Wavefront Correction

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Iris AO, Inc.

Outline

- Overview of Wavefront Correctors
- Specifications
- Types of DMs
- Fitting Errors
- MEMS DMs: Teaser for the Next Lecture

Wavefront Correctors

- Wavefront Corrector: Any device that corrects wavefront distortions
  - Simplest form: eye glasses
    - Modal, low order, static
  - Time-varying distortions
    - **phase**, intensity, polarization, or direction
  - High spatial frequencies
- Spatial Light Modulator: Transducer that modulates incident light
  - Electrical or optical input

The Deformable Mirror

- Deformable mirrors (DM) physically change shape to correct time-varying wavefront *phase* aberrations

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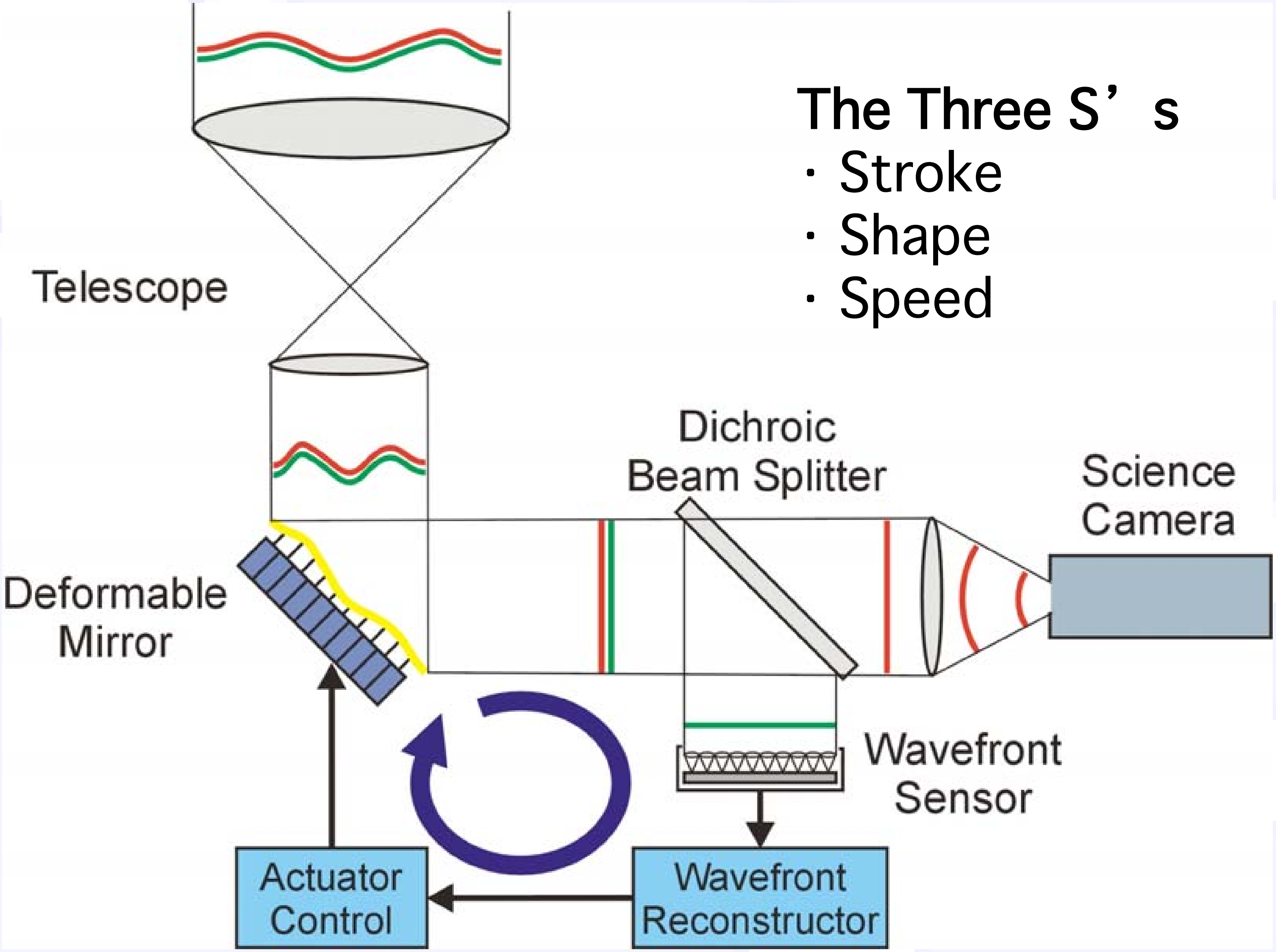
AO System Diagram (Astronomy)



The Three S’s

- Stroke
- Shape
- Speed

Typical DM Requirements

	Astronomy (10m)	Vision Science
Stroke	5 μm	10-20 μm
Number of Actuators* (Shape)	350-2500 $DOF \propto \left(\frac{D}{r_0}\right)^2$	40-100
Frequency Response (Speed)	1-5 kHz	50-200 Hz
Fill Factor	98%	98%
Mirror-Surface Errors (*rms*)	30 nm	30 nm
Aperture Size	1-15 cm	3-9 mm

* Continuous mirror with piston actuators

Equations from John W. Hardy, *AO for Astronomical Telescopes*

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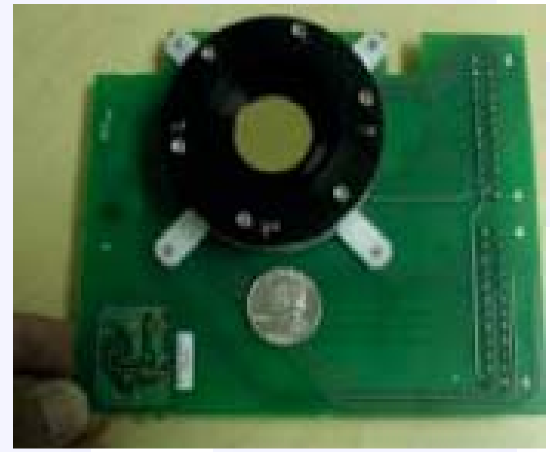
DMs: *All Shapes and Sizes*

Xinetics Website

Hamamatsu LC-SLM



AOptix Bimorph

OKO membrane mirror

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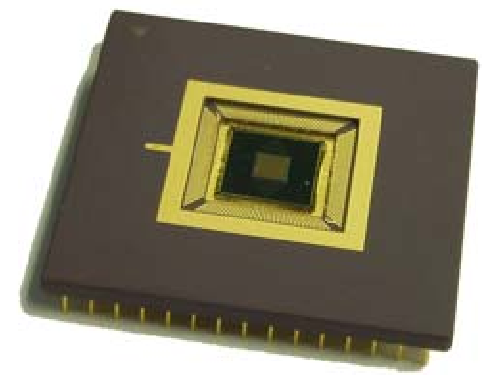

Boston Micromachines Corp.

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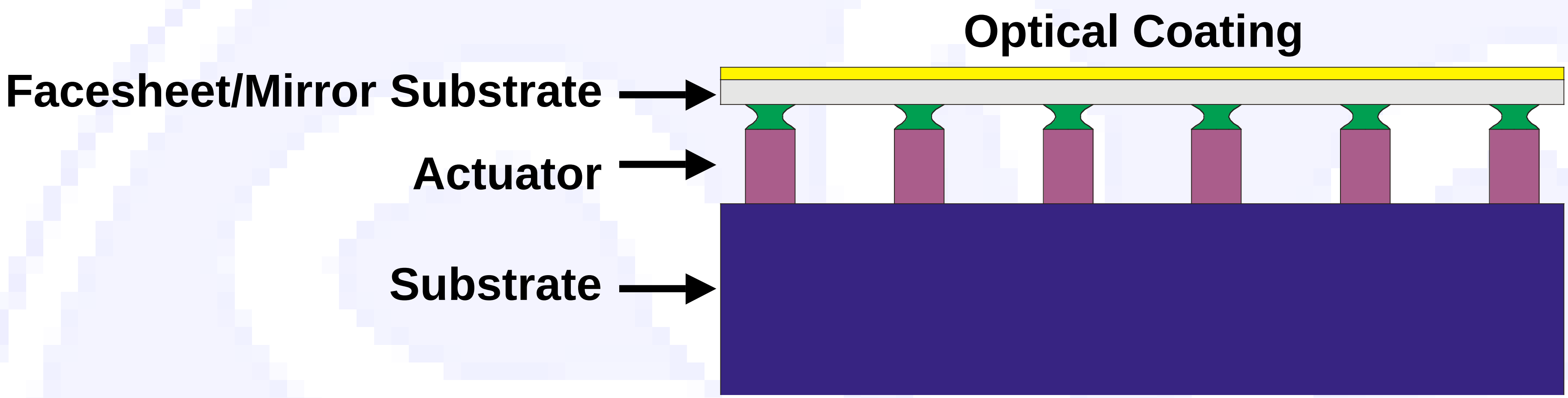
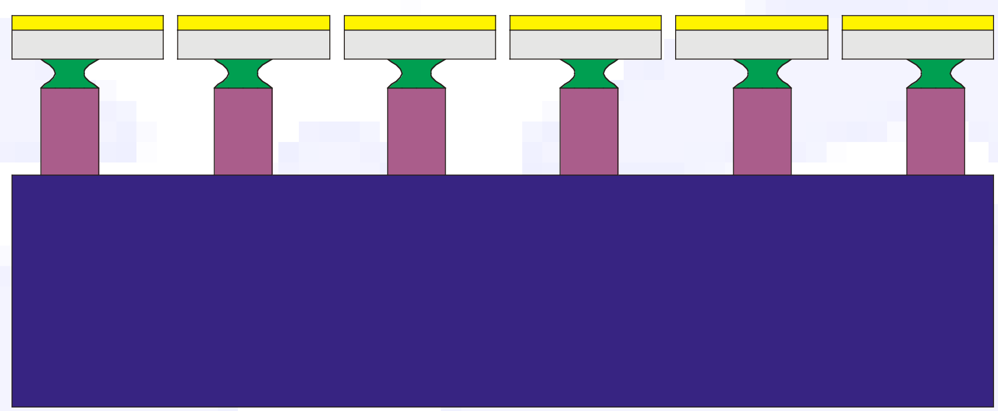
DM Construction

Continuous Facesheet DM



Segmented DM



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DM Actuation Methods

Most Common Types

- **Piezoelectric**
  - Strain µ Electric field
  - +High forces
  - - High voltage ~300V
  - - Hysteresis
- **Electrostatic**
  - Force µ Voltage^2
  - +Low power
  - - Forces weak for large gaps

Less Common Types

- **Magnetic**
  - Force µ Current
  - +High forces
  - - High current (~ 1A)/power
- **Thermal**
  - Strain µ Temperature
  - + High forces
  - - High temperature/power
- **Other Potential Actuators**
  - Pressure
  - Material Phase Change

DM Actuation Classes

- Modal
  - Actuators change curvature locally
  - Stroke depends greatly on adjacent actuators
    - Strong influence function between actuators
    - Displacement between actuators is small
    - Stroke $\propto$ actuator-length^2
- Zonal
  - Arrays of actuators that push/pull on the mirror
  - Stroke “independent” of adjacent actuators
    - Weak influence function between actuators

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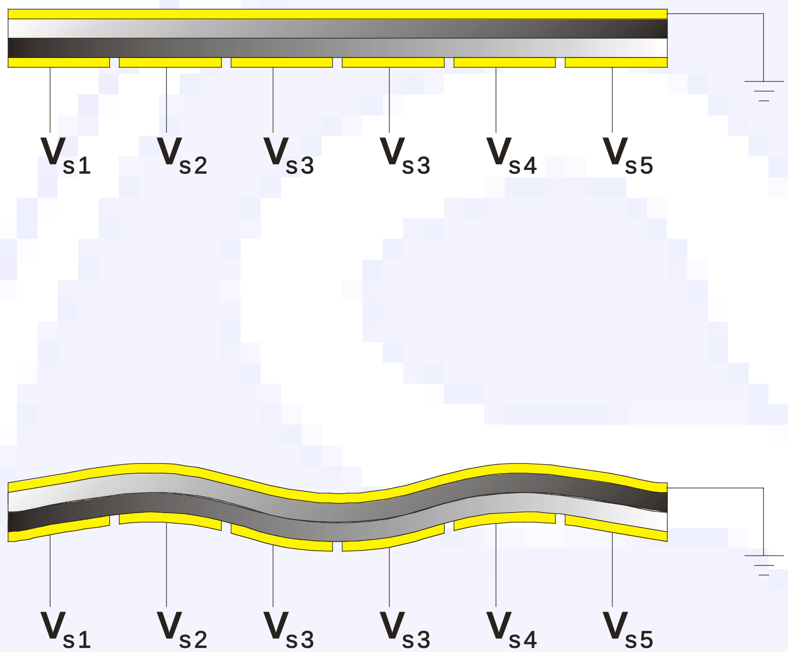
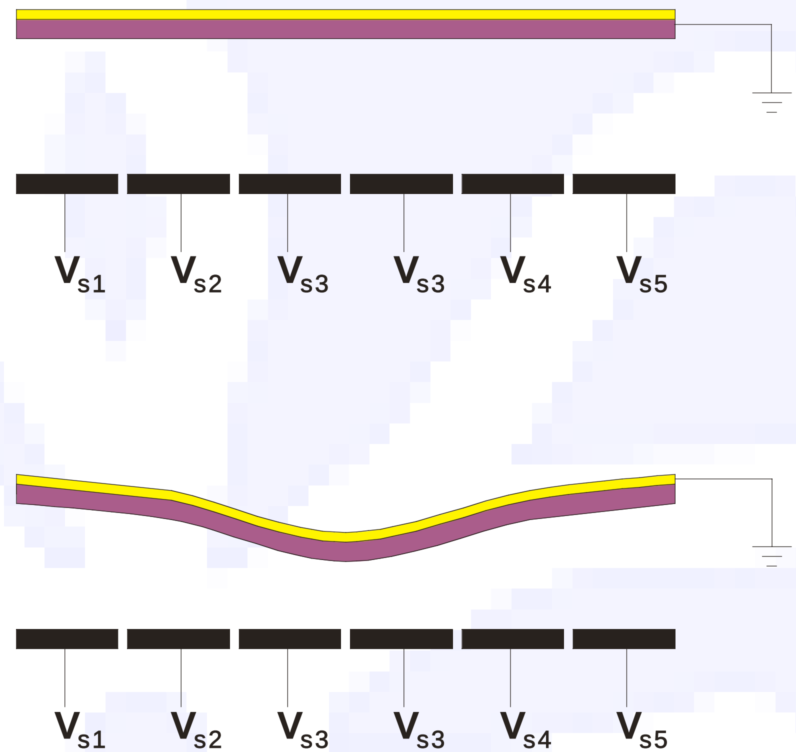
Modal Mirrors

Bimorph Mirror



$$\nabla^2 z \mu \frac{-V(x,y)d_{31}}{t^2}$$

Membrane Mirror

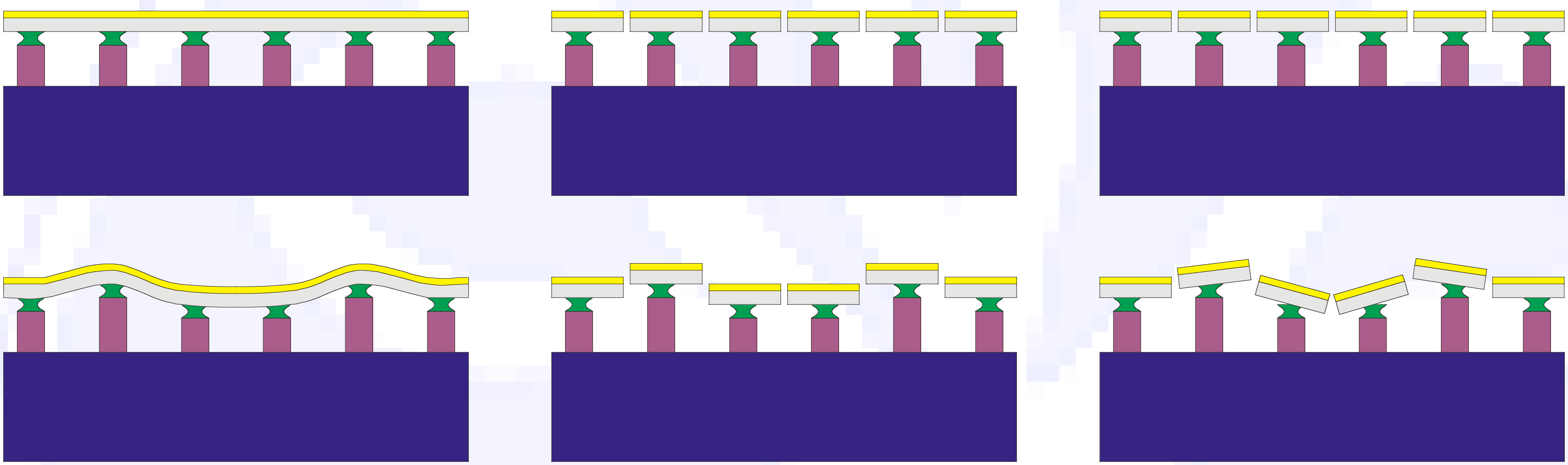


$$\nabla^2 z \mu \frac{-\varepsilon_0 V^2}{d^2 \sigma_m}$$

John W. Hardy, *AO for Astronomical Telescopes*

Zonal Mirrors

Continuous Face Sheet	Segmented: Piston	Segmented: Piston/Tip/Tilt

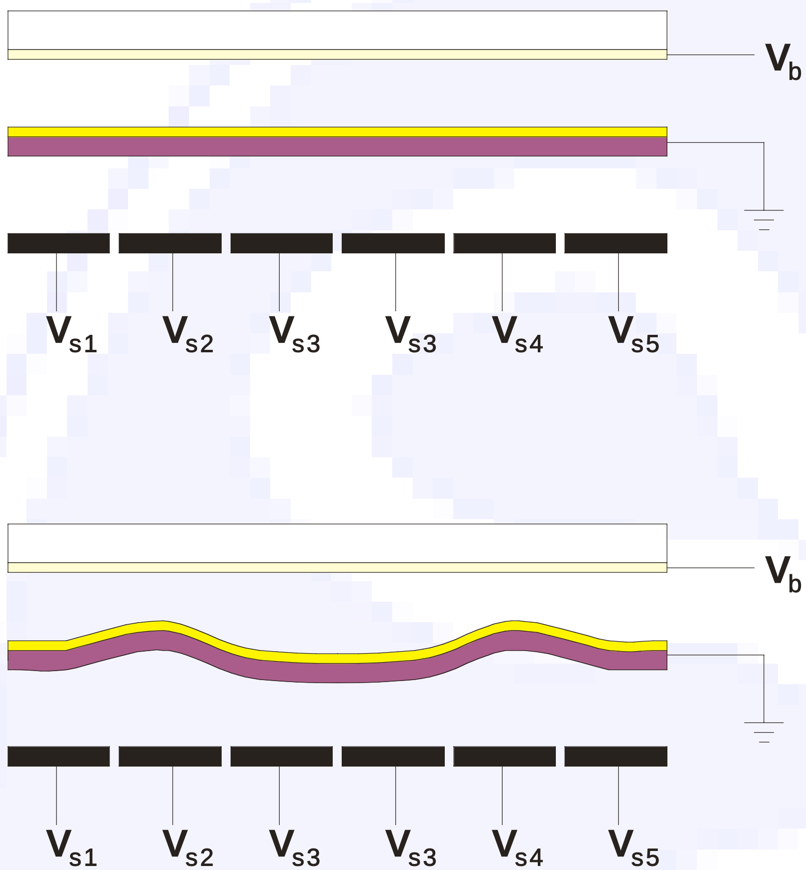


$$z(x,y) \propto V^n$$

n=1-2

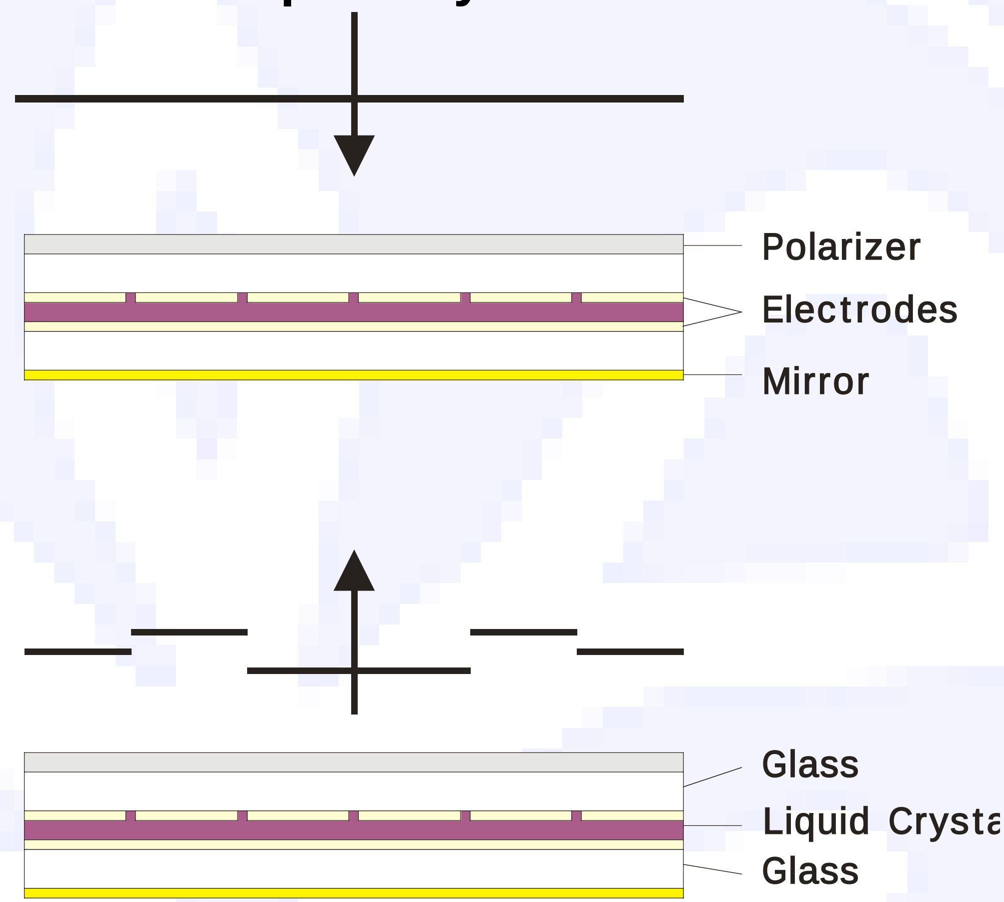
Zonal Mirrors/SLM

Balanced Membrane Mirror



$$z(x, y)\ \mu\ V^n \quad n=1\text{-}2$$

Liquid-Crystal SLM



$$\phi(x, y)\ \mu\ V$$

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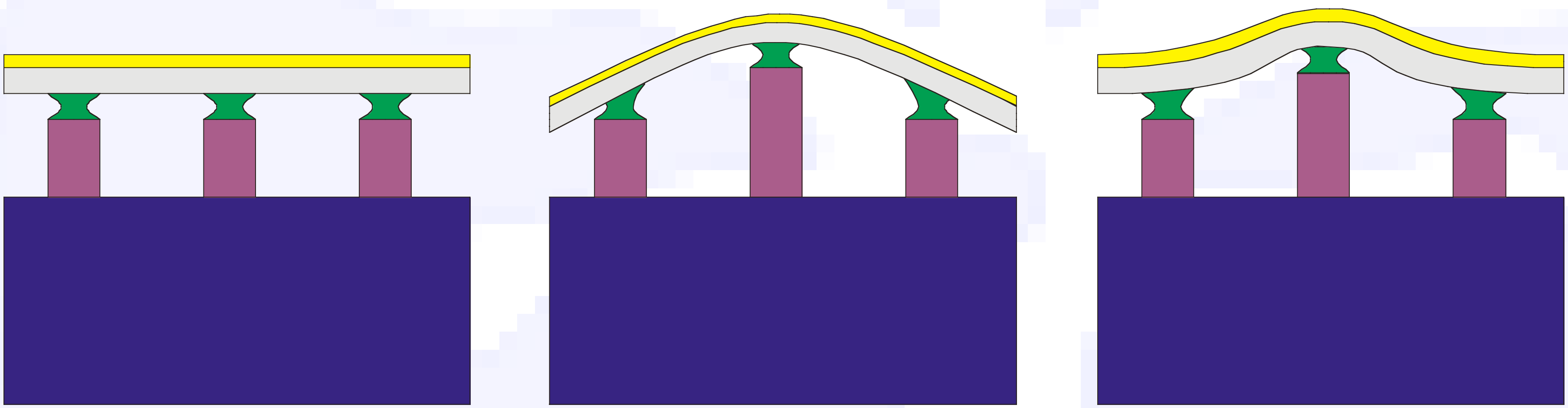
Segmented vs. Continuous

- Continuous
  - High fill factor, “no” diffraction
    - Etch holes and print-through cause diffraction
  - Interactuator coupling
    - Reduced inter-segment stroke
    - Open-loop control more complicated
- Segmented
  - Some diffraction between segments
  - No interactuator coupling
    - High stroke
    - Denser actuator spacing

Influence Function

- Influence function: the shape the mirror will take when pushing one actuator
  - Shape depends on the bending stiffness of the actuators compared to the faceplate stiffness
  - Large influence function (e.g. stiff faceplate) reduces ability to correct



Fitting Error

- Fitting error depends on aberration statistics and mirror type (influence function)
  - Kolmogorov model used for the atmosphere
  - No model for the eye published yet
    - Population studies at U. Indiana, and U. Rochester
      - Doble
- Fitting error (rad^2)
  - a_F = 1.26 P, 0.18PTT, 0.28 C
    - Square segments

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$$\sigma_{fit}^{\ 2} = a_F \left(\frac{d}{r_0} \right)^{\frac{5}{3}}$$

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Comparing Deformable Mirrors

- Equate the wavefront-fitting errors
- Number of subapertures proportional to d^2

$$\frac{N_1}{N_2} = \left(\frac{d_2}{d_1}\right)^2 = \left(\frac{a_{F1}}{a_{F2}}\right)^{\frac{6}{5}}$$

- Subapertures (PTT:C:P) -- 1:1.7:10
- Actuators (PTT:C:P) -- 3:1.7:10

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MEMS Deformable Mirrors

- MEMS (microelectromechanical systems)
  - Based on integrated-circuit fabrication
    - Silicon as a mechanical material
    - Deposit thin films, pattern, etch and repeat (and repeat, and repeat…)
- High spatial frequencies achievable
  - d=~20-1000µm
- (Potentially) low cost
  - ~$10/actuator compared to ~$1000/actuator
- Scalable to large numbers (>10,000) of actuators

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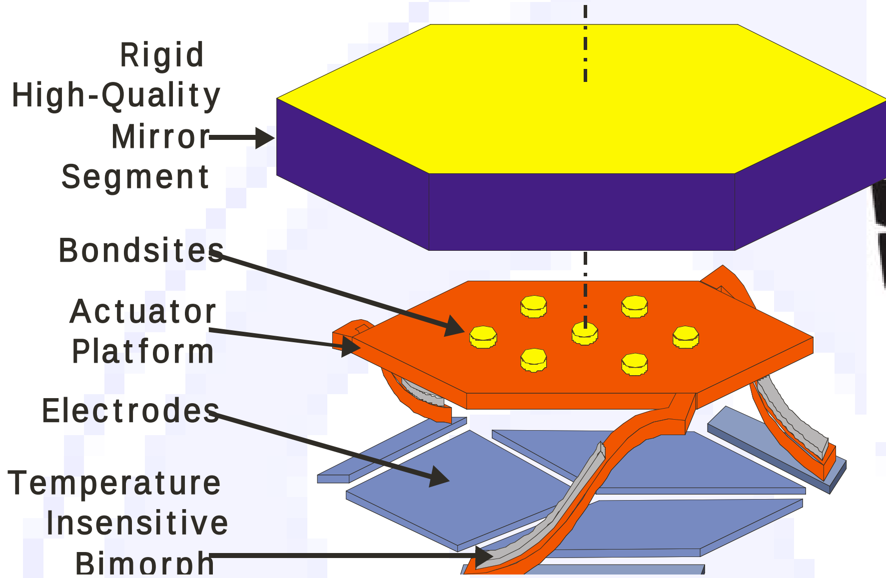
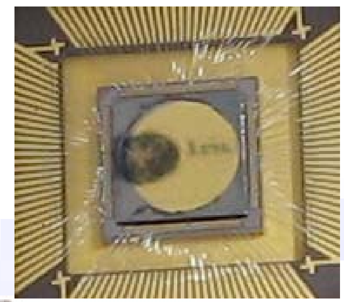
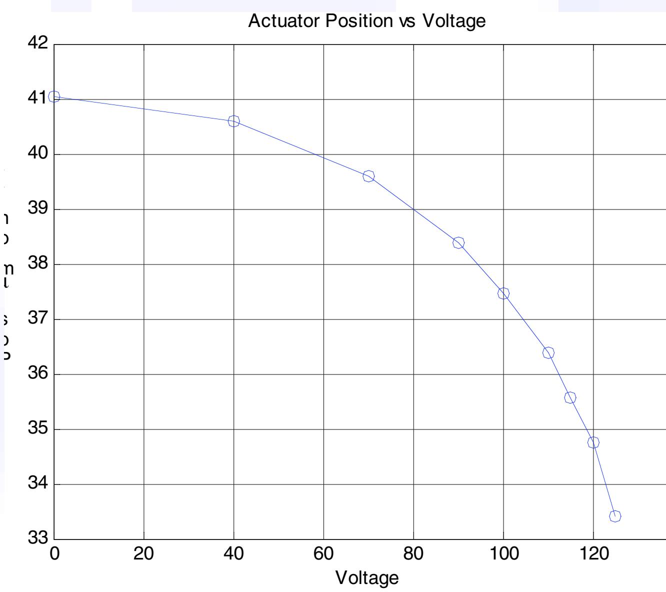
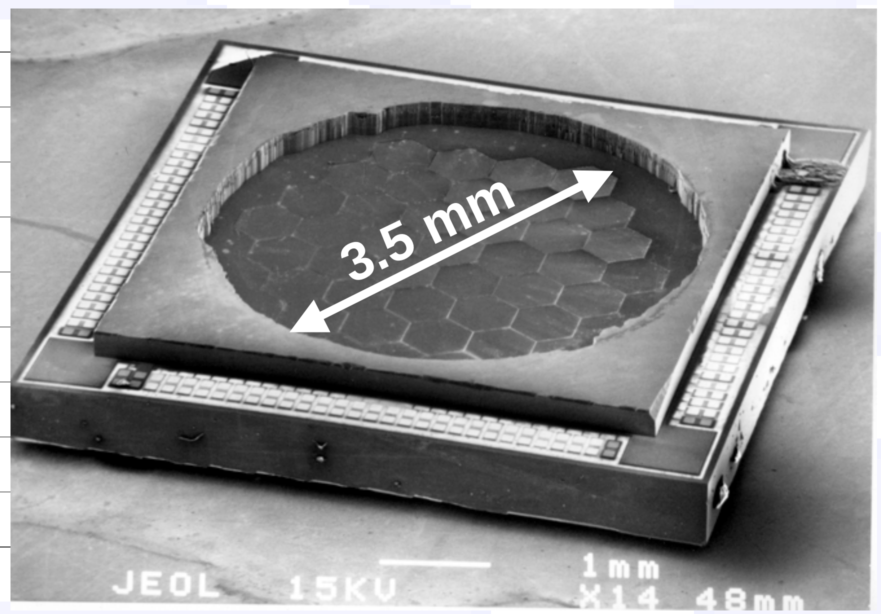
Iris AO MEMS Segmented DM









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Open-Loop DM Positioning: *Pseudo Fringes (_=600 nm)*

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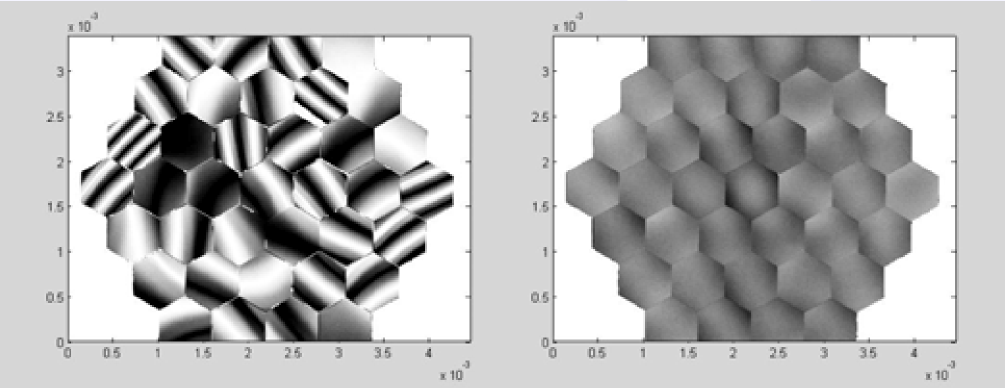
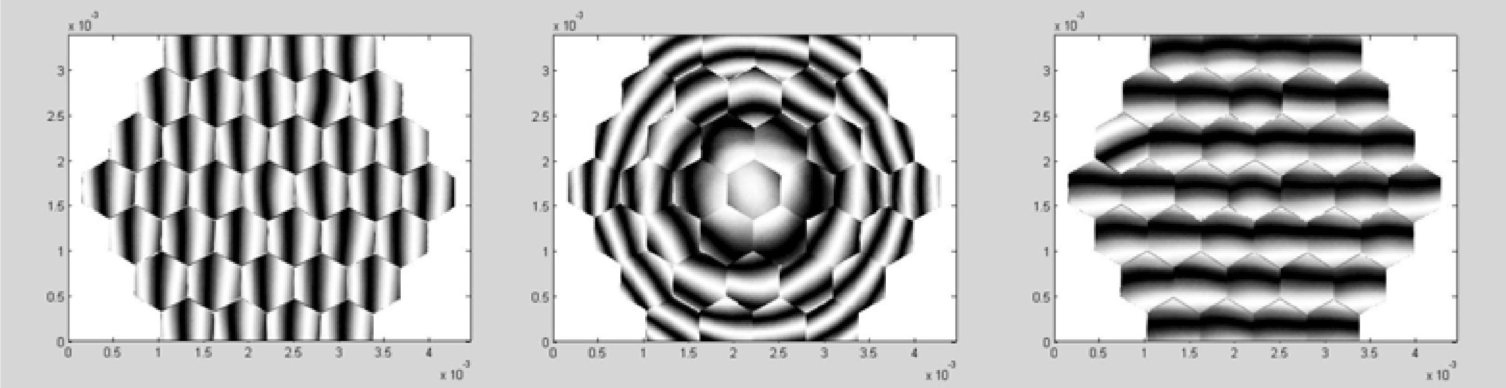
As Released **Flattened**



Only 19 nm *rms* residual wavefront errors

Various Commanded Positions



Hysteresis free actuation enables open-loop positioning

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Summary

- DMs change the phase of a wavefront in real time
- DMs can be classified as zonal or modal
  - Continuous and segmented is another classification
- Different types perform differently
  - Match fitting error to compare
- Telescope primary determines DOF and stroke
- MEMS DMs promise to increase DOF and reduce cost