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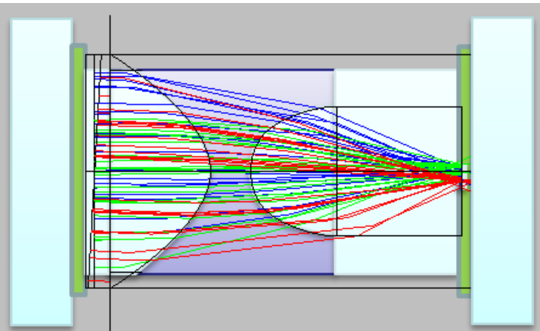

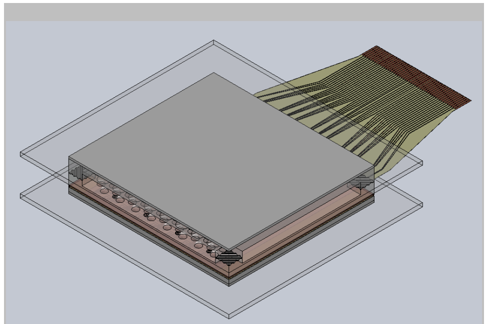

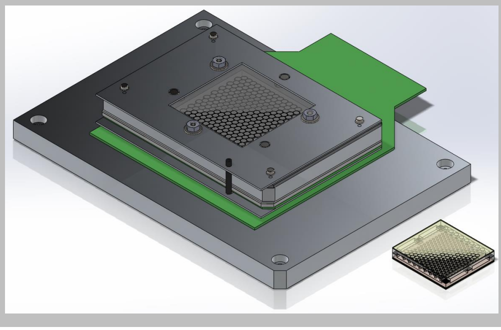

Optics and Packaging Materials in Microsystems Enabled Photovoltaic Solar Modules

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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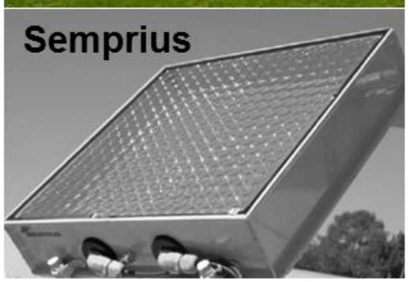
Outline

- MEPV Introduction
  - What is MEPV?
  - Why MEPV?
- Prototype I
  - Can it be done?
- Prototype II
  - Can it be made efficient?
- Prototype …

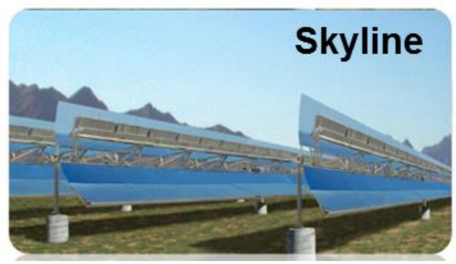
Current Solar Technologies: Optics and BOS

HCPV (500-1000x)



- Fresnel Lens Systems
- High Efficiency III-V Cells (~ 37-42%)
- High System Efficiencies (24-28%)
- Large, Stiff, Accurate Tracking Structures
- High Balance of Systems Costs

Low CPV (5-15x)



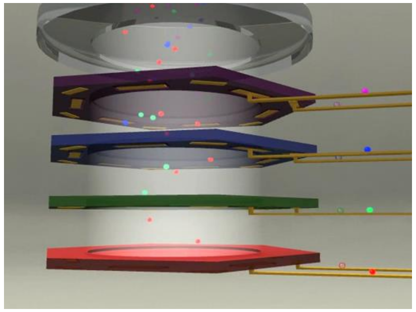
- Reflective Optics, (Trough)
- Moderate Efficiency Si Cells (~ 18-22%)
- Moderate System Efficiencies (16-20%)
- Moderate Complexity Tracking Structures
- Moderate Balance of System Costs

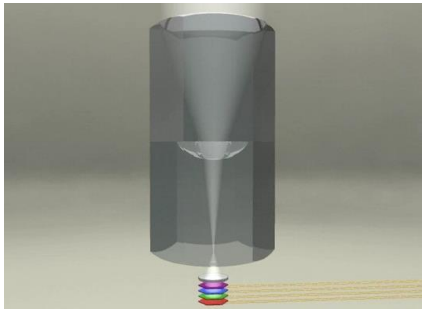
PV

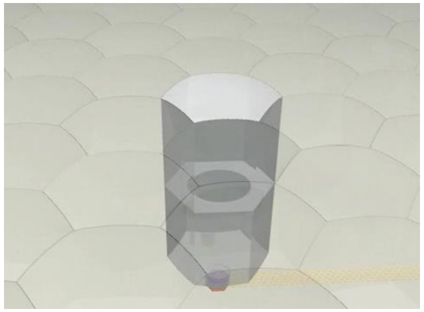
- No Optical System (Flat Glass)
- Low-to-Mod Efficiency Cells (~ 10-22%)
- Low-to-Mod System Efficiencies (8-18%)
- Simple Tracking Structures
- Low Balance of Systems Costs

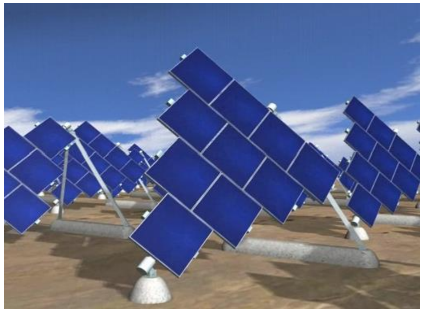
MEPV

- **Microsystems Enabled Photovoltaics (MEPV)**
  - Very small cell sizes allow high-quality refractive optics to be molded inexpensively in microlens arrays, opening up a broad new design space of solar concentrators.


Micro-PV Cells


Micro-optics


High Performance Modules


Low-cost, MEPV Systems

- **Purpose:**
  - Explore fundamental scale effects within photovoltaic cells, modules, and systems for enhanced performance, reduced costs, and new functionality
- **Goal:**
  - 40% efficient PV system with the potential for $0.10/kWh levelized cost of energy (LCOE)

MEPV Optical Systems Vision

Create a micro-optical concentrator system with the performance of high-concentration CPV, with the balance-of-system advantages of flat-plate PV.

Final Optical System Attributes:	**Prototype I**	**Prototype II**	**Prototype …**
• Moderate concentration (100-200x)		★	★
• Moderate acceptance angle (±2-6°)	★	★	★
• Low-cost materials and usage		★	★
• High-reliability materials and design			★
• High-Volume manufacturing approaches			★
• Optical system thickness less than 1cm	★	★	★
• Optical system weight consistent with low-cost trackers		★	★

Extensive systems design requirements for Prototype II and beyond

Prototype I

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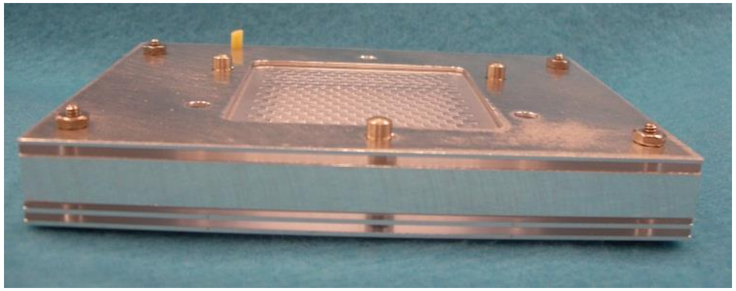
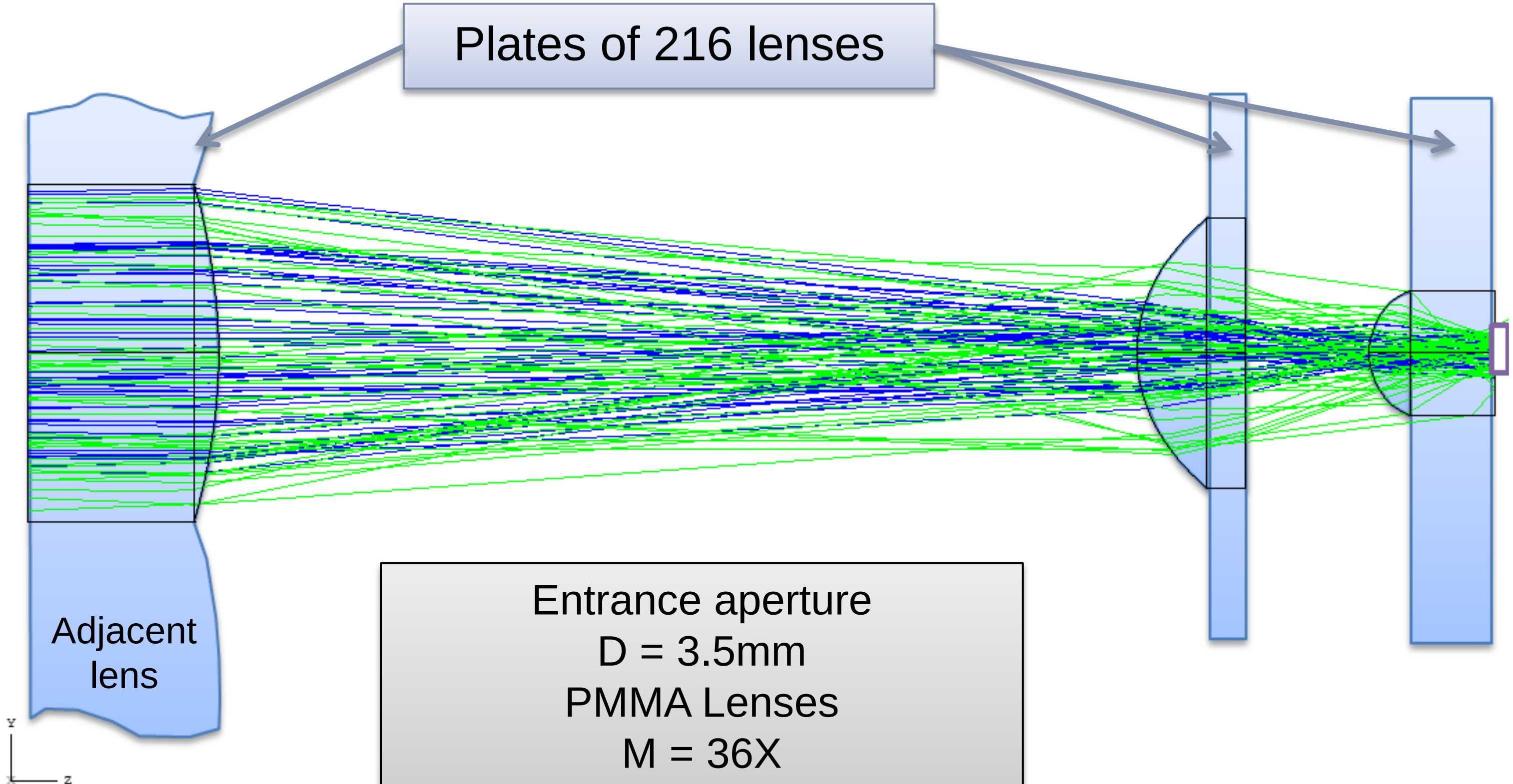


Prototype I Optical System

- 5cm x 5cm area
- 216 element micro-lens array
- Design and in-house fabrication took 9 months
- Using ordinary plastic – PMMA
- 36 sun magnification
- Original design was 50X, FOV= $\pm 6^{o}$, with PMMA & Polycarbonate, but we couldn't machine the Polycarbonate with acceptable surface finish
- Field of view (@90% throughput) = $\pm 4^{o}$
- Allows reduced tracking requirements
- Can use less rigid support structures
- Collects low-angle forward scatter
- The completed lens array is being used to illuminate the first microconcentrator array of PV cells

Prototype I Optics



Entrance aperture
D = 3.5mm
PMMA Lenses
M = 36X
FOV = ± 4^0

Microlens Array Fabrication

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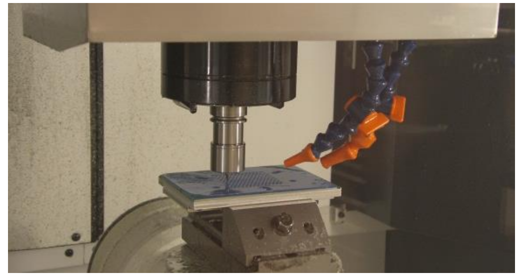
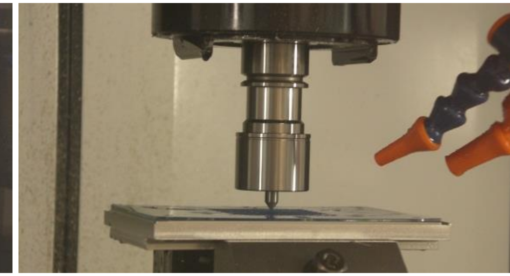
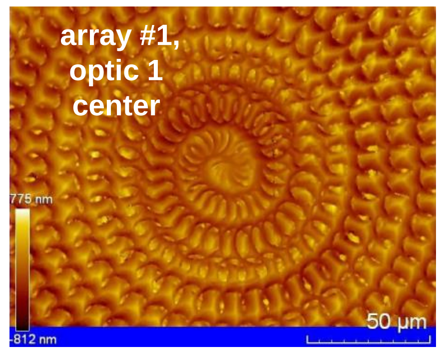
- Machining
  - Yasda micro-milling
    - ~0.5 µm machine accuracy
    - multiple tools for roughing & finishing
    - final cut w/diamond tool
- Discoveries
  - PC milling gives very poor finish
    - switched to a M=36X, all-PMMA design
    - The original PMMA/PC design gave a 50X magnification

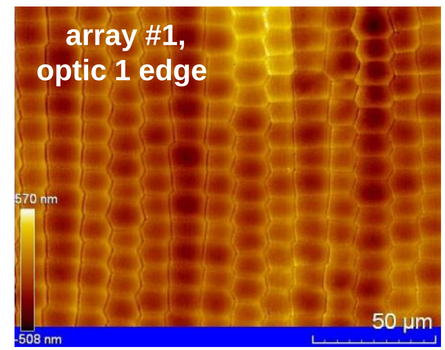


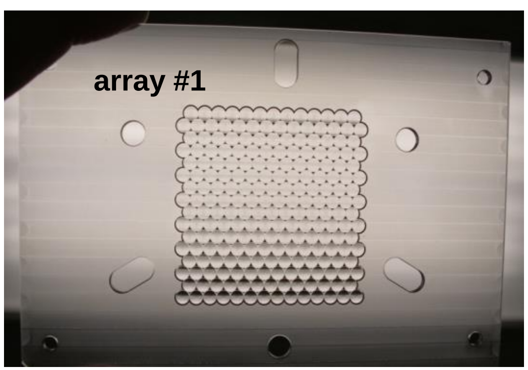
rough cutting optics

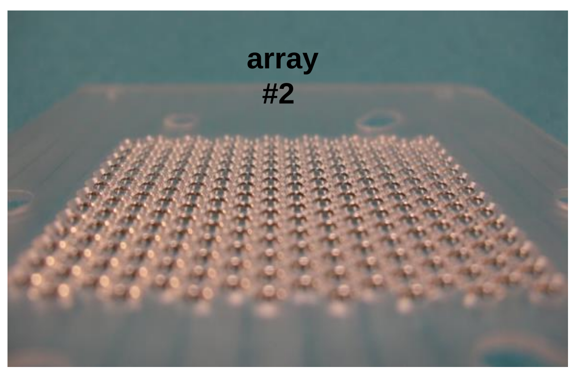


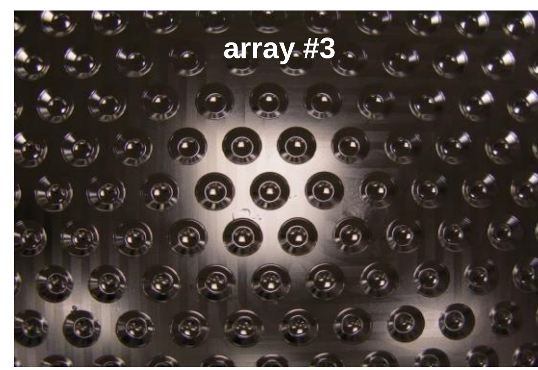
finish cutting optics





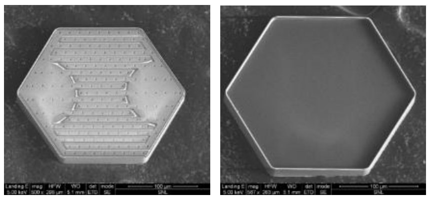




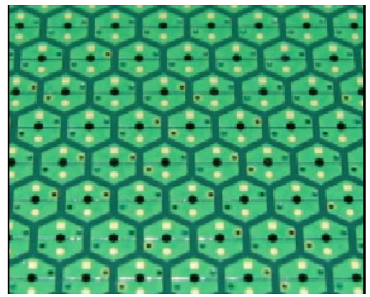


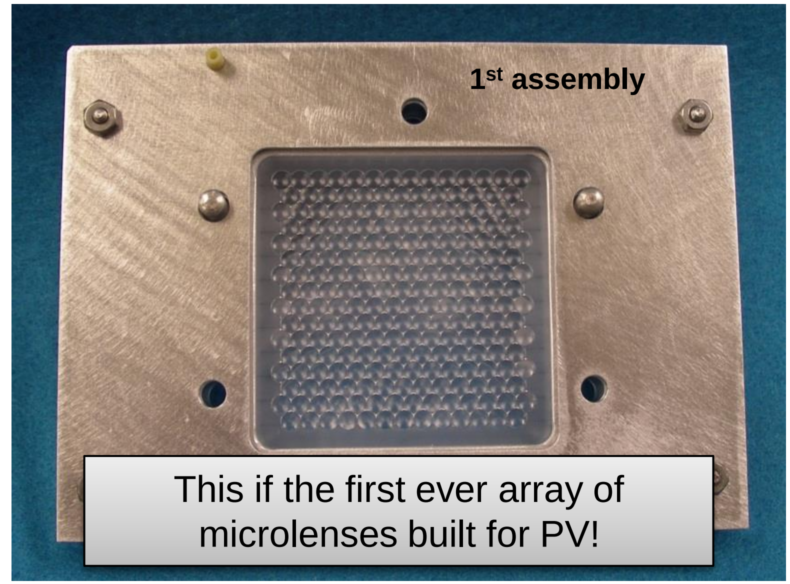
Prototype I Module

- Hexagonal closed packed arrays
  - 5 cm^2 (216 cells)

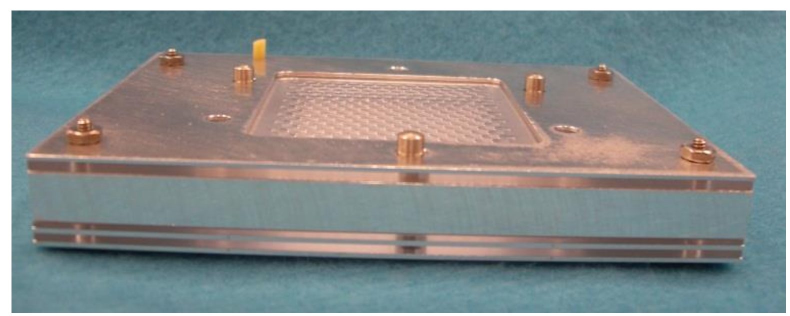


250 micron across, 14 micron thick crystalline silicon cells





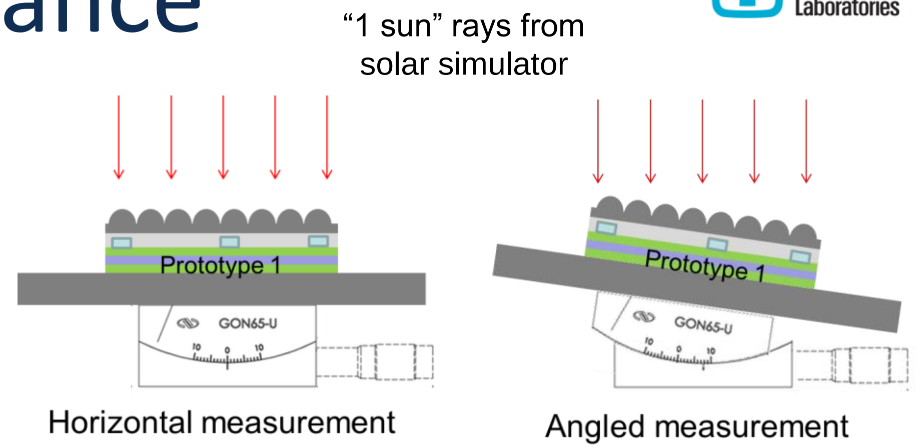
- Kinematic mounting
  - passive optic-to-cell alignment
  - athermal assembly

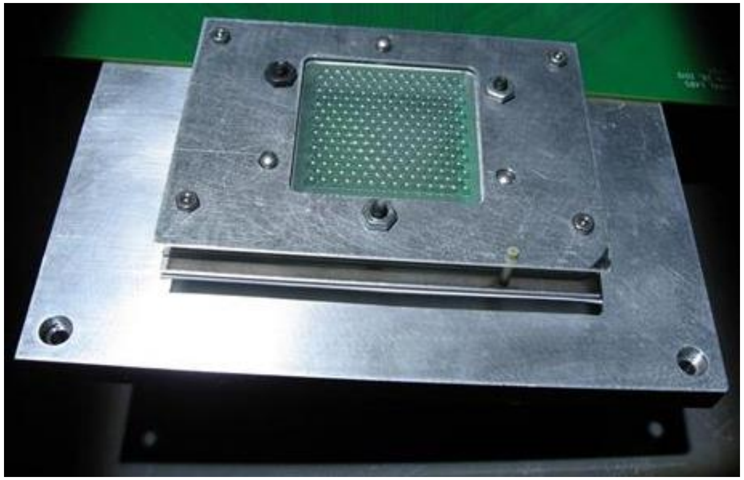


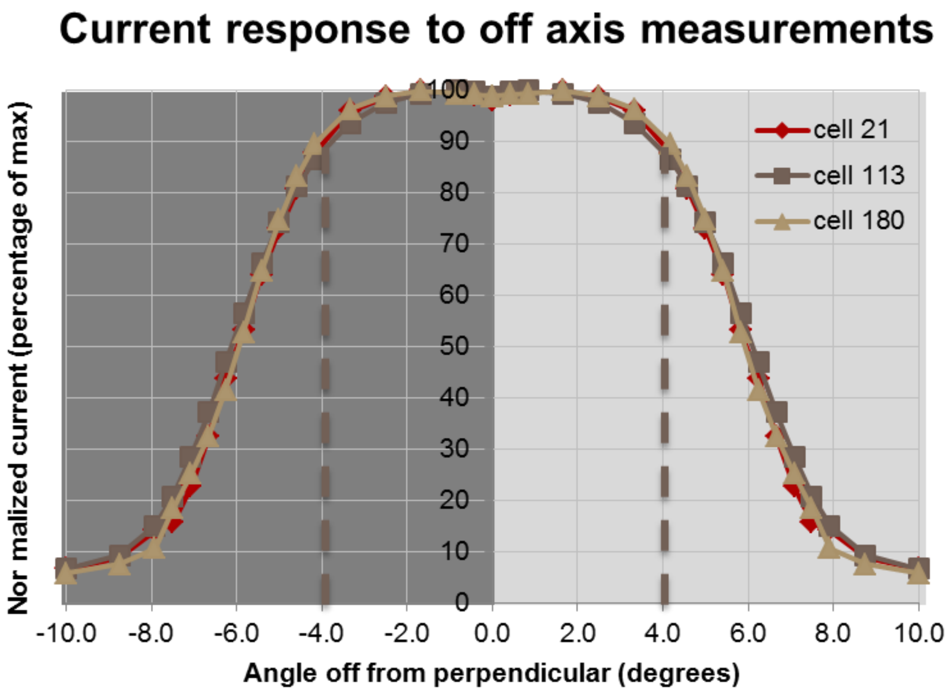
- Fresnel and Scattering Losses
  - No AR coatings & Rough surfaces
  - Calculated Losses: 39%
  - Measured Losses: 42%

Prototype I Performance

- 36X Concentration
- ±4° degree acceptance angle (90% of peak power)
- ~1 cm focal length
- 12% module efficiency



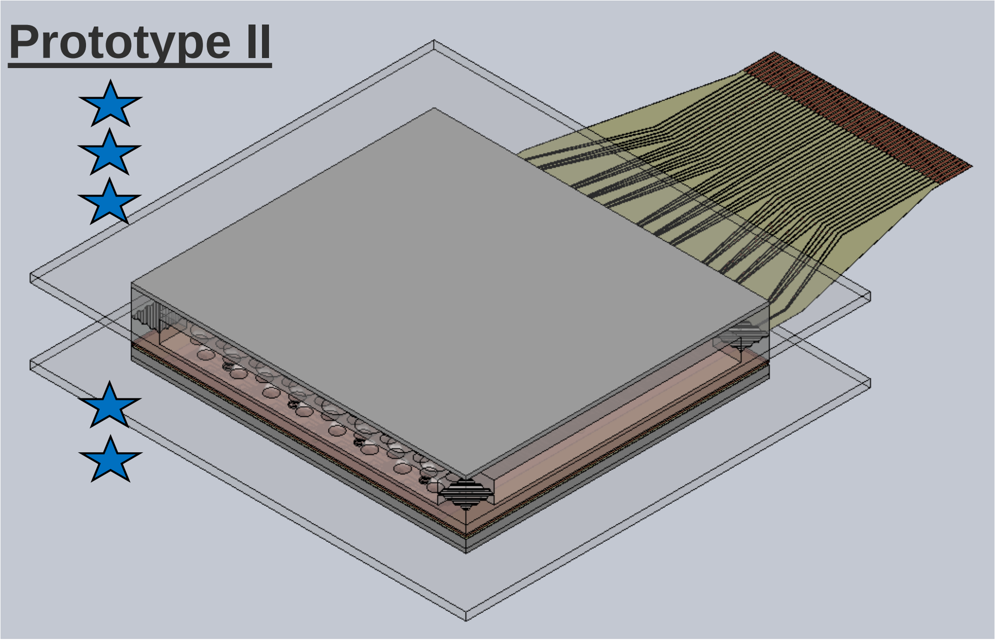




Prototype II

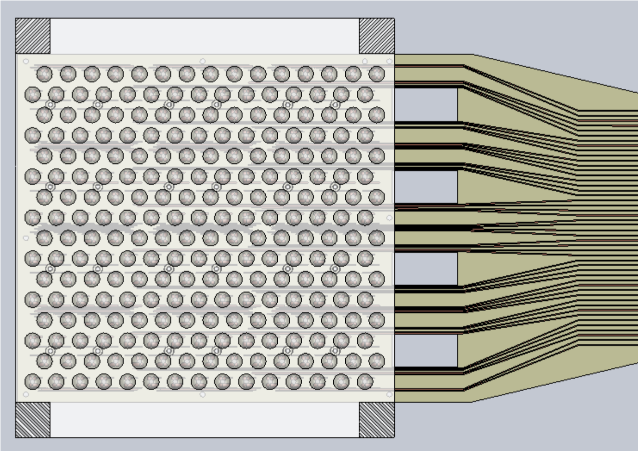
Final Optical System Attributes:

- Moderate concentration (100x)
- Moderate acceptance angle (±2-6°)
- Low-cost materials and usage
- High-reliability materials and design
- High-volume manufacturing approaches
- Optical system thickness less than 1cm
- Optical system weight consistent with low-cost trackers

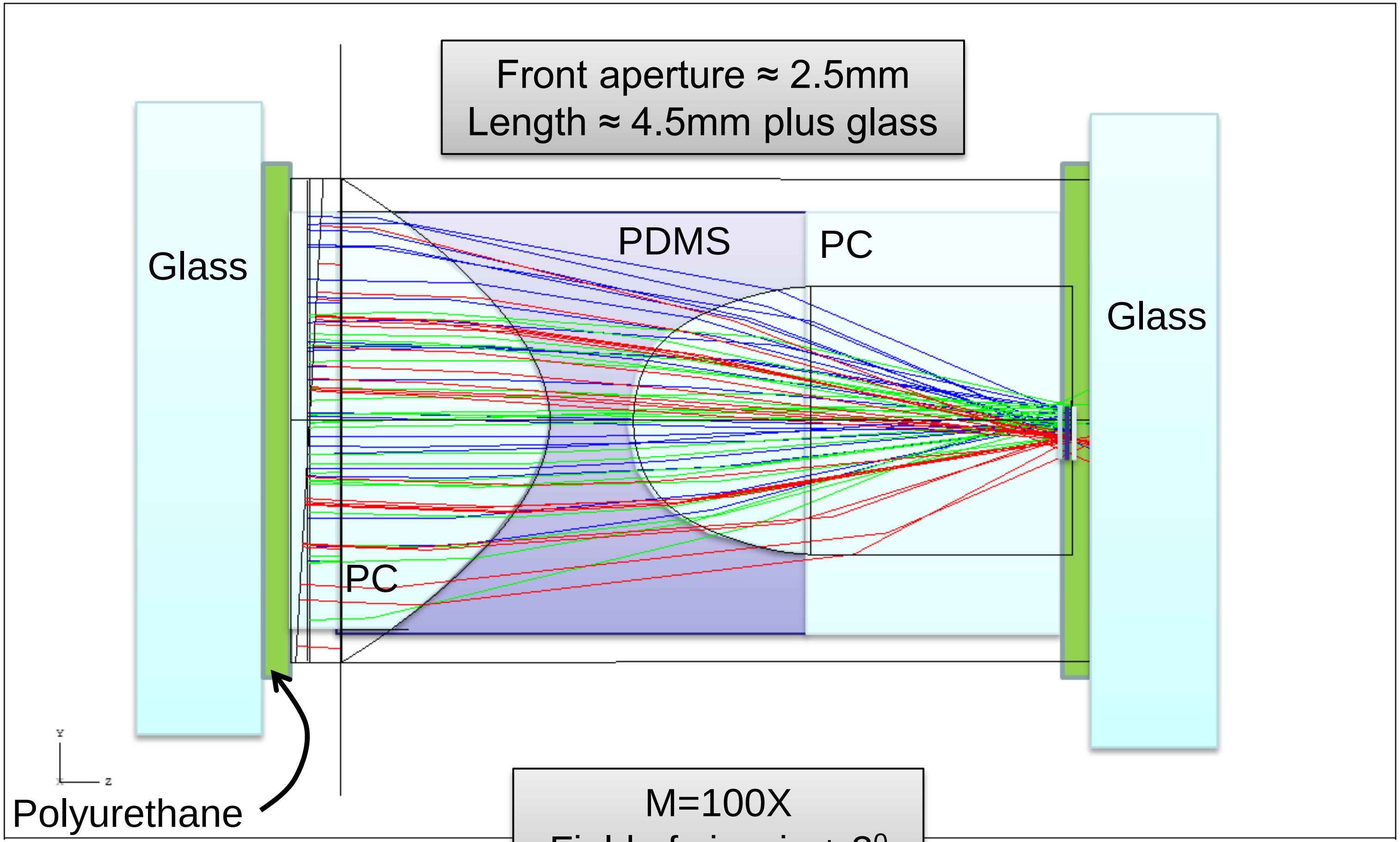


Engineering Challenges

- Plastics have large CTE's
- Must maintain alignment during temperature cycling
- Alignment during assembly
- Maintaining tolerances during molding
- "Hot Spots" in plastic
- "Hot Spots" on PV cells
- Must keep costs down
- Avoid air gaps in the optics which could leak over the years
- Glass bonding and seal
- ……………. and many more requirements



Prototype II Optics

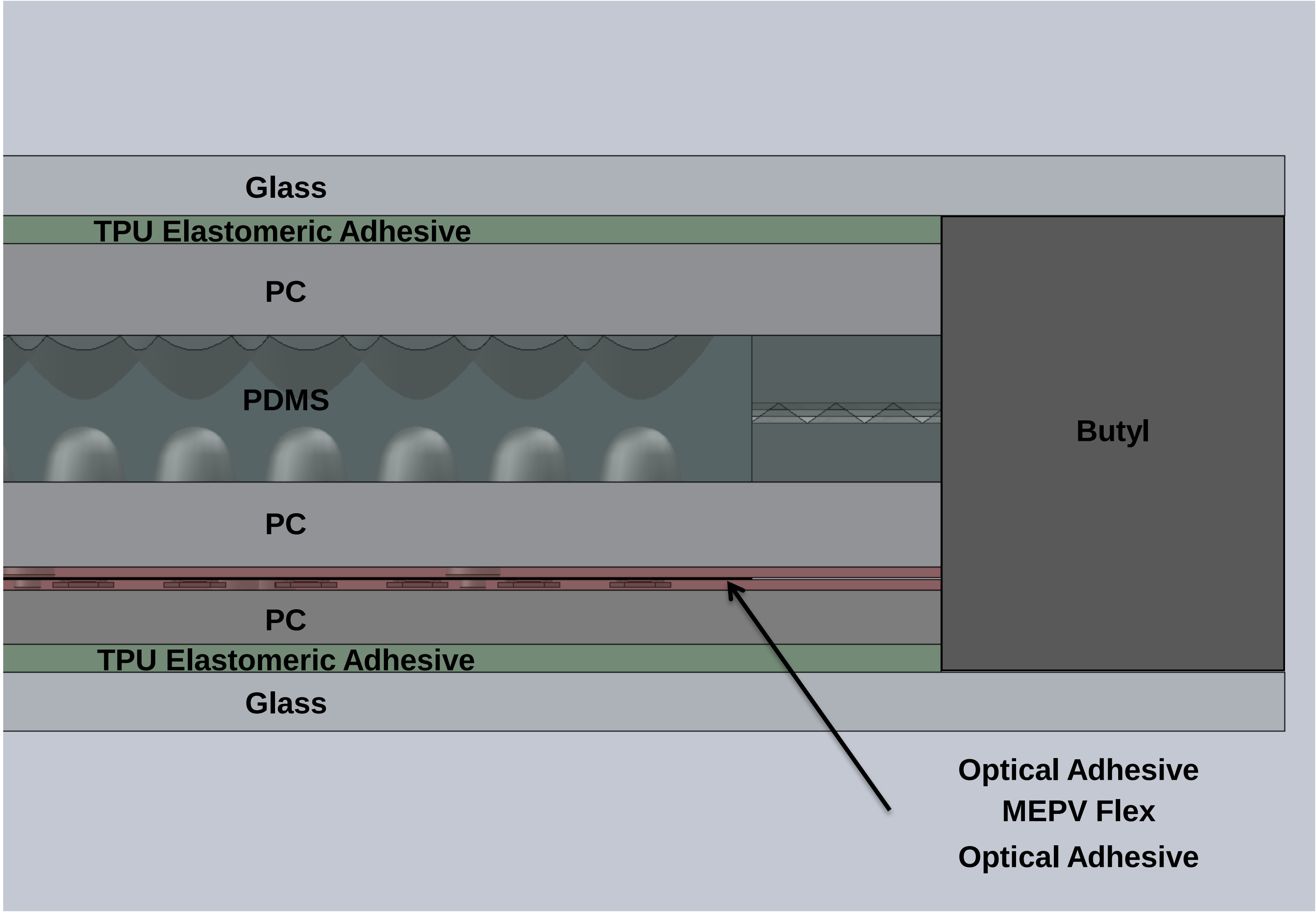


M=100X

Field of view is ± 3^0

Transmission > 90%

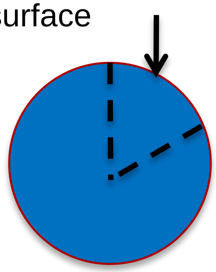
Assembled Optic Module

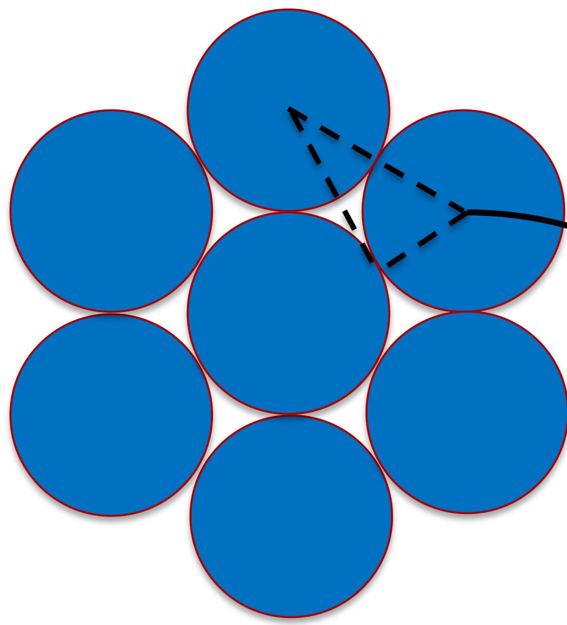


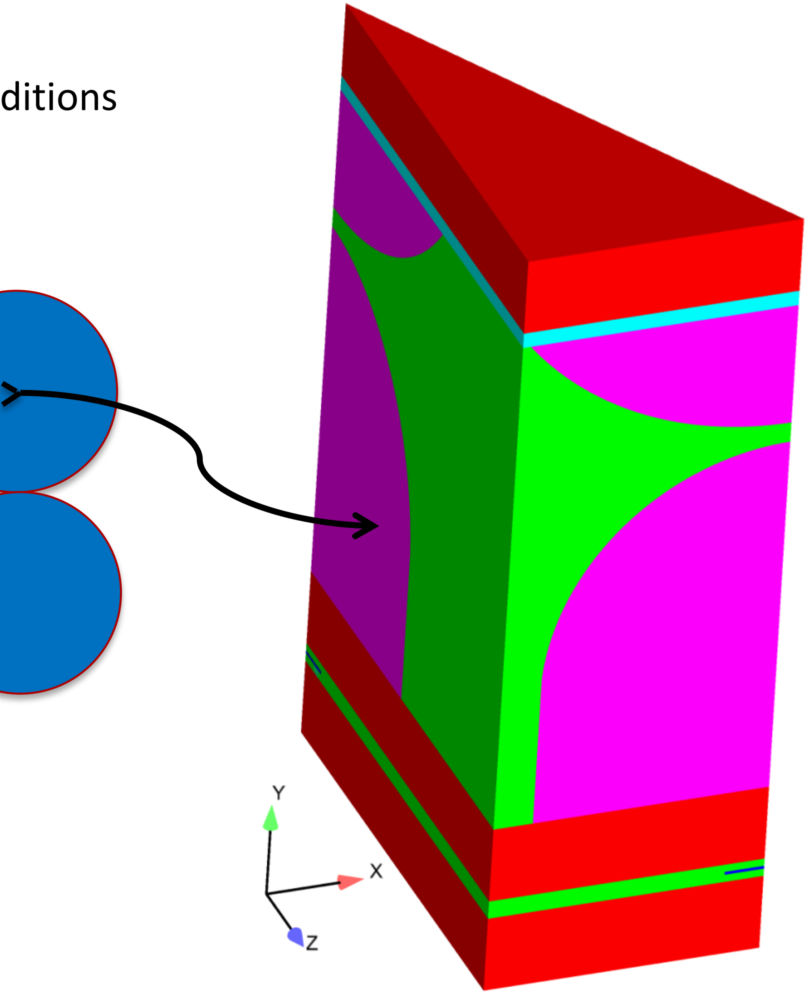
Modeling Approach / Symmetry View

- Model the boxed triangle
- Using 3 Symmetry Planes for imposed boundary conditions (no normal displacements on each side of triangle)

we cannot just model the 1/6 of circular region because we lack a known boundary condition on the radial surface



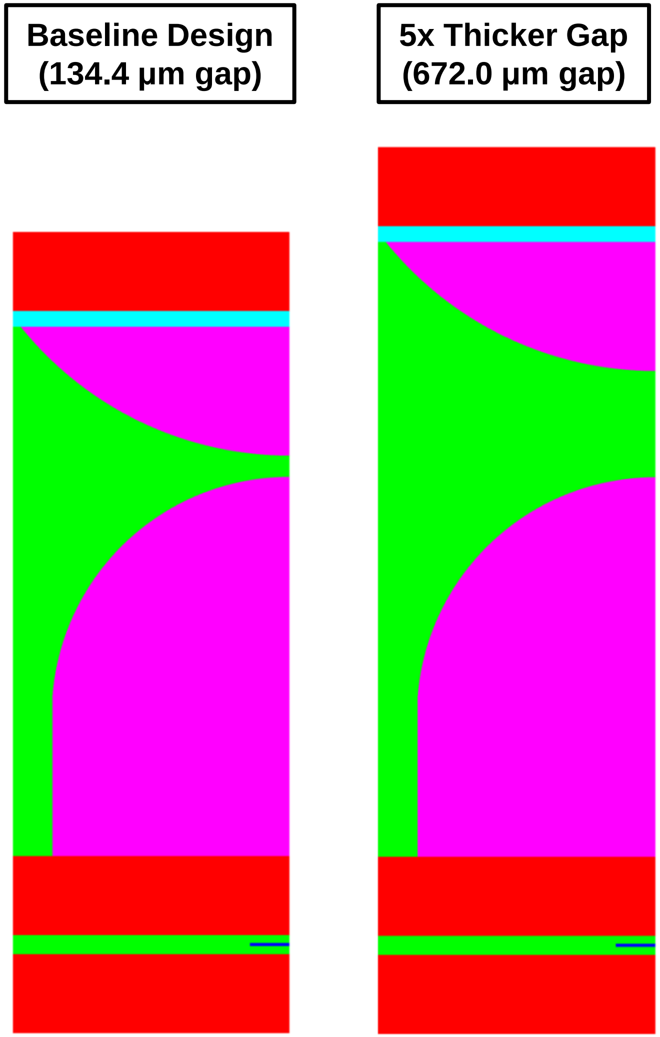




RED – Glass
GREEN – PDMS
MAGENTA – PC
Cyan – Rubbery Adhesive
BLUE – PV cell

**solder is a cylinder beneath PV cell, but can't be seen

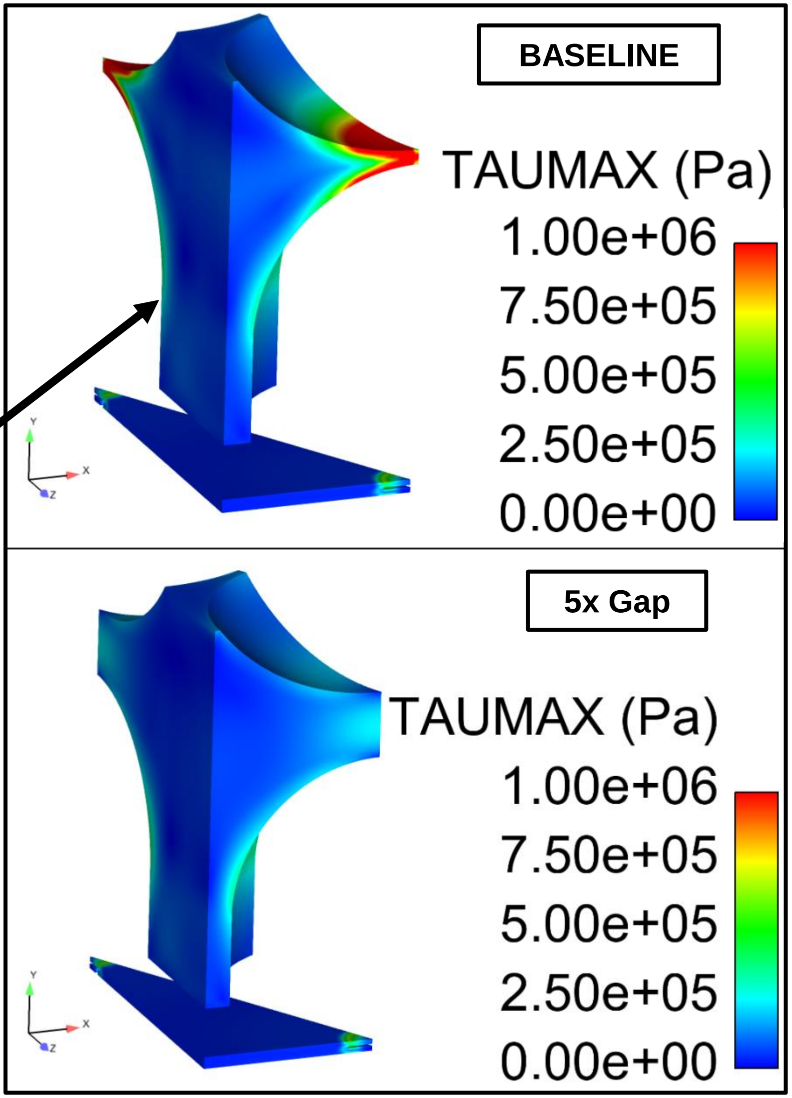
Reduce Stress in PDMS by Increasing Gap Between Lenses



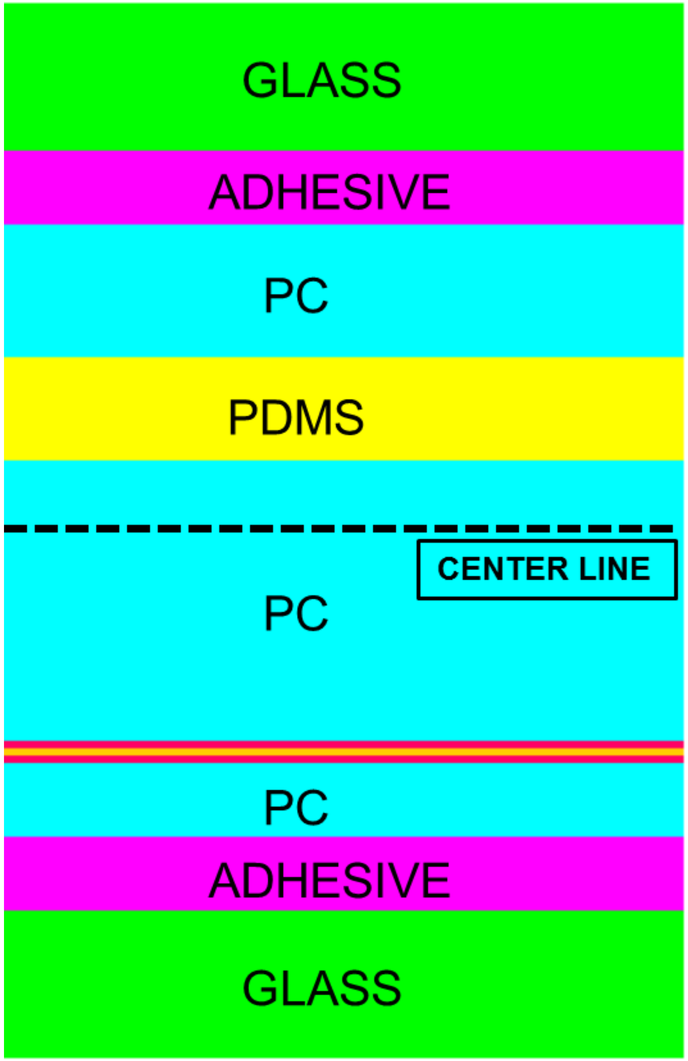
- Analysis ΔT = 40ºC
- Stress scales linearly with ΔT (elastic properties)

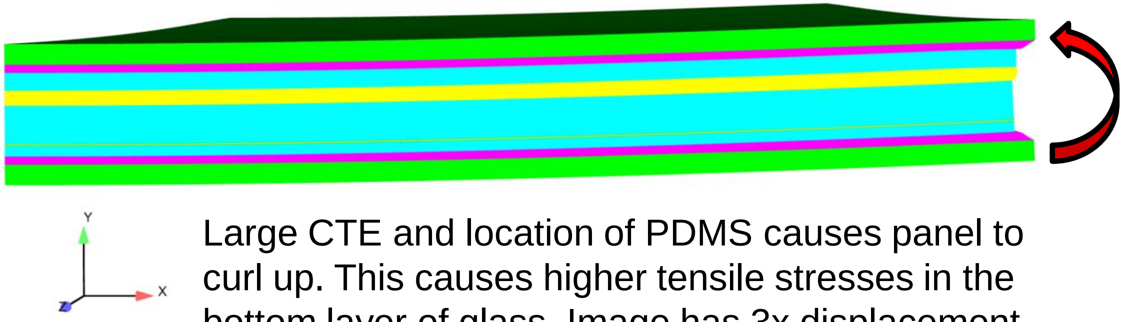
PDMS

TAUMAX = max shear stress



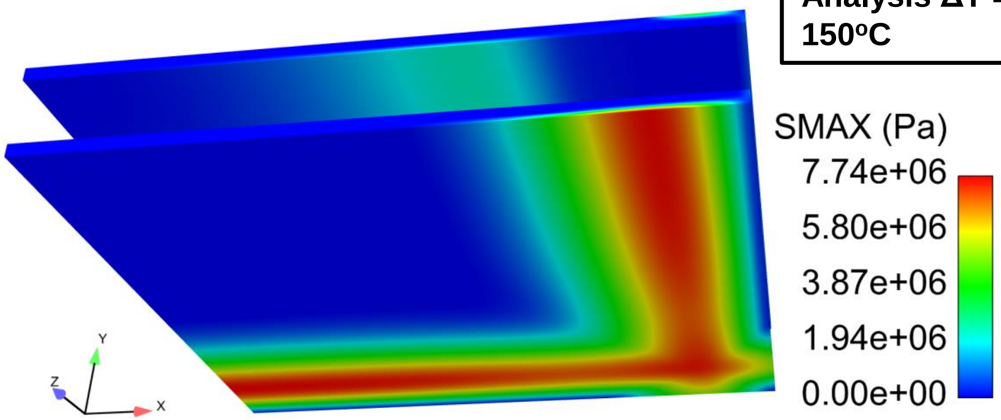
Benefits of Implementing Symmetry in Manufacturing (10cm panel)





Large CTE and location of PDMS causes panel to curl up. This causes higher tensile stresses in the bottom layer of glass. Image has 3x displacement magnification.

Analysis ΔT = 150°C



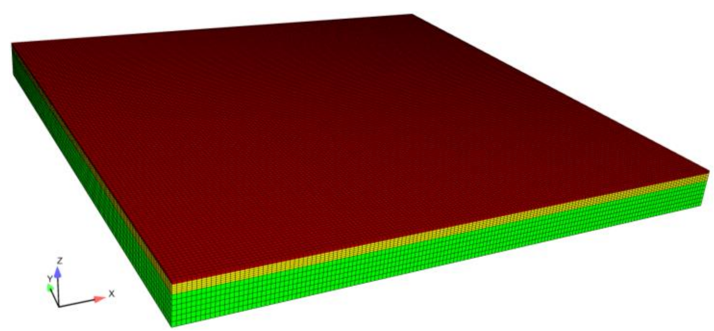
- Top glass layer peak stress: $\sigma_{max} \approx 5.2$ MPa
- Bottom glass layer peak stress: $\sigma_{max} \approx 7.75$ MPa

Misalignment after Cool Down of Flex Circuit Layup

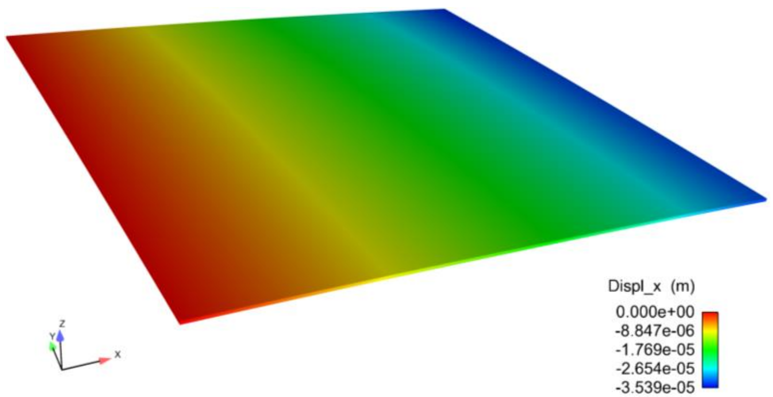
- Assume perfect alignment and stress/strain-free at T=90°C
- Cool bonded composite to T = 20°C

MEPV Flex – Adhesive – Polycarbonate Layers

¼ Symmetry
FEA Mesh



2 cm x 2 cm x .07 cm



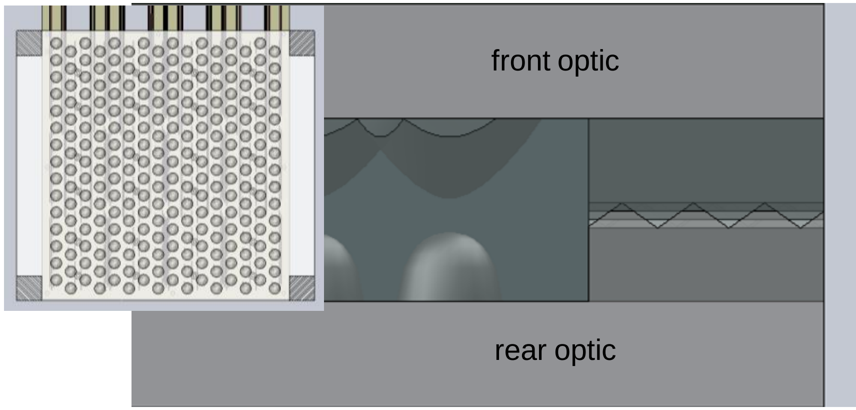
X-Displacement in MEPV Flex at T = 20 C

Alignment

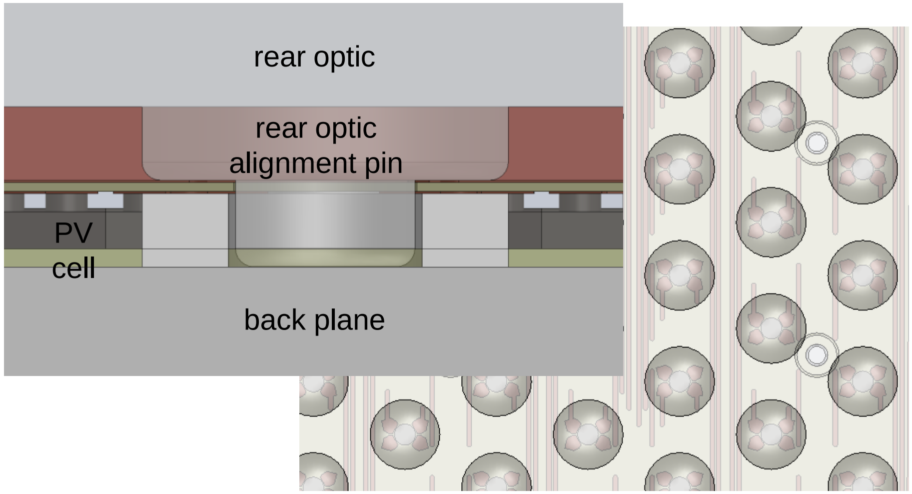
Lens/Flex/Backplane Assembly

- Challenges
  - precision alignment
  - fabrication of passive features
  - minimal restriction to adhesive flow
  - CTE mismatches during processing
- Solution
  - Molded lens alignment structures
  - rear optic pin & spacer
  - flex holes
  - backplane spacer

Microlens Array Alignment



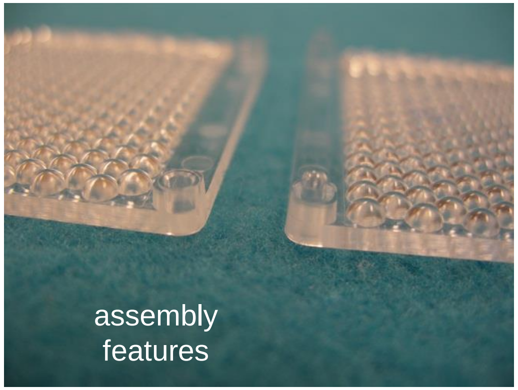
PV Cell to Optic Alignment

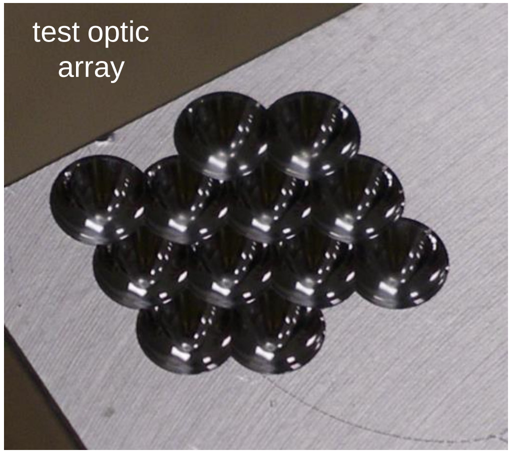


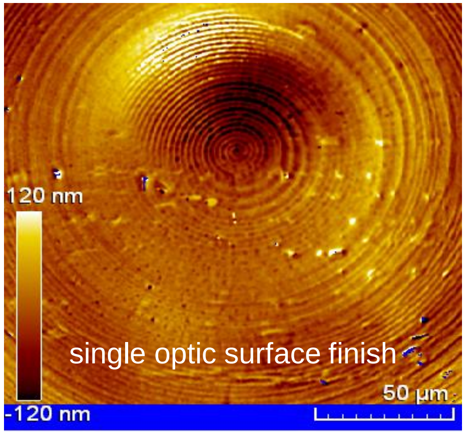
Optics Molding

- Molded Test Parts
  - ball milled "optics" w/pin-in-slot assembly features
  - Enabled process development, mold shrinkage measurement, and dimensional stability
- Test optic mold array
  - 4x4 hexagonal array
    - incorporated micro- & diamond-milling
  - form accuracy ~ 1.5 µm
  - surface finish ~ 30 nm S_a

Greenlight Optics
Performance... for the Real World





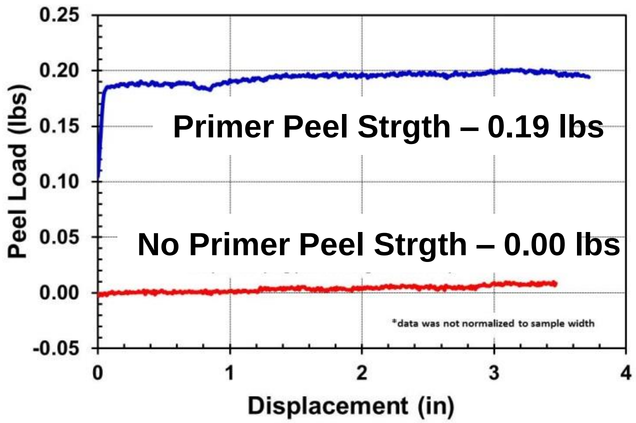


Yasda diamond milled
S_a = 30 nm

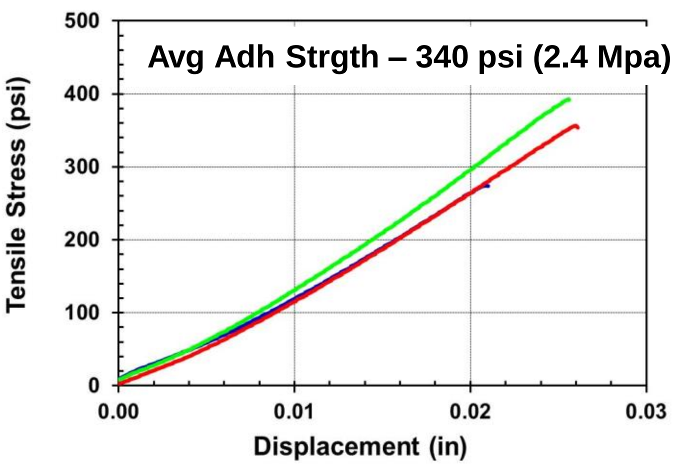
PC/PDMS/PC Lens Assembly

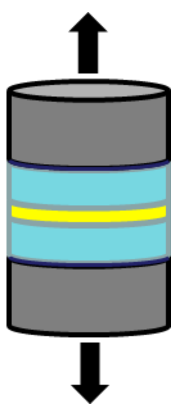
Silane Primer to promote adhesion

Peel Test – Sylgard184 to PC

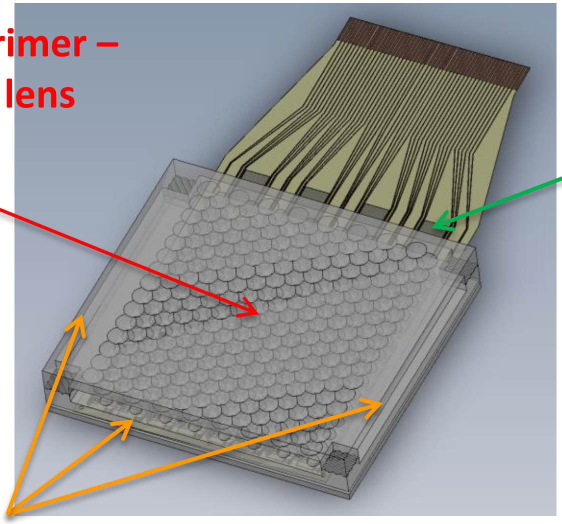


Butt Tensile – Sylgard184 to PC

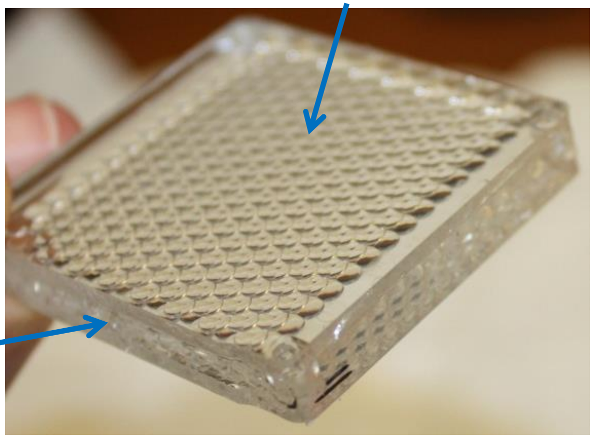




1. Apply Primer – internal lens surfaces
2. Seal edges
3. PDMS fill – Bottom up
4. Degas

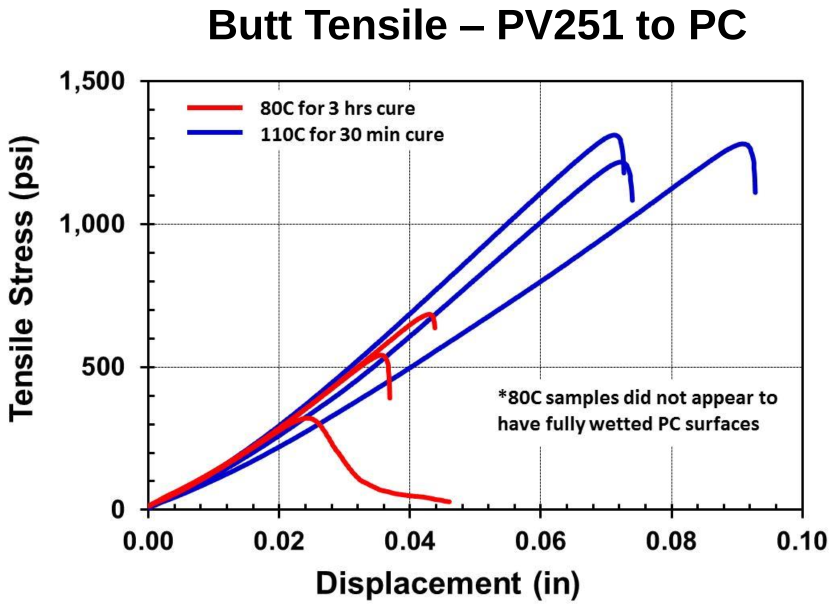


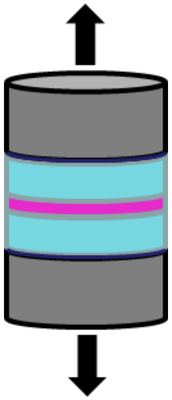
Primer applied to internal lens surfaces



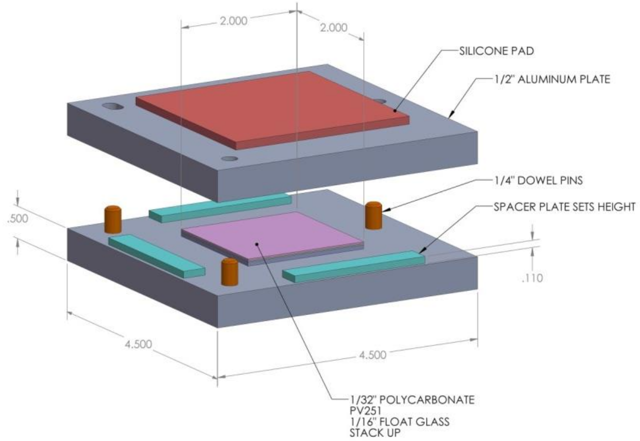
PDMS fill

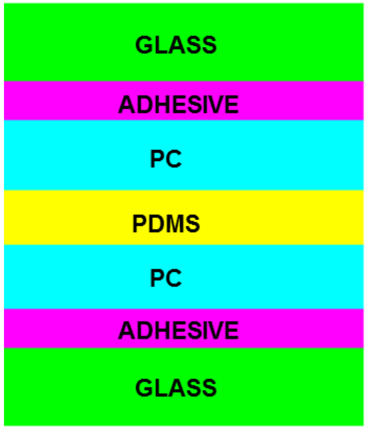
Glass to PC Lamination

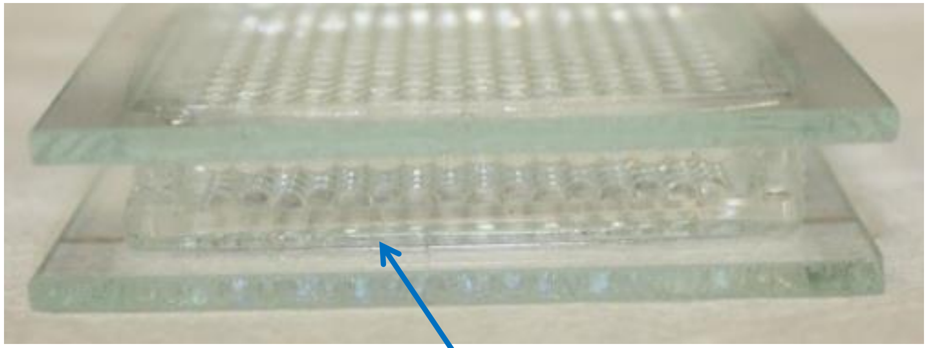




Laminator custom tooling







TPU elastomer bonds PC to glass

Flex to PC Assembly

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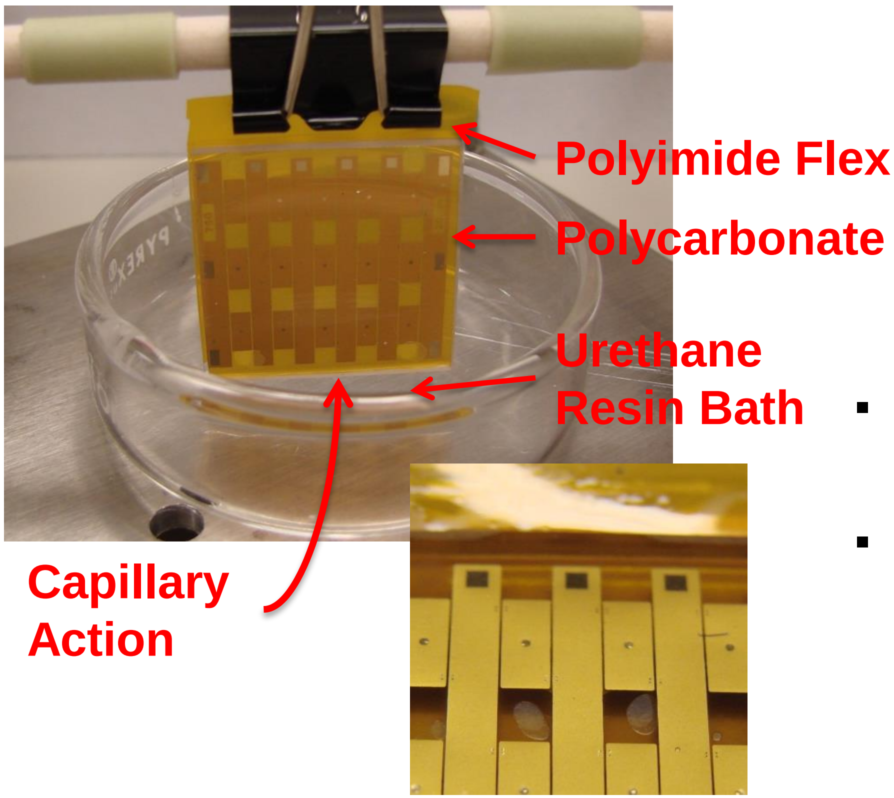
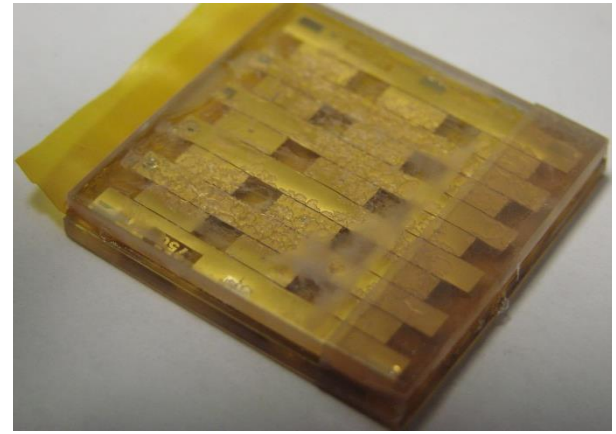
Urethane Optical Adhesive
formulated to be index and CTE matched to polycarbonate to reduce stress and maintain alignment of flex with PC microlens array



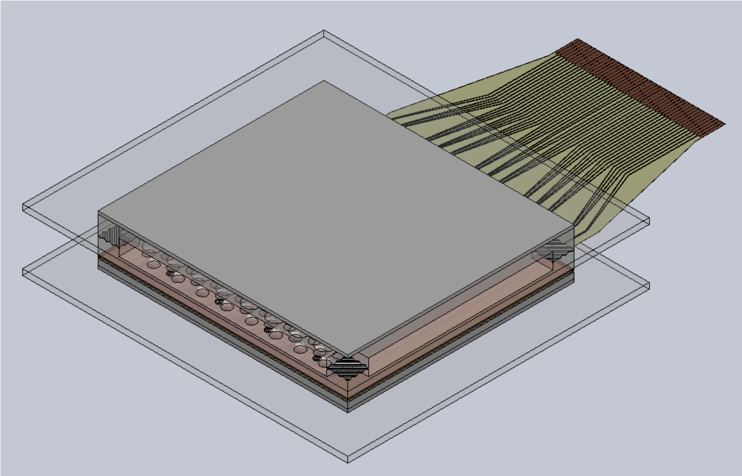


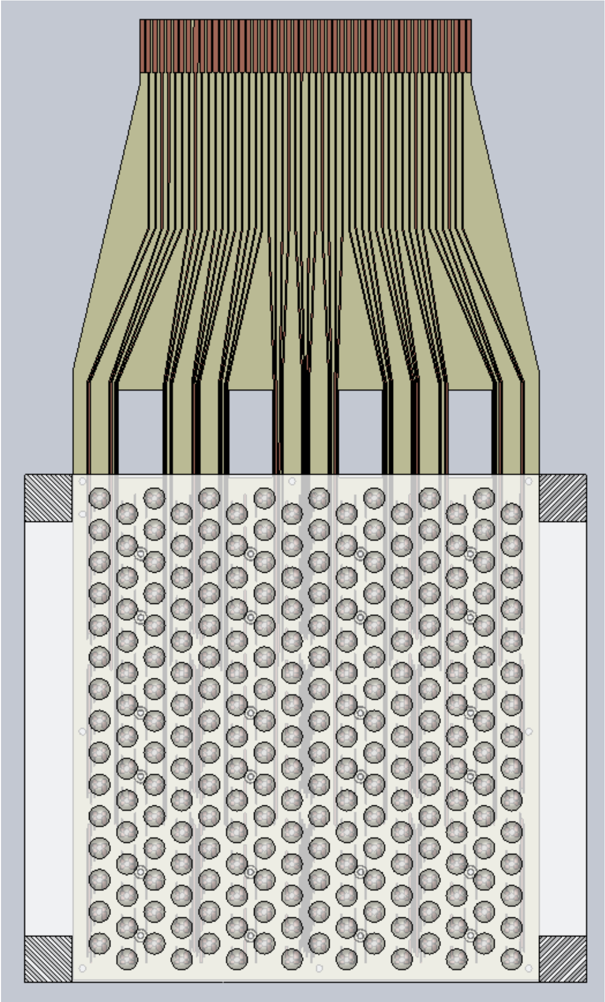
Dry assembly prior to fill → Prevent Rxn with water

- Dried assembly prevents water rxn
- Lack of mechanical tie btwn PC and Flex leads to wrinkling of Flex -> Prone to misalignment

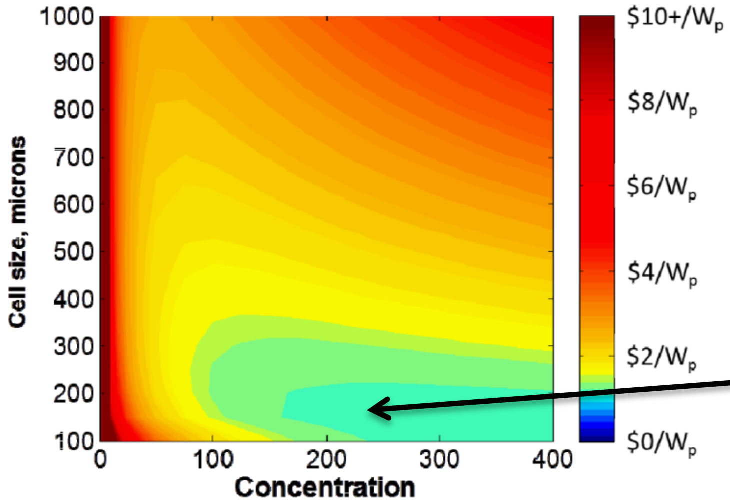
Prototype II Performance

- Expected Performance
  - 100X Concentration
  - ±3° degree acceptance angle (90% of peak power)
  - >1 cm focal length
  - 28% module efficiency





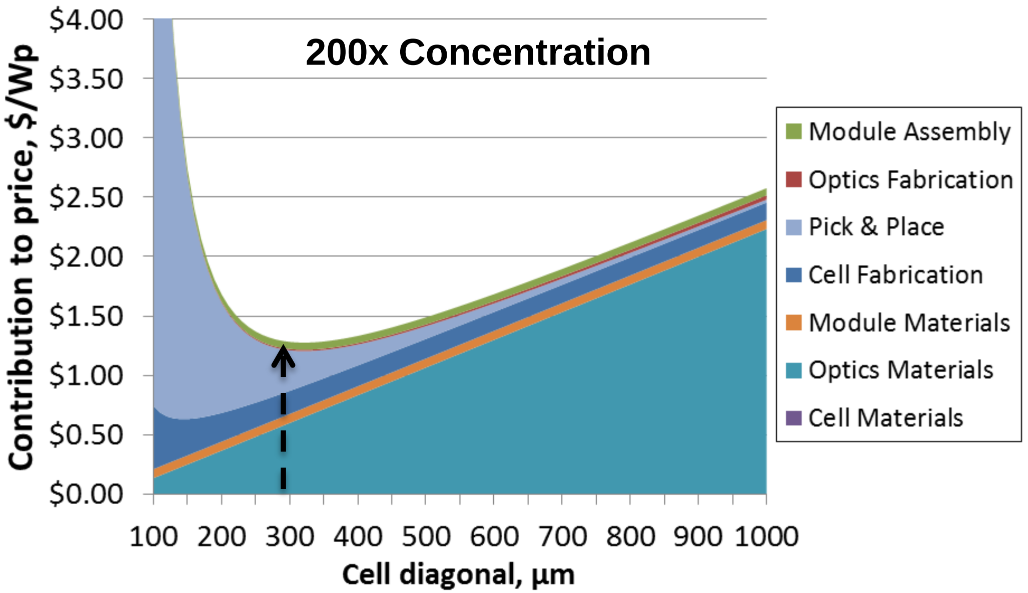
Cost Modeling



- Concentration enables cost reduction by reducing amount of PV material

Where we need to be

- Manufacturing costs push for larger cells
- Material costs push for smaller cells



Prototype Comparison