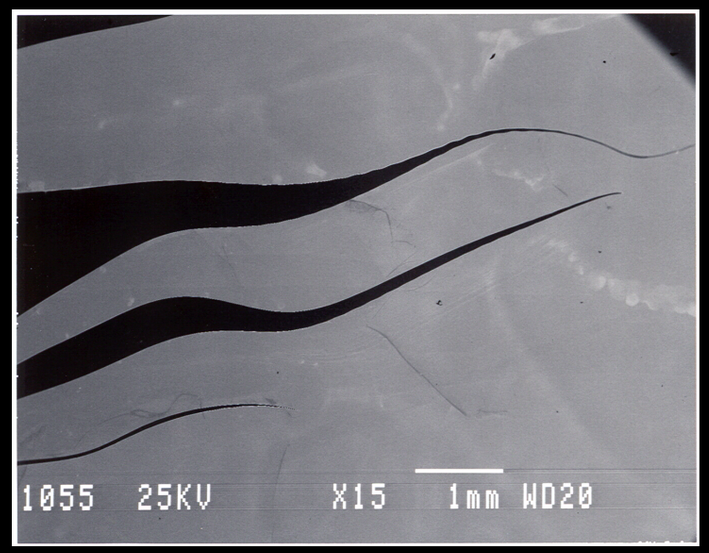
Etched Ripple 3 Mask at JPL MDL

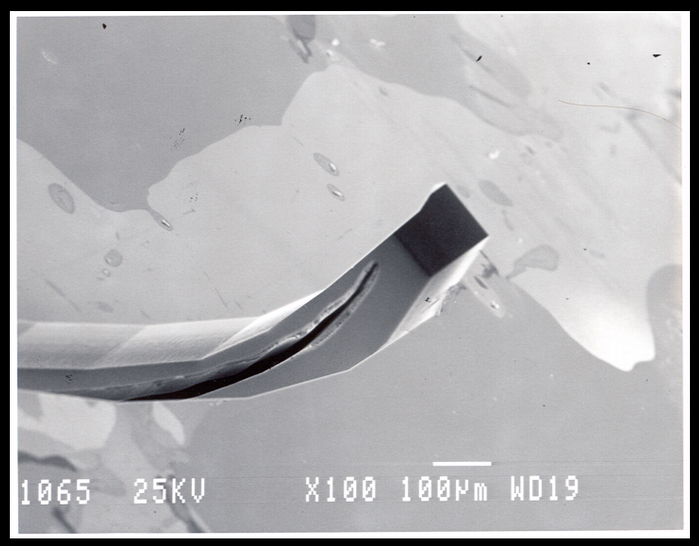
Design

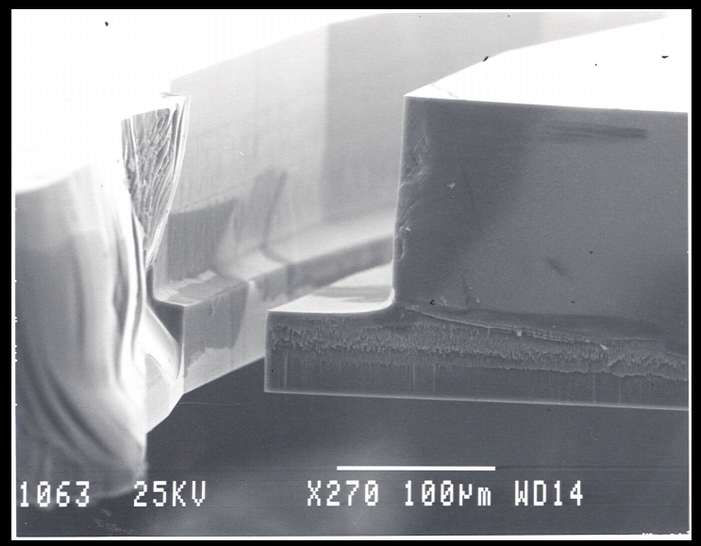


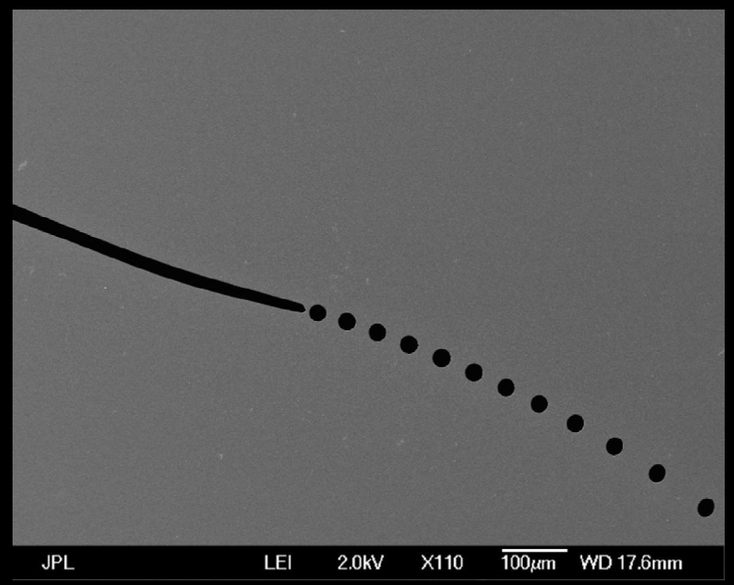


1 micron precision

SEM Images

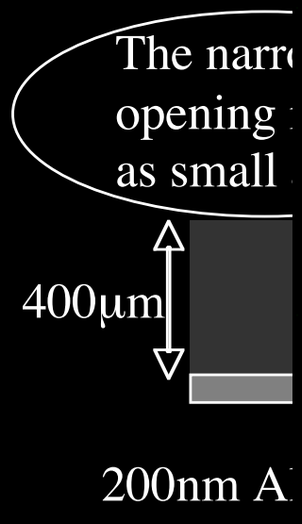


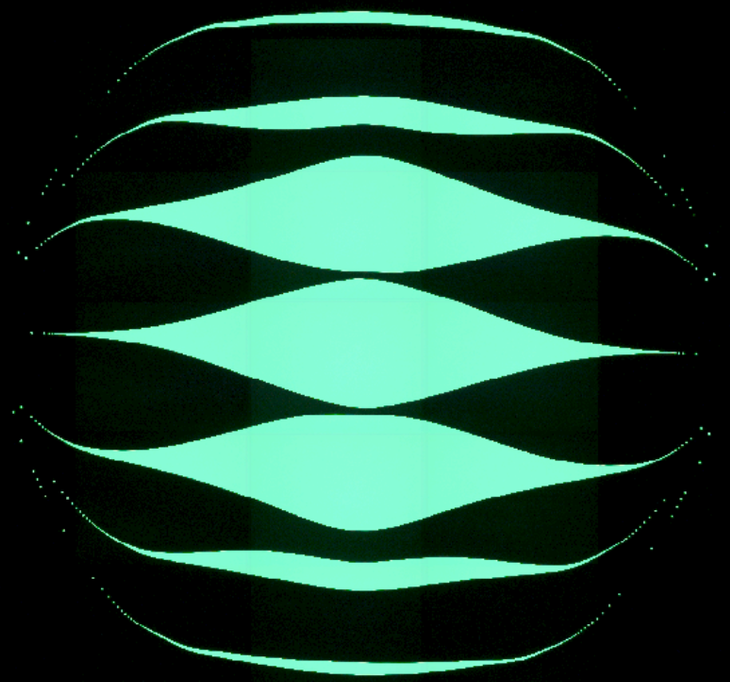


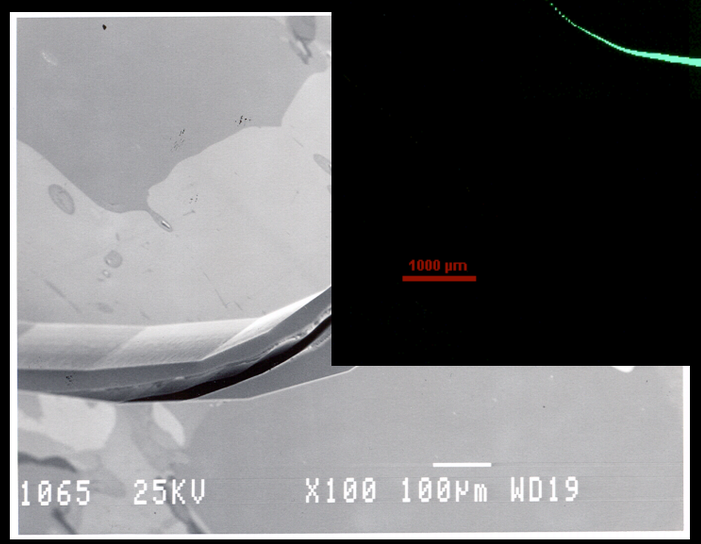


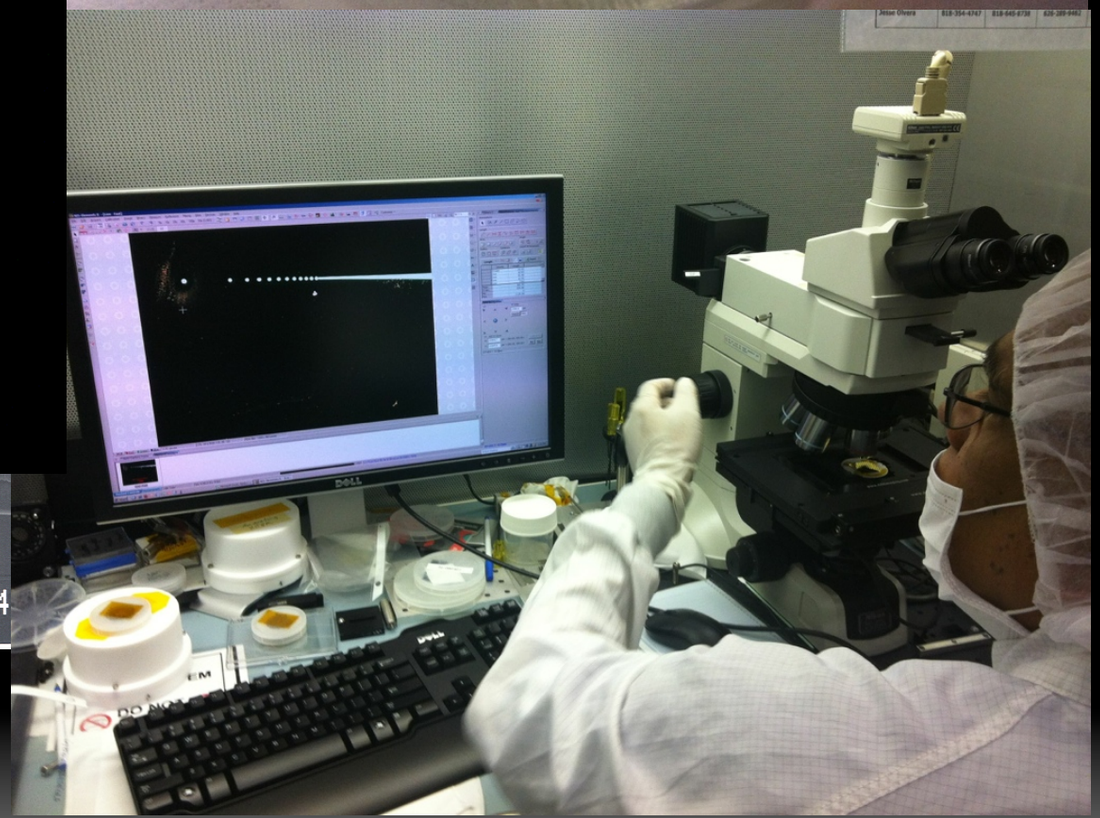
Courtesy of K. Balasubramanian, JPL MDL

Etched Ripple 3 Mask at JPL MDL









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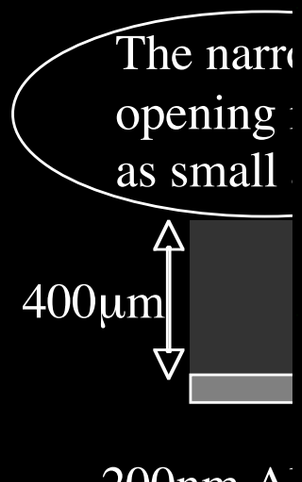
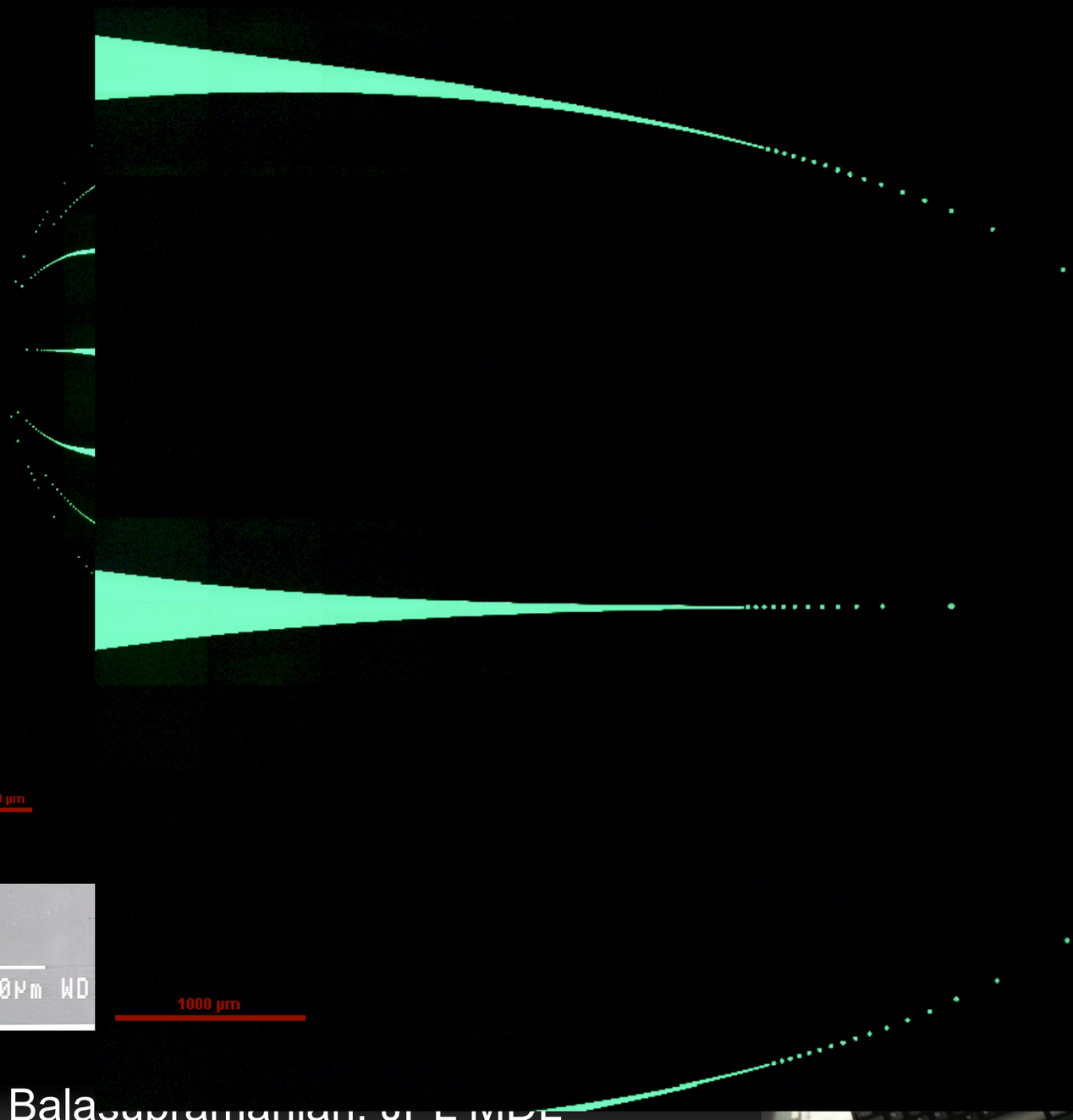
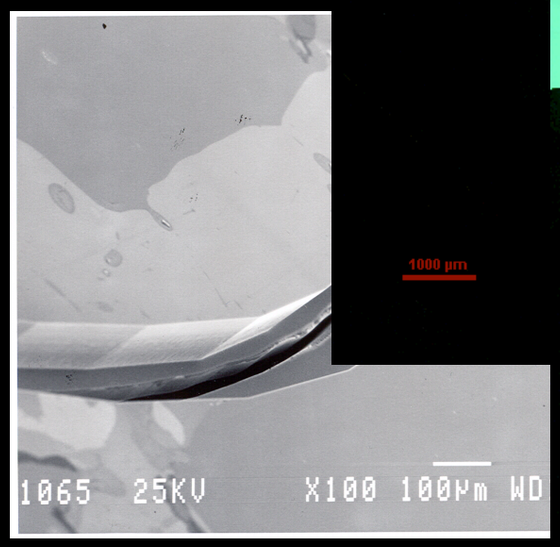
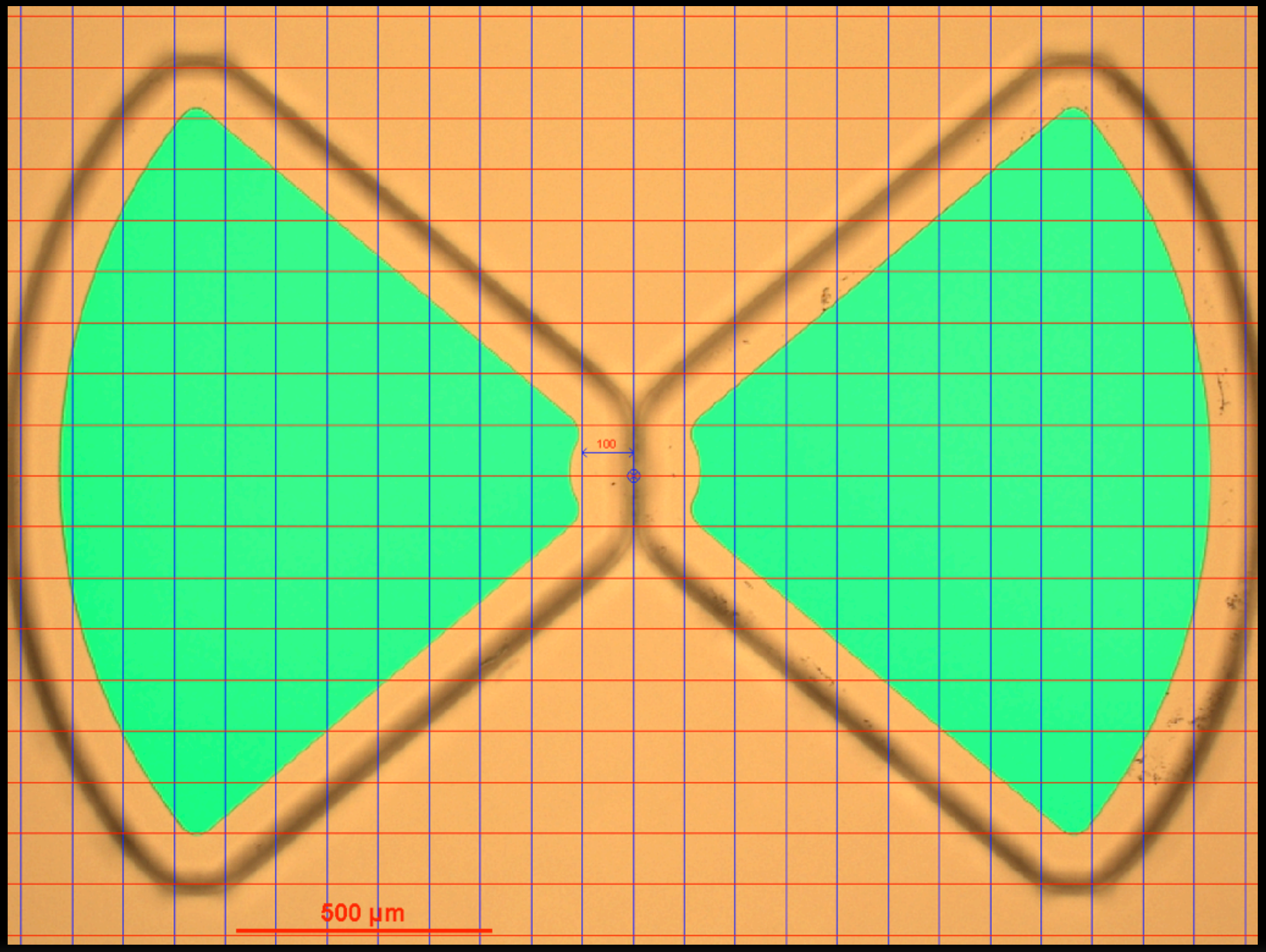






Courtesy of K. Balasubramanian, JPL MDL

Etched “Bowtie” Mask for Focal Plane

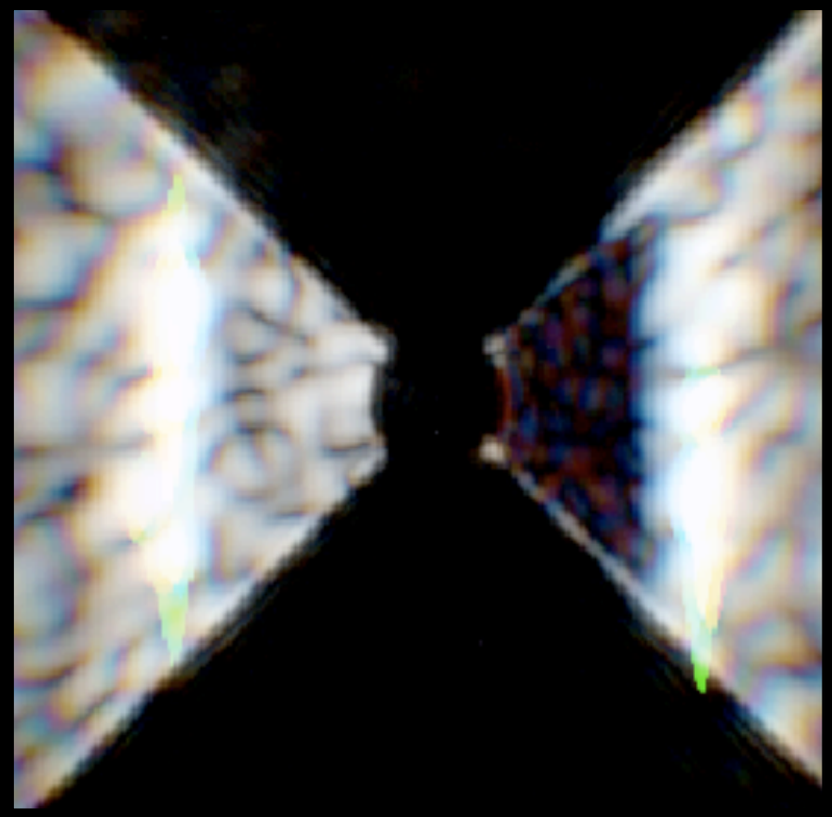


Solid focal plane mask to block core of PSF. Etched from Si using same DRIE process.

Same mask would be used for AFTA; not considered technology development.

Experimental Results - Single-Sided Dark Hole

Ripple 3 Shaped Pupils at HCIT
2 x 10^{-9} in 10% band
(2007)



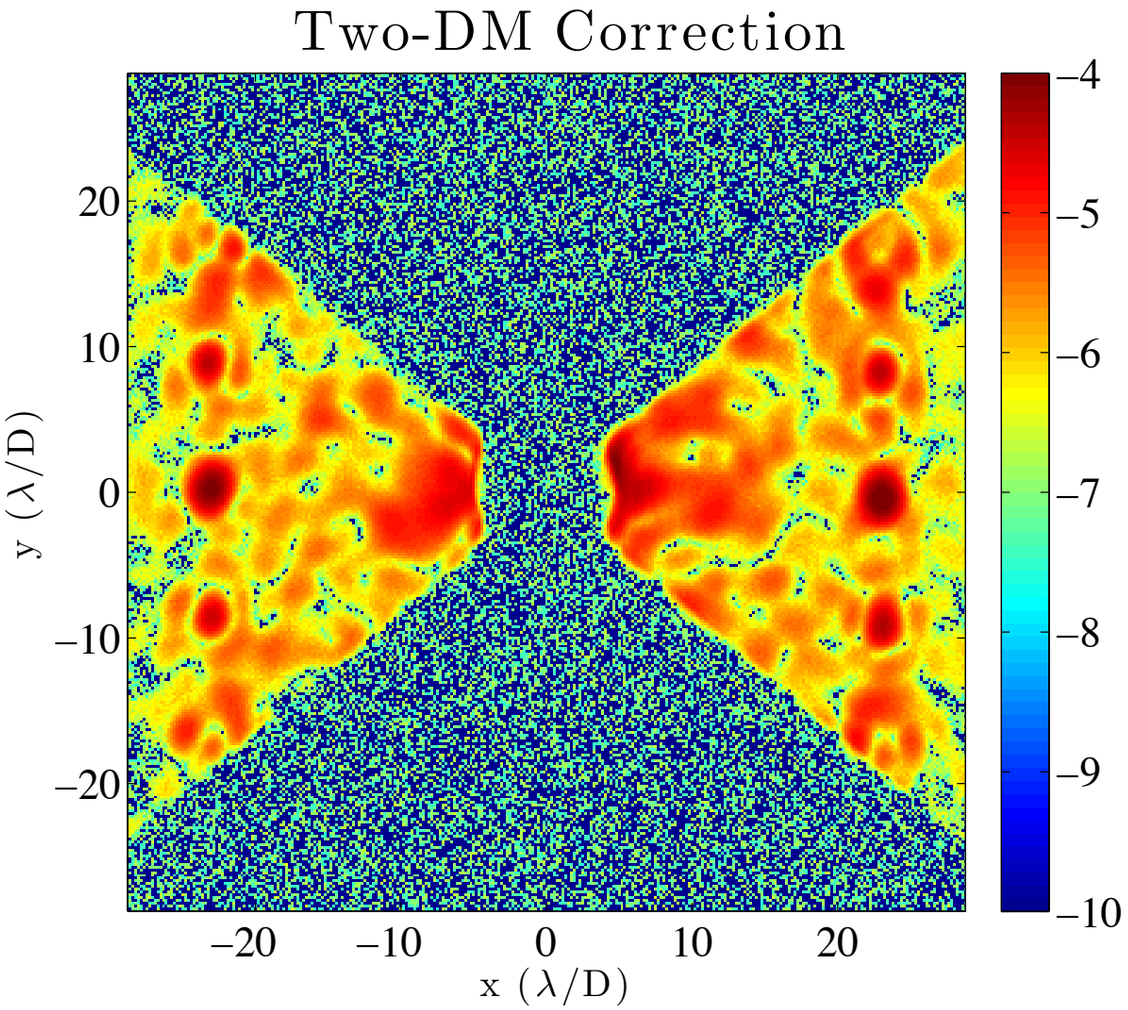
EFC control algorithm with DM diversity estimation.

Note: Modeling showed that waveguiding through small openings with 50 μm walls has an effect at roughly the 10^{-9} level for these size masks.

Two-DM Control at the HCIT

- Monochromatic correction at 790 nm

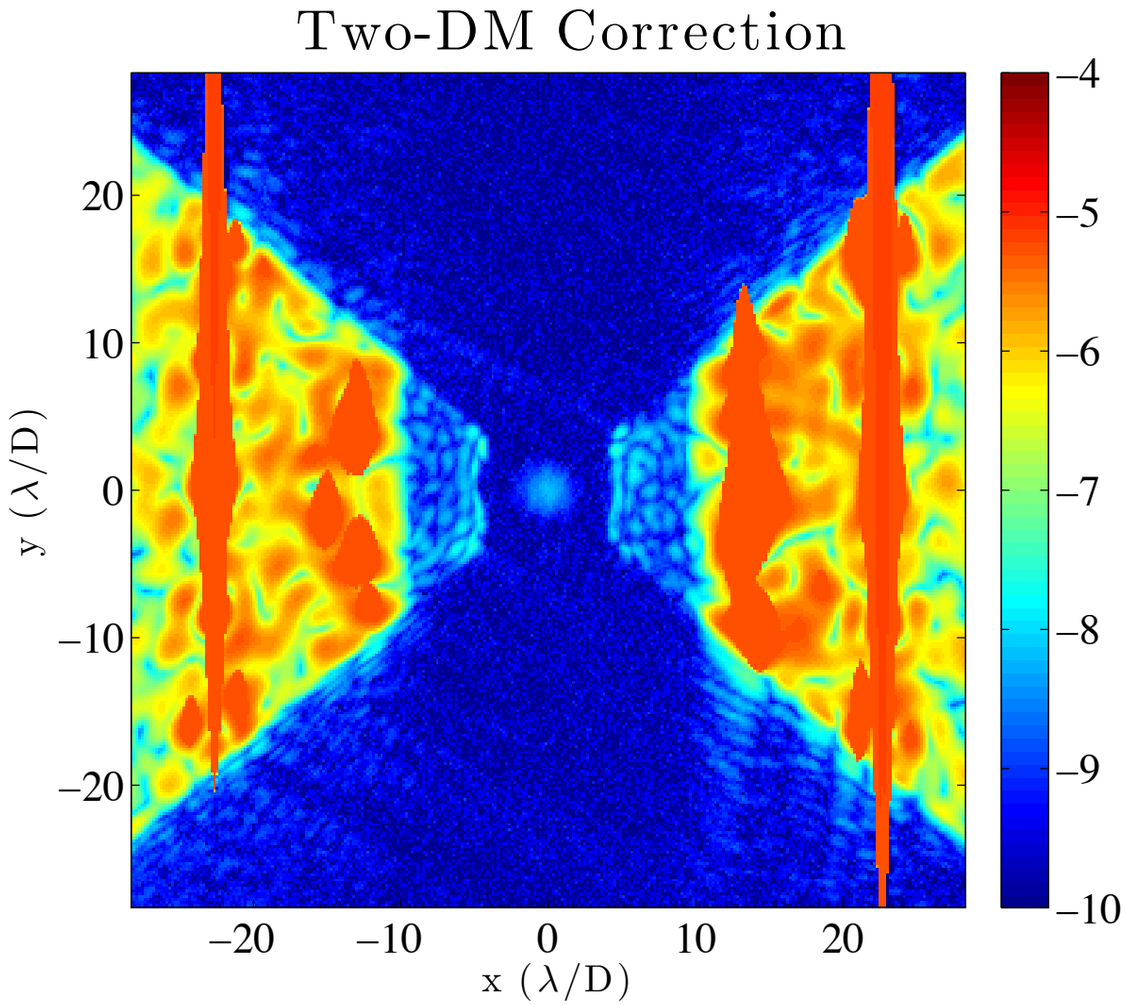
Before Correction:



7.8 x 10^{-6} contrast

5 to 9.5 λ/D

After Correction:



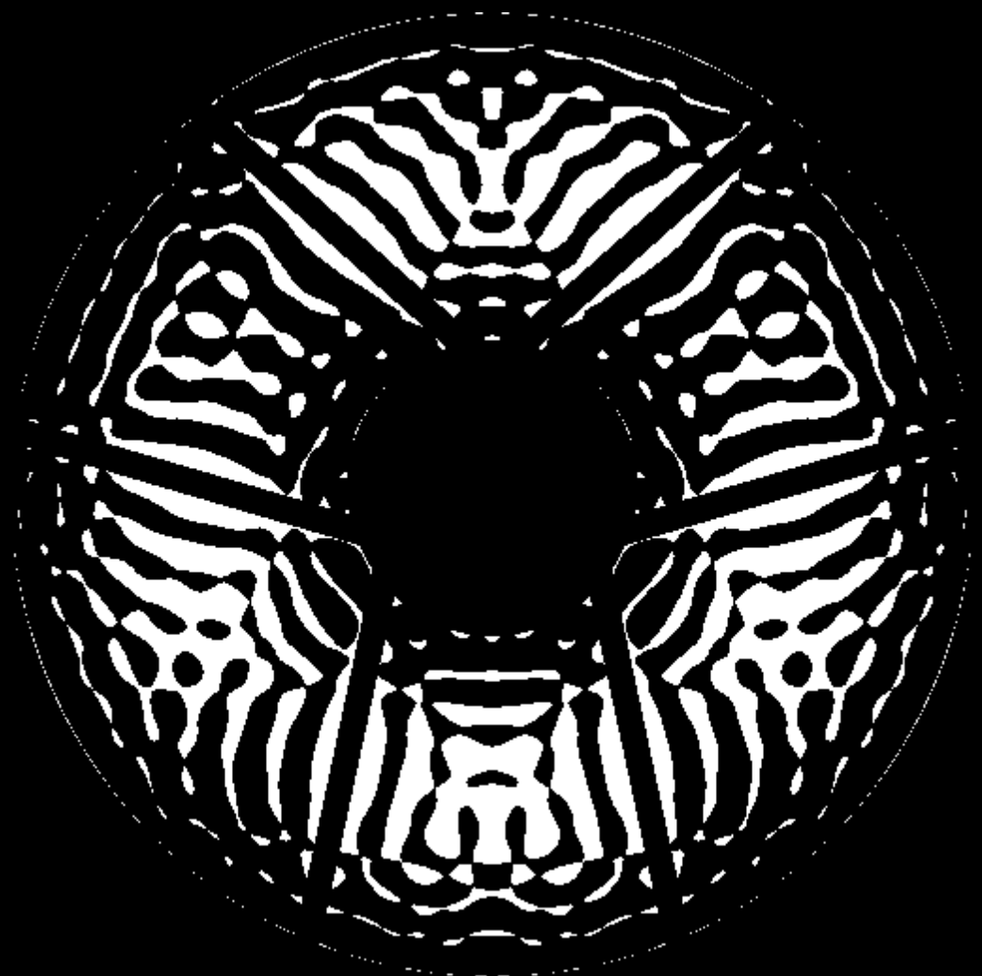
3.6 x 10^{-9} contrast

5 to 9.5 λ/D

Kalman Filter with Stroke Minimization, 8/2013

AFTA Style 2-D Shaped Pupils

Because of disconnected structures, need different manufacturing approach.



<u>3 Approaches Considered</u>

- Pattern Al on Glass (rejected)
- Use DRIE on Si with overlayed grid (heritage)
- Use in reflection with Black Si (baseline)

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Mask defined on a binary grid, usually about 1000 x 1000 pixels, with size matching pupil.

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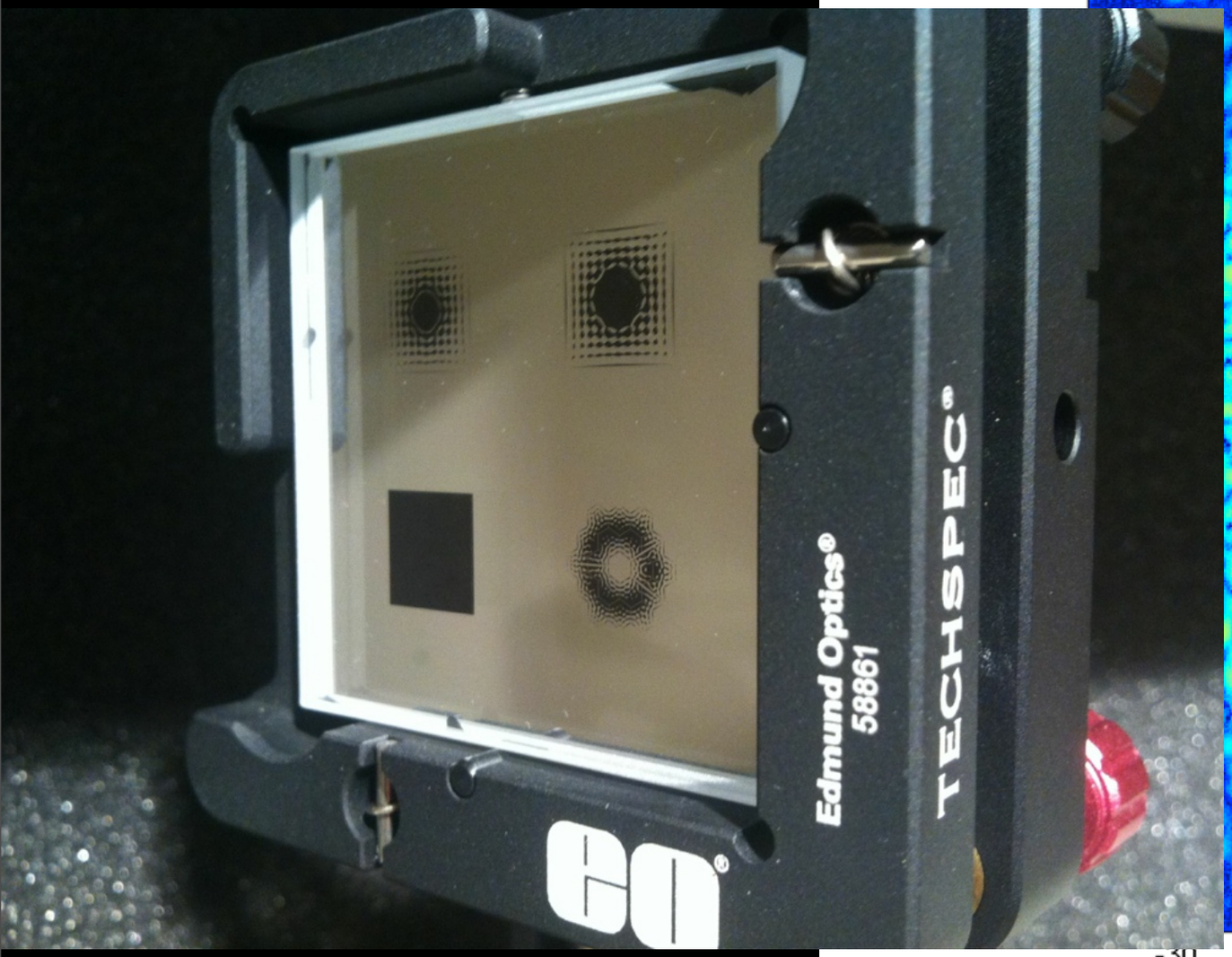
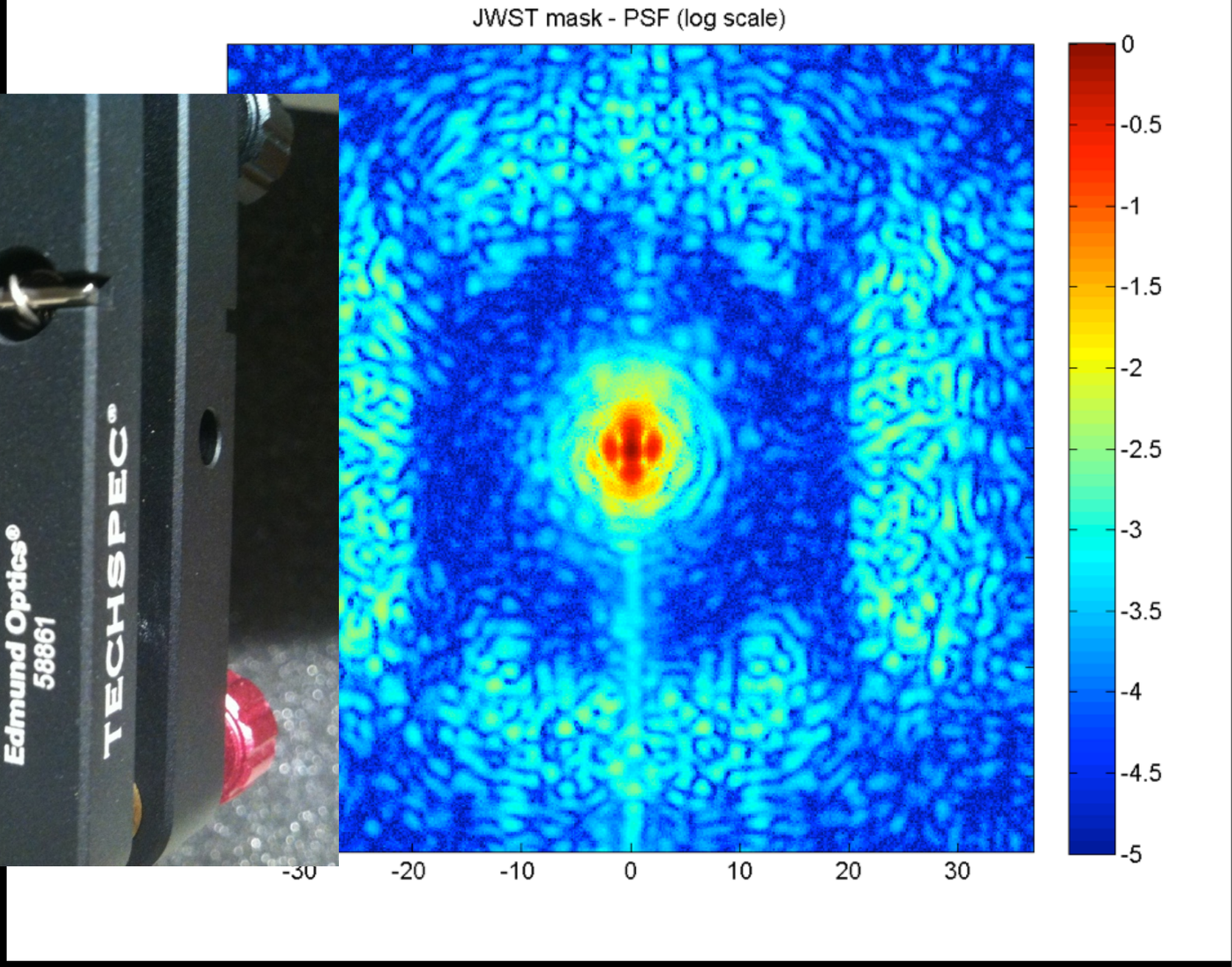
A fourth option is to place the shaped pupil directly on the outer barrel of the telescope.

Aluminum on Glass

First Lab Test of 2D SP on Glass at Princeton





A. Carlotti, E. Young, G. Che

New Shaped Pupil for Subaru Tested in July, ’12

Comments

Established confidence in producing correct PSF for 2 D Shaped Pupils.

However, while cheapest and easiest approach, rejected due to concerns with glass (ghosting, dispersion, aberrations, uniformity, etc.).

DRIE Etching of Si

Use Grid Overlay to Support Binary Pattern

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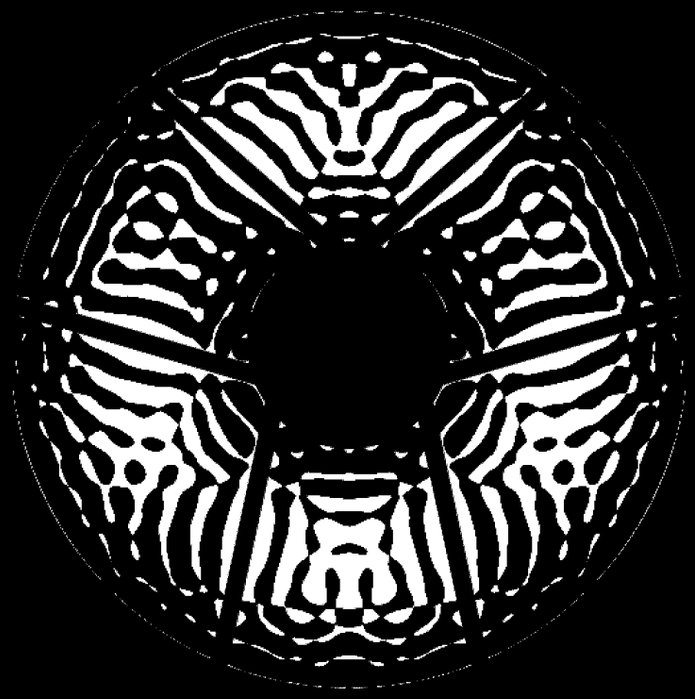

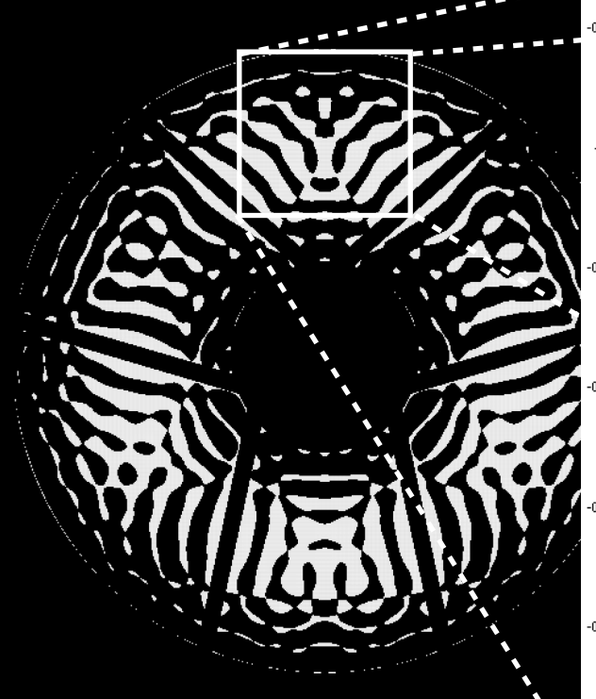

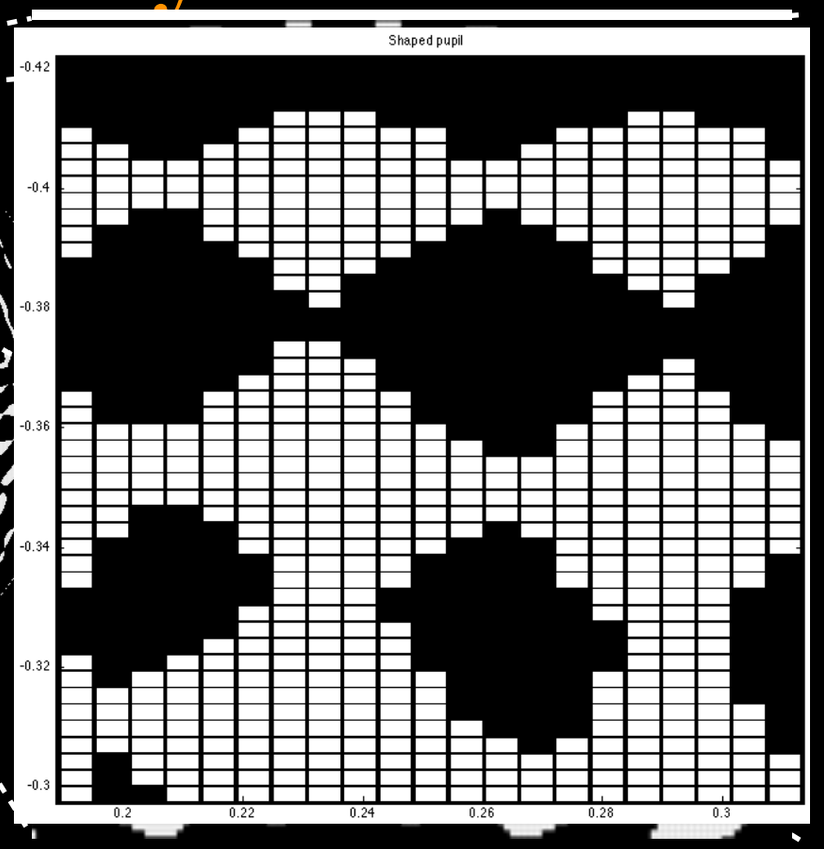

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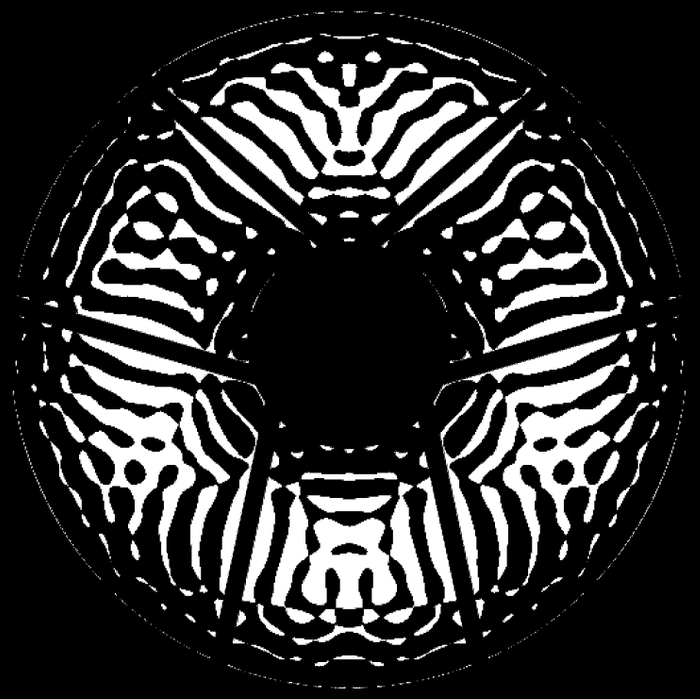

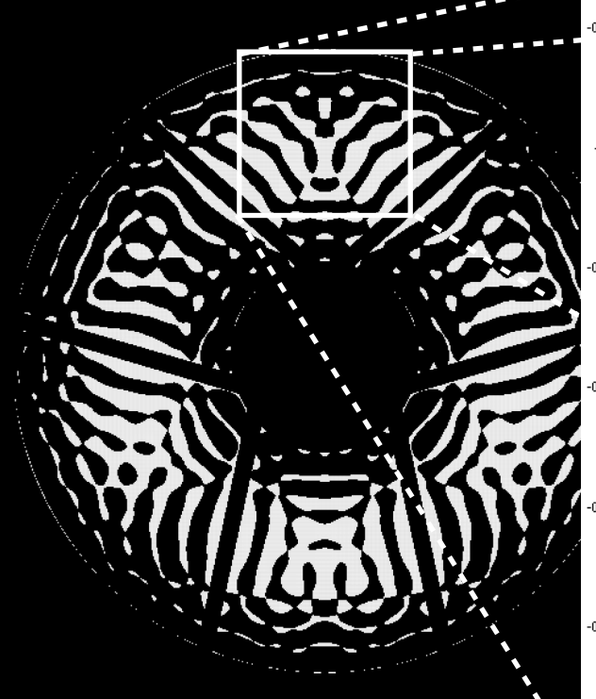

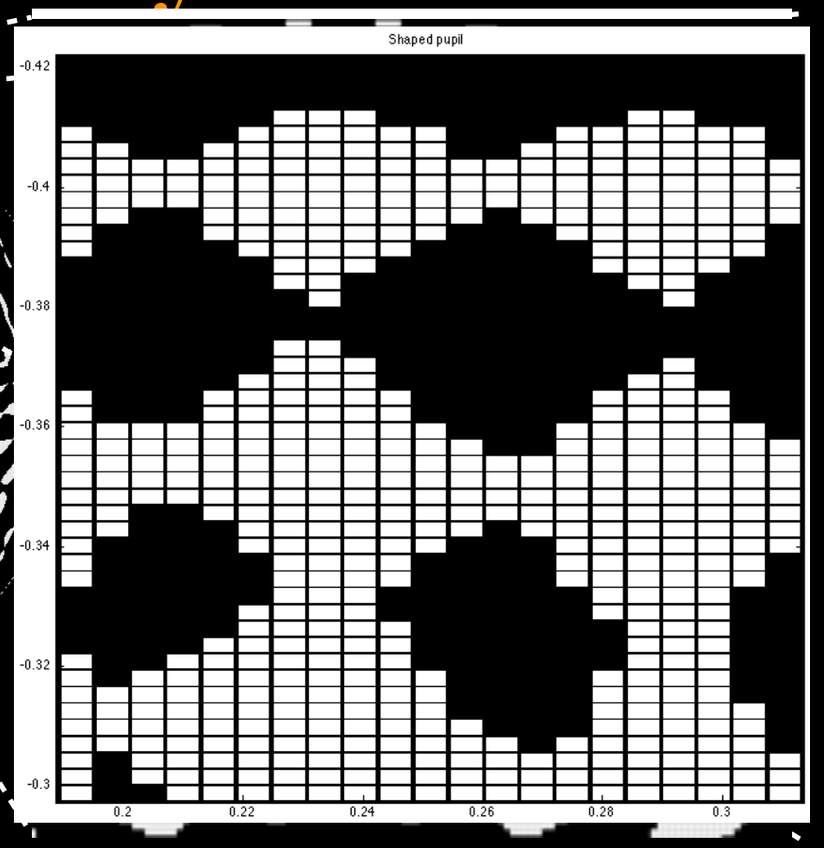

For 20 mm pupil and 1000 x 1000 pixels, cells roughly 20 microns in size.

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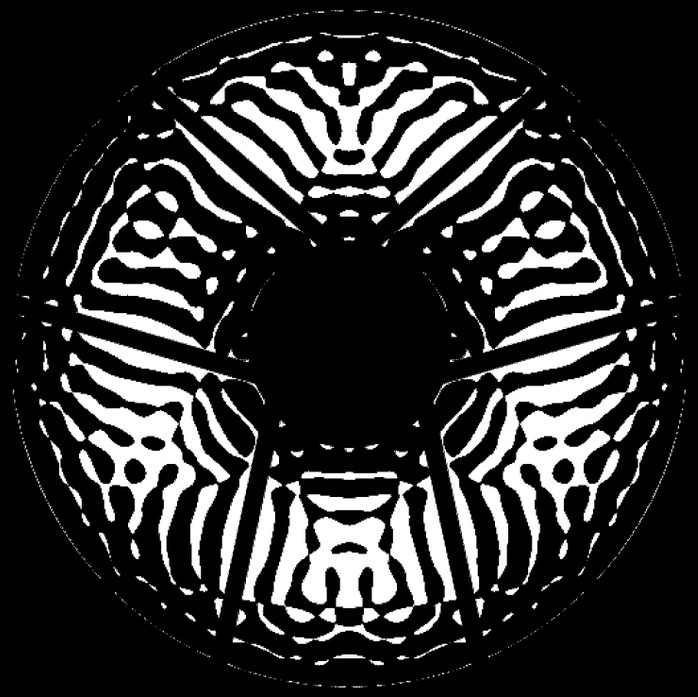

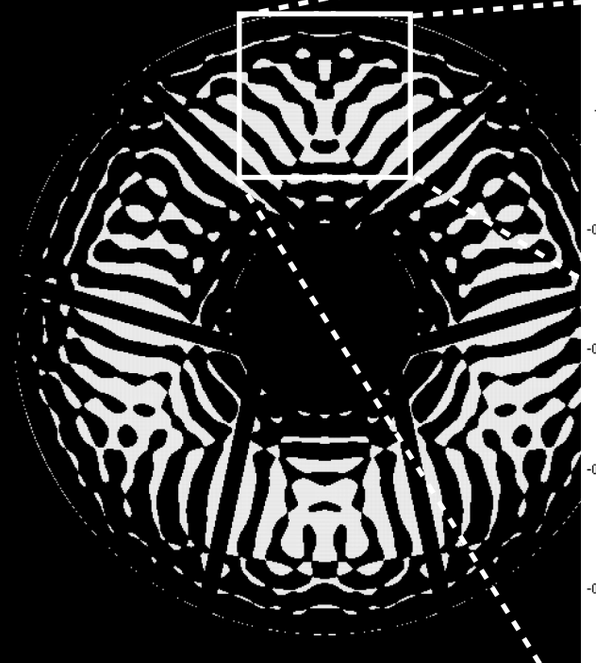

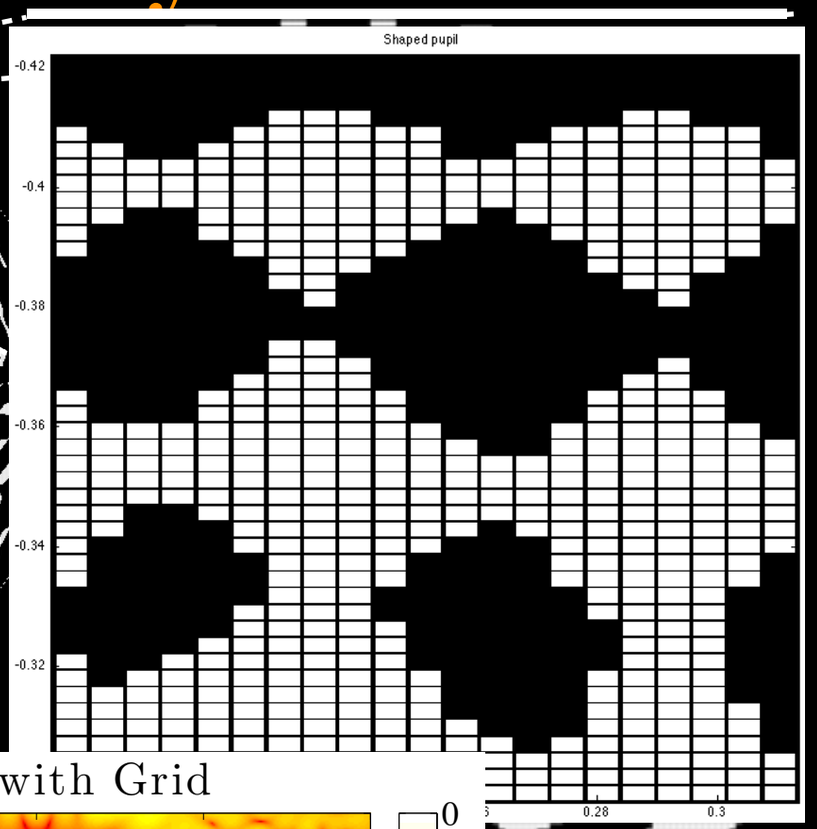

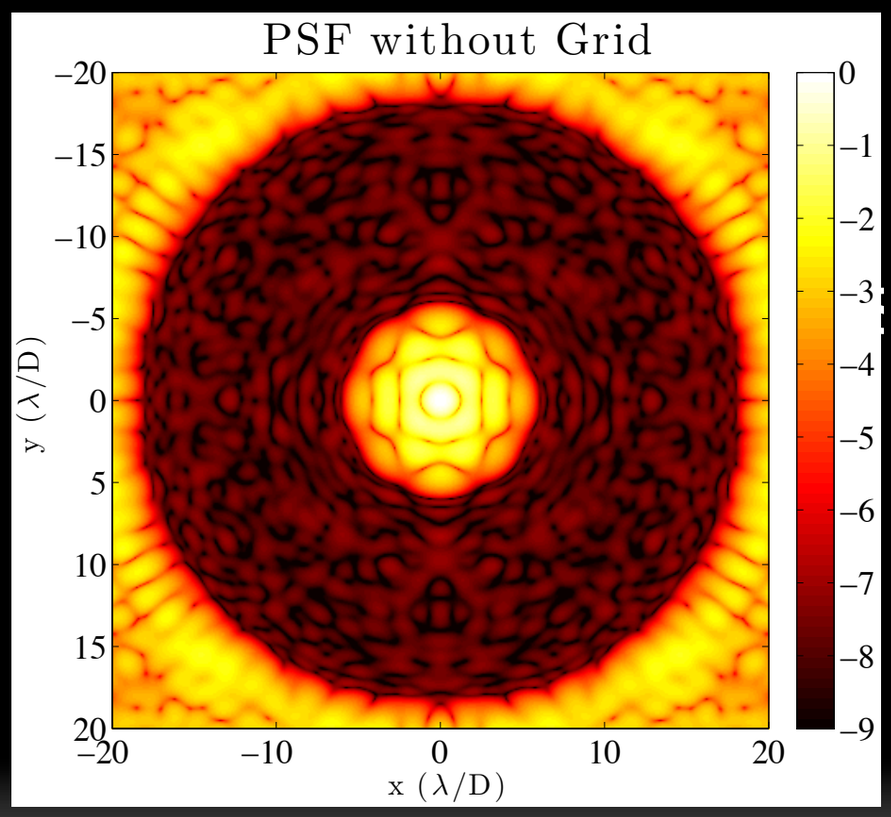

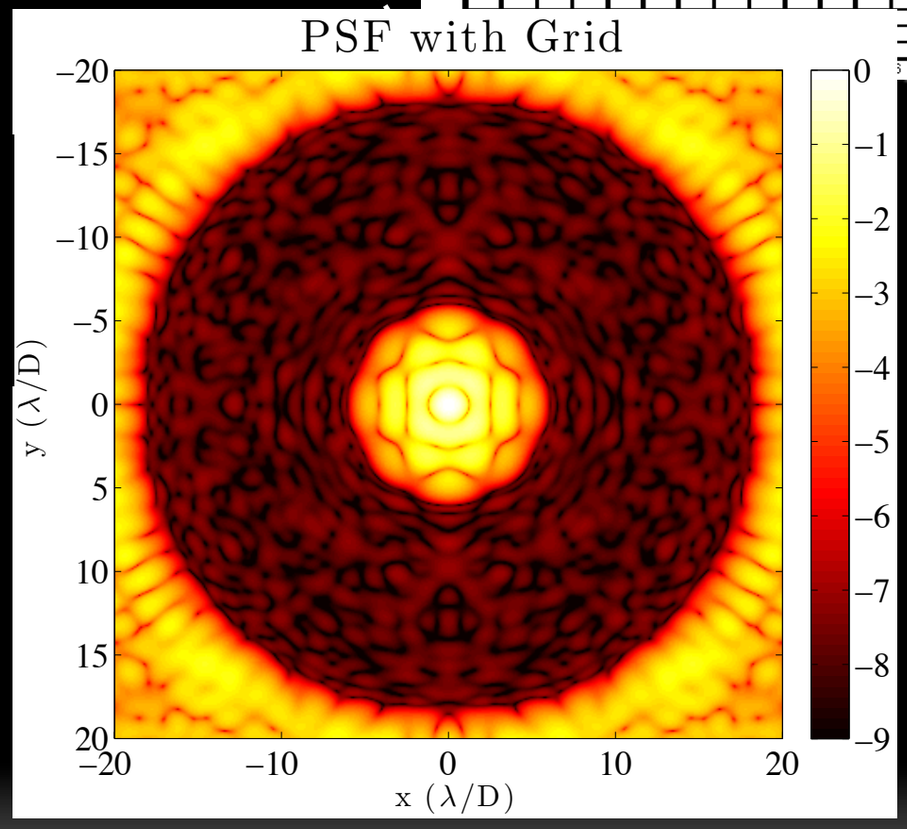

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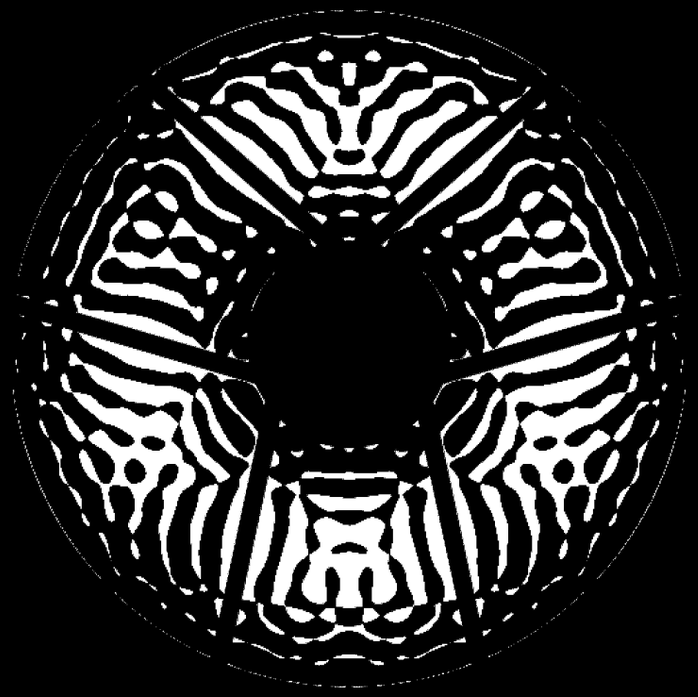
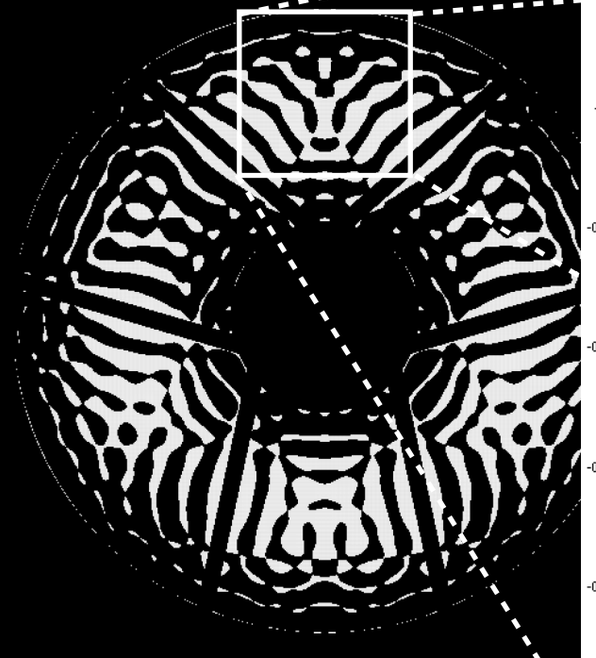
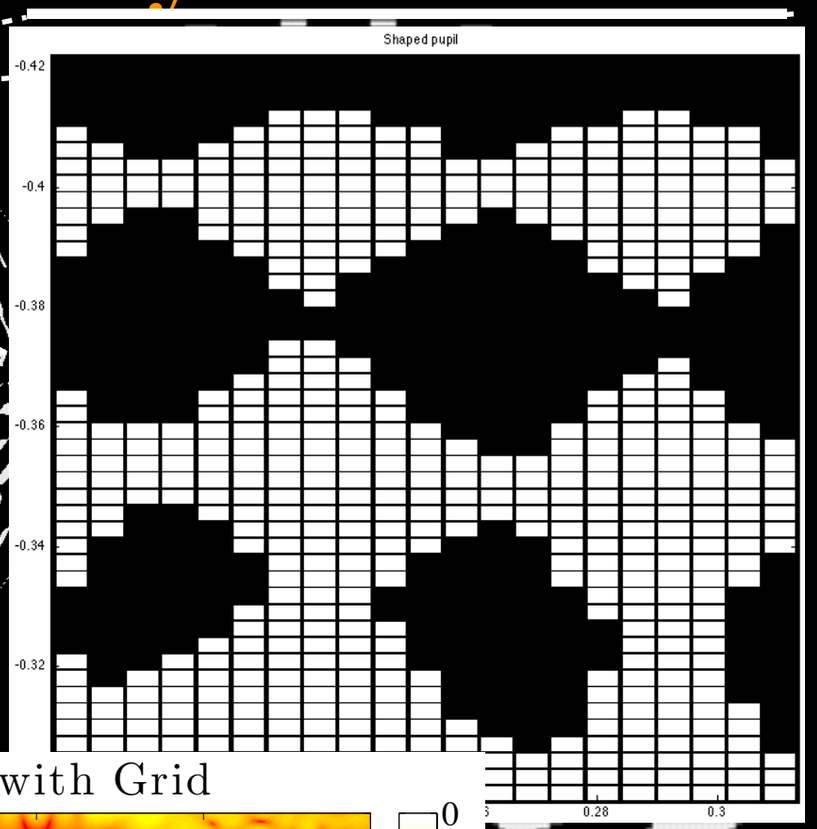
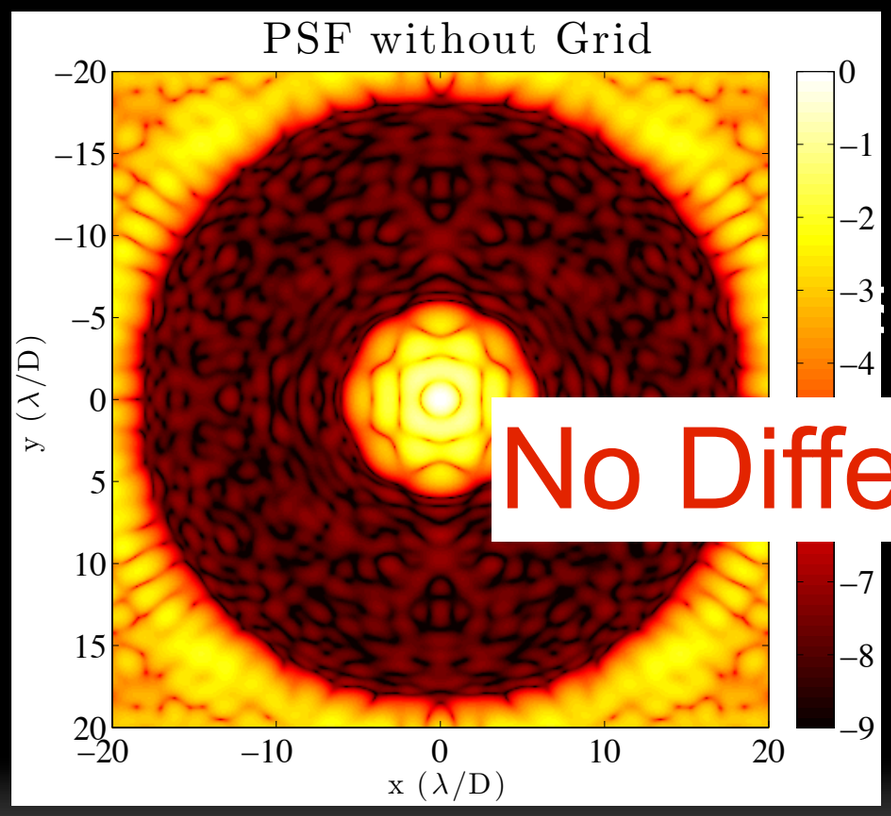
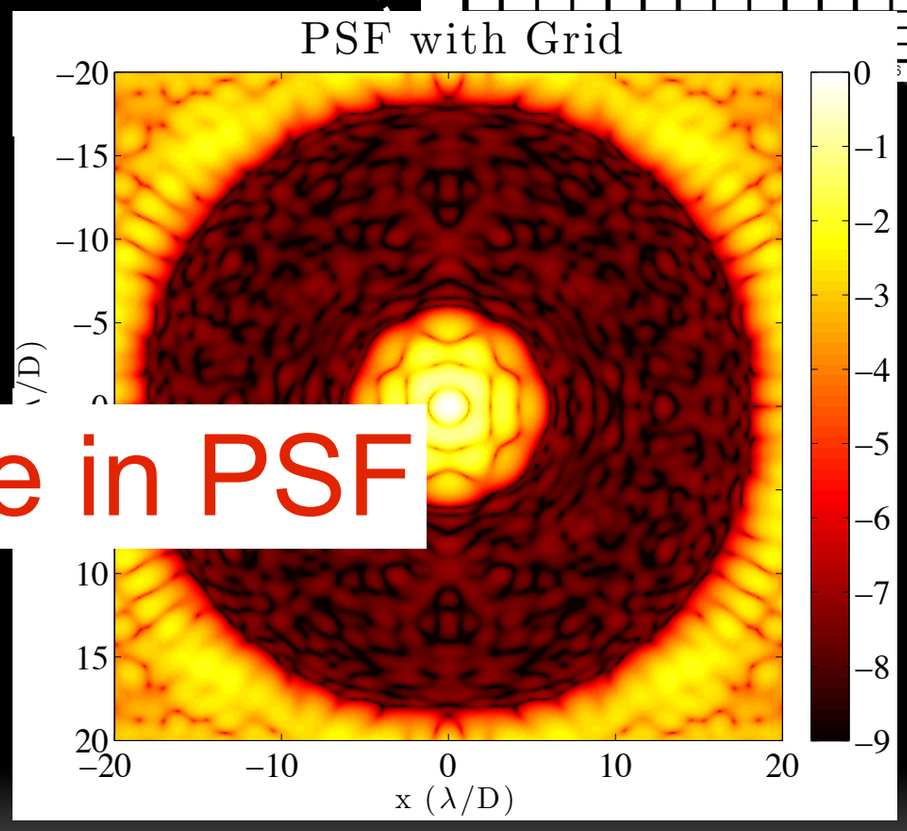




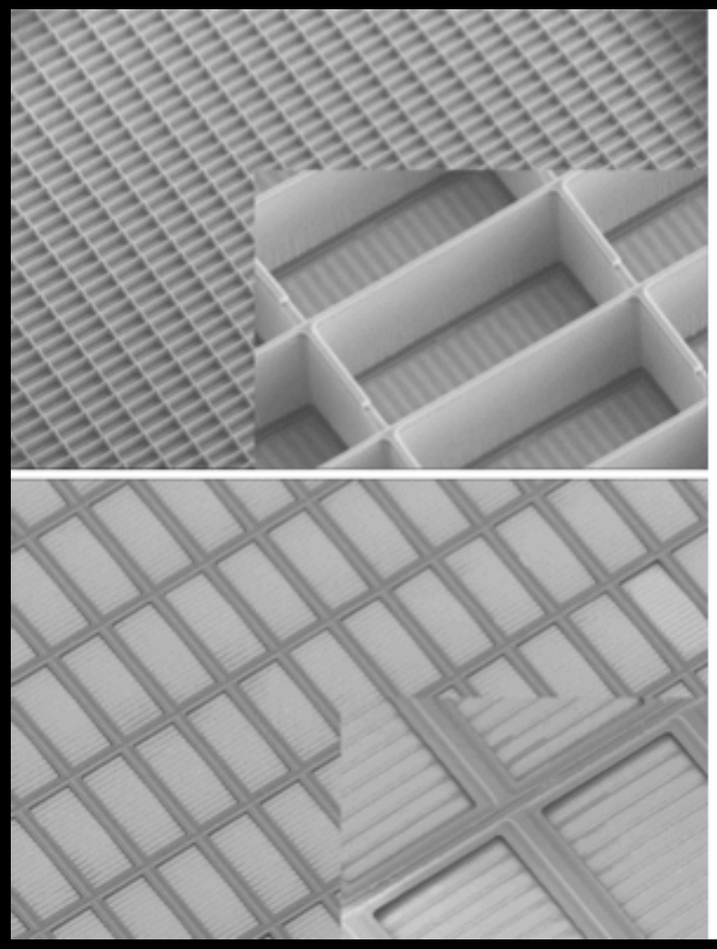


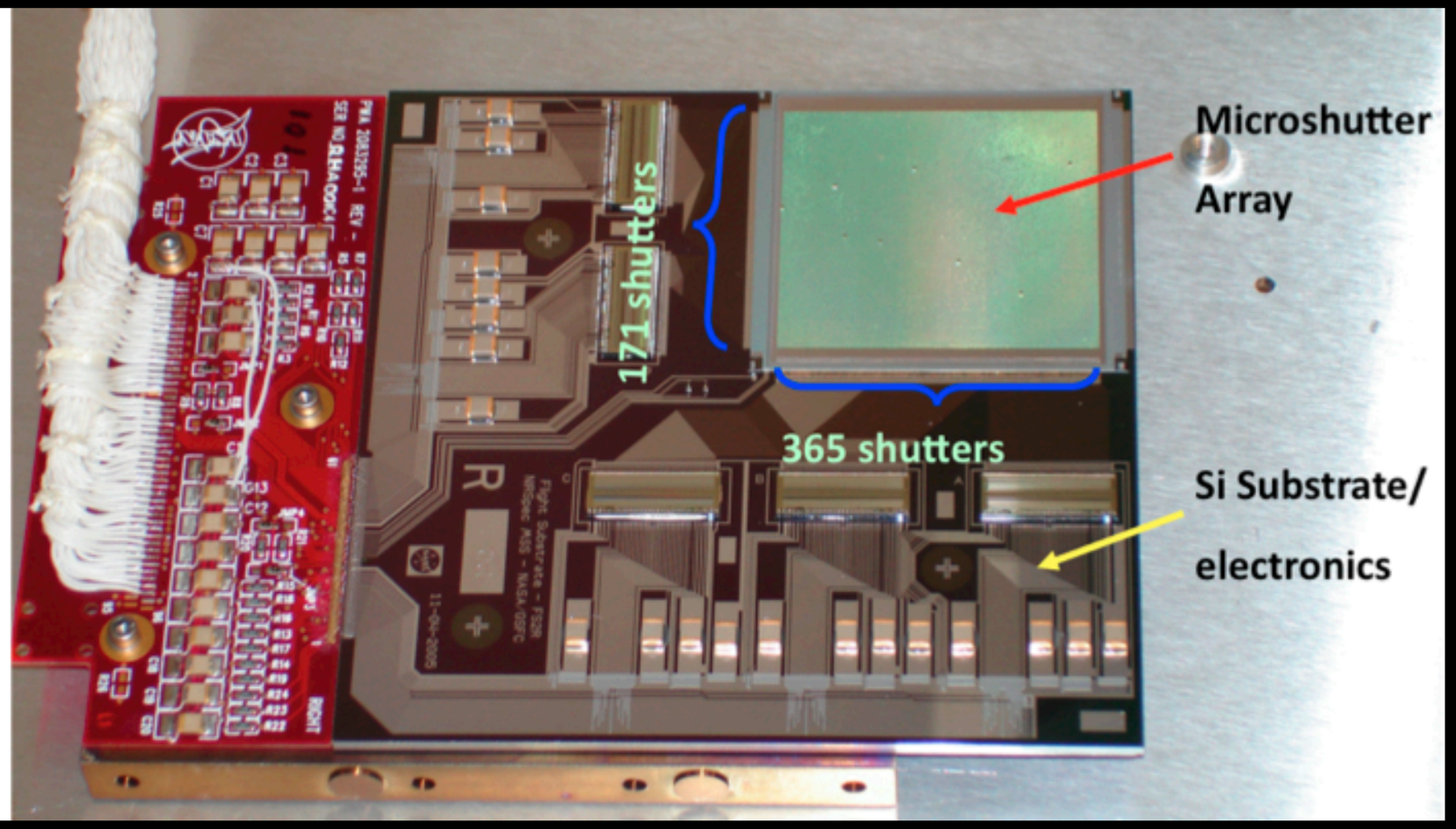




No Difference in PSF

Etch with Same DRIE as for Ripple Type





Mask uses similar underlying grid as for microshutter array on JWST (but without the shutters). Array is 171 by 365 shutters with pitch of 200 x 100 μm. Sidewalls ~ 10 μm.

GSFC uses same DRIE process for JWST shutters.
Shutters at TRL > 6.

Questions and Comments

- Grid structure reduces mask throughput by ~20 to 30%.
- What is effect of thinner 2-3 micron walls? (Current JWST shutter has thicker walls.)
- Need to assess stiffness and strength.
- Check that field propagation the same as in dashed mask.
- Glint and edge reflections need to be evaluated.

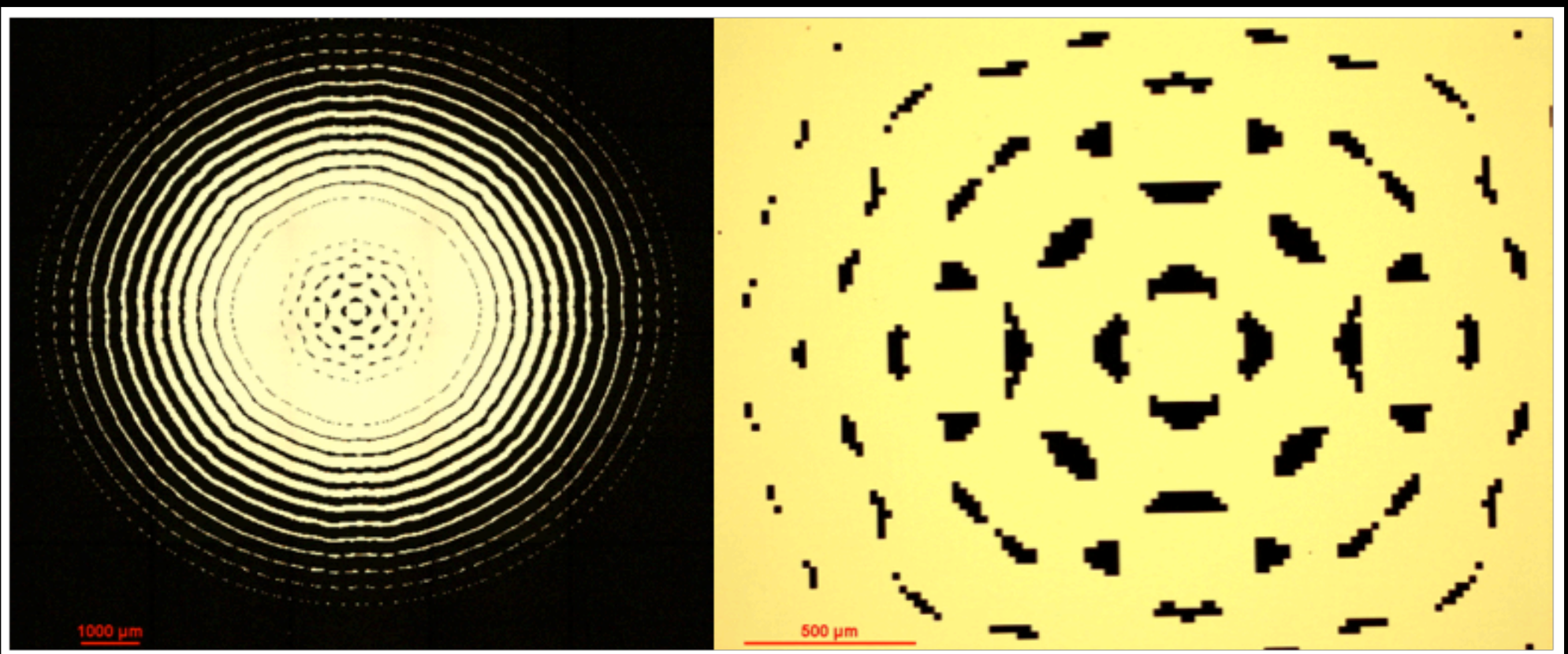
Relatively easy to make and test. Can make at Princeton, GSFC or MDL (where experience base is). Resulting instrument operates in transmission with fewer optical components and folds.

<u>Acceptance Criteria</u>

- Microscope inspection for flaws
- Imaging test in HCIL followed by HCIT

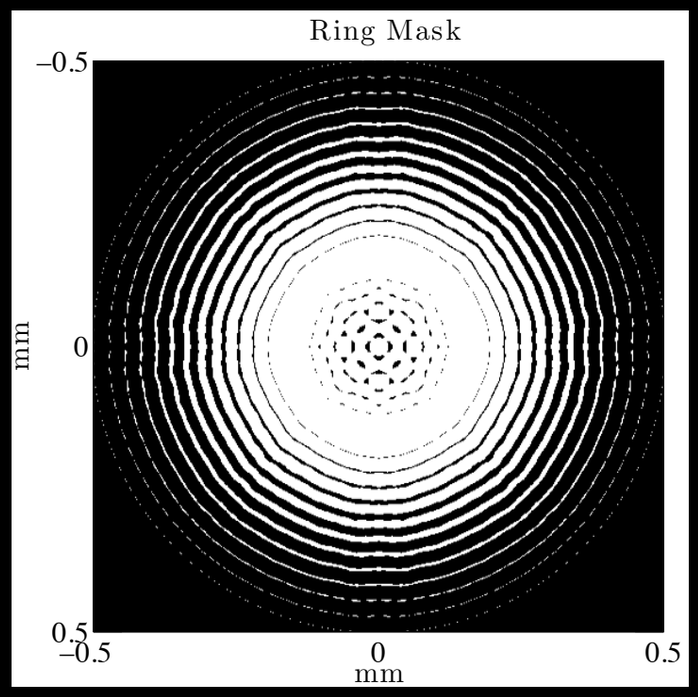
Reflective SP with Black Si

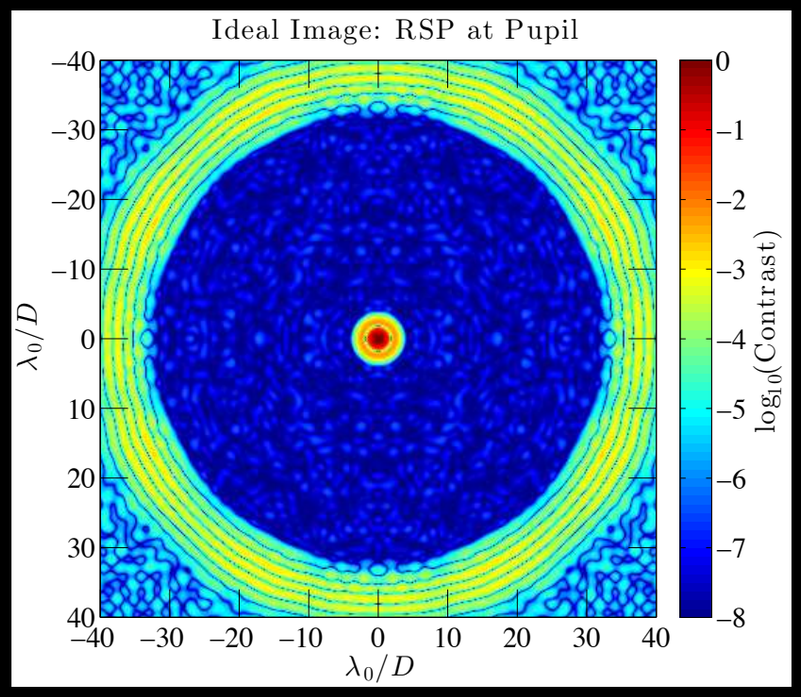
Reflective Shaped Pupils with Black Si

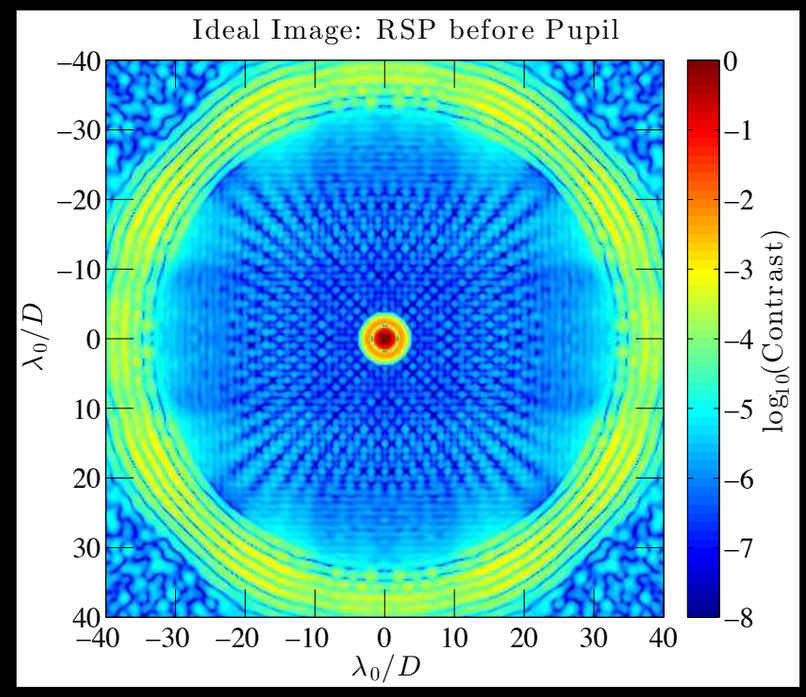


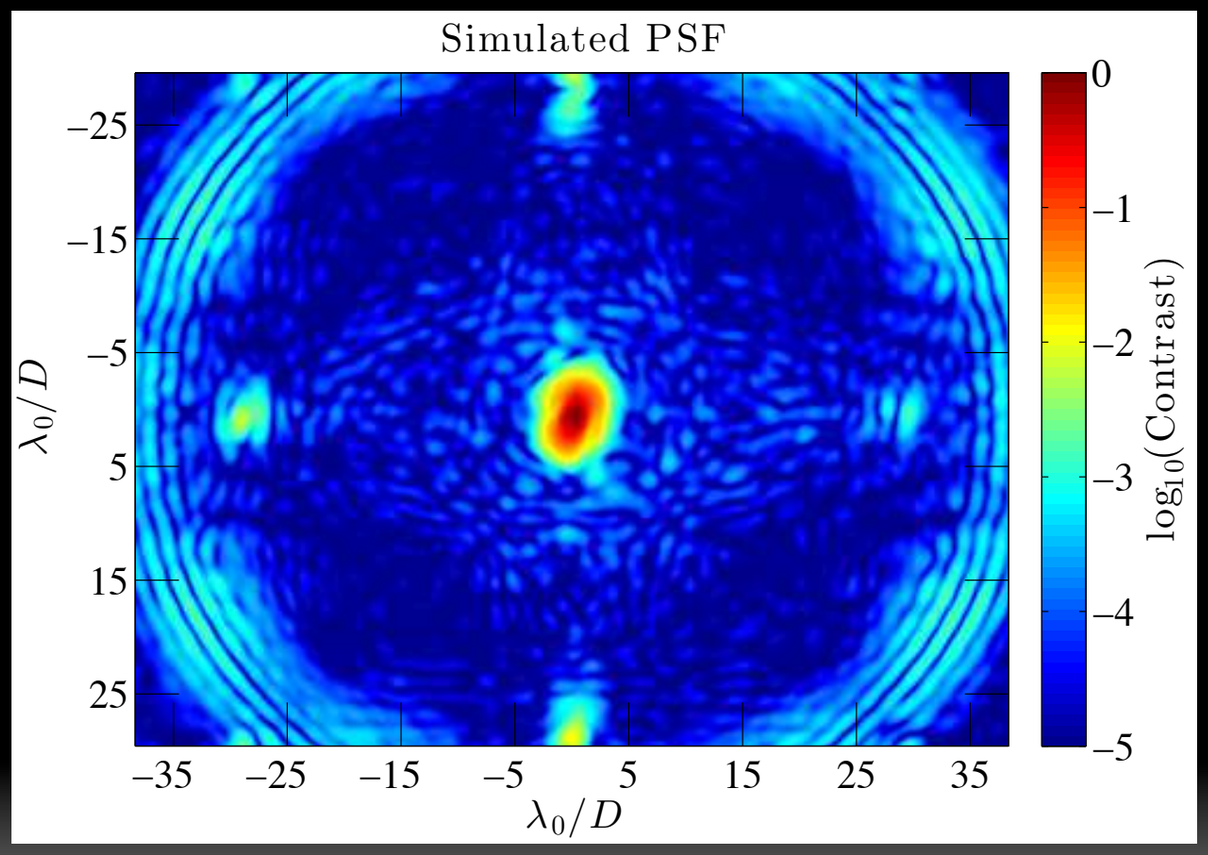
Microscope image of black Si concentric ring mask made in Feburary, 2013 at MDL/CalTech and installed at Princeton. Yellow is reflective surface of Si (white in transmission masks).

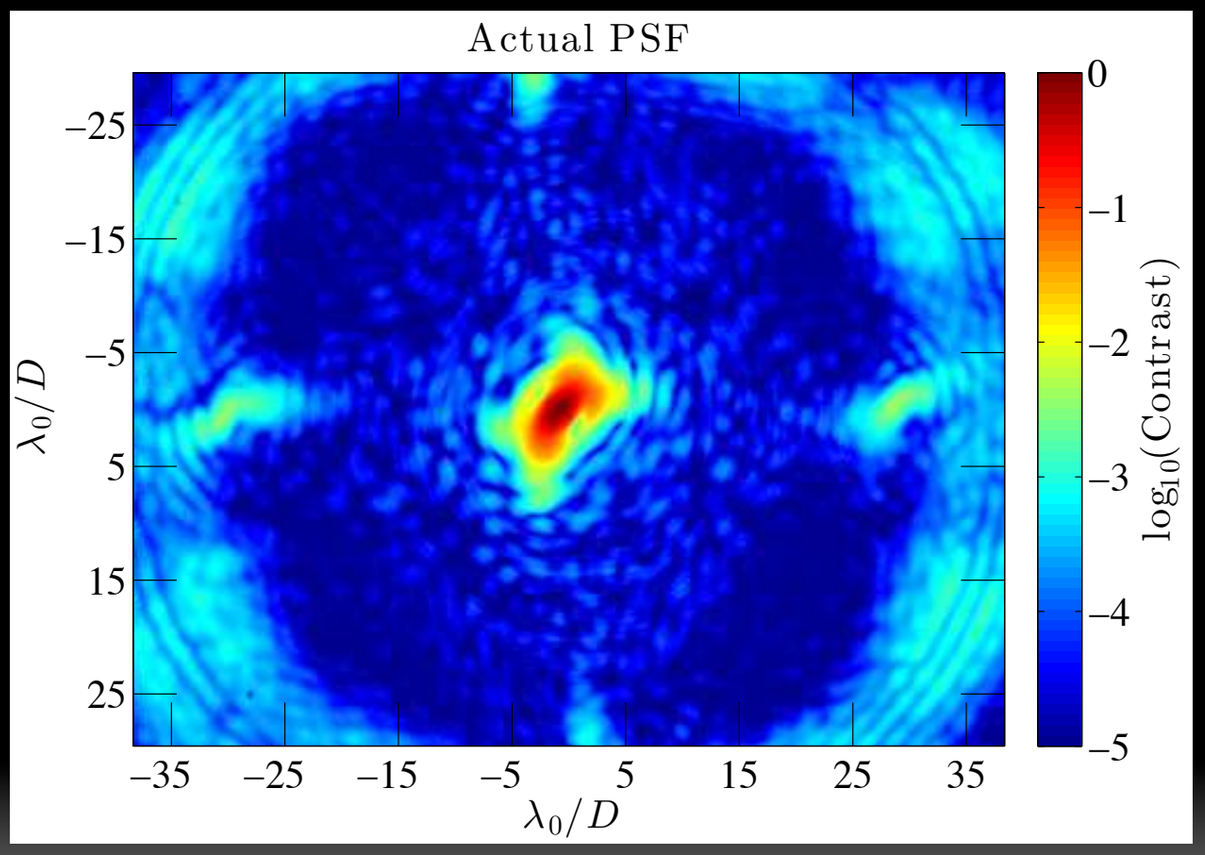
First images in Princeton's HCIL











Questions and Comments

- Relatively easy to manufacture and proven last year.
- Bare Si reflectivity < 40%. Coating process not defined yet.
- Will it survive environmental testing?
- Still need to confirm with wavefront control, but don't expect any problem.
- What is residual background due to low reflectivity of Black Si (~ 0.1 % **diffuse** reflection)?

Our current baseline approach.

Acceptance Criteria

- Microscope inspection for flaws
- Wavefront measurement
- Imaging test in HCIL followed by HCIT

Work Scope

Make 6 transmissive and 6 reflective masks (with and without DM settings).

- Micro Devices Lab / JPL and Kavli Nano Institute, Caltech
- Deep Reactive Ion Etching at MDL (for transmissive type) or Cryo Etching of Black Silicon at Caltech (for reflective type) after necessary patterning at MDL
- Transmissive Shaped Pupil Masks have been fabricated successfully several times at MDL and tested in the HCIT and at Princeton High Contrast Lab
- Reflective type black silicon incorporated Si masks have been fabricated at MDL/Caltech; tests are in progress at Princeton.

For 20 mm pupil, can fit up to 4 masks + 4 image plane masks on a single wafer. Entire task will take 3 wafers.

Reflective / Transmissive	Reflective
Size / Shape	slightly elliptical or with 3 fold symmetry
Substrate Material	Si coated with Al and patterned
Substrate Dimensions	50mm x50mm x 1mm
Clear aperture	
AR Coating	No
AR spec	NA
R of Reflective regions	>95% at 500nm to 600nm
R of black regions	<0.1% Lambertian
Materials	Si, black Si, and Al
Fab Technology or Vendor	Lithography, Black Si etch, JPL, Caltech Or MEMS Shutters for transmissive (GSFC)
Mask Specs and measurements	
Map of R vs x,y over the entire mask area	
Reflected wavefront	
Defects or errors, e.g., irregular features	
Image masks (bow tie masks)	
# of masks to be produced	4
Desired target date	Mid April 2014

Testing

- Configure HCIT 1 for SP in reflection.
- Test Black Si masks in reflection in HCIT 1 starting in May, 2014.
- Configure HCIT 2 for SP in transmission.
- Test DRIE transmissive masks starting in July 2014.

Note: testing can be done in parallel at Princeton, as can manufacturing of the DRIE masks.

Schedule to get to TRL 5 for Key Component

- Iniital design completed and tolerances defined by Princeton - 10/22/2013
- Design performance evaluated by John Krist at JPL - 11/21/2013
- Final design completed by Princeton - 1/10/2014
- manufacturer on contract (if relevant) - JPL/MDL 01/10/2014
- Process development and manufacturing begins at MDL/Caltech - 01/15/2014
- Microscopic inspections of iterative samples - at JPL 3/1/2014 to 5/1/2014
- Iterative wavefront measurements - at JPL 3/1/2014 to 5/1/2014
- component delivered to HCIT 5/1/2014 first iteration
- Second iteration design from Princeton 06/9/2014
- component delivered to HCIT 07/14/2014 second iteration

Concerns and Risks

- Producing black silicon island features on Al coated silicon wafers have never been produced for the SPM. Some key experimental runs are needed to develop the process to succeed.
- Deep DRIE is a well established technique at MDL. However, the structural integrity of micro grid based devices with very thin walls (~ 2-3 um) is a subject of concern. Yield may be an issue.

TRL 6 Technical Concerns

- **What risks exist in your key components not passing environmental testing for a TRL 6 assessment? The following are possible tests:**
  - Radiation testing
    - GEO surface charging concern (not a likely concern)
  - Survival temperatures (typically between +5 to +50 C) (to be tested, unlikely concern)
  - Thermal vacuum (to be tested)
  - Random vibration (to be tested, likely concern)
    - note: Vibe levels for low mass items are very high prior to coupled loads analysis.
  - Shock (to be tested, likely concern)
  - Acoustic (to be tested, likely concern)
  - Pre- and post- alignment, functionality (not a likely concern)

- **Any other environmental exposure risks that could damage a flight part?**
  - Humidity? (high humidity could be a concern, but easy to protect)
  - Contamination? (a likely concern, need protection in handling, storage and deployment)

- **Are there any concerns in fabricating your key components to meet TRL 6 fit, form, and function requirements by FY19.** None known at this time.