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14. ABSTRACT Large-actuator-count deformable mirrors (DM) are essential for high-contrast imaging systems NASA is developing for exoplanet detection. These same mirrors can be used to correct aberrations from atmospheric turbulence for free-space communications and imaging applications. This presentation presents recent results on improving performance of DMs and scaling the DM technology to nearly 500 actuators. Performance improvements include the development of dielectric coatings and the demonstration of DMs with snap-in-failure mitigation devices. The presentation further describes work towards extending the DM technology to thousands of actuators.					
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Large-Actuator-Count MEMS Deformable Mirror Development

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NIH/NEI Phase II SBIR: 2 R44 EY015381-02A1

NASA Phase I SBIR: NNX09CE01P

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PTT489-5 Segmented PTT Deformable Mirror

*Iris AO, Inc.
Berkeley, CA*

INNOVATION

PTT489 Segmented MEMS Deformable Mirror: A 489 actuator, piston/tip/tilt positionable deformable mirror used to correct optical aberrations.

ACCOMPLISHMENTS

- ◆ Conducting production runs
- ◆ Dramatic improvement in reliability and failure proofing
- ◆ Beta devices delivered with > 99% segment yield
- ◆ Segment figure < 5 nm *rms*
- ◆ Dielectric coatings demonstrated
- ◆ Path-finding research demonstrating 3000 actuator devices
- ◆ Beta devices purchased from NASA GSFC and by customers using them for other SBIR projects

COMMERCIALIZATION

- ◆ PTT489, 489 actuator piston/tip/tilt deformable mirror
- ◆ 6 patents awarded, 1 patent pending
- ◆ PTT111 and PTT489 DM currently being sold
- ◆ DMs purchased by NASA/GSFC and researchers in vision science, astronomy, and defense
- ◆ Factory calibrated position controller linearizes operation and limits operation to safe bounds.
- ◆ Larger stroke than competing large-actuator technologies while maintaining speed
- ◆ Rigid mirror segments enable dielectric coatings



PTT489-5 DM

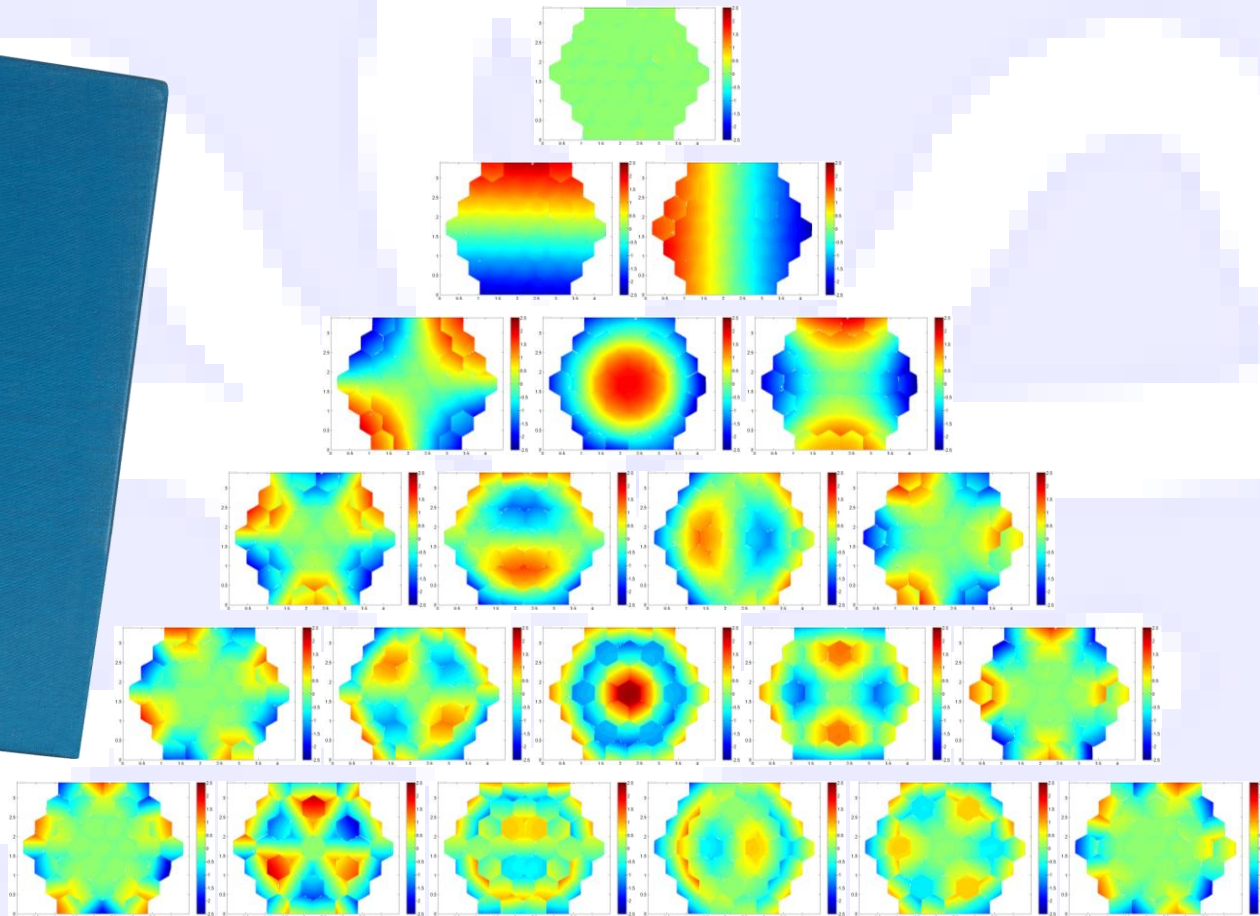
GOVERNMENT/SCIENCE APPLICATIONS

- ◆ High-stroke micromachined deformable mirror to correct aberrations caused by turbulence or to actively correct optical system aberrations
- ◆ Extend to 1000 actuator devices for high turbulence imaging and laser communication applications (DOD) and 3000 actuators for high-contrast imaging applications (NASA)
- ◆ Actual applications: Nulling coronagraphs for exoplanet imaging, Atmospheric turbulence compensation for free-space laser communication, laser guide star uplink correction
- ◆ Actual applications: Potential applications: High-speed focus correction for laser machining
- ◆ Phase III purchase of DM by NASA GSFC for Extrasolar Planetary Imaging Coronagraph (EPIC), GSFC, Clampin et al.
- ◆ Purchases of PTT489 by DOD SBIR winners using DM for their projects

Outline

- **Background: *PTT111-X (S37-X)***
- **PTT111 Improvements**
- **Scaling up: *PTT489-X and beyond***
- **10^3 segment DM pathfinding research**

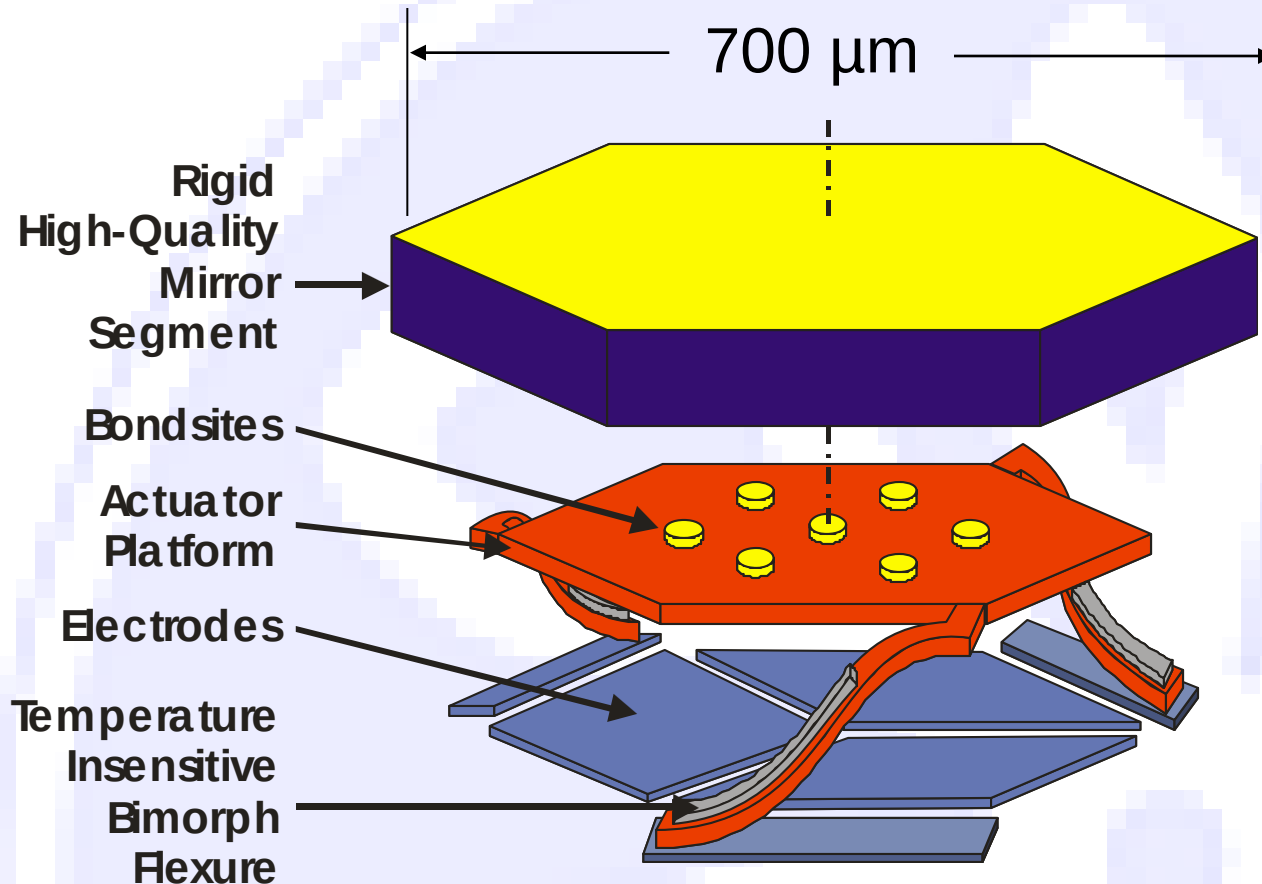
PTT111: *A Solid Foundation*



June 7th, 2010

NASA Mirror Technology Days 2010

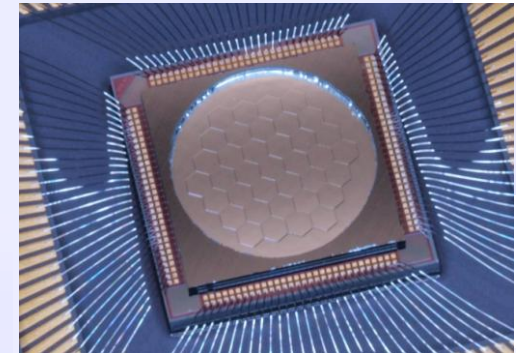
DM Segment Schematic



- 3 DOF: Piston/tip/tilt electrostatic actuation
- Hybrid fabrication process
 - 3-poly surface micromachining
 - Single-crystal-silicon assembled mirror
- Unit cell easily tiled to create large arrays

1st Generation DM Attributes

- **High Stroke: 5 μm , 8 μm**
 - 10+ μm in controlled environments
- **Flat mirror segments: < 30 nm *rms***
 - 0.25 – 4 nm PV bow /°C
- **Fast mirror rise time**
 - 120/140 μs rise/fall times, 20-80%;
1.63 μm , 36 V
- **Precision factory-calibrated controller**
 - Linear, open-loop operation
 - Implements position limiting
- **Compact drive electronics**
- **Open-air operation**
 - Tested >1000 hrs, 20-70% RH



Smart Driver II – 128 USB

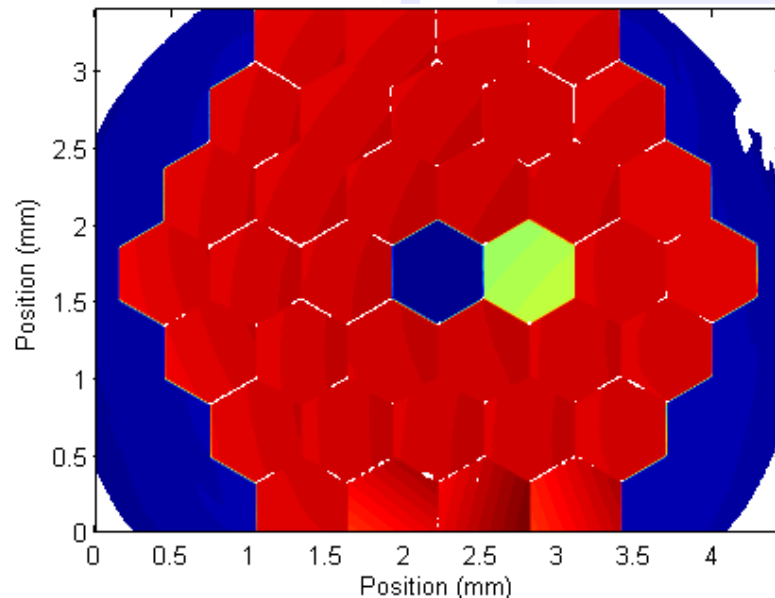
- 128 Channels
- High resolution
 - 14 bit, 200 V
- Low Noise:< 4mV *rms*
- Factory calibrated

PTT111-X Design and Process Improvements: *Better, then Bigger*

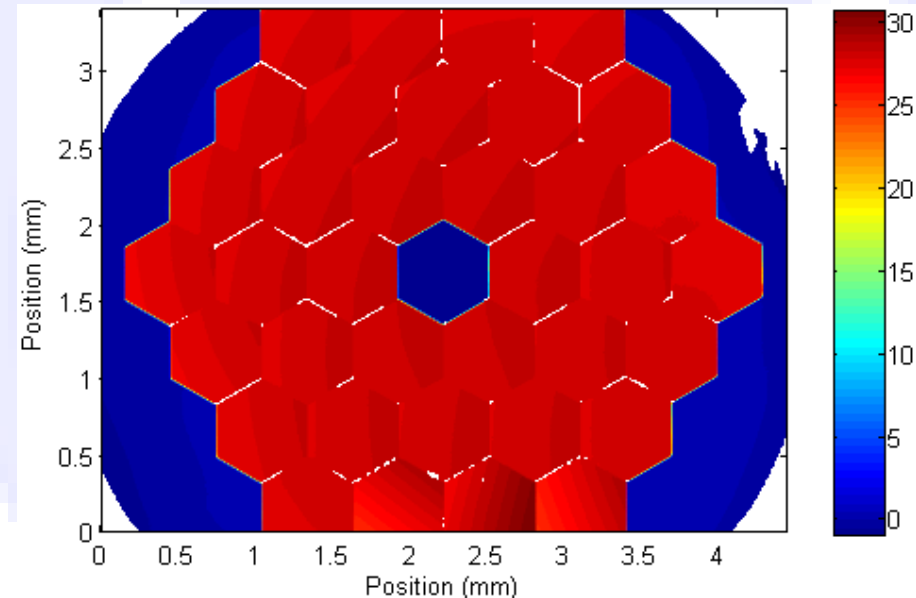
PTT111 DM Improvements

- **Flatter mirror segments**
 - **<5 nm rms**
- **Improved reliability**
 - **Snap-in prevention structures**
- **Relatively high-laser fluence demonstrated**
 - **Off-the shelf DM w/ protected-aluminum coating: $\sim 95 \text{ W/cm}^2$**
- **Dielectric coatings demonstrated**

Anti Snap-In Device: *After 100,000,000 Snap-In Events*



Segments Over Driven

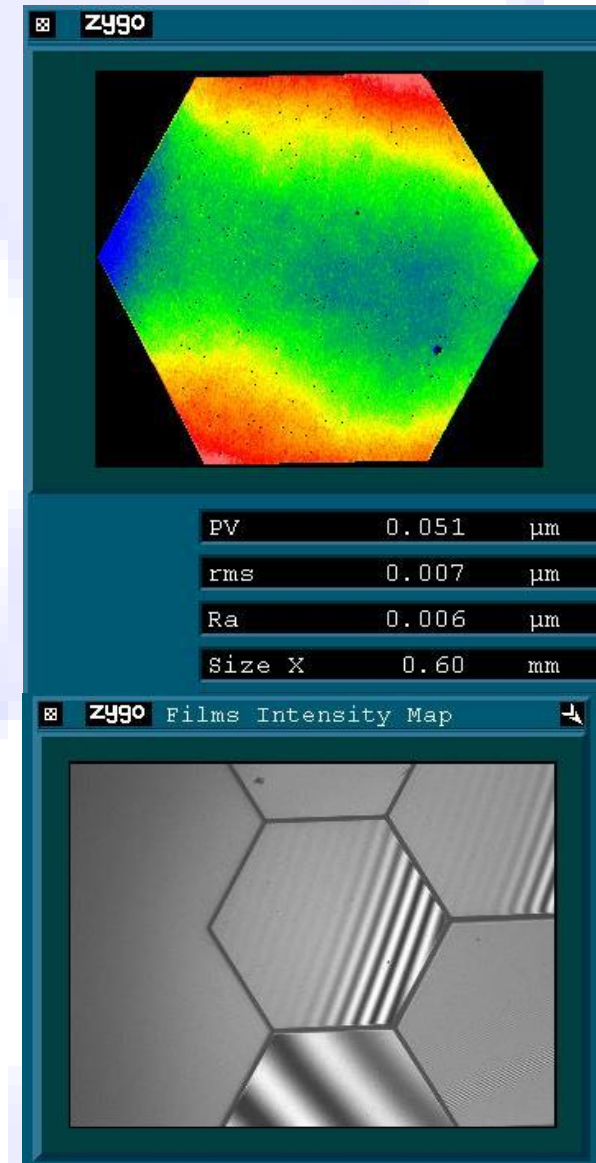


Voltage Removed

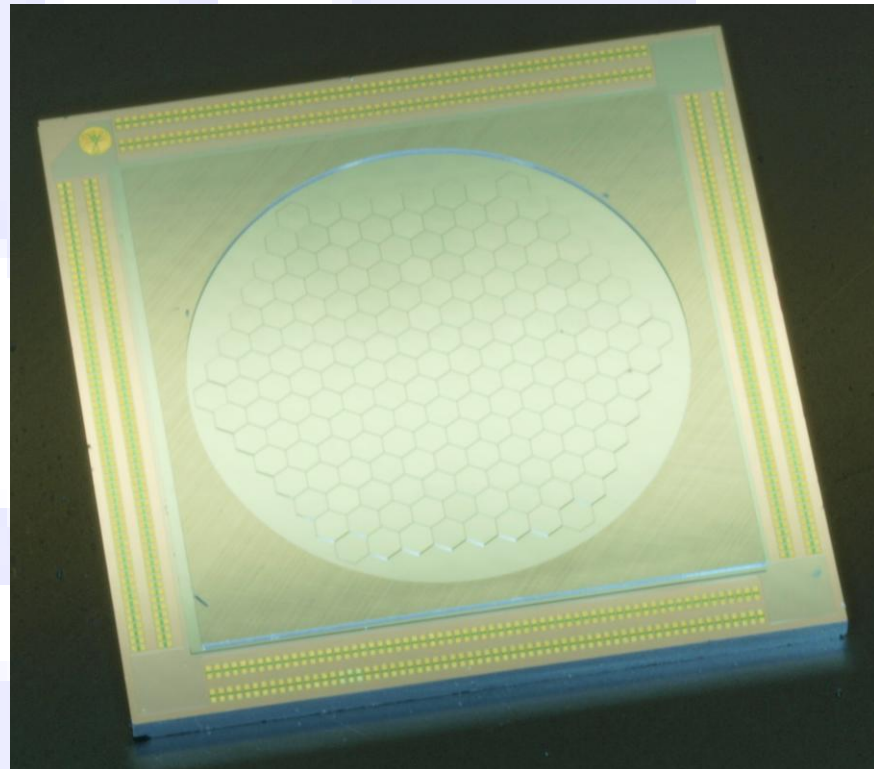
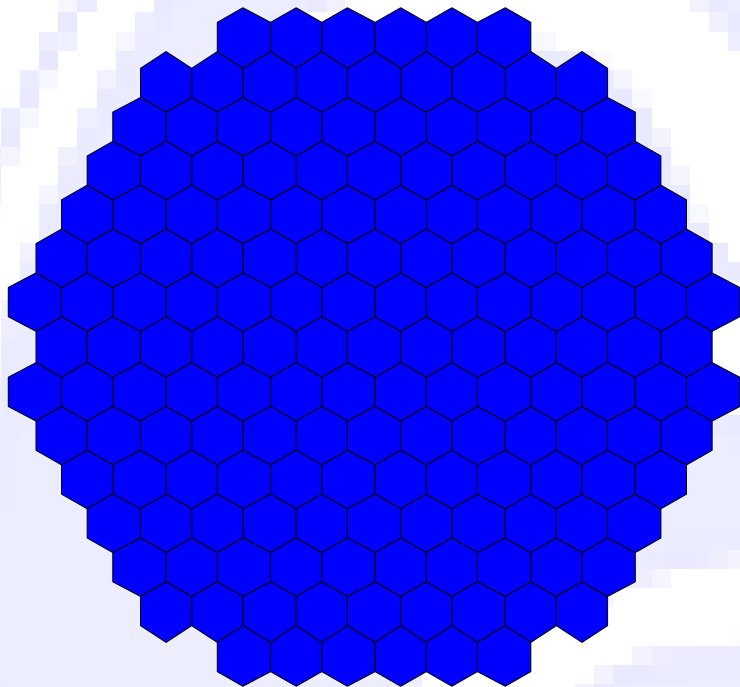
- Center segment fails because no snap-in protection
- Adjacent segment with protection survives
 - Testing stopped after 100,000,000 snap-in events with no failure

High-Quality Dielectric Coatings

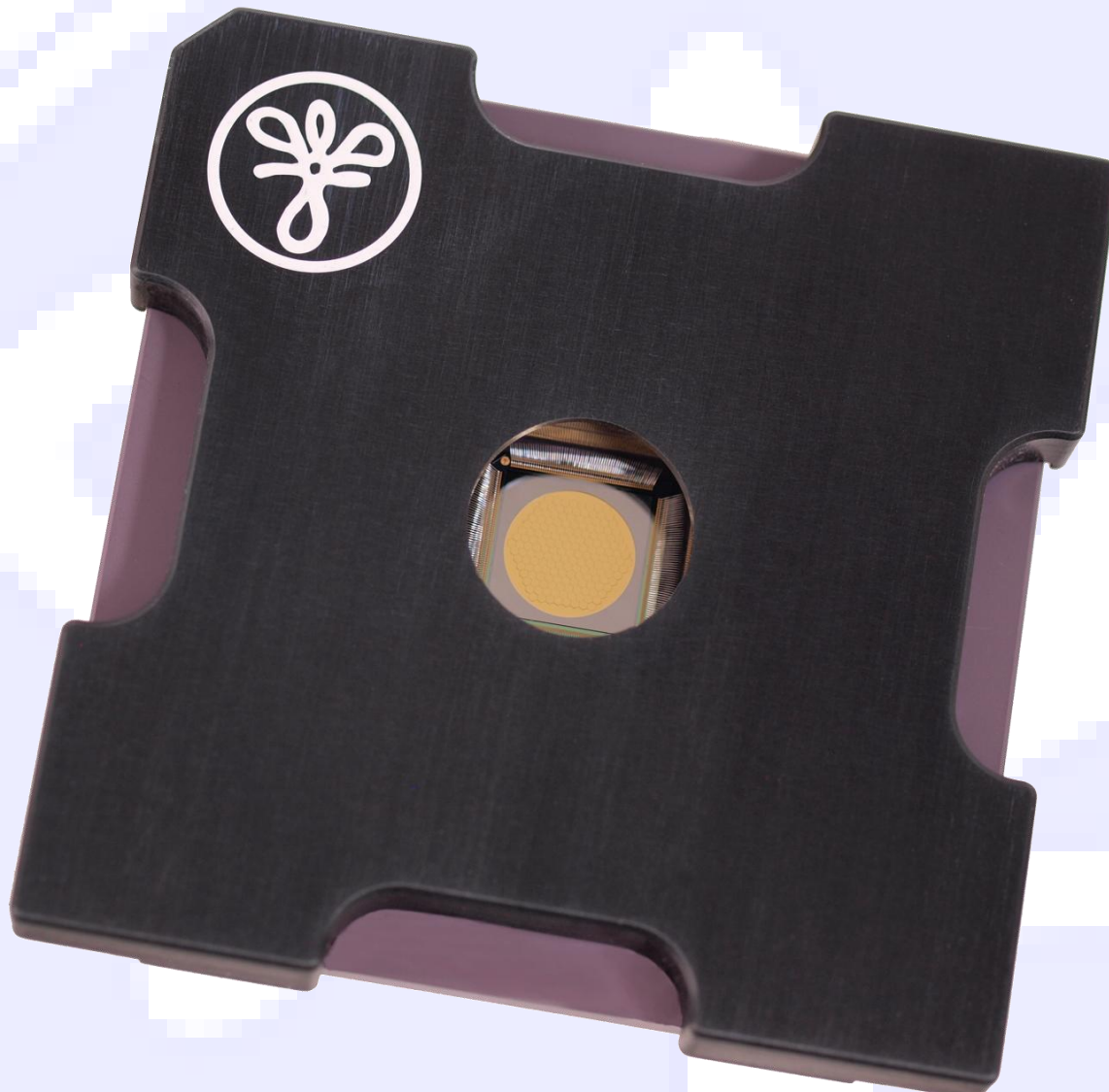
- **>99.9% reflectance dielectric coatings @ 532 nm**
 - **< 30 nm *rms* residual surface figure errors**
 - **~1.5 μm thick coating**
 - **Backside stress compensation layer**
- **Protected-Al coatings survived ~95 W/cm²**
 - **Off-the-shelf DMs**
 - **Laser testing done at Laboratory for Adaptive Optics (LAO)**
- **Expect off-the-shelf dielectric coated DMs to be at least 10X higher**



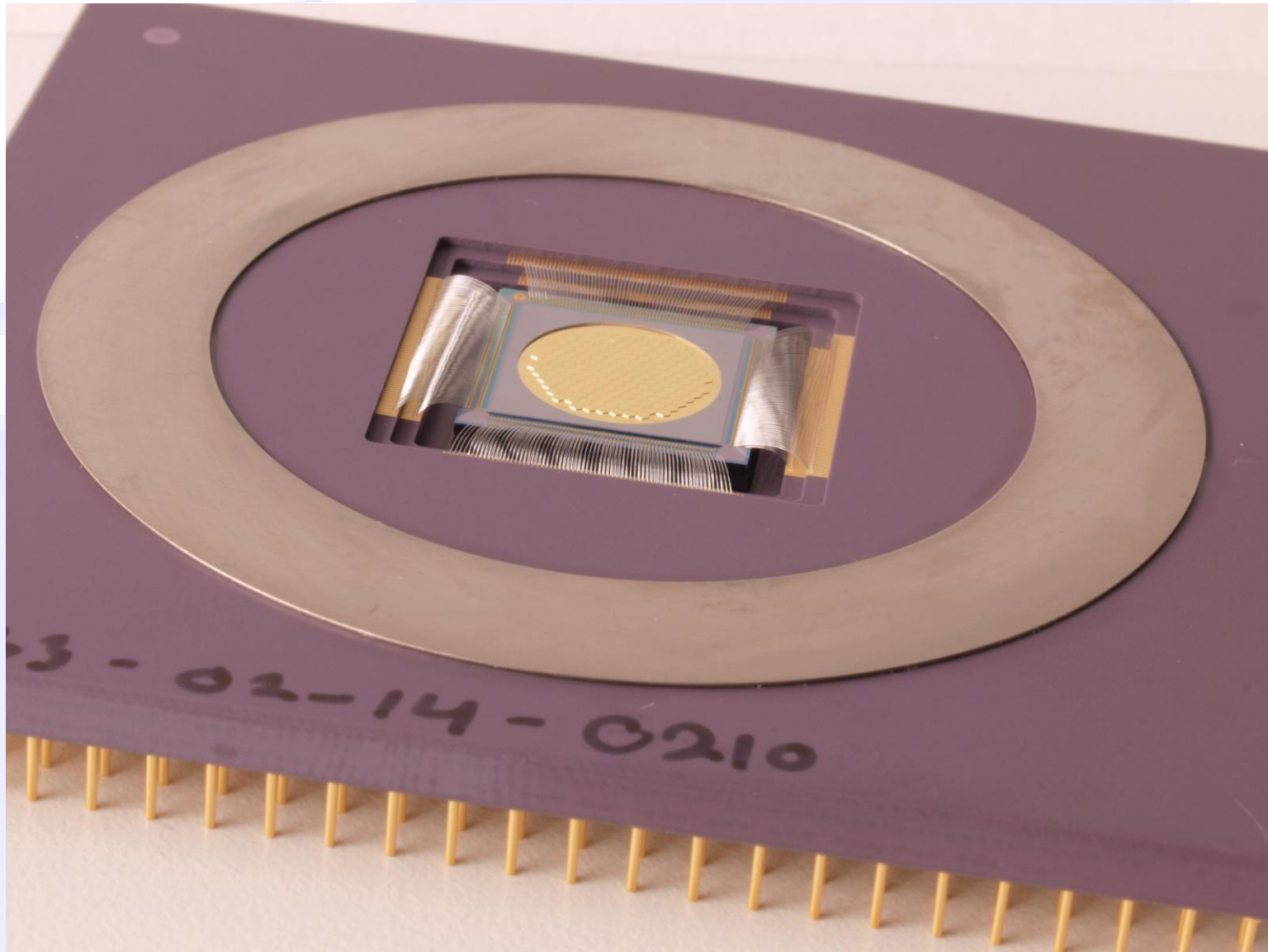
Scaling Up: *PTT489-X DM*



PTT489-5 DM with Removable Cover



PTT489-5 DM



1st Generation DM: *PTT111*

- **PTT111 used to develop basic systems and conduct testing**
 - **MEMS process development**
 - **Electrical characterization**
 - **Calibration**
 - **Software drivers**
 - **AO controllers**
 - **Reliability testing**
 - **Optical coating development**
- **Most aspects were tailored to PTT111**

Scaling Up: *Creating an Extensible Design*

- **MEMS design/process inherently scales well**
 - Demonstrated stepper and contact photolithography
 - Existing design extensible to ~4000 actuators
 - Larger possible with development of interconnect
- **New electrical tester for MEMS testing and characterization**
 - Extensible to > 10,000 of actuators
- **New calibration interferometer (ARRA Stimulus grant from NIH)**
 - Larger FOV
 - Precision field stitching
 - Extensible to 100 mm aperture
- **New PC-based software driver**
 - Unlimited extensibility
 - Much faster update rates

MEMS Process Development

- **Standing start to delivery of beta devices in <2 years**
- **Timeline**
 - **Tape out**
 - May 2008
 - **Actuator mechanical-only run**
 - August 2008
 - **Actuator electrical run**
 - March 2009
 - **Mirror wafer run**
 - August 2009
 - **Beta device delivery**
 - March 2010
 - **Production runs:**
 - Mirror wafers: June 2010
 - Actuator wafers: August 2010



PTT Controller Speed Enhancements

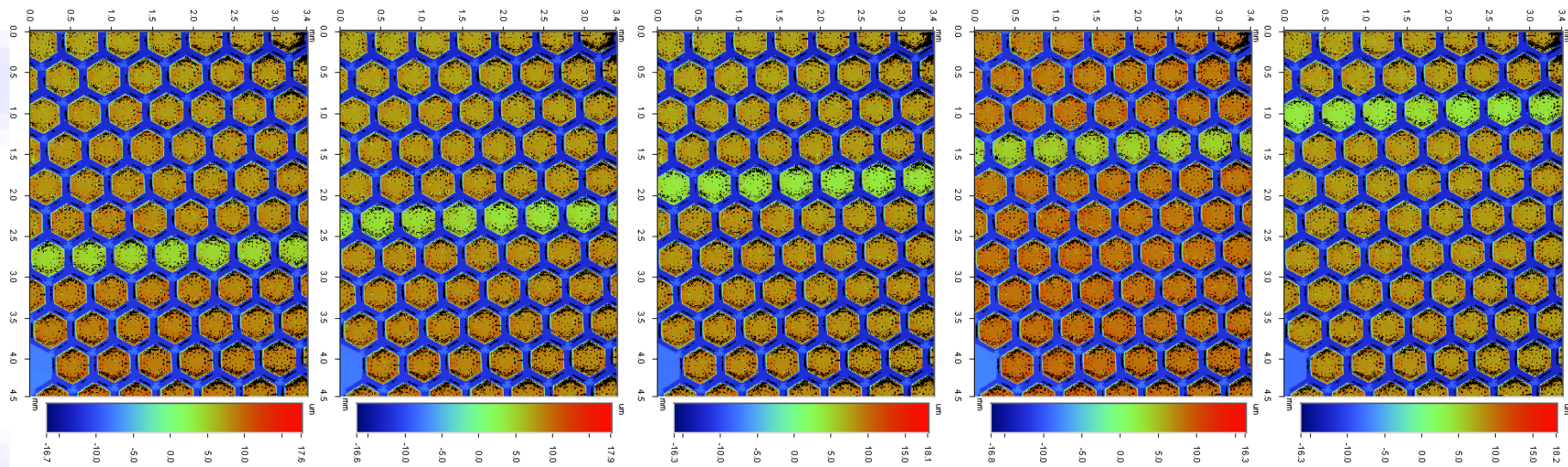
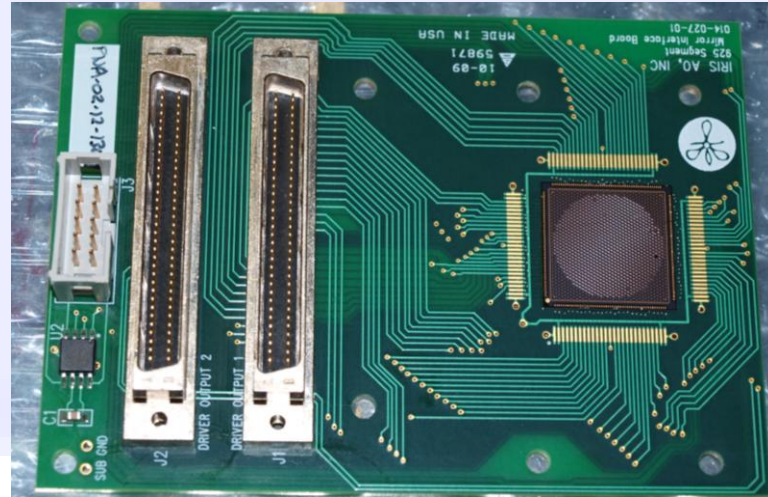
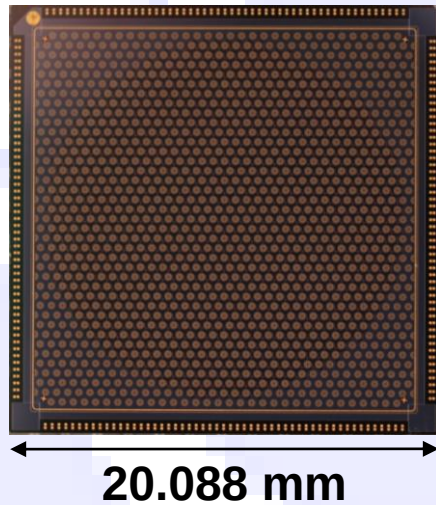
- **PCI/PCIe interface: v1.0**
 - 2.5 kHz array update rates for PTT111 DM controller
- **PCI/PCIe driver: v2.0**
 - 6.3 kHz PTT489 array update rates
- **Custom FPGA PTT controller demonstrated**
 - Array update rates > 35 kHz



Pathfinding Research: 3×10^3 *Actuator DMs*

10³ Segment DM Path-Finding Research

925 Segment Path Finder



Summary

- **PTT111 DM Improvements**
 - **Flatter segments**
 - **Faster interface**
 - **Dielectric coatings**
 - **Anti snap-in devices**
- **Technology scaled to PTT489**
 - **Beta DMs delivered**
- **All infrastructure revamped to be extensible**
- **Path-finding research demonstrates ability to scale to 3×10^3 actuator DMs**

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- NASA – SBIRs, (DM control, DM Fabrication)

- Phase I/II: NNG07CA06C, Phase I: NNX09CE01P



- Center for Adaptive Optics (DM Process Development)

- National Science Foundation Science and Technology: No. AST – 9876783



- National Eye Institute – Phase II SBIR (DM Process Development)

- 2 R44 EY015381-02A1



- National Science Foundation – Phase II SBIR (2-Poly Process Development)

- DMI-0522321

R&D Fabrication Facility



- Berkeley Microfabrication Laboratory

Research Collaboration



- Berkeley Sensor & Actuator Center