Adaptive Optics Development for LIGO

L S C

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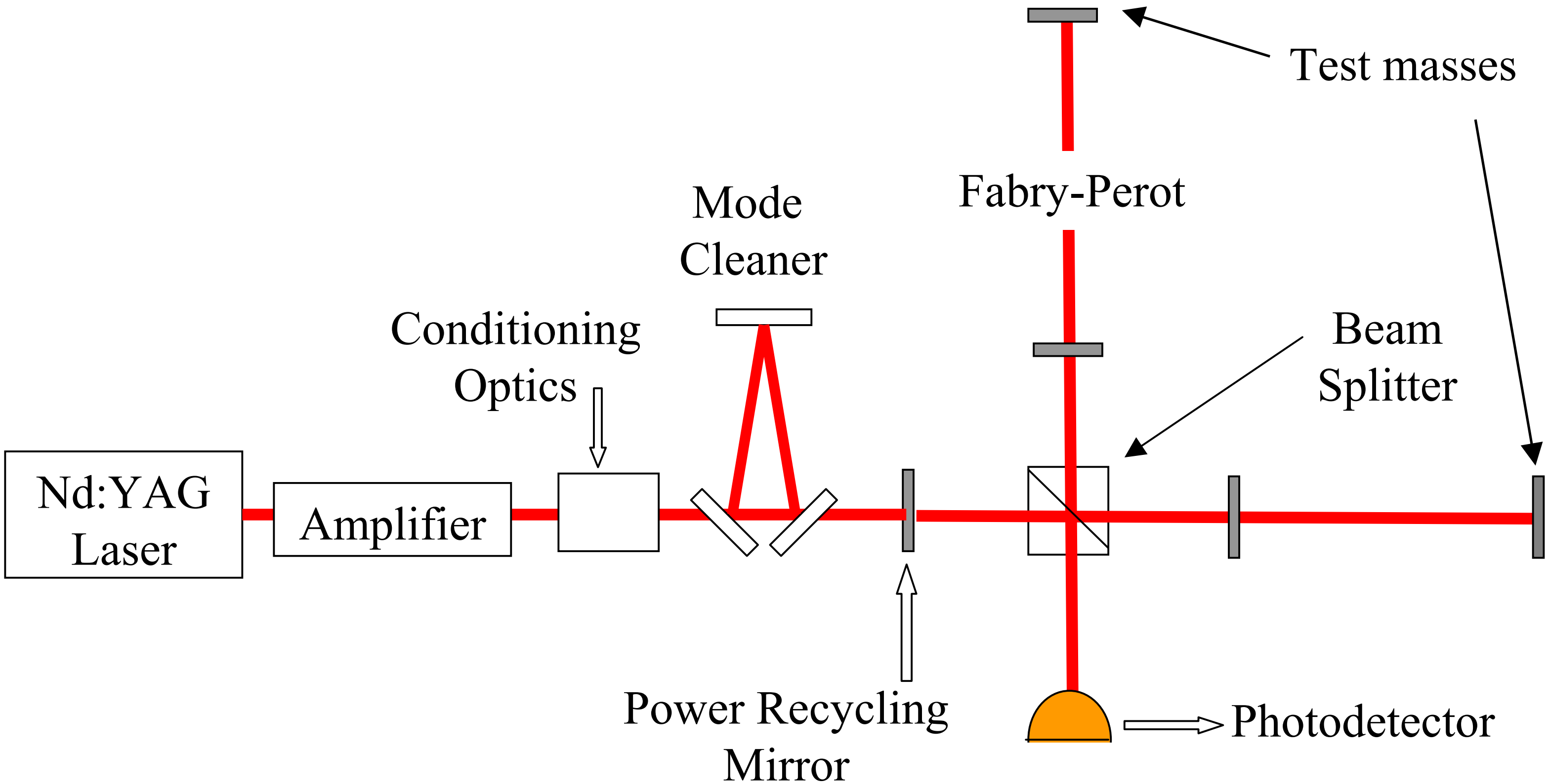
LIGO-G010351-00-Z

Outline

- Motivation
- Deformable Mirror (DM) Design
- Experimental results
- Future Work
- Conclusions

Laser Inteferometer Gravitational-Wave Observatory



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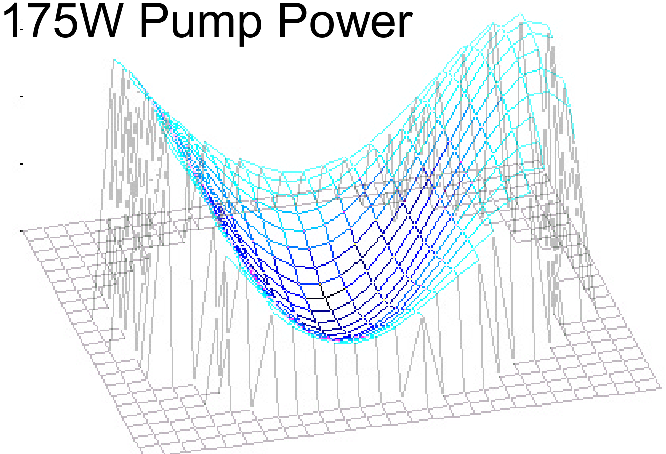
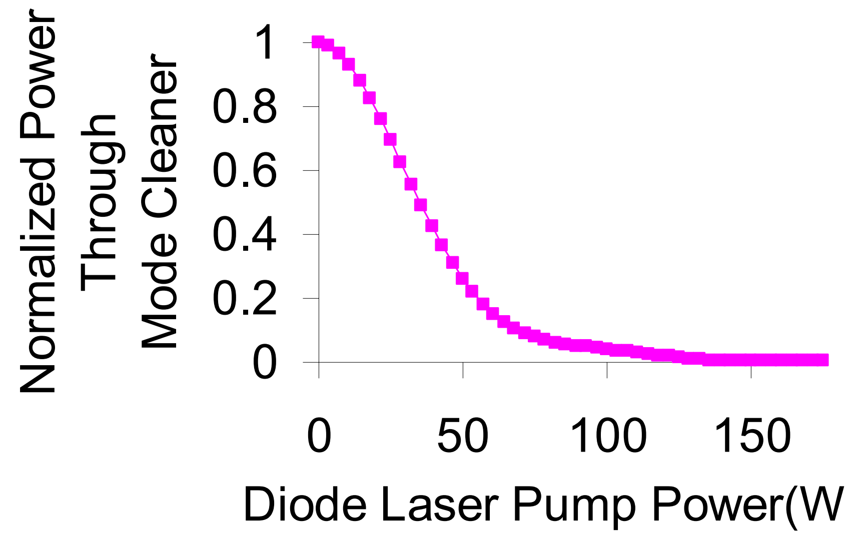
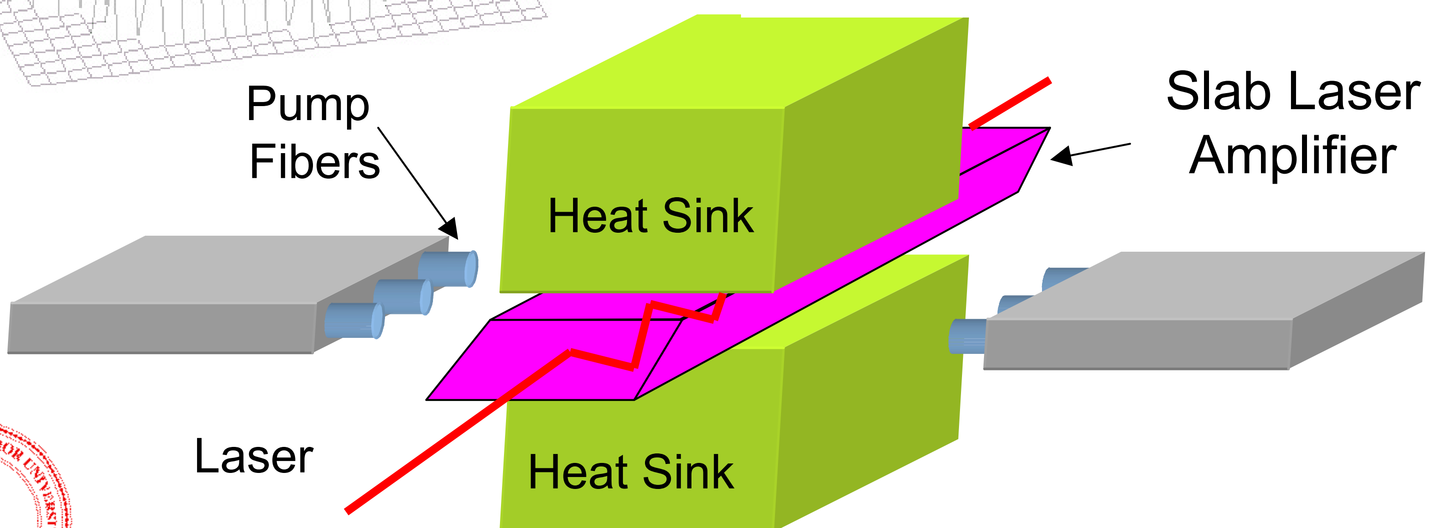
Slab Thermal Distortions

Tilt-Removed Wavefront

Peak-to-Valley: 813nm
175W Pump Power







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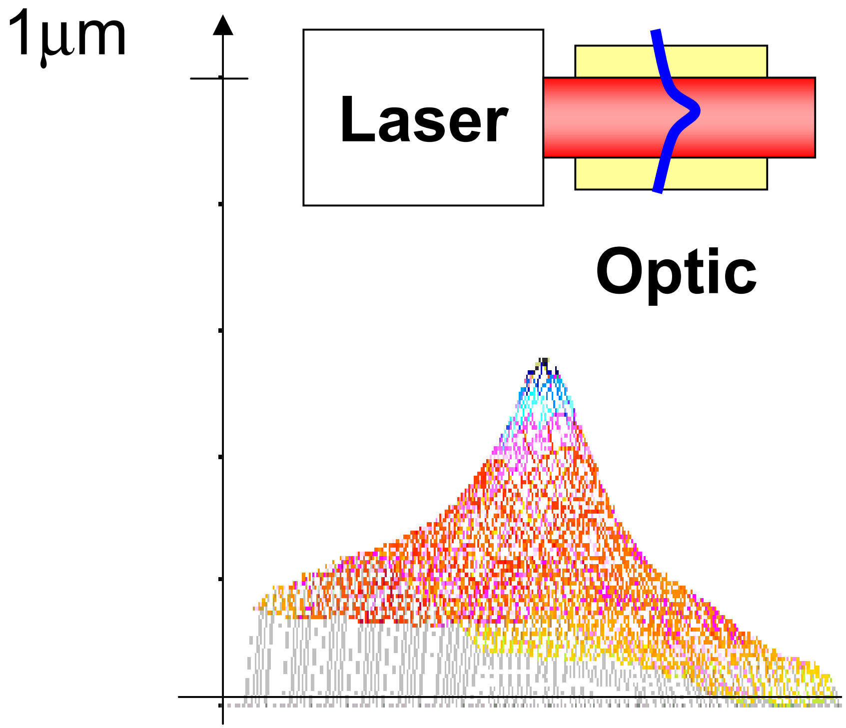
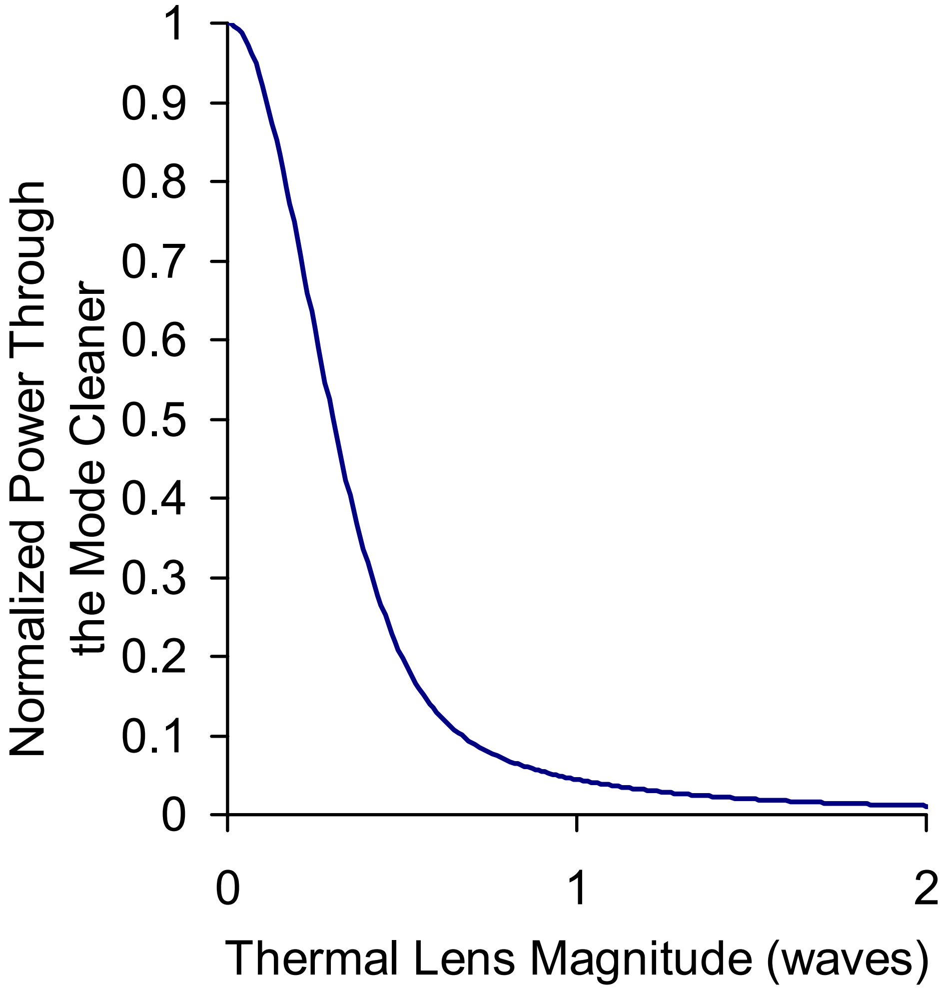
Transmissive Optic Thermal Lens



250mW Nd:YAG in
Lithium Niobate



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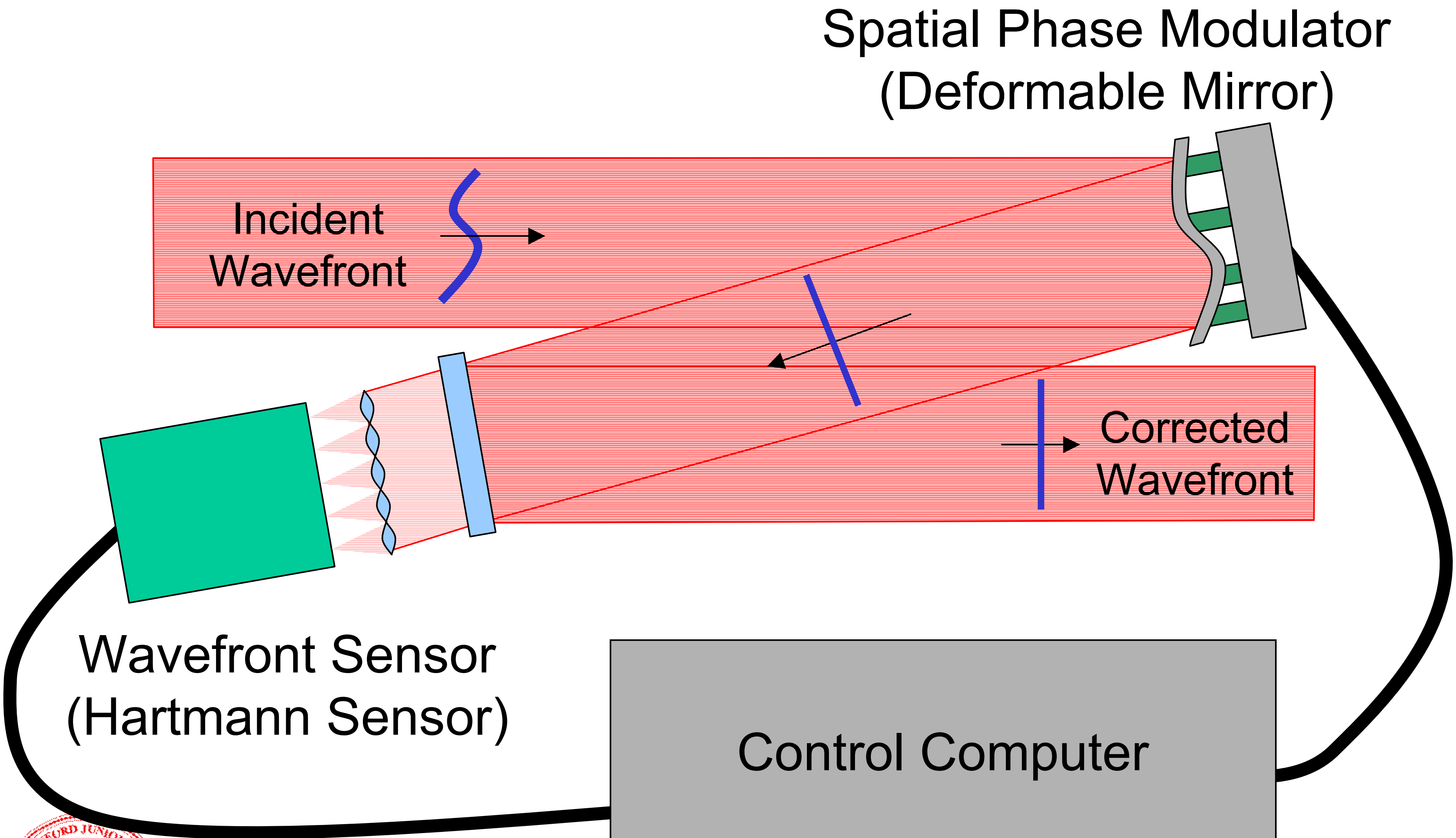
Basic Adaptive Optics (AO) System



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What architecture for high power?

- Liquid crystal spatial phase modulators
  - Absorbing ITO damages easily
- Segmented mirrors
  - Diffractive effects, edges damage
- Surface micromachined mirrors
  - Surface perforations are damage sites
- Bulk micromachined mirrors
  - Most have high crosstalk

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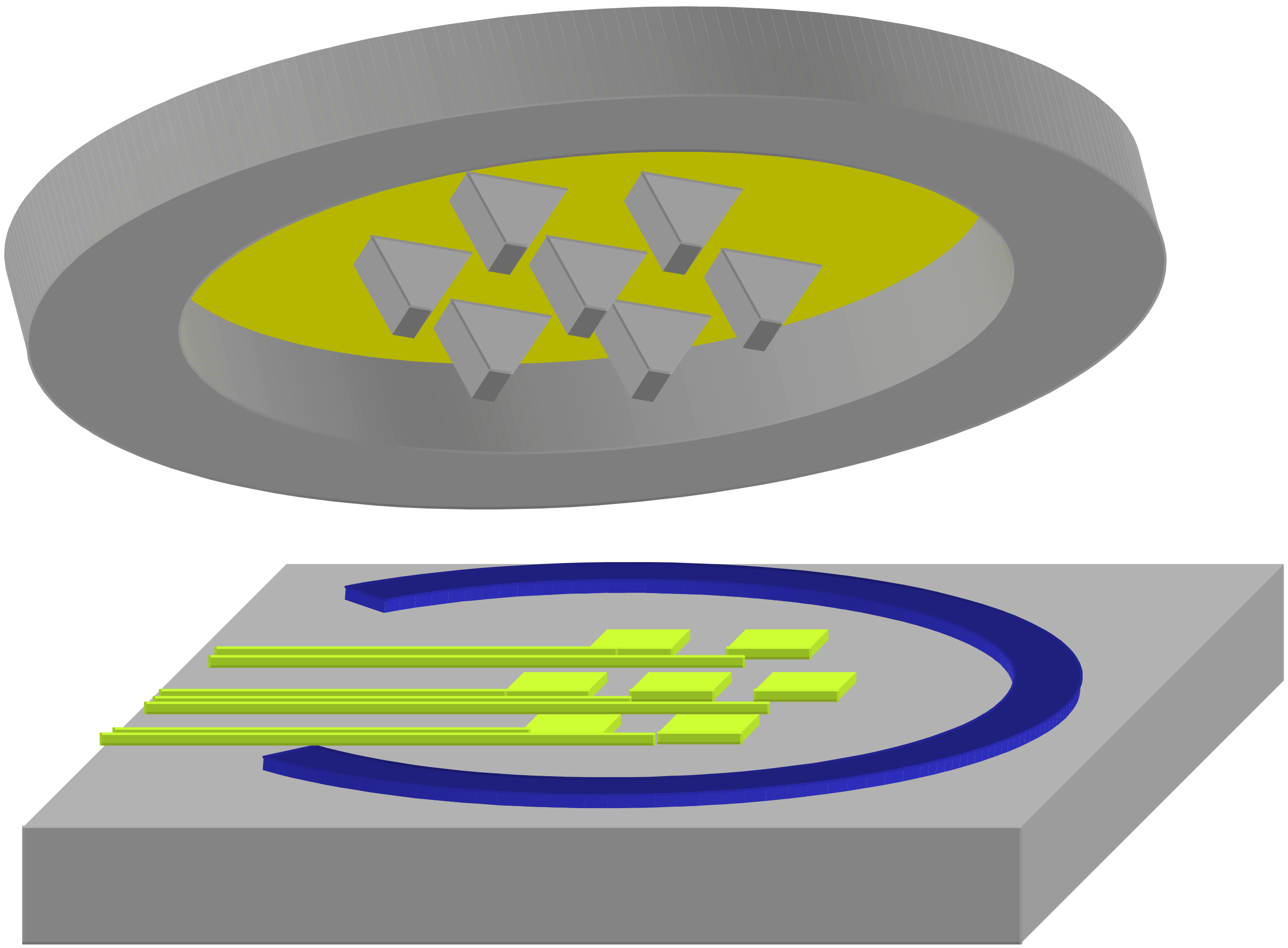
3D View of Mirror Architecture



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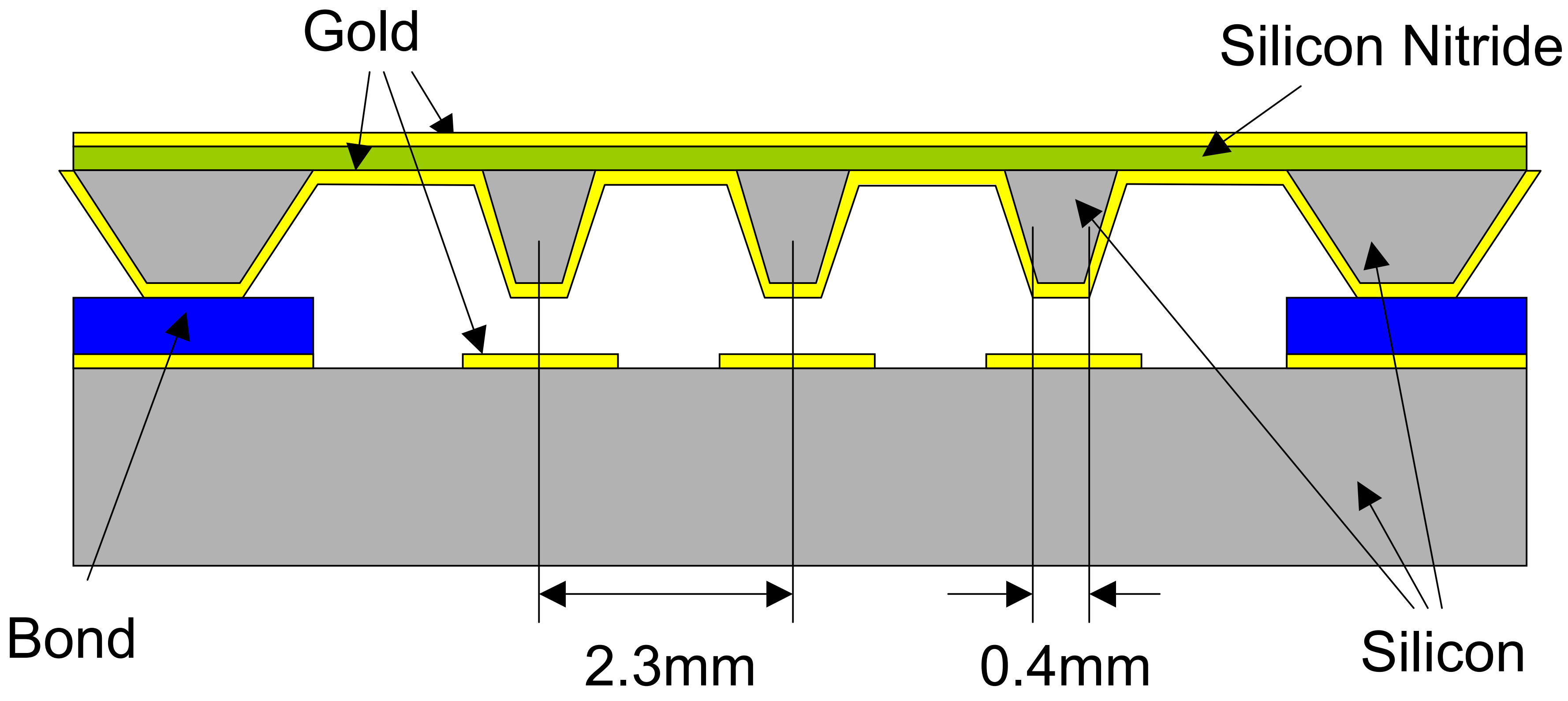
Cross-Section of Mirror Architecture



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Stanford DM Photograph

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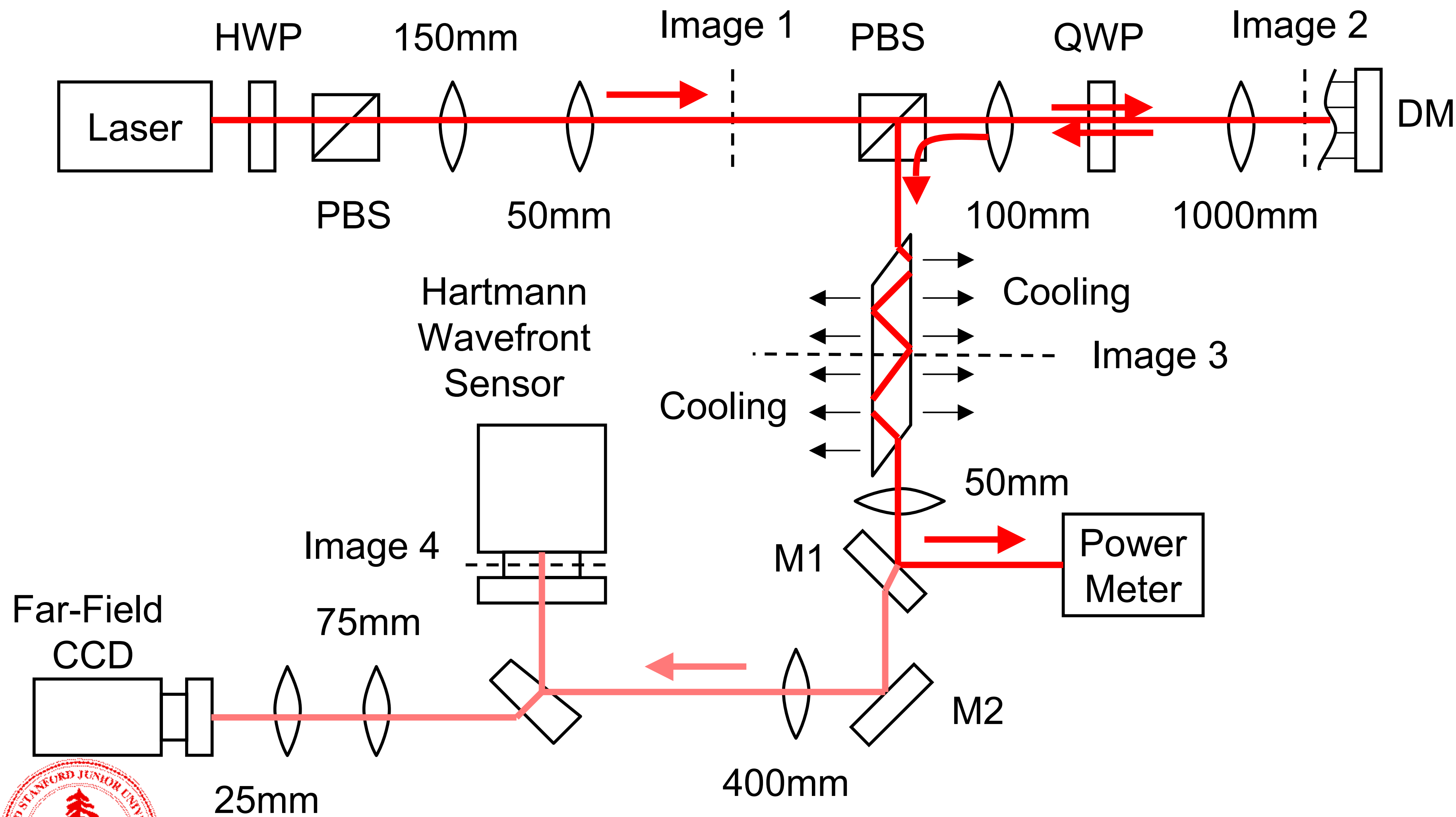
Two-Layer DM Characteristics

- 19 actuators with 2.3 mm spacing
- 1.6 cm aperture
- 10 μm throw in center actuator
- Low electrical power consumption
- 3.7 kHz mechanical resonance frequency
- Low-cost fabrication
  - Class 1000 clean room
  - Two-Mask Process

Thermal Distortion Compensation



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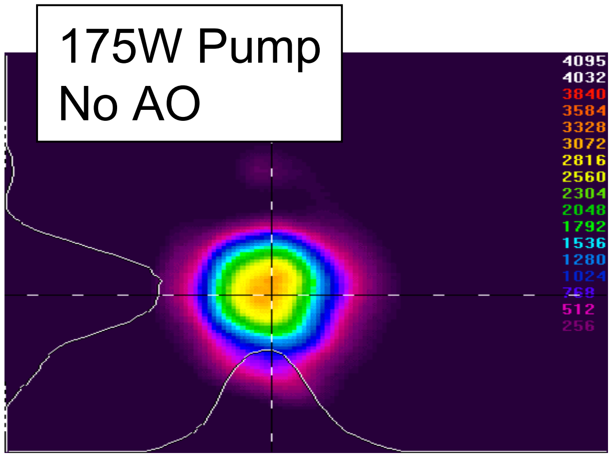
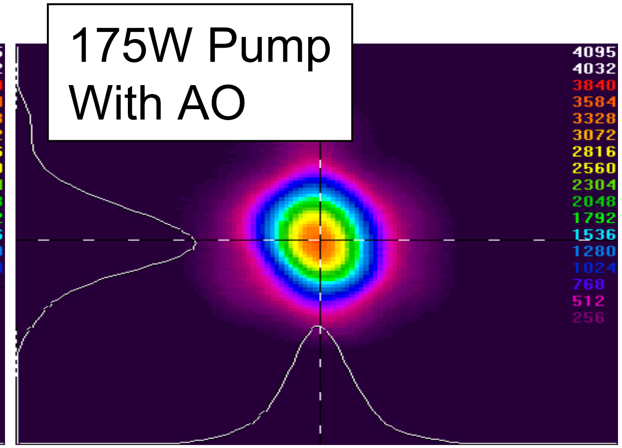
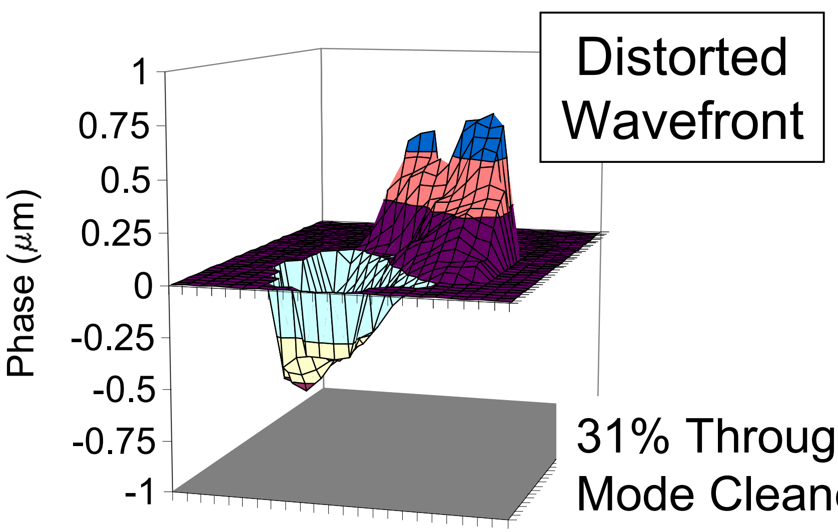
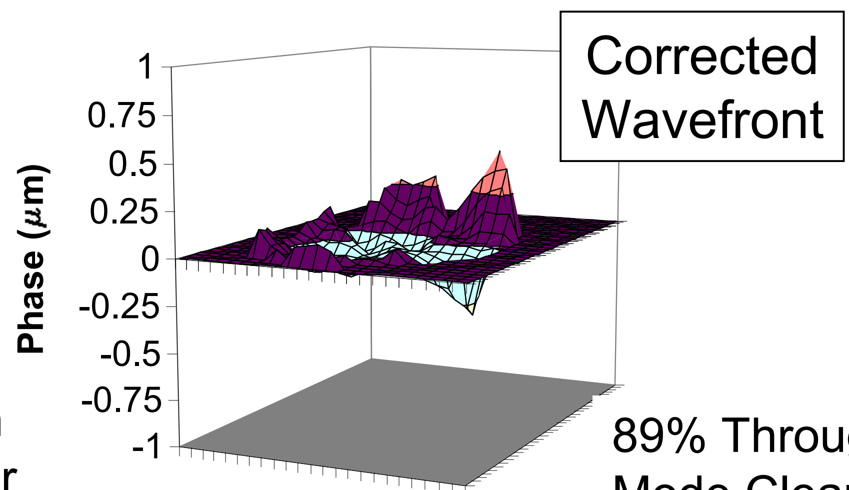
Compensation Results







31% Through
Mode Cleaner

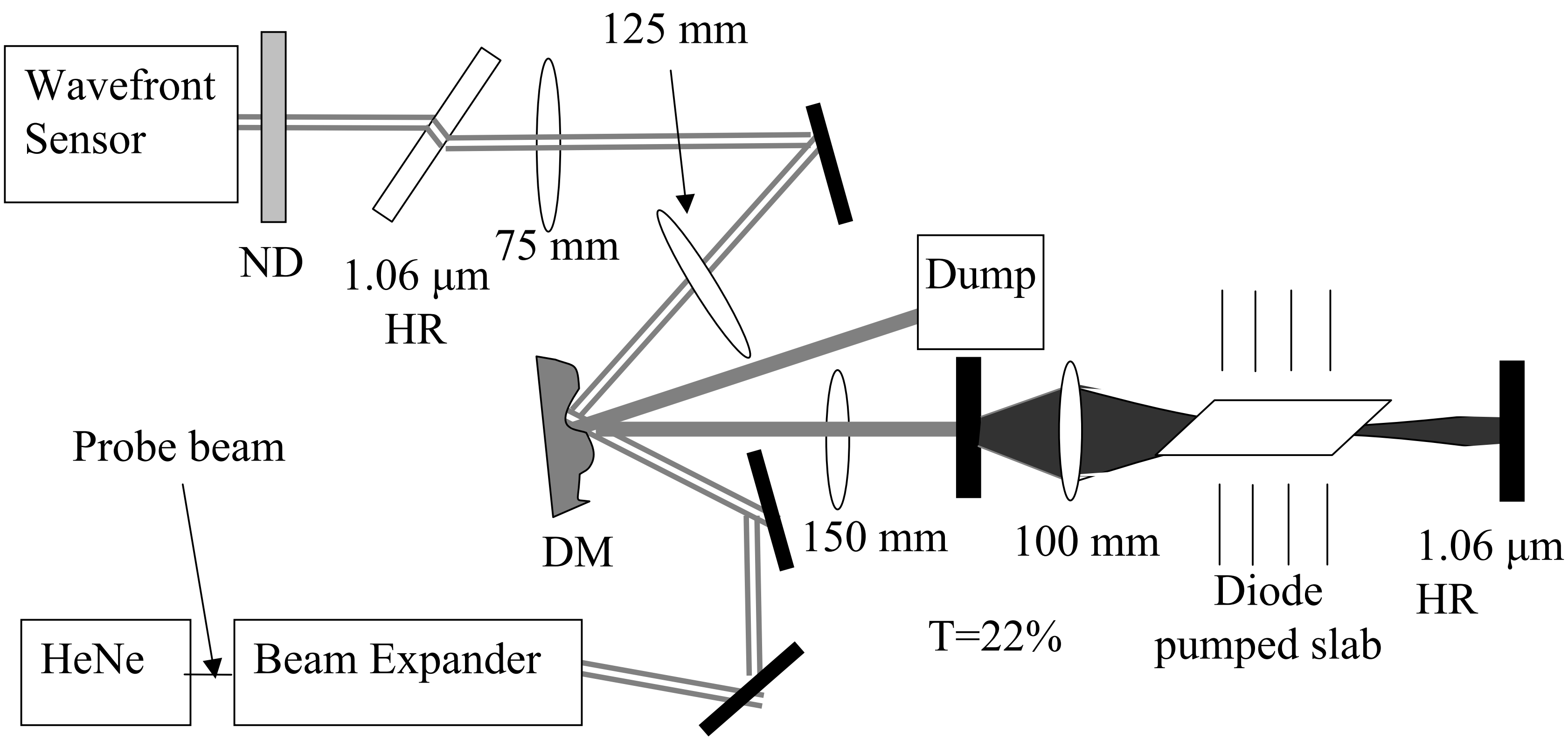


89% Through
Mode Cleaner

Two-Layer DM Advances

- **Possible to Preserve Mirror Surface**
  - All polishing and coating complete before processing
  - Mirror surface never exposed to etchant
- **Low Static Aberrations**
  - Bond annealing relaxed bonding stress
  - ~50 nm rms static aberration in an astigmatic term
- **Capable of bonding to silicon circuitry**
  - Can use CMOS to address for large actuator count
  - A polished silicon surface for electrode uniformity
  - No mismatch between layers
- **Robust**
  - Electrostatic snap-down does not cause damage.
  - Mirror is fully recovered by reducing voltage.

Power Handling Characterization



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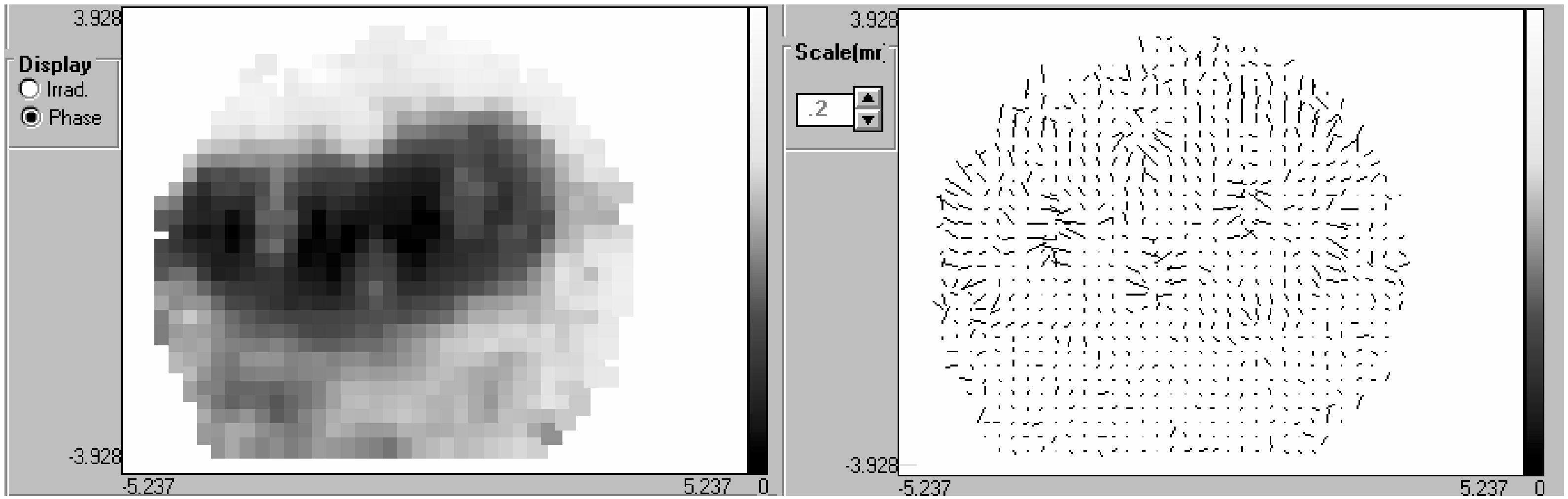
Gold-Coated DM Power Handling



Wavefront distortion when loaded with 41 W of cw 1064 nm laser power (212 W/cm^2) with 39.1 nm of rms distortion

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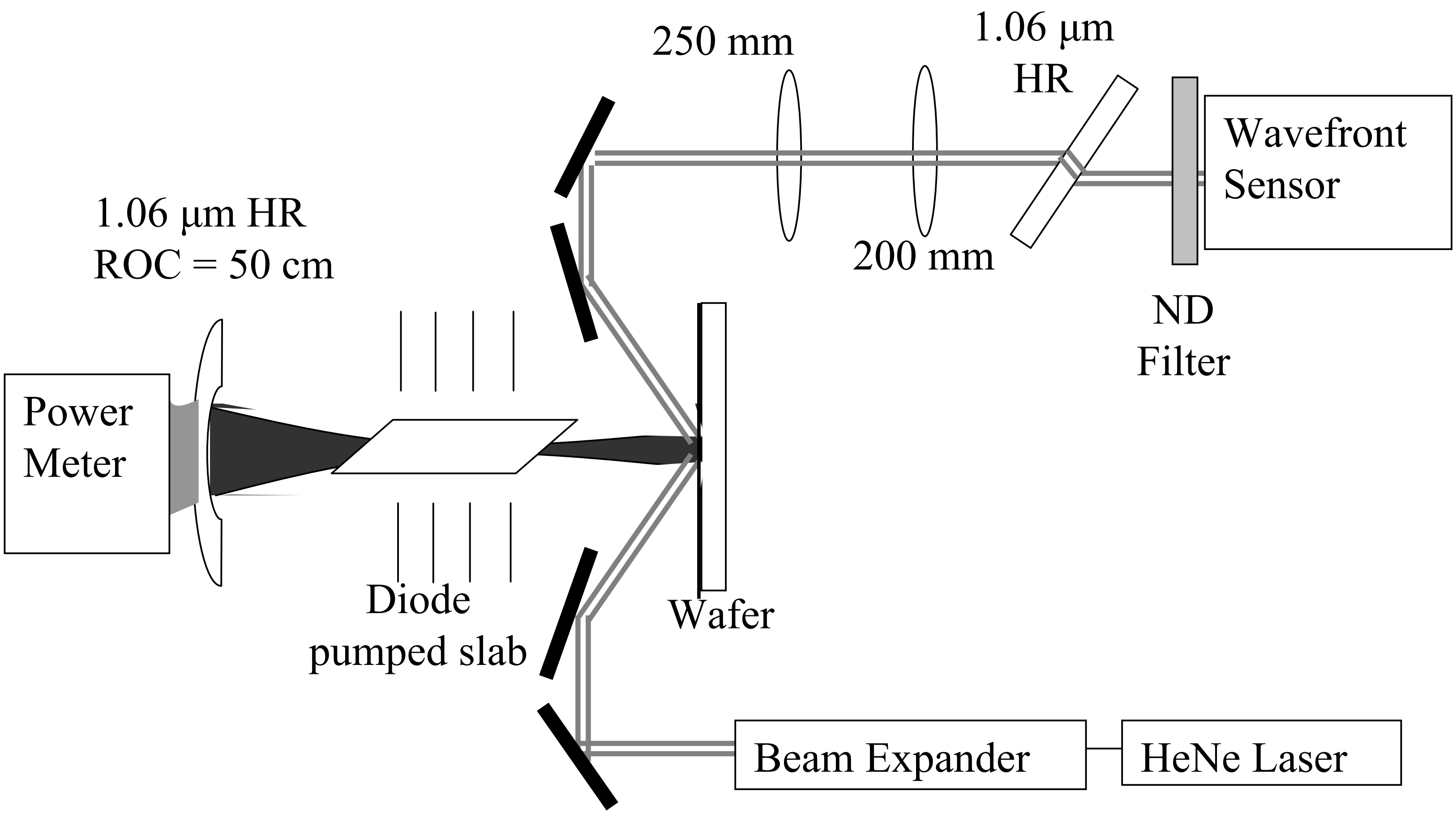
HR Wafer Power Handling



With 1.1 kW (39 kW/cm^2) of cw 1064 nm laser power, no thermally induced distortion was observed.

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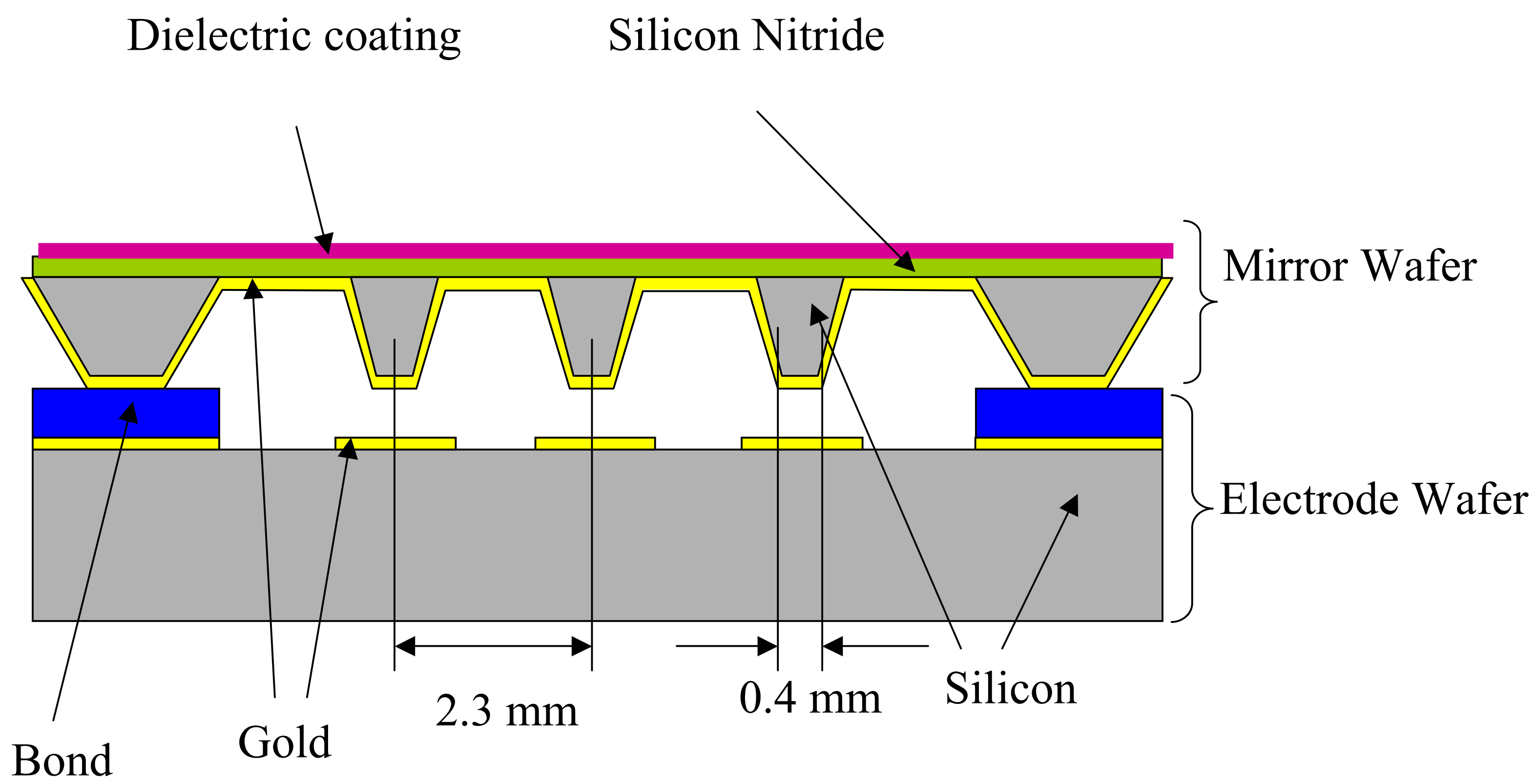
High Reflectivity Deformable Mirror



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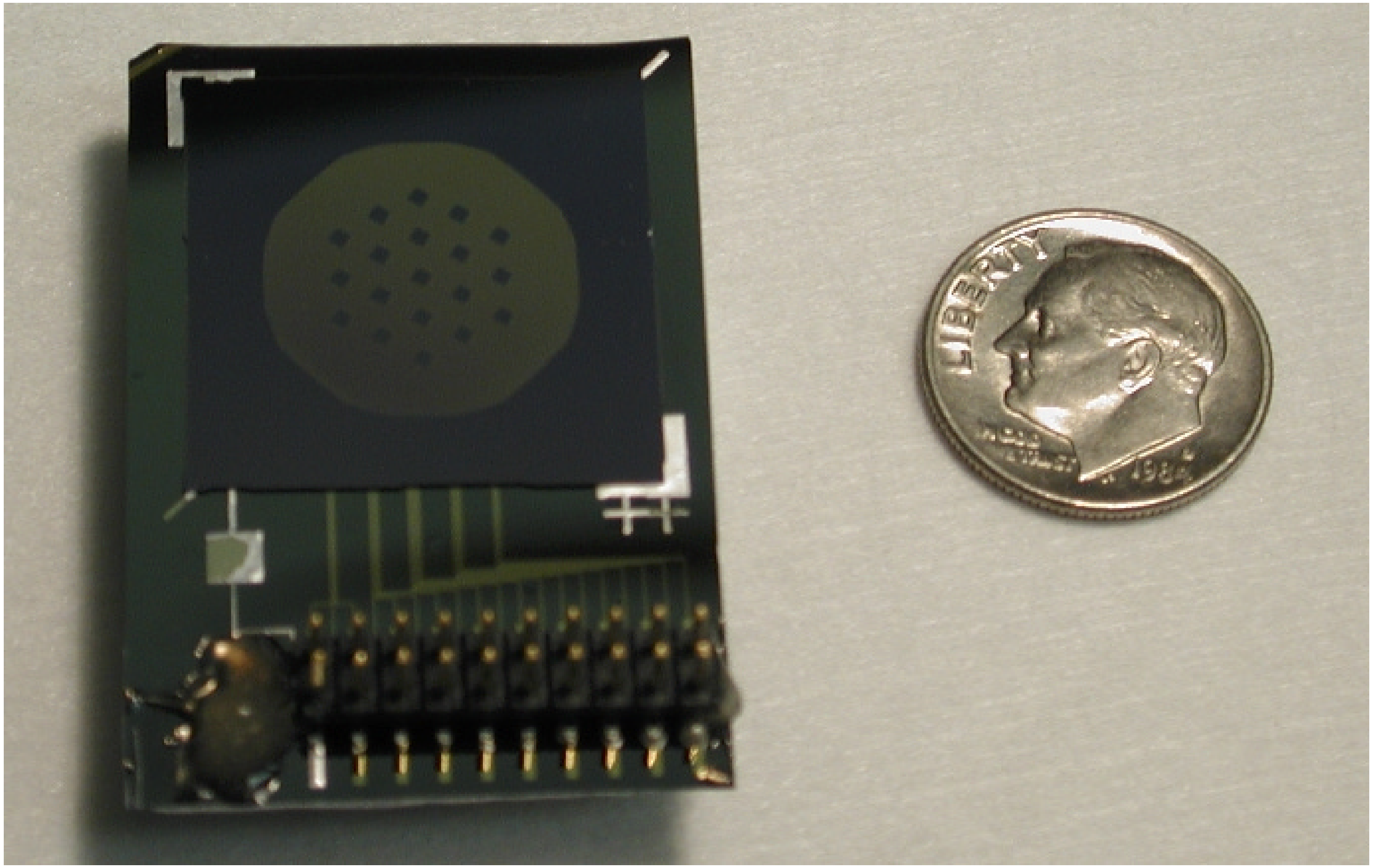
High Reflectivity DM Photograph



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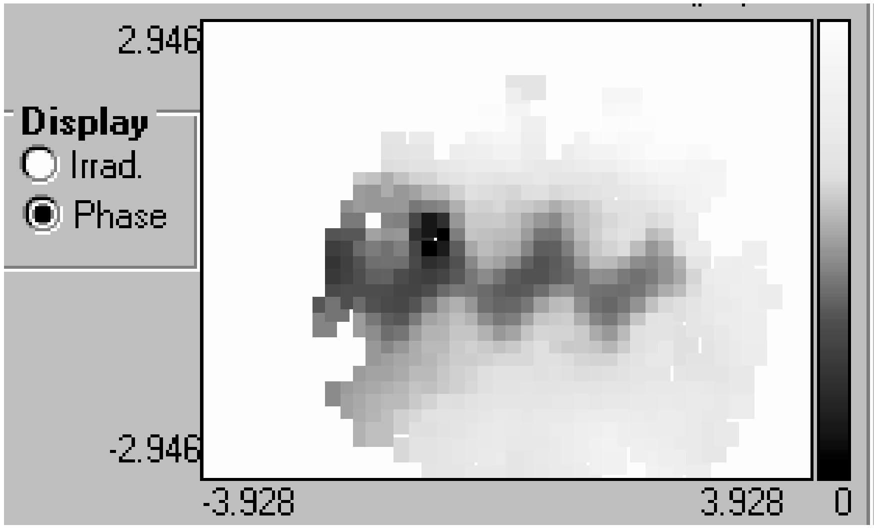
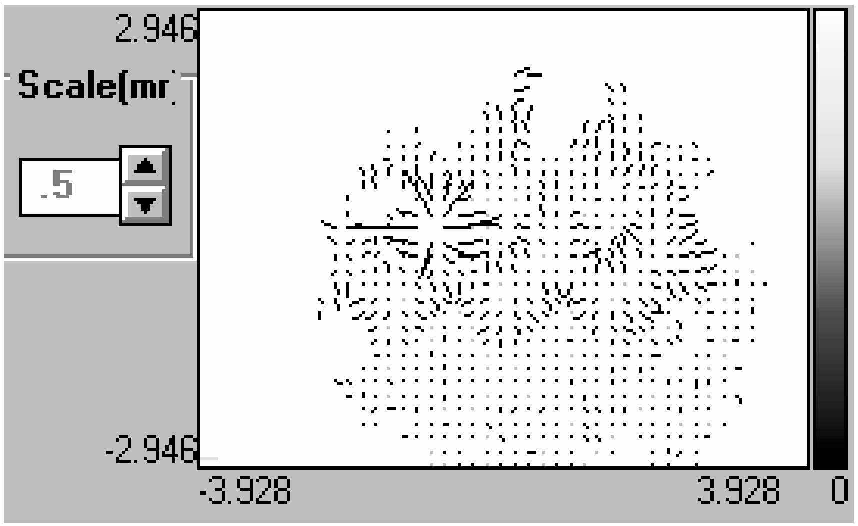
Reliability Characterization

- Deformable mirror was cycled at 150V for 500 million cycles & no damage was observed
- 30 hours with 36 W of cw 1064 nm laser power with no damage
- Fully recoverable from electrostatic snap-down.

MLD-Coated DM Power Handling





Wavefront distortion when loaded with 41 W of cw 1064 nm laser power (212 W/cm^2) with 61.3 nm of rms distortion

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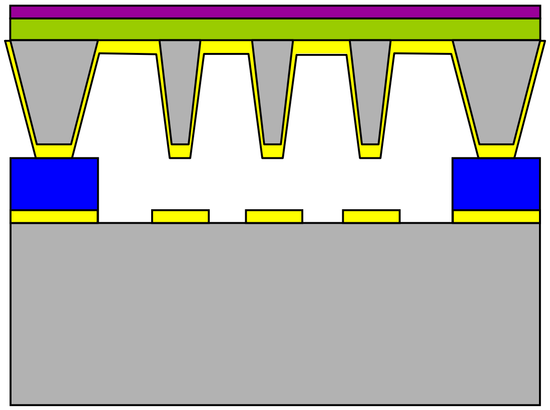
Thermally Induced Aberration Compensation

- Thermally loaded the MLD-coated DM with 22 W (350 W/cm^2) of cw 1064 nm laser light
- Induced 88 nm rms distortion
- Used a dithering adaptive optics algorithm to reduce the distortion to 31 nm rms.

Thermal Loading Results

- Distortions concentrated on pillar edges
- Gold-coated DM had less thermally induced distortion
- Thermal Distortion Explanations
  - Differential thermal expansion between silicon pillars and silicon nitride
  - Non-uniform temperature distribution
    - Silicon pillars as effective "radiators"
    - Silicon pillars absorbed more light than gold



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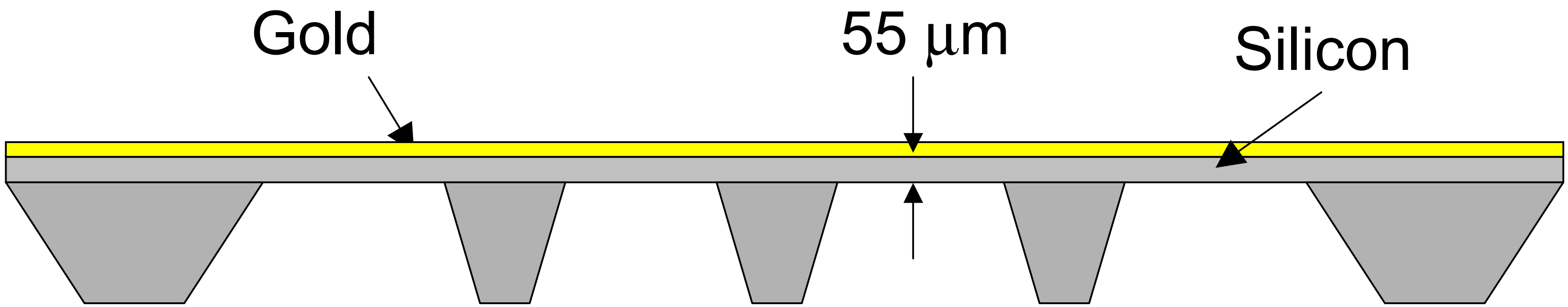
Gold-Coated All-Silicon DM Architecture



No wavefront distortion was observed even when loaded with 55 W of cw 1064 nm laser power (300W/cm^2).

Non-tensile silicon had ~10λ of sphere.

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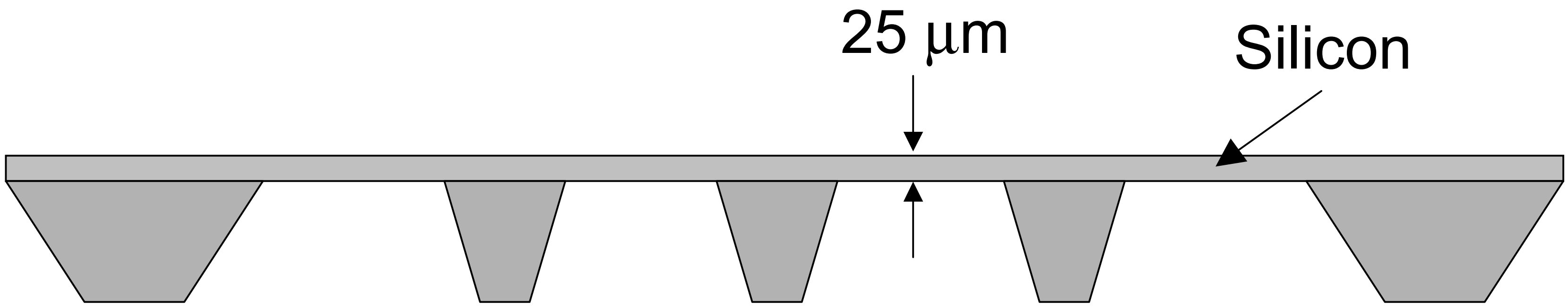
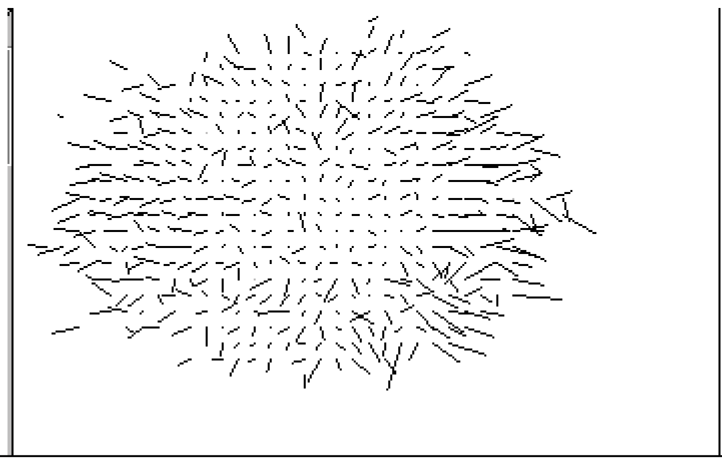
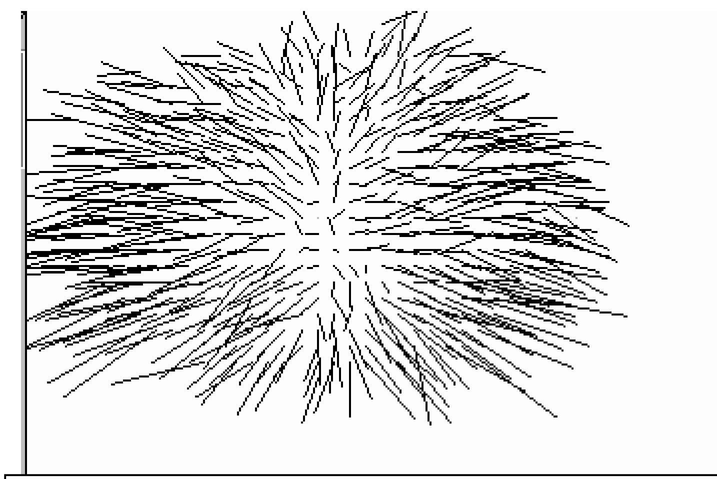
All-Silicon DM Architecture





274 nm rms distortion with 1.3 W.



1123 nm rms distortion with 2.2 W.

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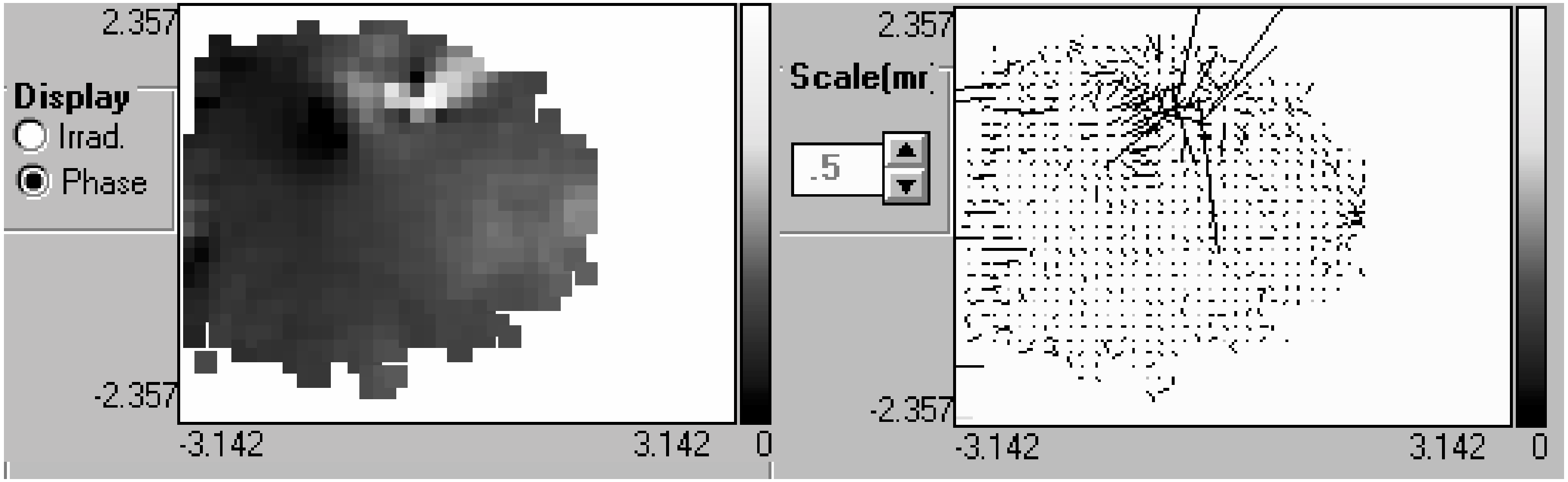
Damage Threshold



- 25 kW/cm^2 (~600 W) appeared to increase temperature enough to permanently distort the mirror surface.
- Mechanism is probably thermal annealing.

Future Work

- Conclusively determine cause of distortions.
- Fabrication of a single-crystal silicon MLD-coated deformable mirror with gold flash coating.
- Superior control algorithms
- Three-layer architecture

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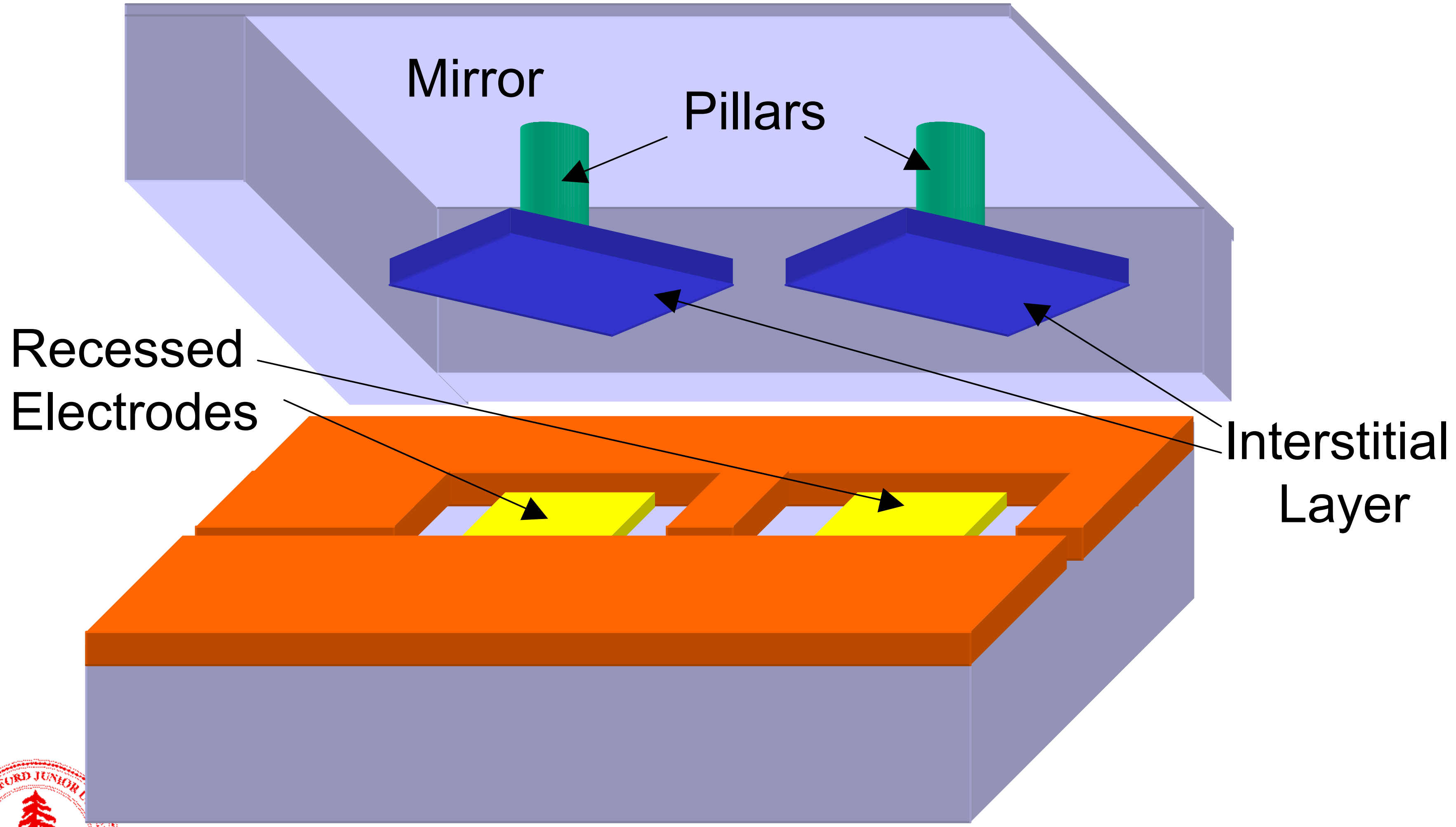
New Three-Layer Structure



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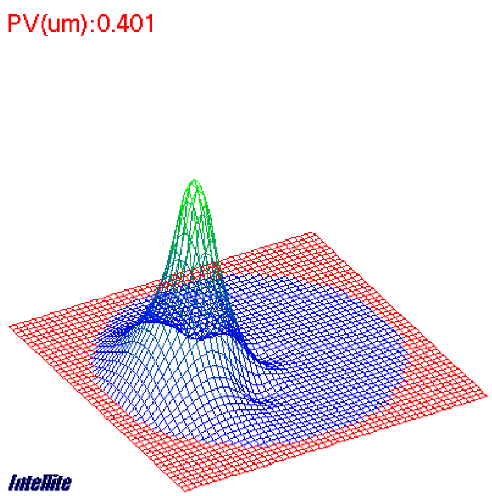
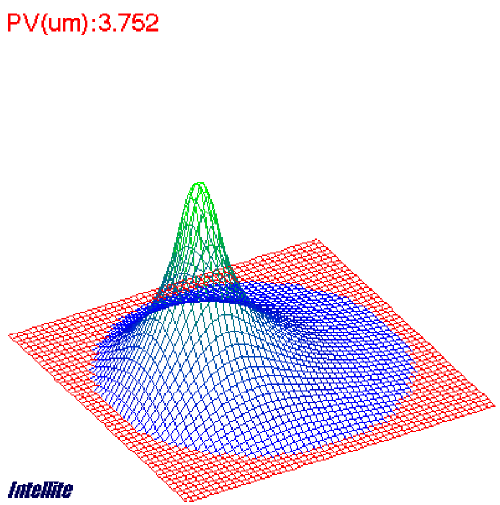
Advantages of Three Layer DM

- Less actuator crosstalk





- Resonance frequency that is fairly independent of mirror diameter

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Conclusions

- We have demonstrated a robust, good surface quality DM that can compensate (to a large degree) for thermal distortions in transmissive optics
- We have presented an architecture that permits MLD stack to be deposited easily
- We have presented an architecture that can be easily integrated with silicon circuitry.
- We have demonstrated a closed loop system.

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