MEMS Deformable Mirror Development for Exoplanet Detection and Laser Applications

NASA Phase II SBIR: NNX11CE94P
NSF Phase II SBIR: NNX12CA42C

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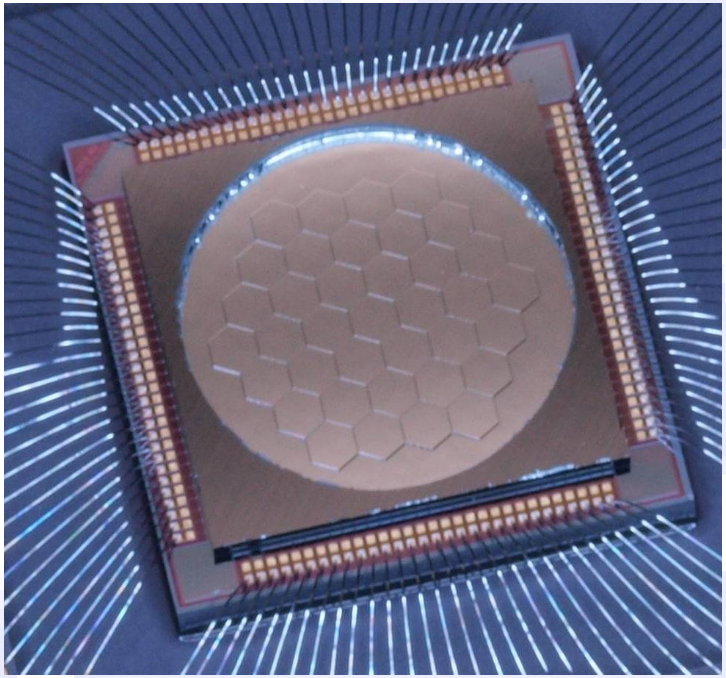
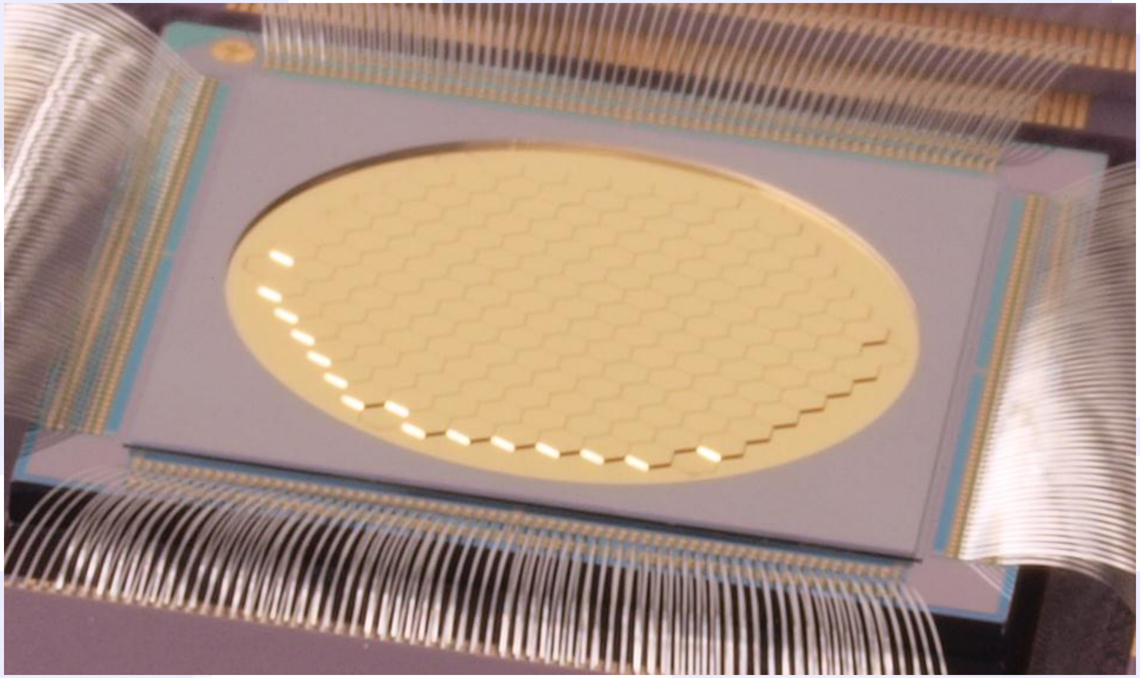
Iris AO MEMS Segmented Deformable Mirrors





PTT111 DM
- 111 Actuators
- 37 PTT Segments
- 3.5 mm inscribed aperture
- Factory calibrated

PTT489 DM
- 489 Actuators
- 163 PTT Segments
- 7.7 mm inscribed aperture
- Factory calibrated

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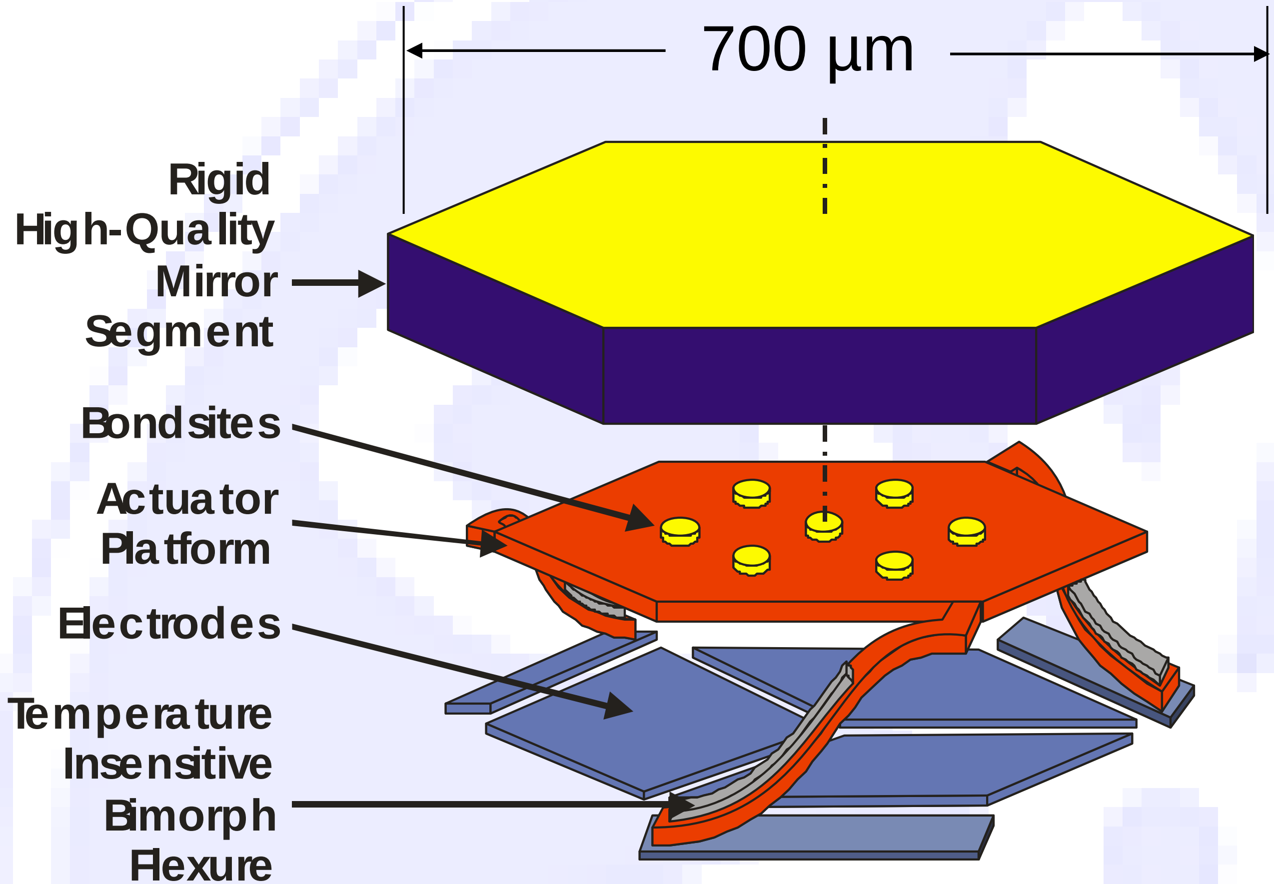
Iris AO Segmented DM Background



- **3 DOF: Piston/tip/tilt electrostatic actuation – no hysteresis**
- **Hybrid fabrication process**
  - **3-poly surface micromachining**
  - **Single-crystal-silicon assembled mirror**
- **Unit cell easily tiled to create large arrays**
- **Hybrid technology**
  - **Thick mirror segments**
  - **Enables back-side stress-compensation coatings**

Small
Business
Innovation
Research

NASA Phase II SBIR Picometer-Resolution MEMS Segmented DM

Iris AO, Inc.
Berkeley, CA

INNOVATION

Demonstration and delivery of a 313-segment MEMS-based deformable mirror (DM) with picometer resolution.

TRL Assessment - Start: 3 End: 4

PTT489-5 DM

TECHNICAL ACCOMPLISHMENTS

- Reduced systematic segment tilts for PTT489 DM (489 actuators, 163 segments)
- Modified fabrication process to reduce low-order chip bow
- Preliminary development of post-processing technique to compensate for chip-bow variations post release
- Modified DM actuator design to make it more robust to misalignment and manufacturing tolerances
- Increased fabrication yield
- Demonstrated fully-functional PTT489 DM

FUTURE PLANS

- Design and fabrication process changes on a production run of the PTT489 DM (489 actuator 163-piston/tip/tilt-segment deformable mirror)
- Build and deliver a fully functional 939-actuator, 313-PTT segment DM

GOVERNMENT/SCIENCE APPLICATIONS

- PTT489 DM being used for the Extrasolar Planetary Imaging Coronagraph (EPIC), PI: Mark Clampin, NASA/GSFC
- PTT111 DM (111-actuator, 37-piston/tip/tilt segment) used as a hardware simulator to test co-phasing of the JWST segments
- Extend to 1000 actuator devices for high turbulence imaging and laser communication applications (DoD) and 3000 actuators for high-contrast imaging applications (NASA)
- Demonstrate control to 15 pm *rms*
- Pending NASA SAT-TDEM award ($764k)

COMMERCIALIZATION

- Commercially Available Products:
    - PTT111 and PTT489 deformable mirrors
    - Smart Driver II: High voltage drive electronics
    - PTT111 and PTT489 AO Engine: Closed-loop adaptive optics system
- 6 patents awarded
- DMs purchased by academic and commercial researchers in vision science, ophthalmology, laser manufacturing, astronomy, and defense
- Better SWAP compared to piezoelectric stacked-actuator DMs
- No hysteresis
- Factory calibrated position controller linearizes operation and limits operation to safe bounds.
- Larger stroke than competing large-actuator technologies while maintaining speed

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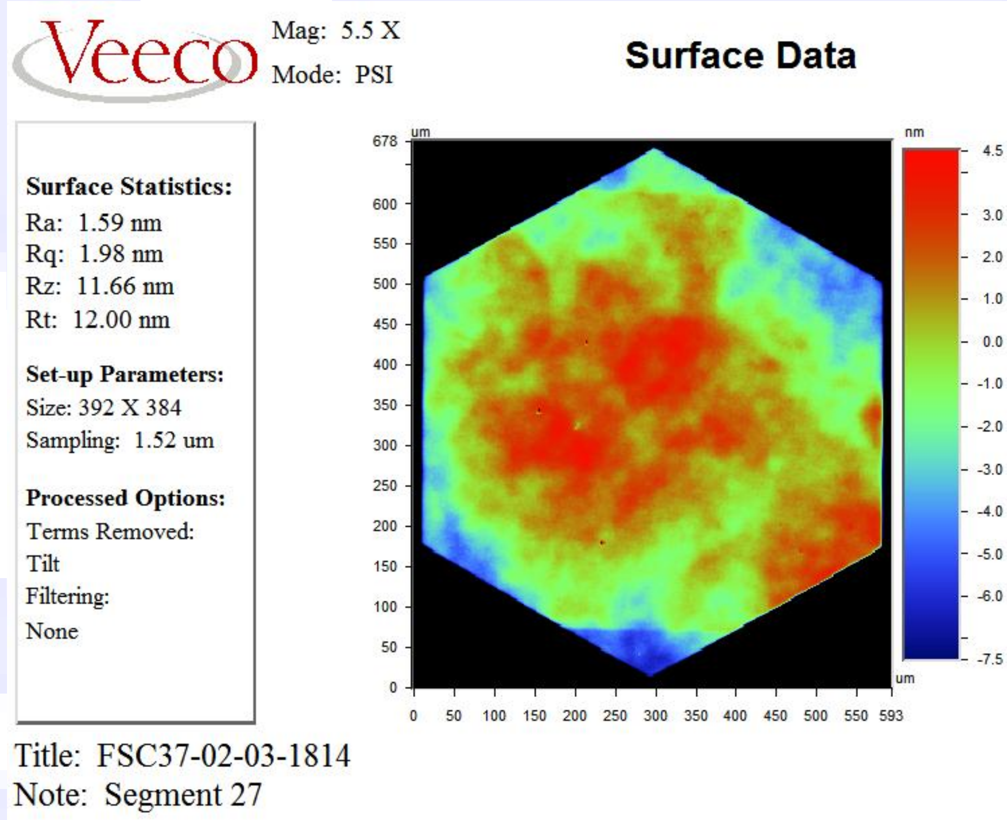
Exoplanet Imaging Requirements: *VNC Technology*

- **Usable Dynamic Range (Stroke): 0.5 µm**
- **Segment Control Resolution: 50 pm**
- **~1000 Segment DM**

- **Segment Flatness: 1-3 nm *rms***
  - **2 nm *rms* demonstrated**
- **Robust to snap-in failures**
  - **Anti-snap-in device (ASD) technology survives 100M snap-in events**



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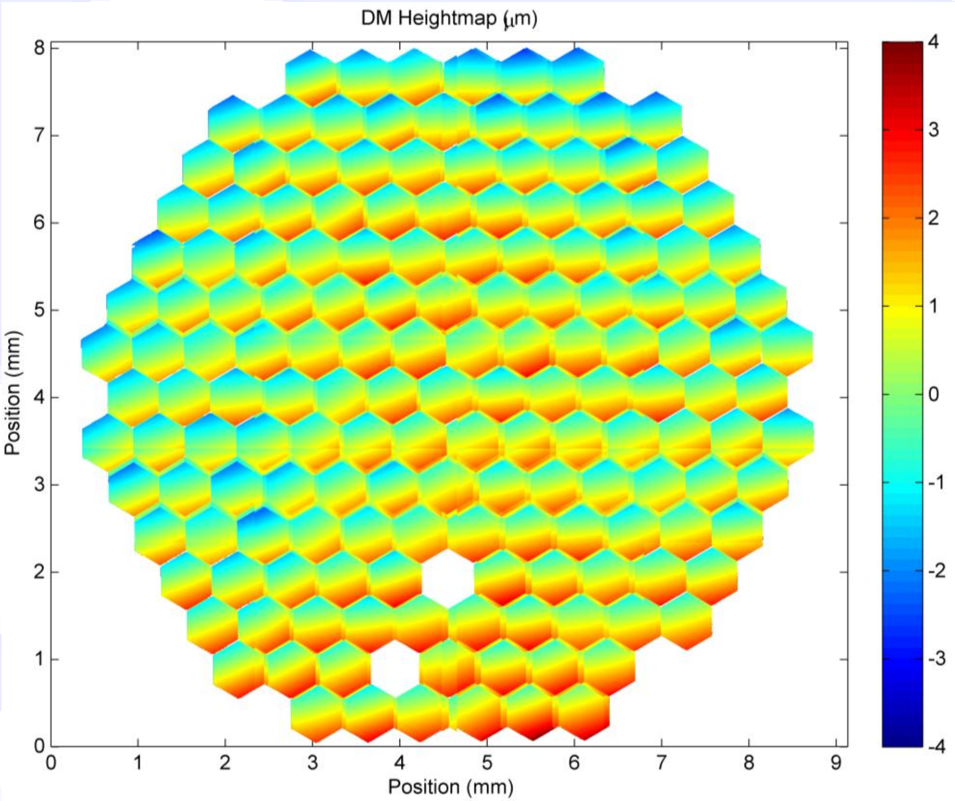
NASA Phase I SBIR (NNX11CE94P) Objectives

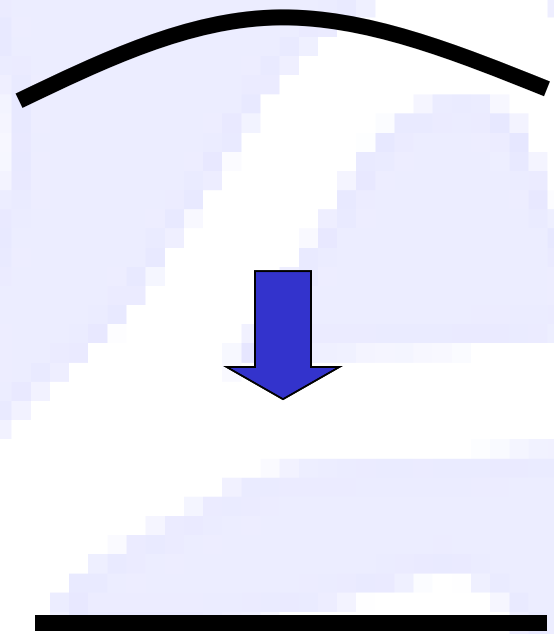
- Mitigate chip bow effects that cause deformation in the array
- Eliminate systematic tilts in the mirror arrays caused by misalignment in contact lithography system
- Mitigate random segment position variations
- Continue to improve DM yield by tracking and codifying fabrication defects and failure modes



Unpowered PTT489 DM

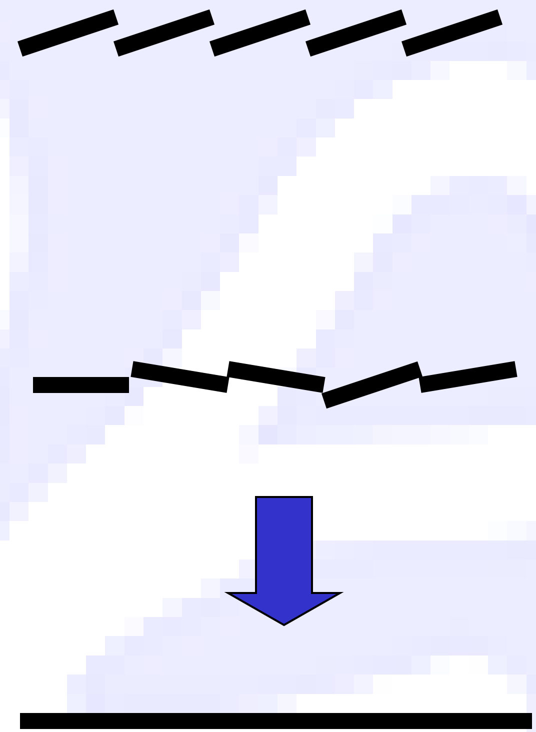
NASA Phase I Results – Chip Bow

- **Chip bow reduction critical for larger DMs**
- **Systematic: stresses in thin films on top of wafer**
  - **<u>Objective</u>: Modify layer thickness to reduce net bow**
  - **<u>Result</u>: Mean bow negligible, chip-chip variations dominate - layer thicknesses already optimized**
  - **<u>Objective</u>: Test thicker wafers in fabrication process**
    - **Increasing wafer from 625-950 μm reduces PV bow 2.3X**
  - **<u>Result</u>: All tools used in fabrication process tested**
    - **Wafer boat in one furnace needs to be replaced for Phase II**
- **Random: run-to-run and wafer-to-wafer variations in thin-film stresses**
  - **<u>Objective</u>: Demonstrate post-process bow compensation technique**
  - **<u>Result</u>: Corrective range: -50 nm – 150 nm for initial tests (with 625 μm thick wafers)**
    - **Require 3X increase in Phase II**

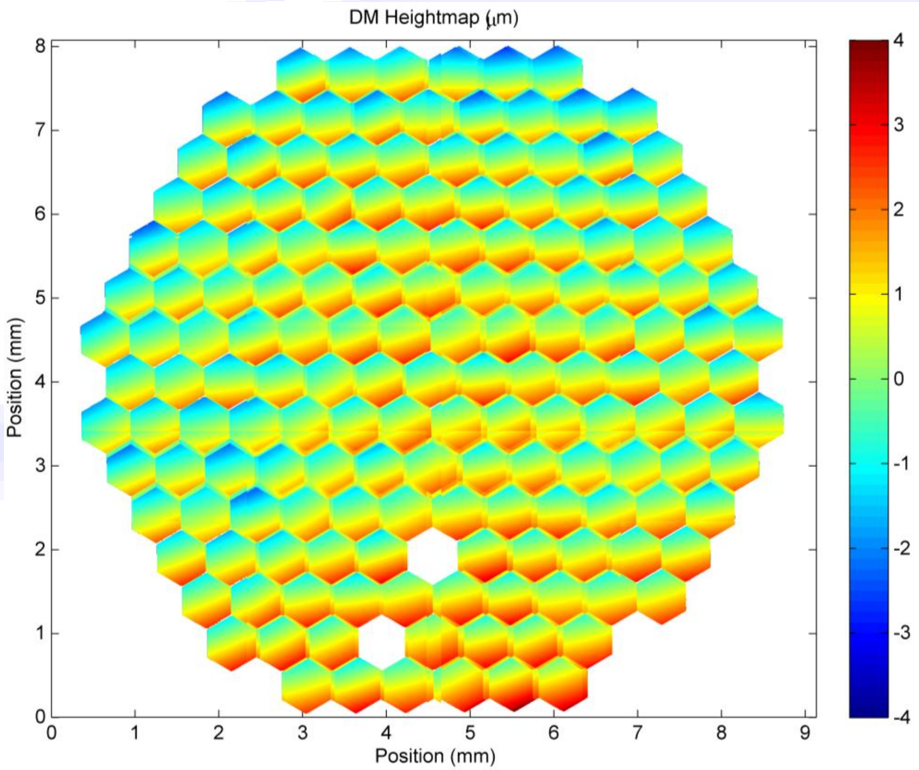


NASA Phase I Results – Segment Position Variations

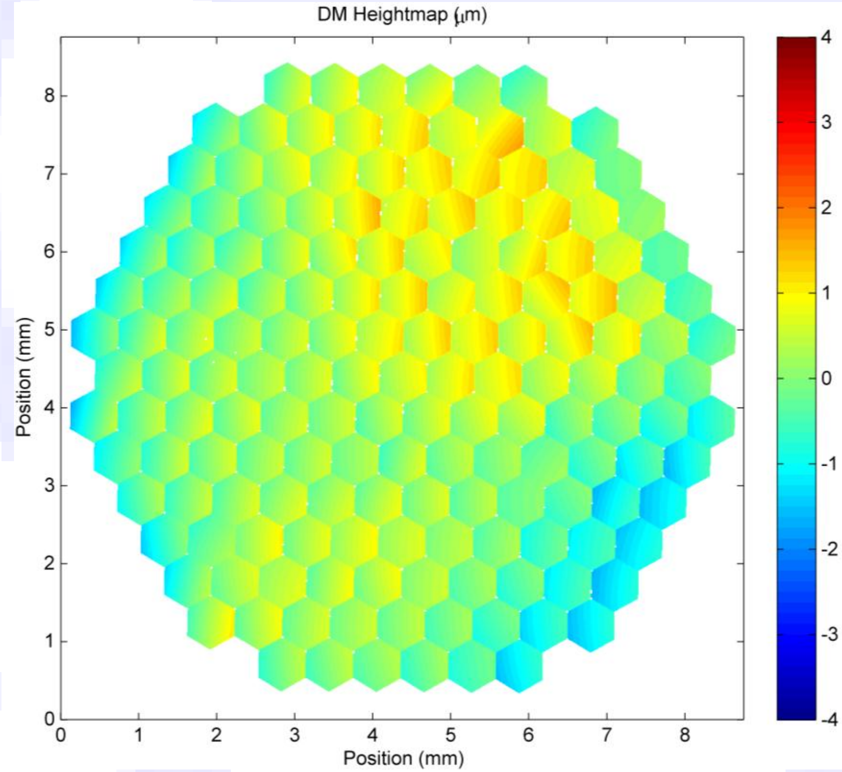
- **Systematic tilts from misalignment during contact lithography**
  - **<u>Objective</u>: Reduce with self-aligned structures**
  - **<u>Results</u>:**
    - **9X reduction in actuator platform on same wafer**
    - **4.2X reduction in DM arrays across wafers**
- **Random segment positions from process variations (lithography, release)**
  - **<u>Objective</u>: Modify designs and process fabrication to make less susceptible to dimensional variations**
  - **<u>Results</u>:**
    - **Flexure dimensional variation reduction: 22.7% to 2.4% across wafer**
    - **Tilt variation reduction in DMs: 16-33%**
    - **Height variation reduction: 11%**



NASA Phase I Improvements – Unpowered PTT489



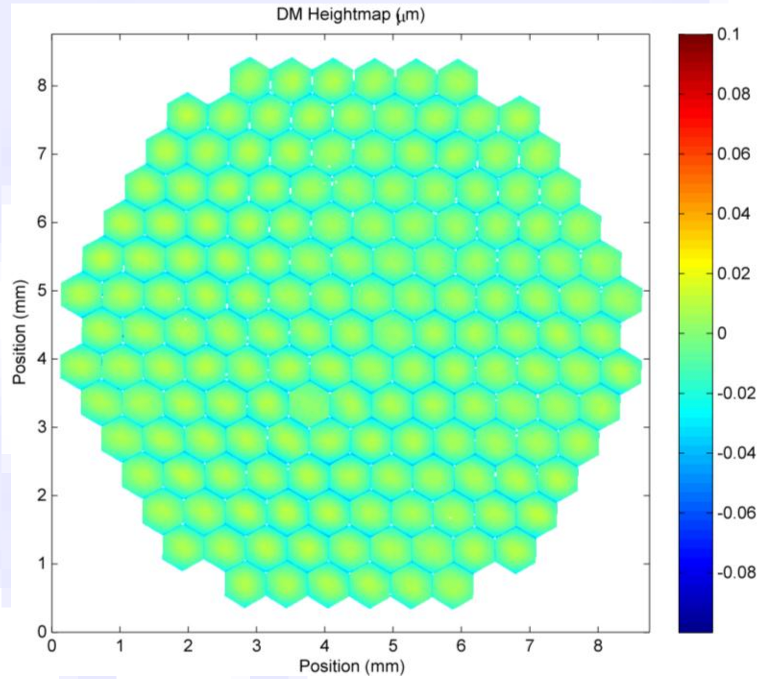
Pre Phase I



Post Phase I

NASA Phase I Results – Yield Increases

- **Objective: Increase yield**
- **Results:**
  - **Dramatic increase in segment yield**
  - **Fully functional PTT489 DMs demonstrated**



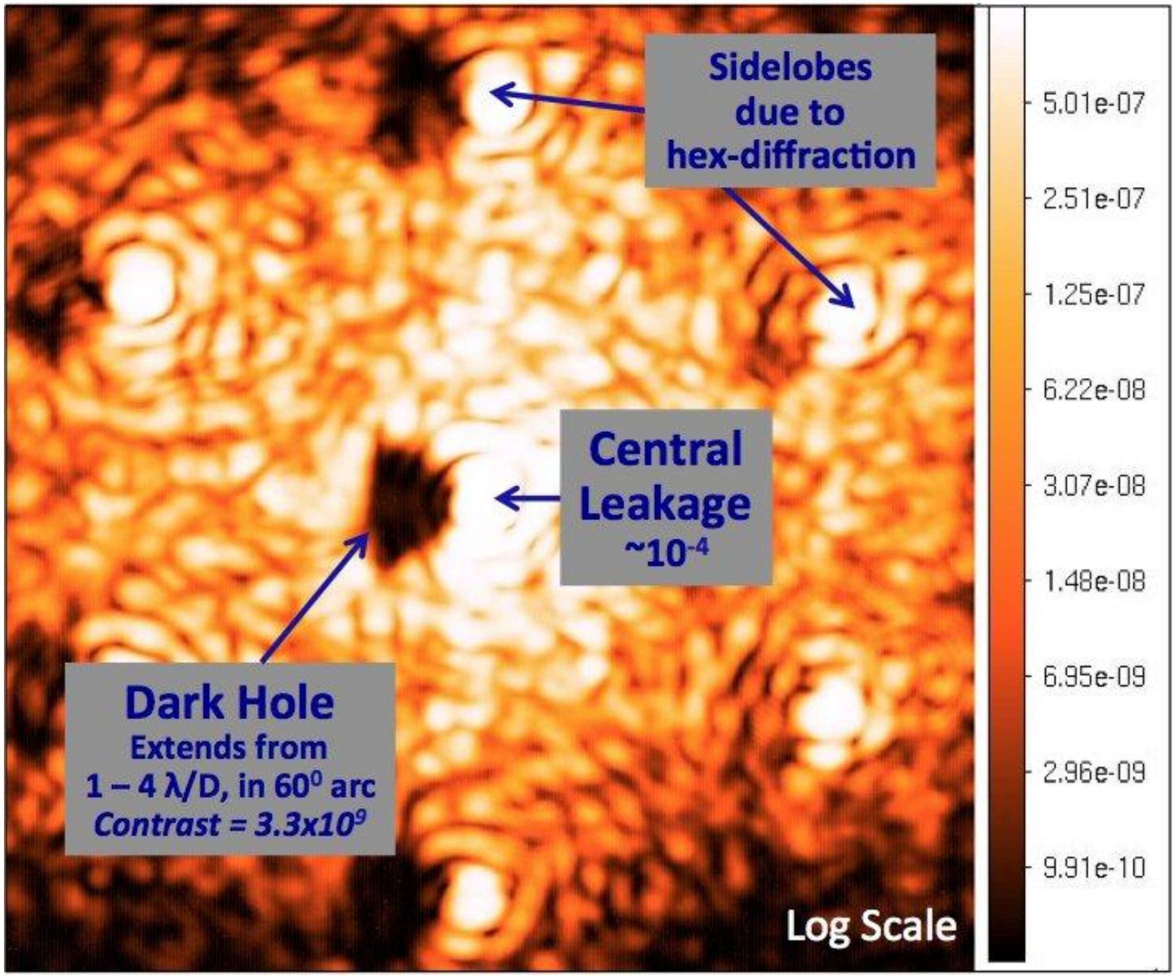
Flattened PTT489 DM

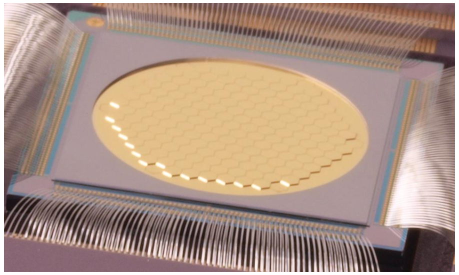
Mirror Build	Actuator Wafer Version	Mirror Wafer Version	Mech. Segment Yield	Electrical Segment Yield	Total Segment Yield	Chip Yield
1	1	1	66.8%	83.4%	55.7%	0.0%
2	1	2	93.9%	92.4%	86.8%	0.0%
3	2	2	97.6%	98.8%	96.8%	18.8%

SBIR Success Story

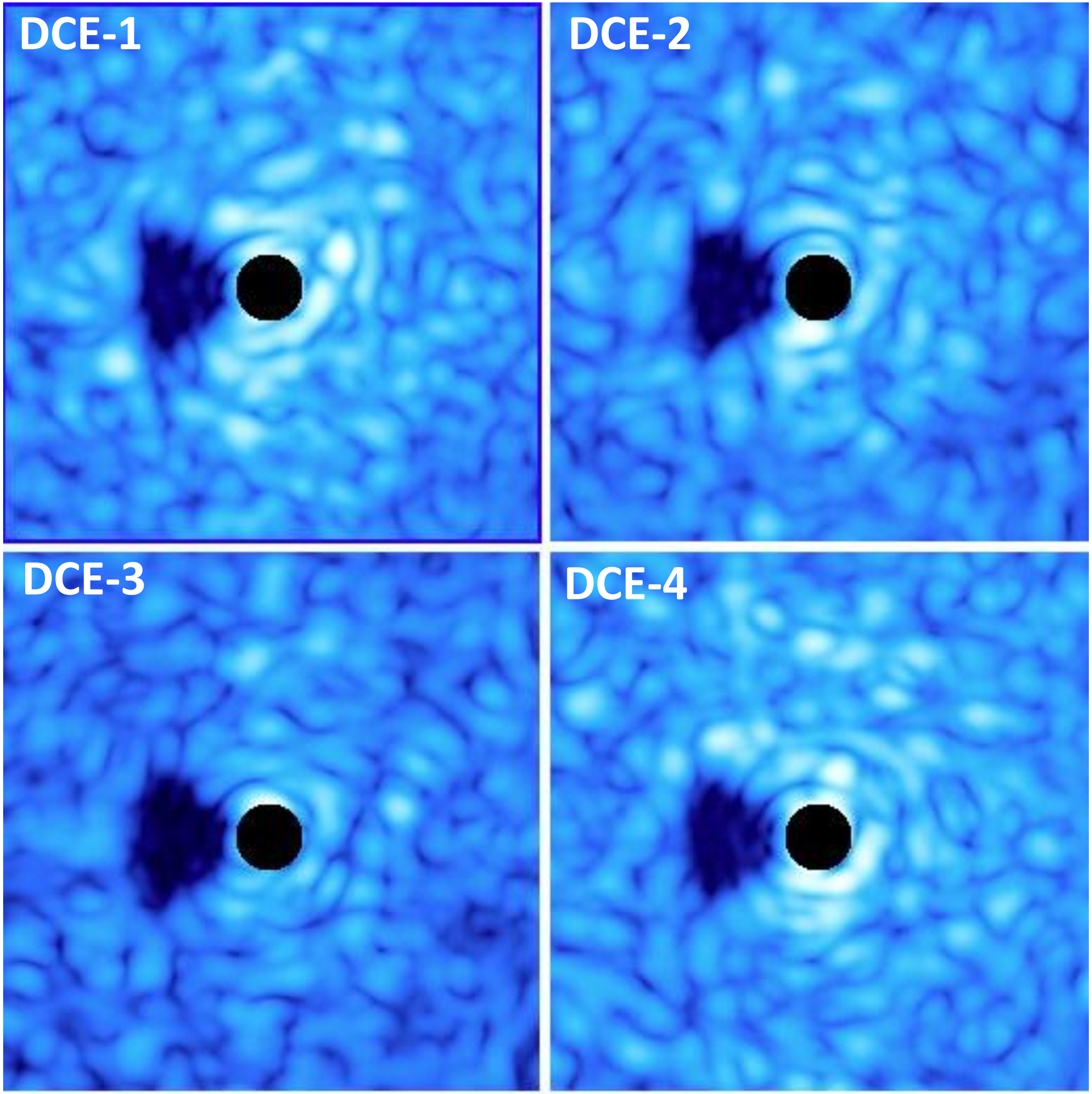
10^9 Contrast @ IWA 1 – 4 λ/D Results
GSFC VNC Instrument on 06/09/12

- GSFC/Visible Nulling Coronagraph
- 4 Data Collection Events (DCE)
  - 50,000 frames per DCE
  - Average last 3,800 frames
  - Closed-loop at 40 Hz / 4 Hz in vacuum tank
  - (λ,Δλ) = (633, 1.2) nm
- **>10^9 Contrast averaged over 1-4 λ/D, 60^0 arc region**
- 1st Demo of segmented aperture coronagraphy
  - hex-packed segmented MEMS DM
- Meets FY10/11 TDEM milestones
- FY12/13 TDEM broaderband
  - increase spectral bandpass from Δλ= 1.2 nm to Δλ= 40 nm
- VNC investigated in 3 Astrophysics Strategic Mission Concept Studies
  - ATLAST, EPIC, DAViNCI





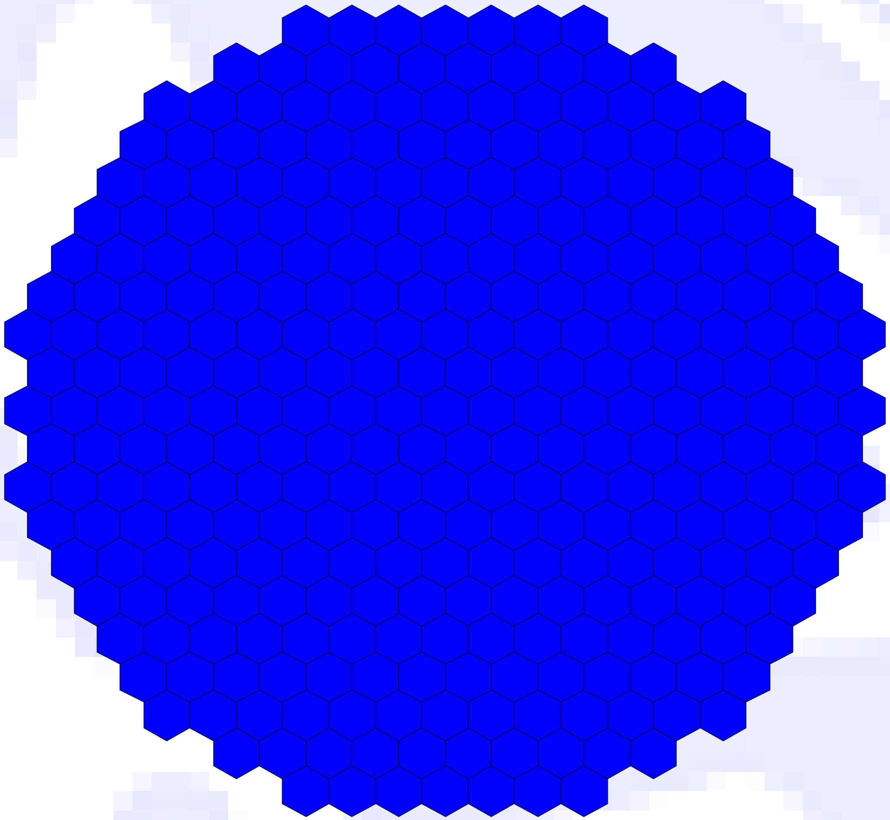
GSFC/VNC Team
06/09/12



Log Scale

NASA Phase II SBIR Objectives

- **Transition fabrication process to DUV stepper lithography system**
- **Improve MEMS design and manufacturing processes to result in DM array flatness <300 nm *rms***
- **Demonstrate a 313-segment DM**
- **Improve manufacturing yields to deliver a fully functional 313-segment DM**
  - **Mechanical and electrical yield > 99.25%**

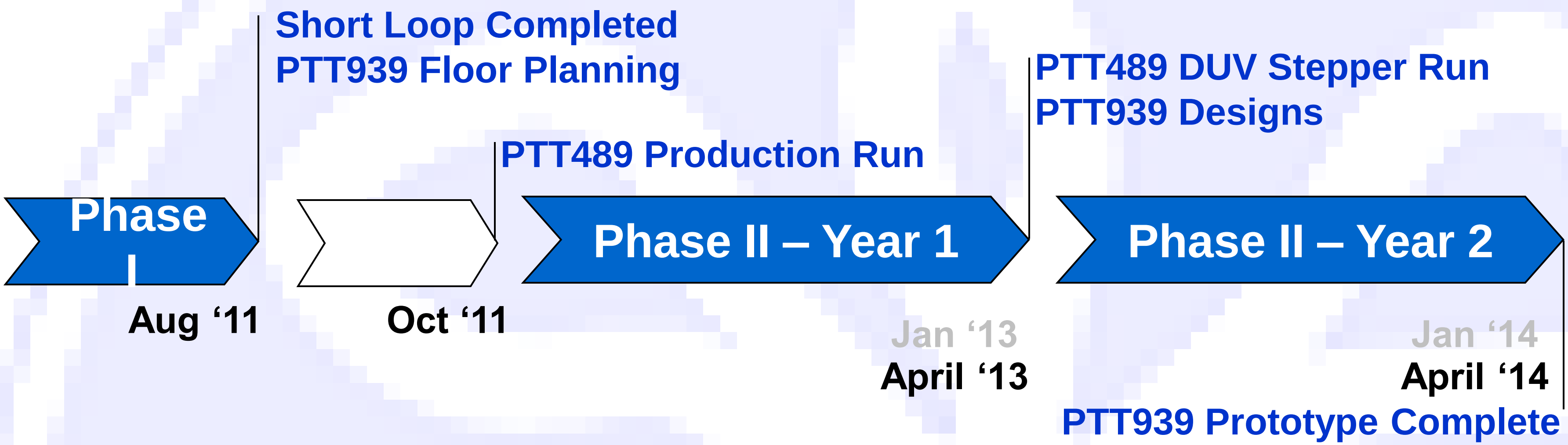


PTT939 DM
10.85 mm aperture
313 PTT segments
939 actuators

NASA Phase II Results (Q1)

- Refined MEMS release step to increase mechanical yield
  - Mechanical yield > 99.25%
- Developed DUV lithography recipes

Development Timeline



SAT-TDEM

- Technology Development for Exoplanet Missions (TDEM) awarded
  - Start date pending contract
- Space qualification of PTT489 DM
  - TRL 4 → 5
  - Shock, vibe, radiation testing
- FEM Modeling, validation, environmental testing, design iteration

Small **B**usiness **I**nnovation **R**esearch

NSF Phase II SBIR: Dielectric Coating of MEMS Deformable Mirrors

Iris AO, Inc.
Berkeley, CA

INNOVATION

Design and fabrication process developments to enable use of DMs with high-power lasers. Developments enable application of highly-reflective dielectric coatings onto DMs that range from 355 nm to 1540 nm.

TRL Assessment - Start: 2/3 End: 3/4

TECHNICAL ACCOMPLISHMENTS

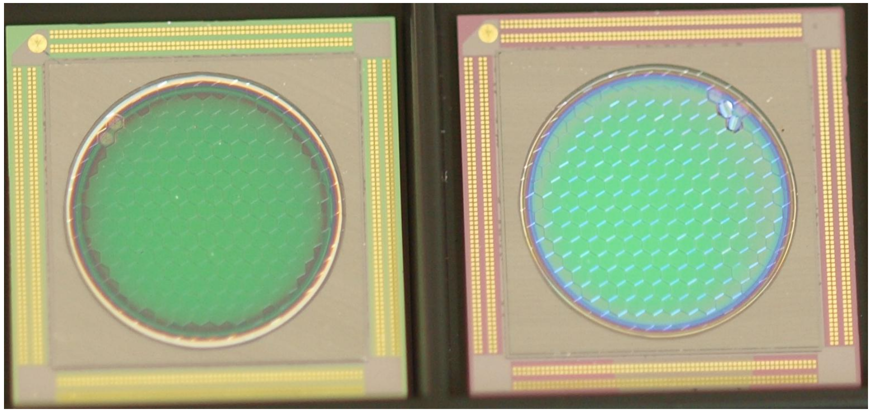
- Developed a compensation layer to enable dielectric coating of DMs for 1064 and 1540 nm
- Fabricated mirror arrays with compensation coatings
- Demonstrated high-quality coatings at 532nm, 1064nm and 1540 nm
- Conducted laser testing showing ability of DMs with existing packaging to handle 300 W/cm^2
- Laser testing and models show with heatsinking, 2800 W/cm^2

FUTURE PLANS

- Improve DM design to enable >2800 W/cm^2 power handling
  - Heatsinking
  - Compensate for CTE mismatches
  - Reduce segment gaps

GOVERNMENT/SCIENCE APPLICATIONS

- Laser guidestar uplink correction
- Free-space laser communications
- Potential DoD and Directed Energy Applications
  - Designator lasers
  - Probe beams for HEL systems
  - Countermeasures for heatseaking missiles



PTT489-5 DMs with Dielectric Coatings (L: 1064 nm, R: 1540 nm)

COMMERCIALIZATION

- Commercially Available Products:
  - PTT111 and PTT489 deformable mirrors
  - Smart Driver II: High voltage drive electronics
  - PTT111 and PTT489 AO Engine: Closed-loop adaptive optics system
- 6 patents awarded
- DMs purchased by academic and commercial researchers in vision science, ophthalmology, laser manufacturing, astronomy, and defense
- High-speed focus correction and beam shaping for laser micromachining
- Better SWAP compared to piezoelectric stacked-actuator DMs
- No hysteresis
- Factory calibrated position controller linearizes operation and limits operation to safe bounds.
- Larger stroke than competing large-actuator technologies while maintaining speed

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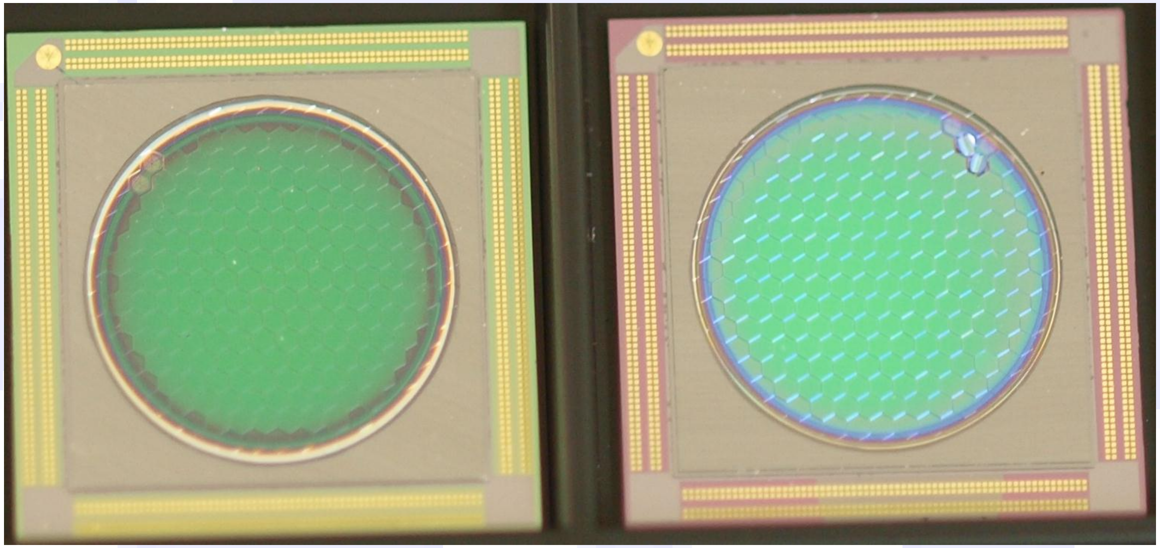
NSF Phase I SBIR: *Longer Wavelengths - 1064 μm, 1540 μm*



PTT489 DMs w/ Dielectric Coatings

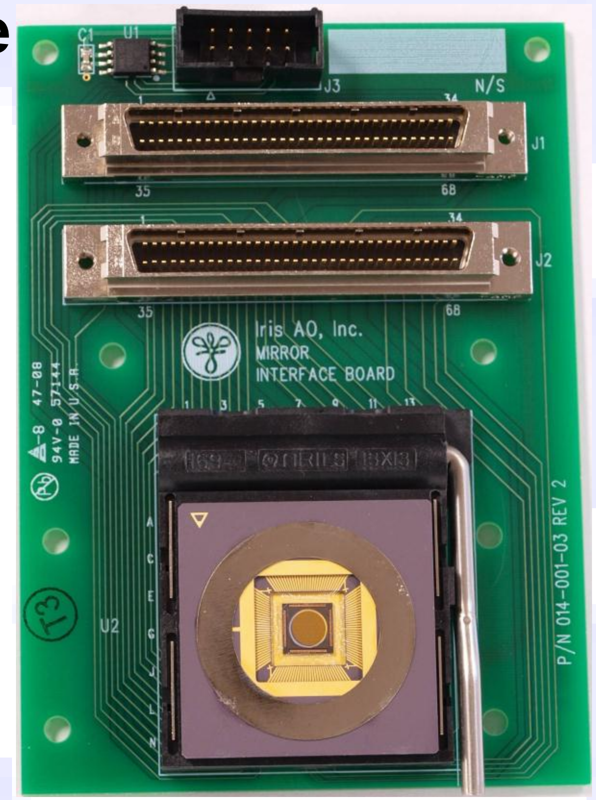
- 1064 nm Coating, R=99.85%
- Coating Thickness: 5.41 μm
- As Coated Flatness
  - λ/27.7 (38.4 nm *rms*)
- Post-Processed Flatness
  - λ/93.3 *rms* (11.4 nm *rms*)

- 1540 nm Coating, R=99.85%
- Coating Thickness: 7.88 μm
- As Coated Flatness
  - λ/20.4 *rms* (75.3 nm *rms*)
- Post-Processed Flatness
  - λ/75.9 *rms* (20.3 nm *rms*)

Same compensation layer used for 1064 and 1540 nm coatings
→ reduces fabrication costs

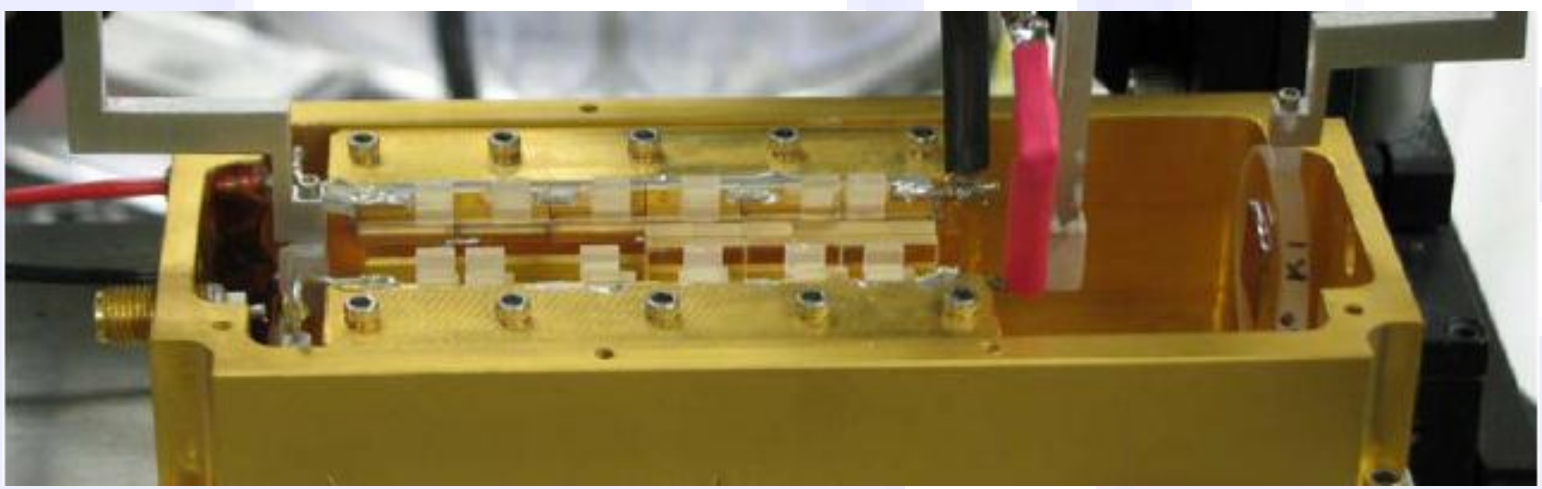
CW Power Handling: 532 nm

- **Limit to λ/20 *rms* increase in figure error**
  - **$\Delta T_{segment}$ = 90 °C**
- **With existing packaging**
  - **300 W/cm^2**
- **With heat sinking**
  - **2,800 W/cm^2**
- **Higher power handling possible**
  - **Higher reflectance coatings**
  - **Reduced gaps**
  - **Conceivable to get to ~10kW/cm^2**



Pulsed-Laser Testing: 1534 nm

- **Sample dielectric coatings tested**
- **Extra-cavity peak power 764 MW/cm^2**
  - **4.2 mJ, 7 ns, 1 mm diameter**
- **Intra-cavity peak power 1.7 GW/cm^2**
  - **42 mJ, 7 ns, 1 mm waist**



Phase II Goals

- Improve power handling capabilities: 2.8 kW/cm^2
  - Compensate for stress *and* CTE mismatches in the coatings
  - Increase fill factor to >98%
  - Packaging for lasers – heatsinking
- Improve mirror figure: <λ/40
- Speed improvements
  - Regain speed loses from using thicker 50 µm segments

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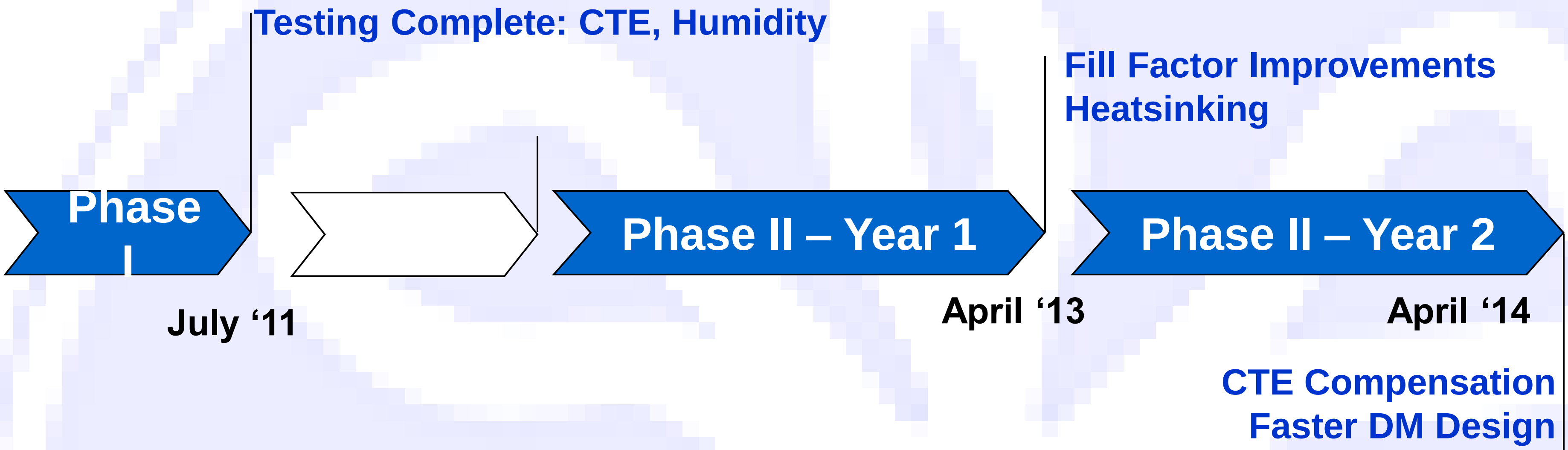
Phase II Results

- **Process development to reduce mirror gaps**
  - **Increase fill factor > 98%**

Development Timeline



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Summary

- **Lower unpowered segment position errors**
  - **< 300 nm *rms***
- **Larger fully-functional DM arrays**
  - **10^3 actuators**
- **Improved laser power handling**
  - **2.8 kW/cm^2**