Planar micro-optic solar concentration using multiple imaging lenses into a common slab waveguide

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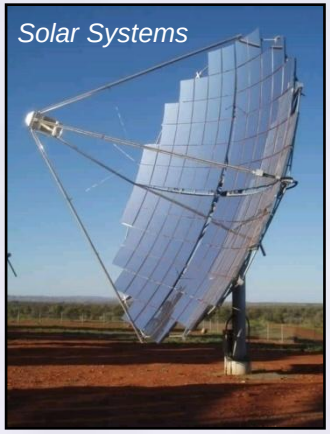
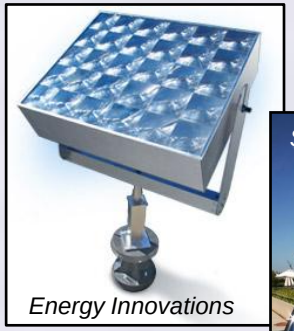
Photo: Kevin Walsh, OLR

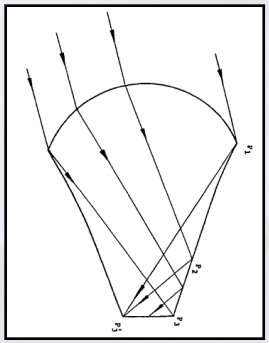
Concentrator Photovoltaics (CPV)

1. Primary Focusing Optic
   - Performs light concentration
   - Large collecting lens or mirror
   - Trend towards multiple apertures

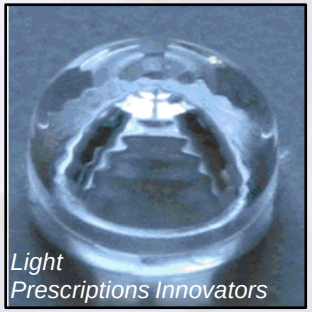




2. Secondary Homogenization Optic
   - Mounted between primary and PV cell
   - Uniform illumination for high efficiency
   - Non-imaging optical design



Xiaohui Ning, Appl. Opt. **26**, 1987

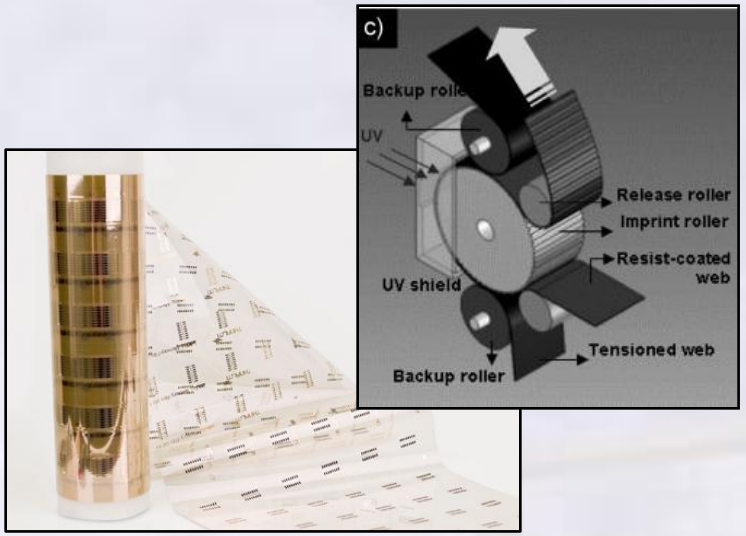


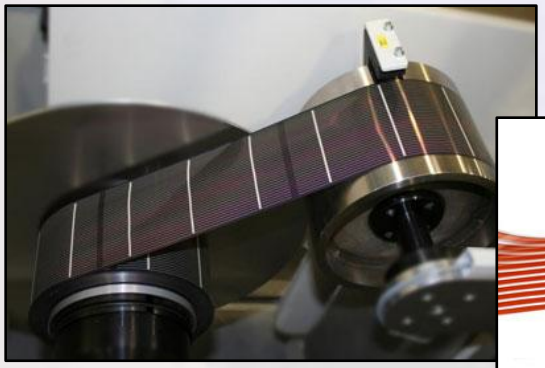
3. Mechanical Tracking
   - Alignment for direct insolation
   - Angular acceptance defines tracking accuracy
   - Wind loading and environmental stability

Flatcon System Tracking

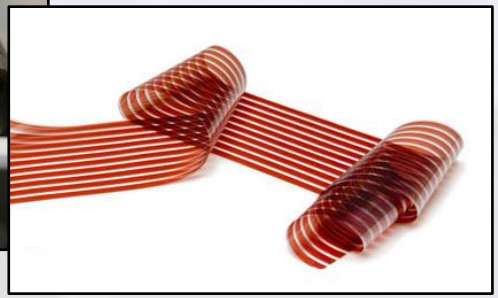
Continuous Roll-to-Roll Fabrication

- Continuous roll-to-roll processing
  - Rigid or flexible substrates
  - Emboss, coat and bond layers
- ***Inexpensive mass-fabrication***
- ***Constraints: Uniform thickness***
  Limited complexity





Global Solar

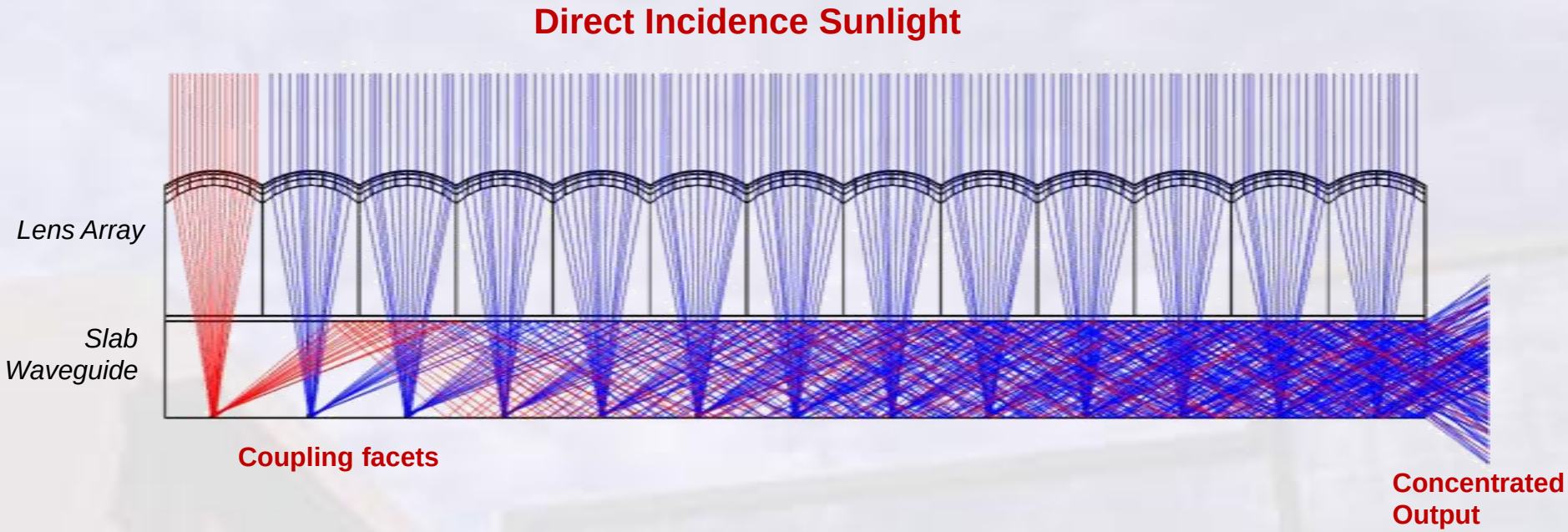


Konarka

Roll-to-Roll for CPV?

Goal: Design a uniform thickness, high-flux solar concentrator compatible with continuous roll-to-roll manufacture

Micro-optic Slab Concentrator

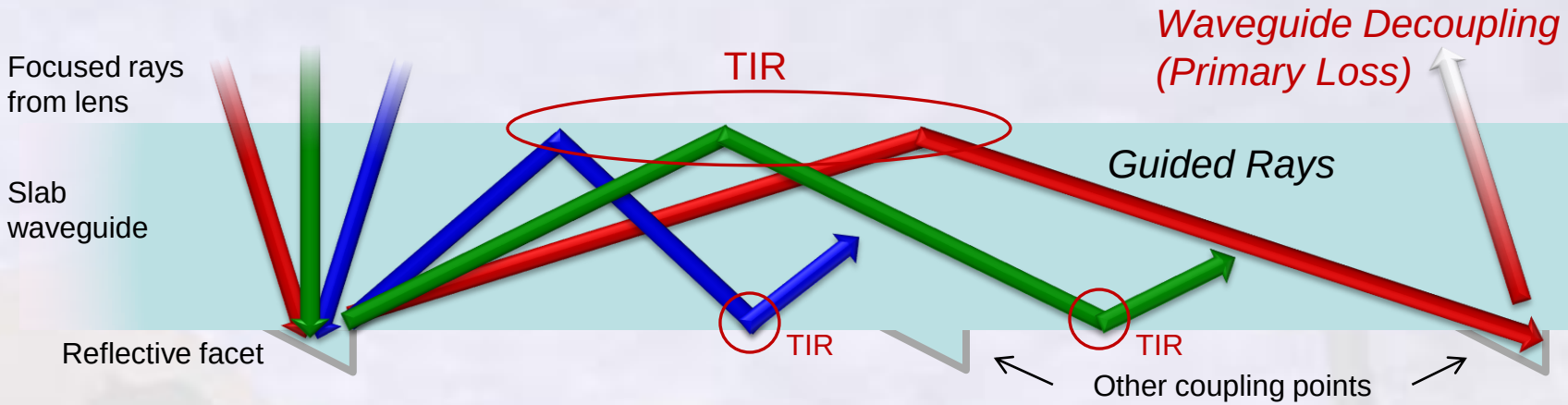


Advantages:

- ***Sub-apertures couple light to single output***
- ***Homogeneous output intensity***
- ***Uniform thickness (roll-to-roll fabrication)***

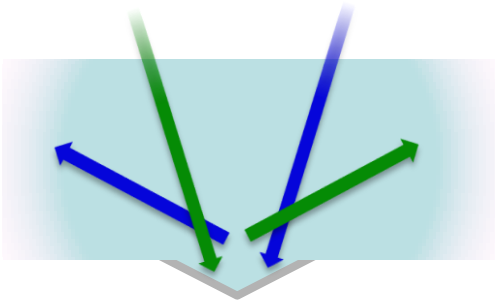
Waveguide Coupling Facets

- Reflective facets tilt light to satisfy TIR
- Couplers are localized at each lens focus (<1% surface area)

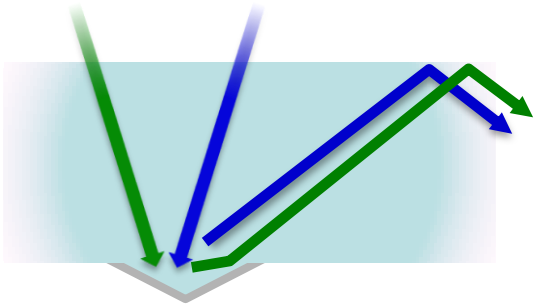


120º Symmetric Prism:

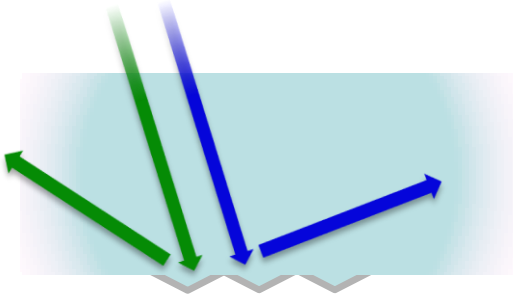
Symmetric coupling



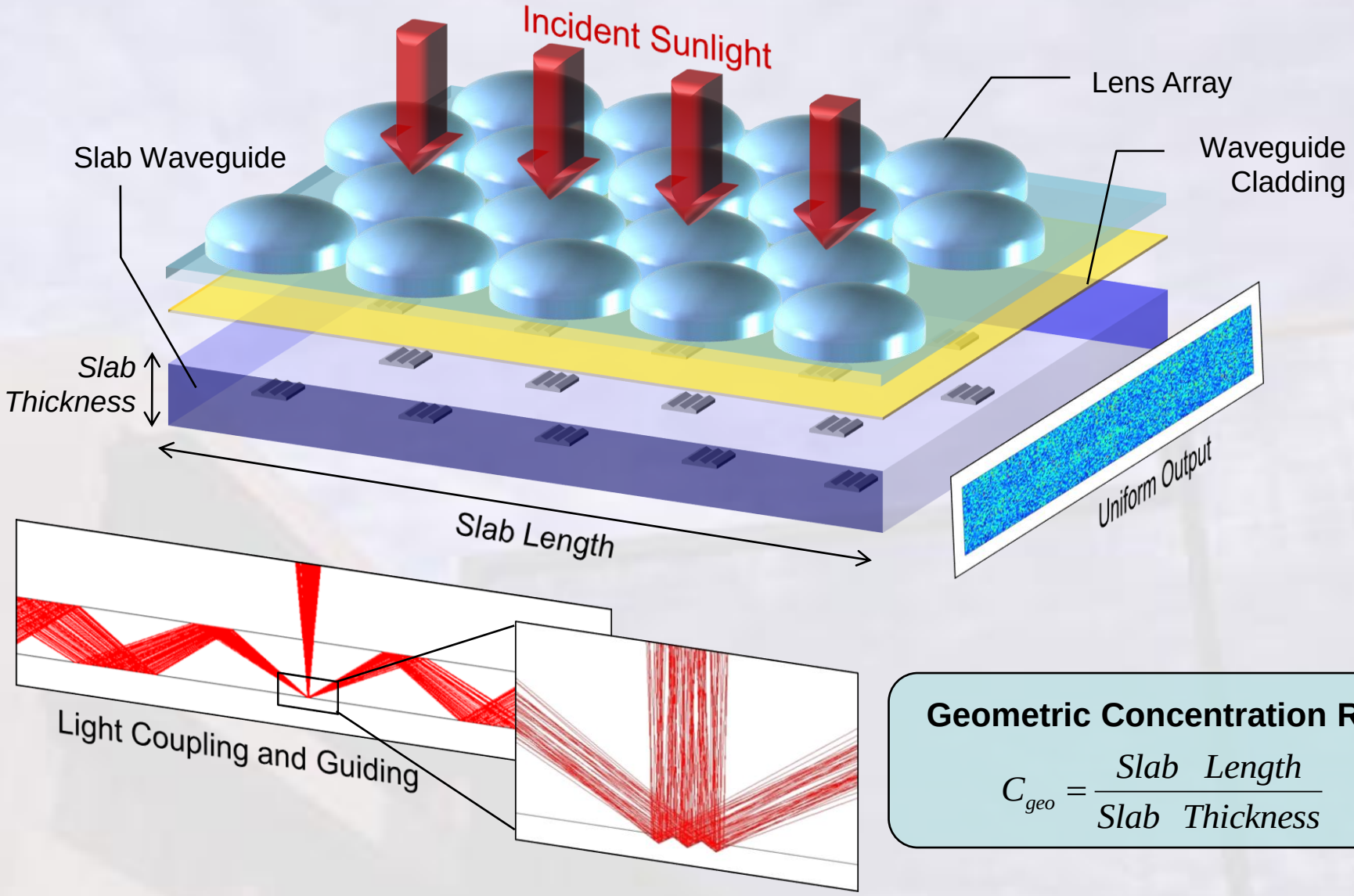
No blocking



Repeatable structure



System Layout



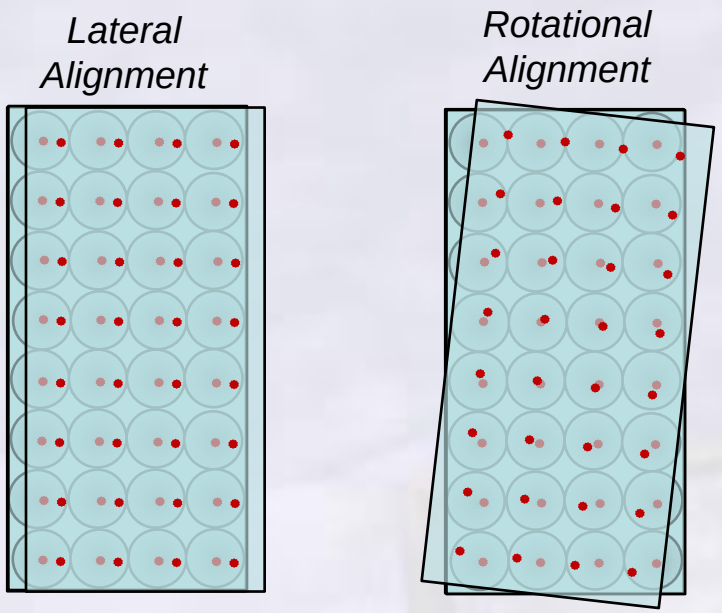
Geometric Concentration Ratio

$$C_{geo} = \frac{Slab\ \ Length}{Slab\ \ Thickness}$$

Coupling Facet Alignment

- Align lens focus to each coupling facet
- Large area concentrators *(~1 meter)*
- ***>100,000 points of alignment***

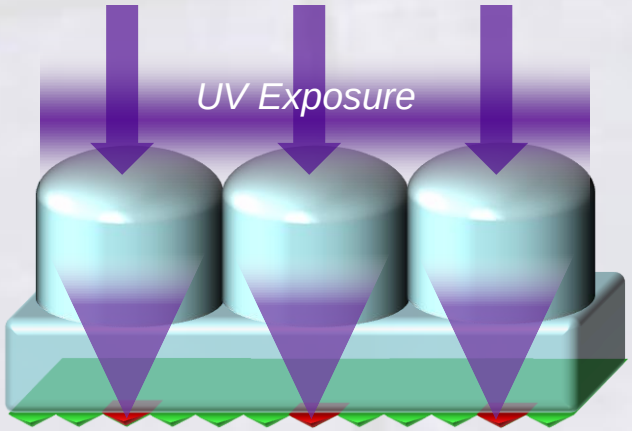
- ***<50µm*** *lateral alignment accuracy*
- ***<0.01°*** *(0.2mrad) rotational alignment*
  - *Difficult over large area*



VERY CRITICAL

Solution: Self-Alignment

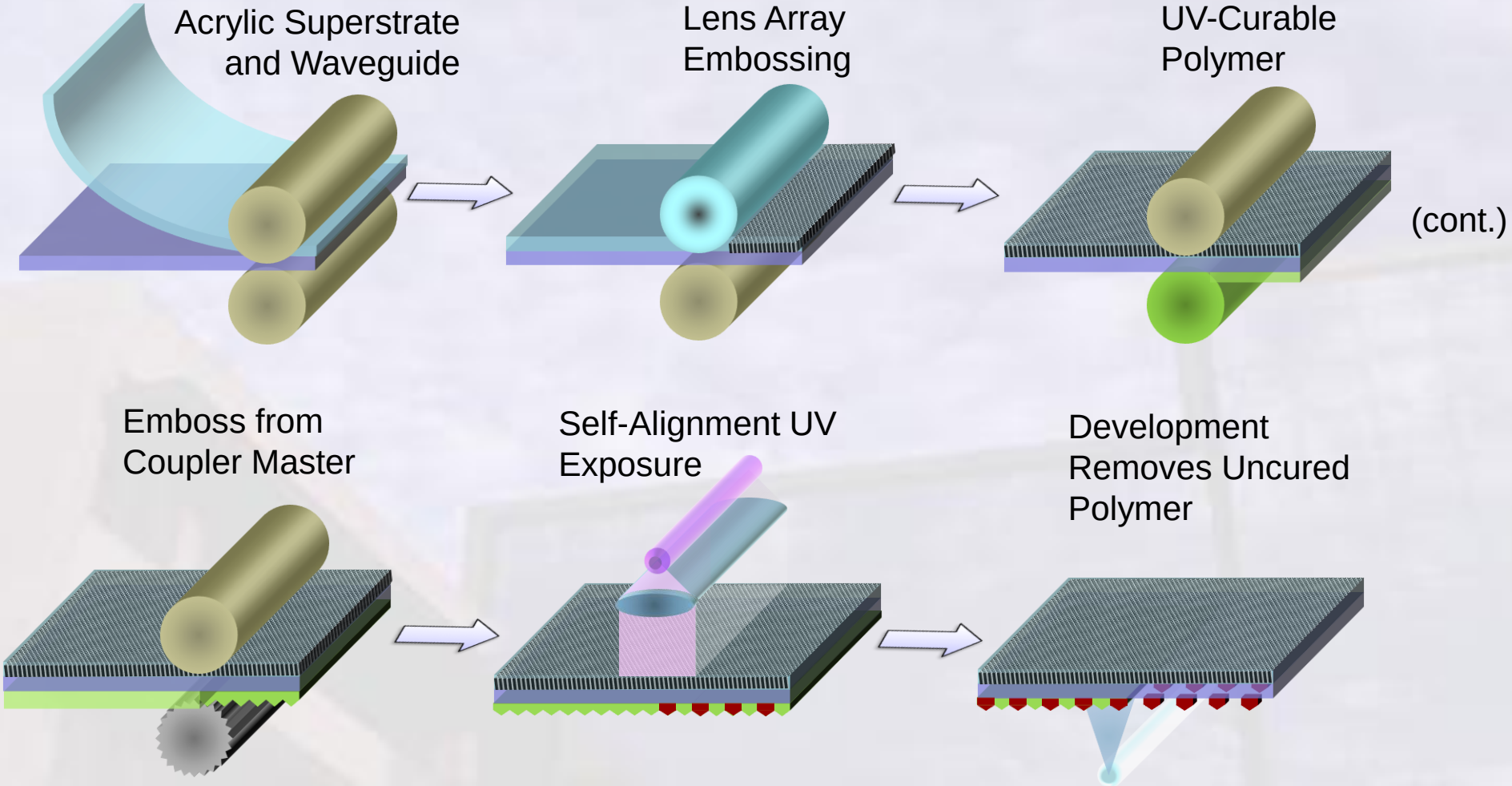
- *Mold prism structure within photopolymer*
- *Crosslink using UV exposure*
- *Cures only at each lens focus*
  - ➢ *Guarantees alignment*



Crosslinked regions remain part of the final concentrator

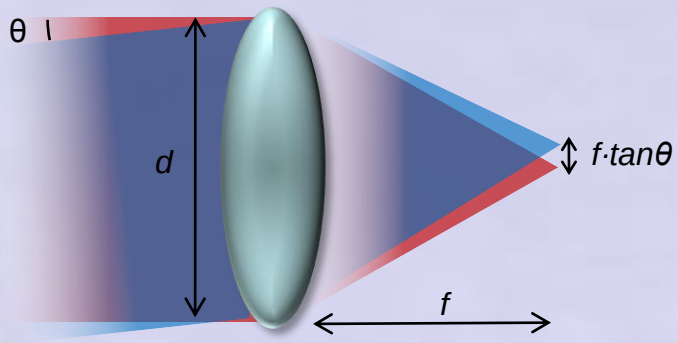
Roll Processing Flowchart

UCSD Photonics

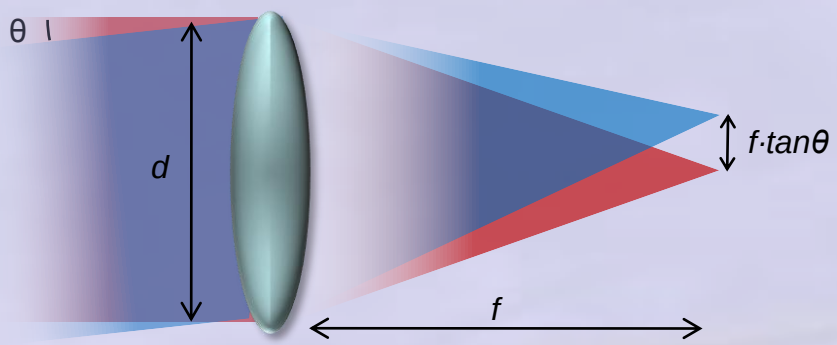


Design Tradeoffs

Field Displacement: *Sun subtends ±0.25°*

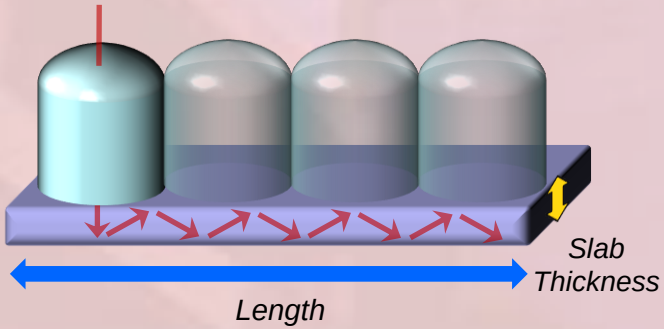


Short focal length → ***small coupling area***

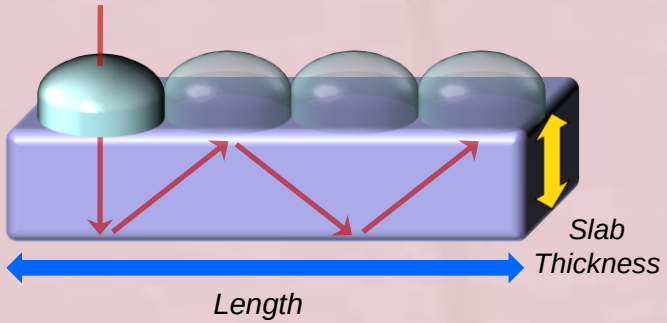


Long focal length → ***easier TIR condition***

Waveguide Thickness: $C_{flux} = \frac{\text{Slab Length}}{\text{Slab Thickness}} \times \text{Efficiency}$

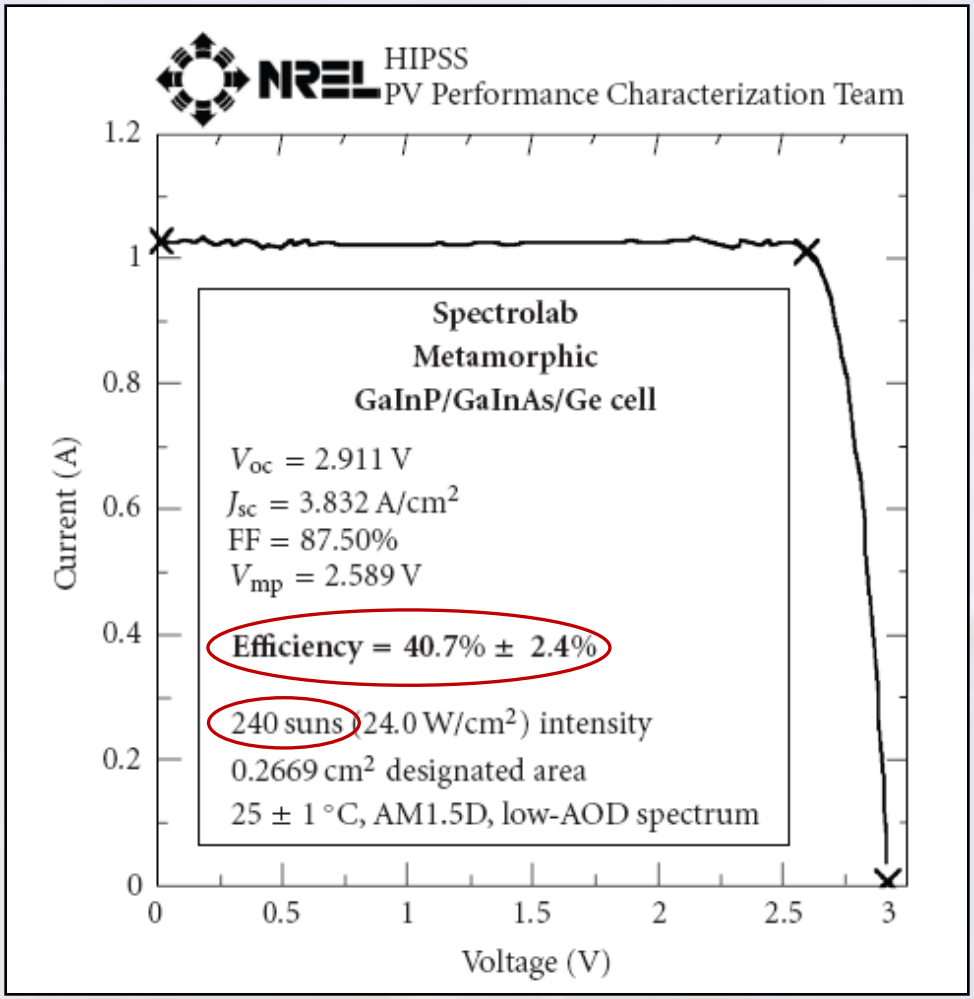


Thin waveguide → ***high concentration***



Thick waveguide → ***increased efficiency***

Optical Model



Richard R. King et al., "Advances in High-Efficiency III-V Multijunction Solar Cells," Advances in OptoElectronics, vol. 2007 (2007).

Spectrolab triple-junction cell

- 240x flux concentration
- 40.7% efficiency

Provide 240x flux per edge

System Simulation:

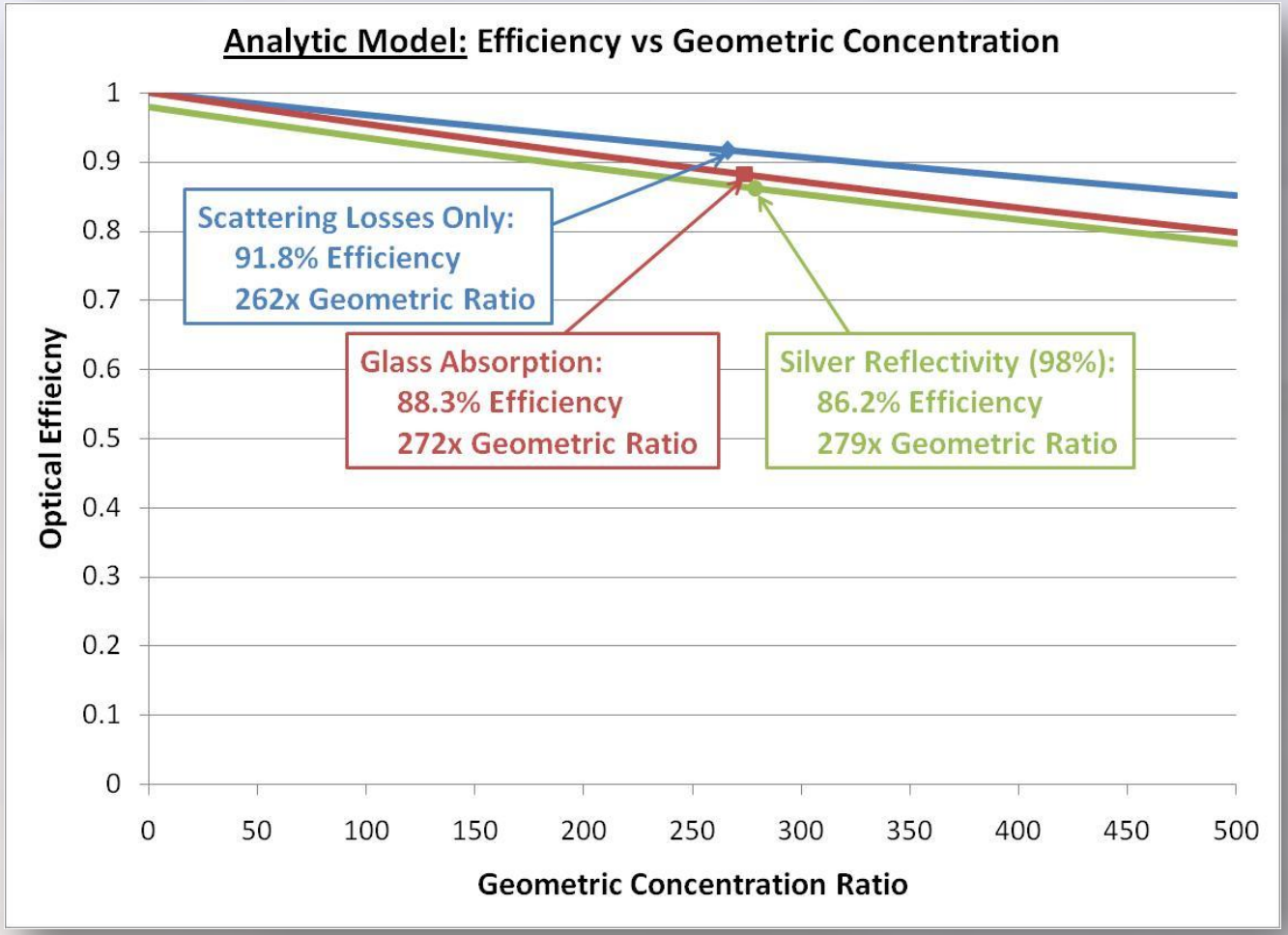
- Model overall efficiency
- Optimize design tradeoffs
- Cladding options

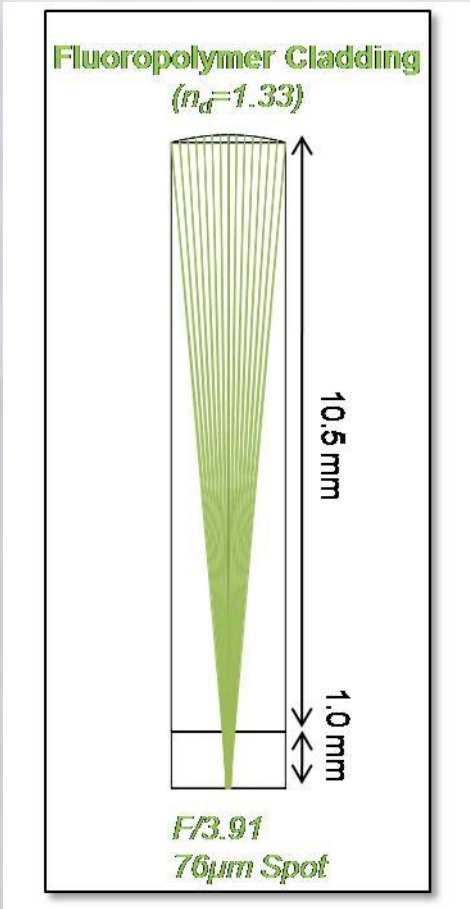
Analytic Model

Simple mathematical simulation

- Scattering loss
- Material absorption
- Mirror reflectivity

Very promising, but incomplete…

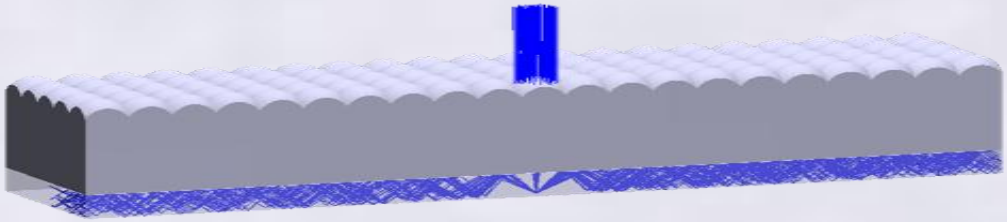


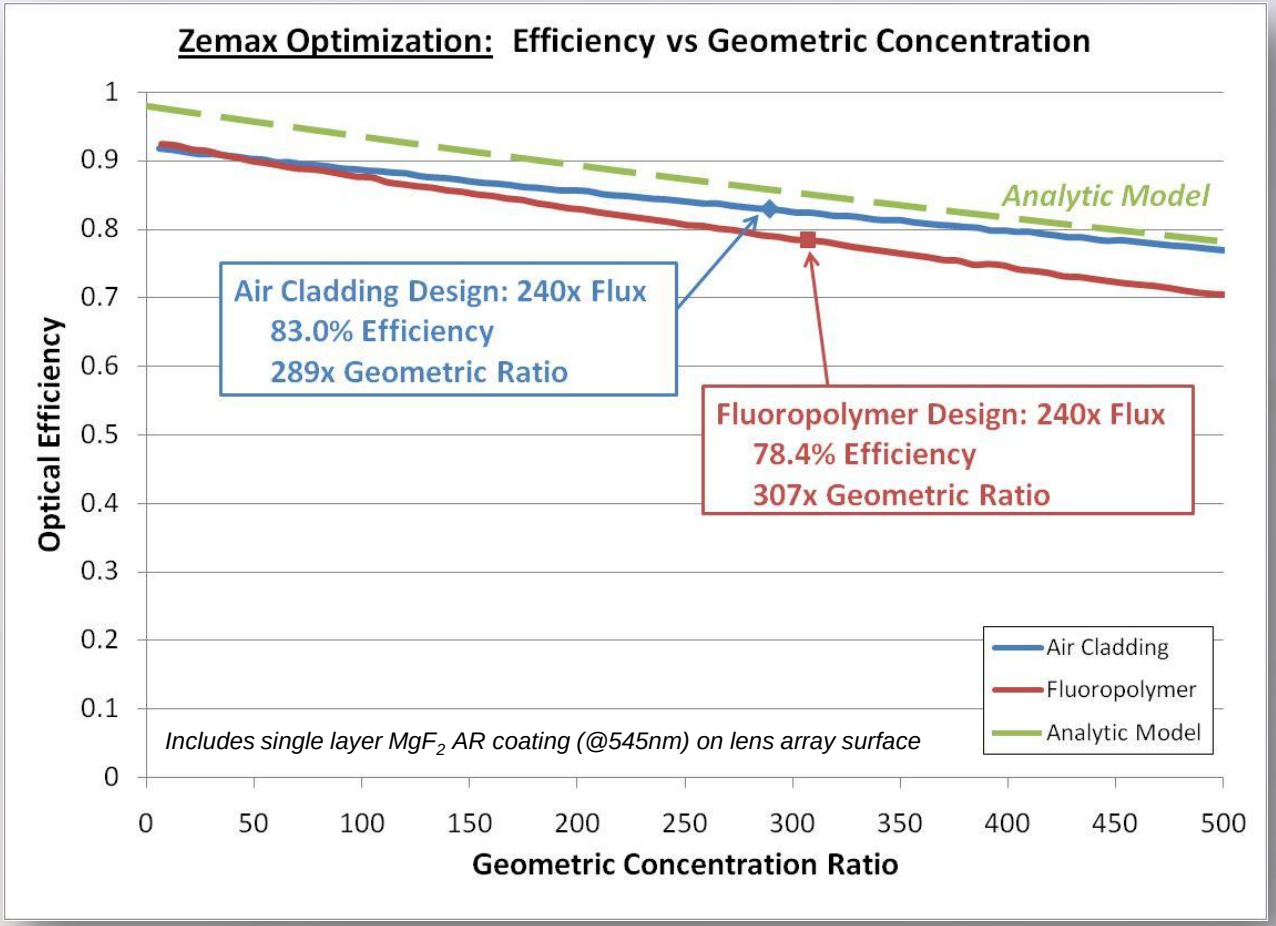


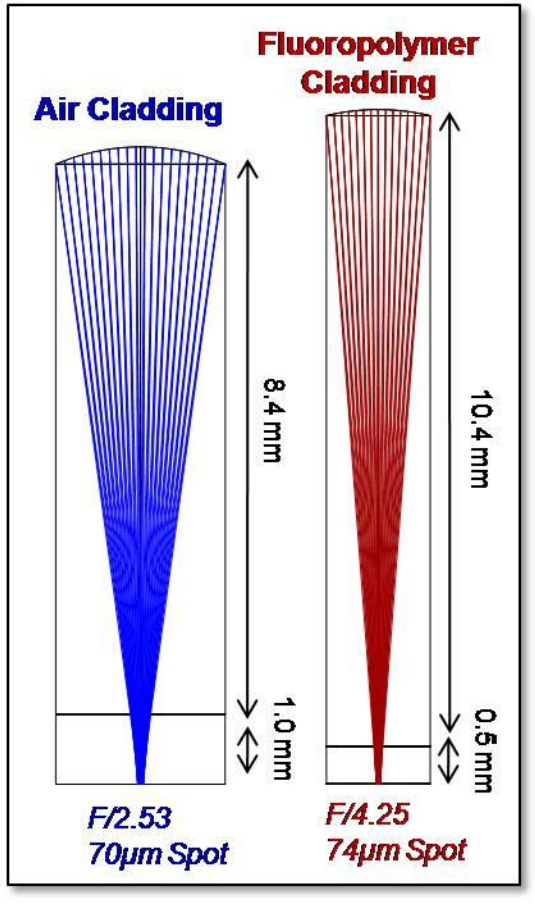
Zemax Raytracing Model

Zemax Non-Sequential Model

- Lens aberrations
- Polychromatic illumination
- Material dispersion
- Coatings and surface reflections



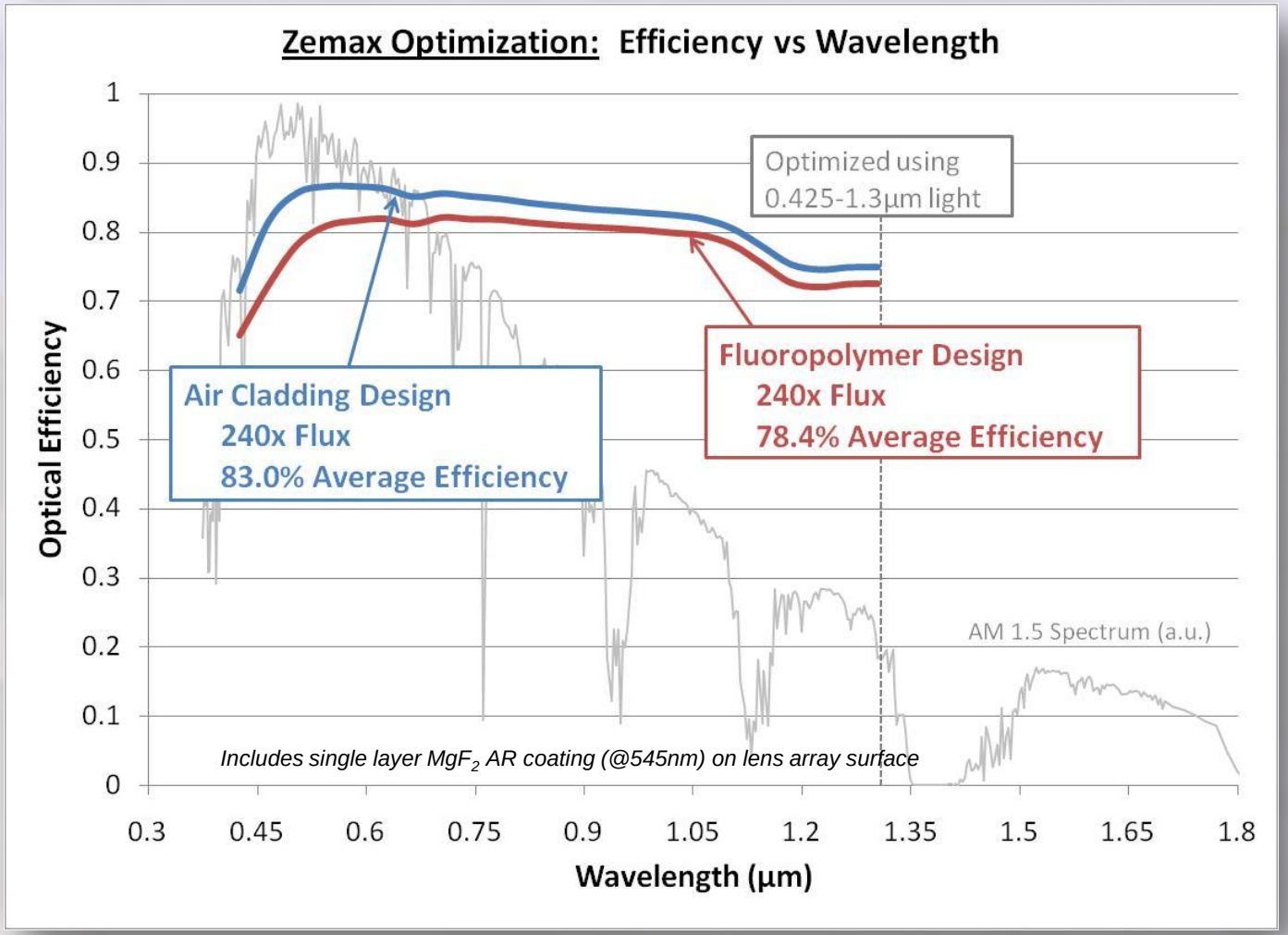




Broad Spectrum Performance

Optimized using 0.425-1.3µm illumination

- Accurate range of material models
- Minimum bandwidth for multi-junction PV cells

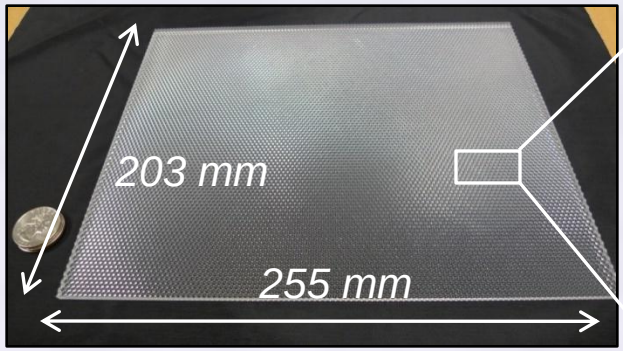


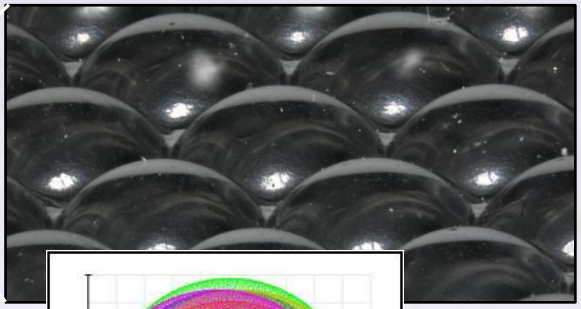
Proof-of-Concept Fabrication

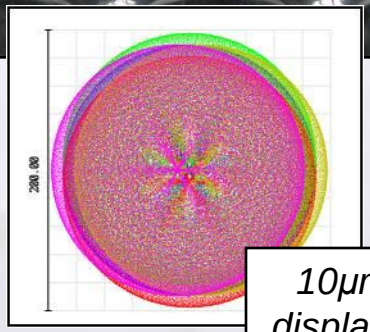
Goal: Demonstrate self-aligned coupling facet fabrication

- *Use off-the shelf components*

- Lens Array: *Fresnel Technologies*
  - F/1.1 hexagonal lens array
  - 200µm image of ±0.25° source
  - UVT acrylic





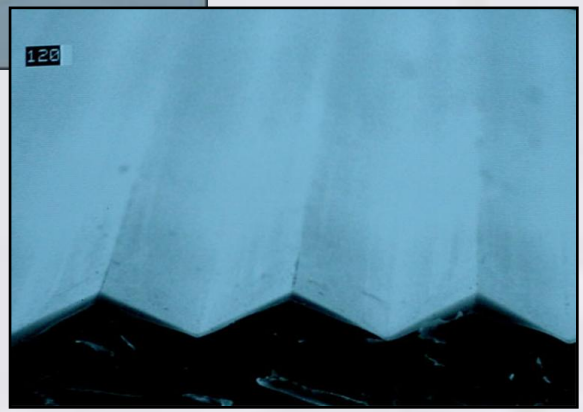


10µm field displacement

- Waveguide: *Fisher Scientific*
  - Microscope slide (75mm x 50mm)
  - BK7 float glass

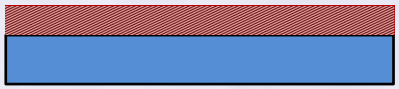
- Molding Polymer: *MicroChem*
  - SU-8 Photoresist
  - Chemical and thermal resistances

- Prism Mold: *Wavefront Technology*
  - 120° symmetric prisms
  - 50µm period, 14.4µm deep

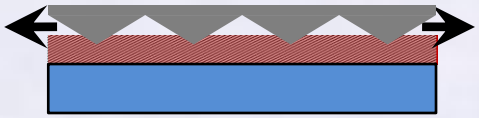


Fabrication Process

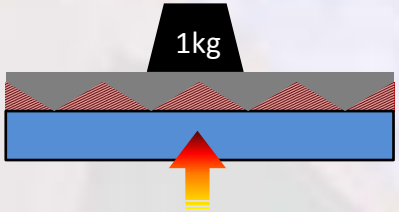
1. Spin SU-8 and Softbake



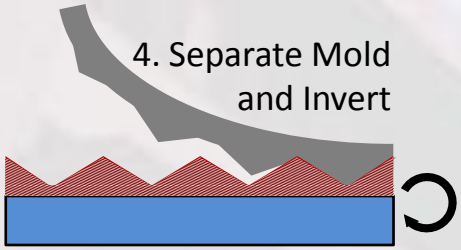
2. Apply Mold and Pull Vacuum



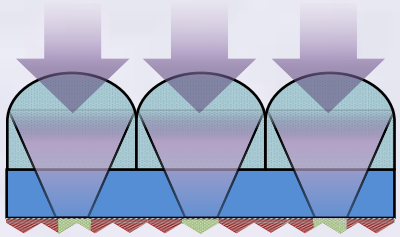
3. Bake Under Weight



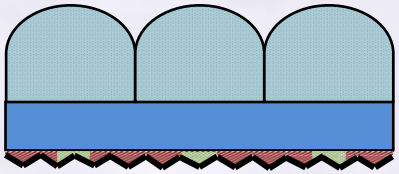
4. Separate Mold and Invert



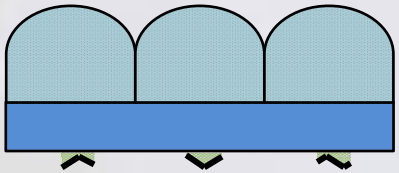
5. UV Exposure



6. Deposit Reflective Coating



7. Heat Above T_g and Develop



Waveguide

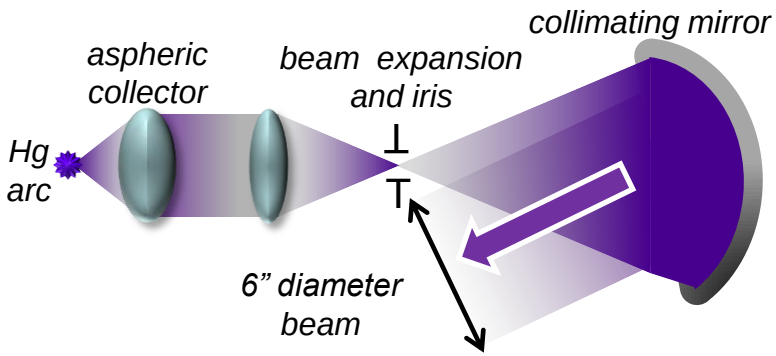
Prism Mold

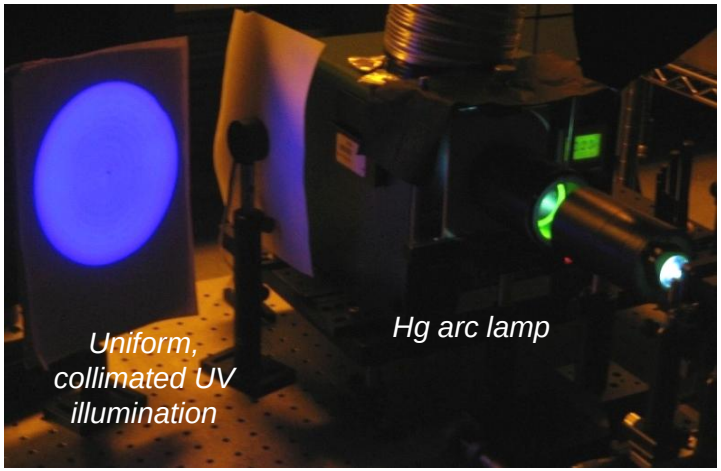
Lens Array

Un-crosslinked SU-8

Crosslinked SU-8

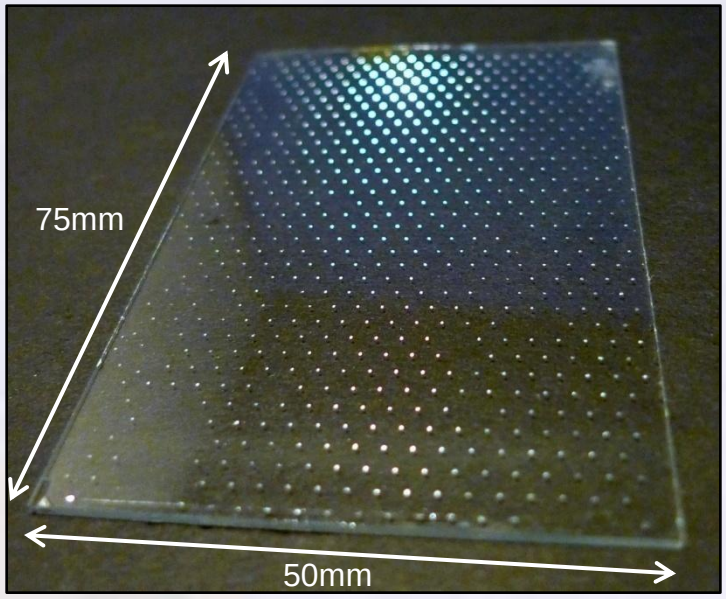
UV Exposure Source

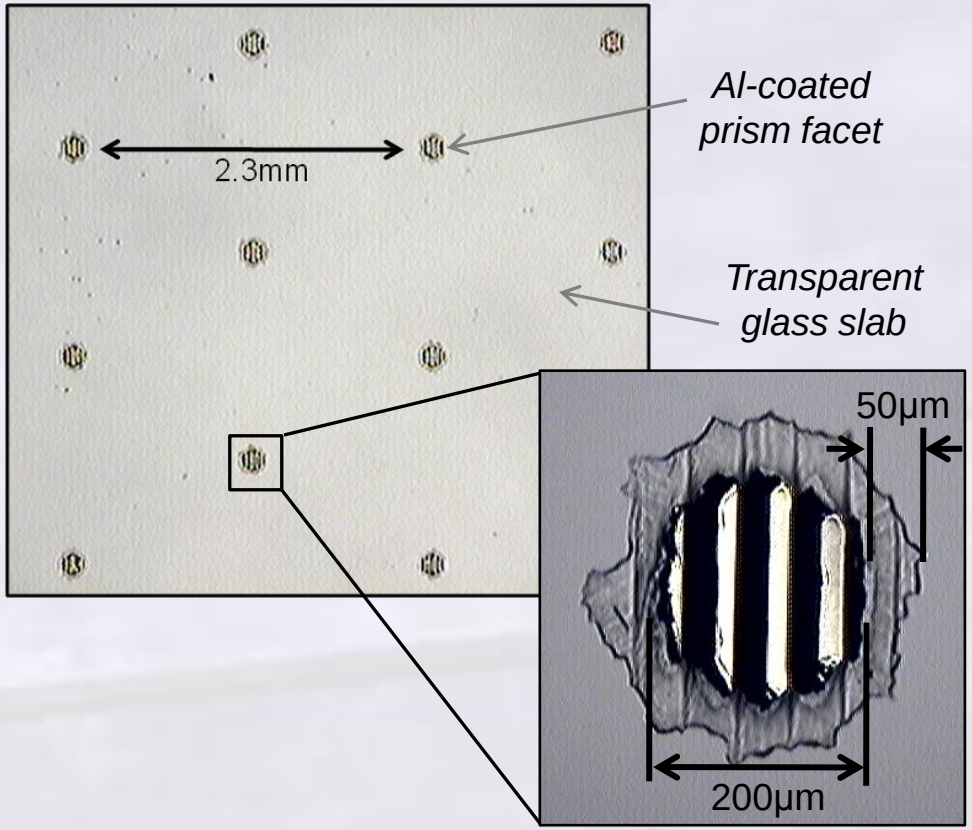


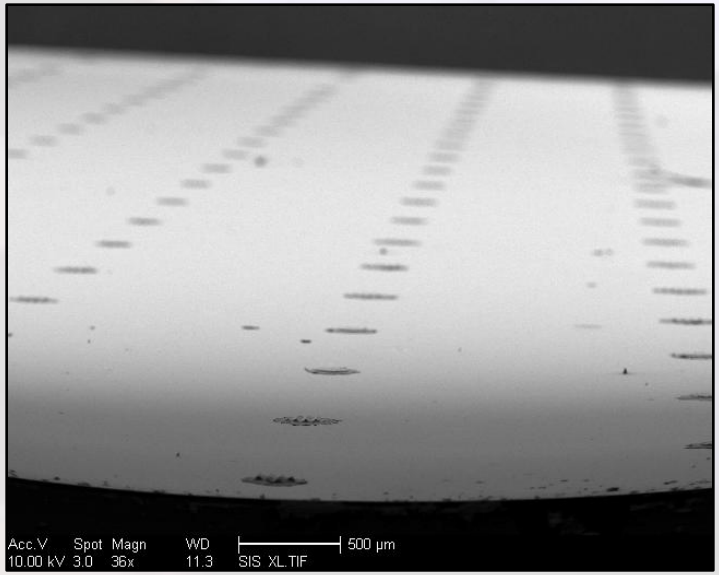


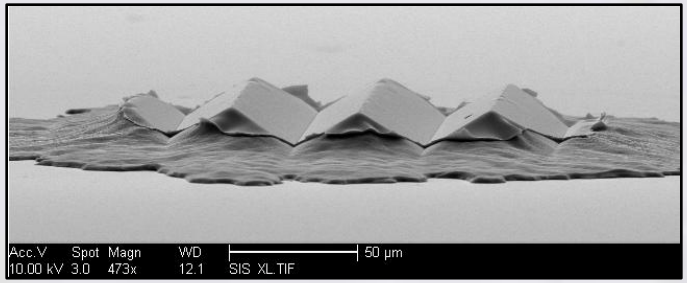
Adjust beam divergence using the iris

Fabricated Couplers



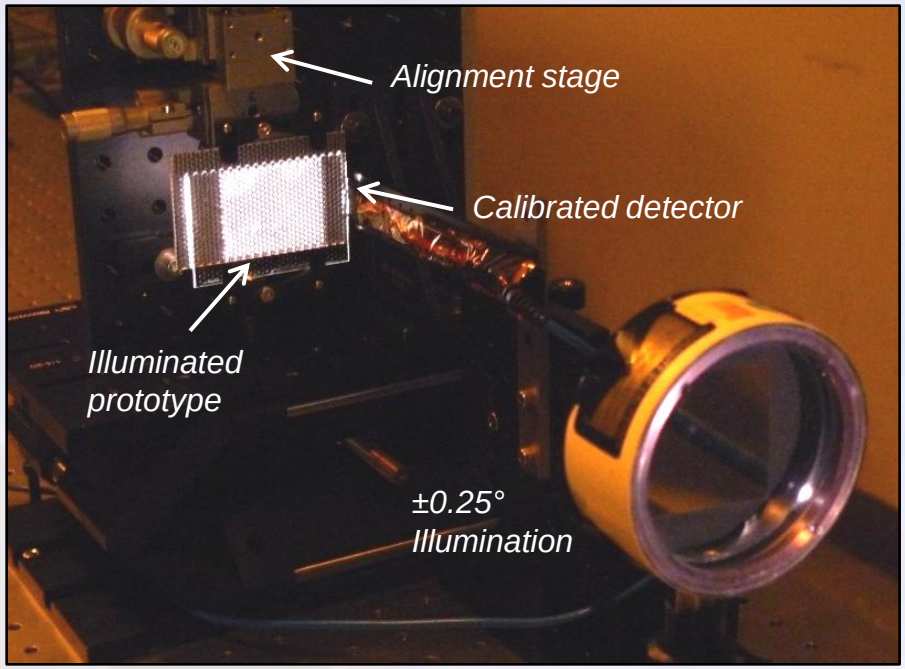






20μm Depth

Prototype Alignment



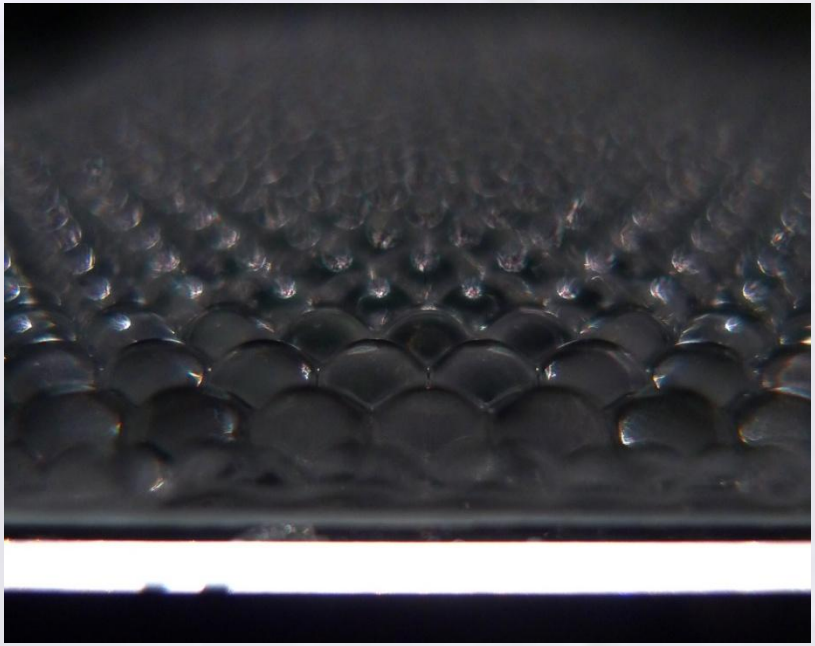
- White light illumination
  - Calibrated to ±0.25°
- Efficiency measurement
  - Newport 818-ST wand detector

- 6-axis alignment
  - Tolerance analysis

SUCCESSFUL COUPLING

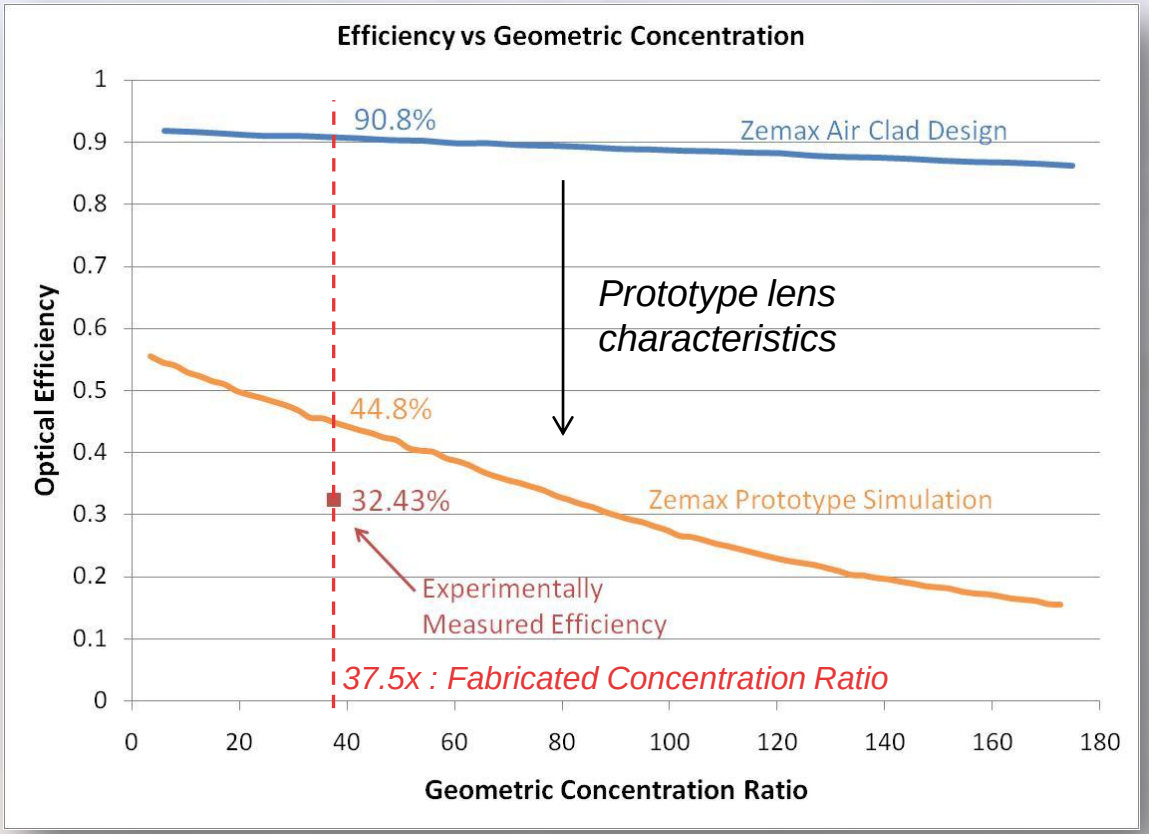
Lens Array ⟶

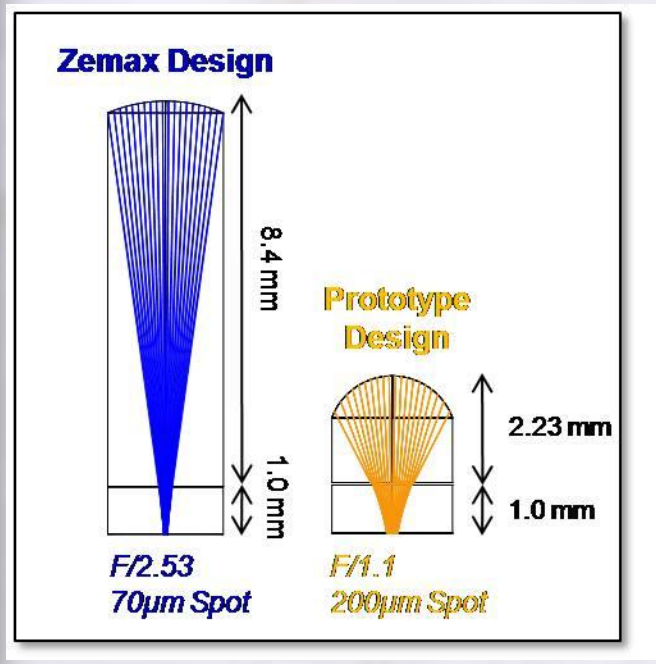
Waveguide ⟶



Prototype Performance

- Zemax model of prototype concentrator
  - Include actual lens performance and coupler size
- Prototype uses off-the-shelf (non-ideal) components

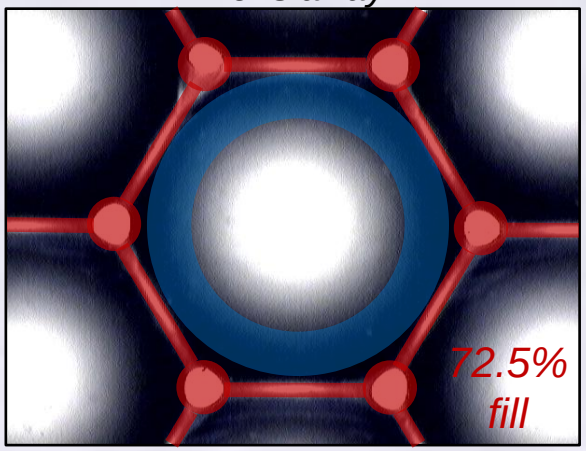




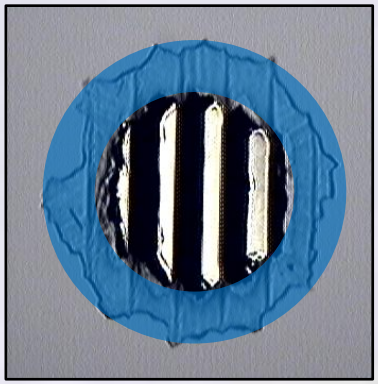
Prototype Loss Mechanisms

- Lens F-Number
  - 72.5% fill factor
  - Spherical aberration
  - Coupler annulus (50μm)

Lens array

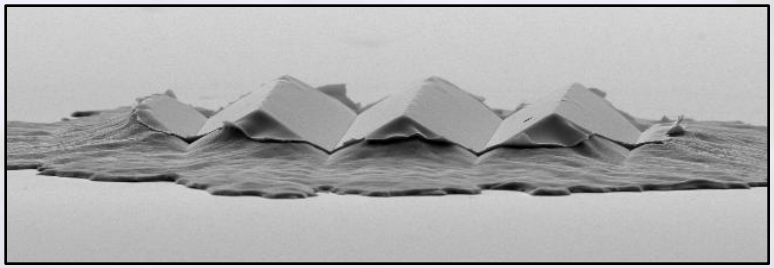


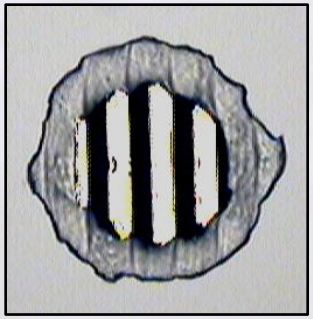
Coupler annulus



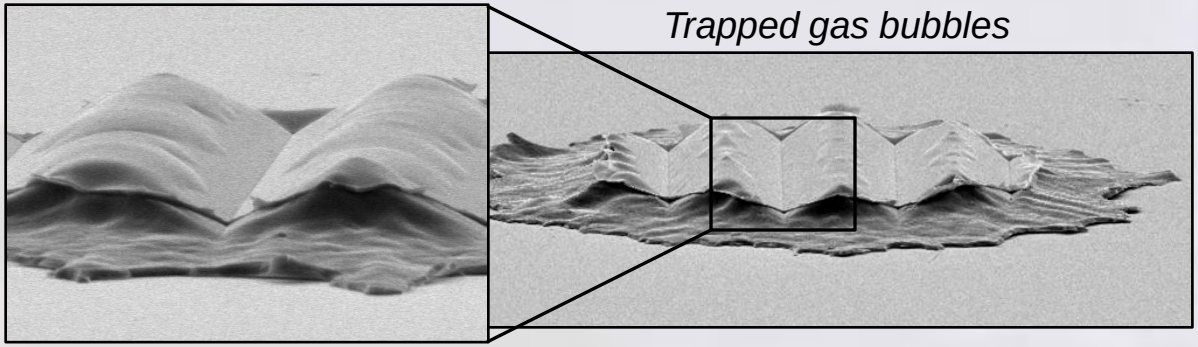
- Coupler Fabrication Yield
  - *Isolated instances*
  - Trapped gas bubbles
  - SU-8 solvent removal

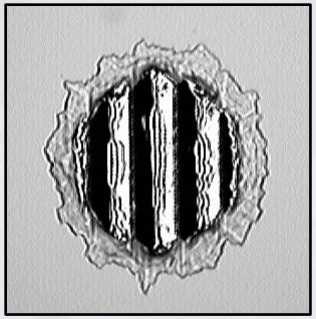
Good prism molding



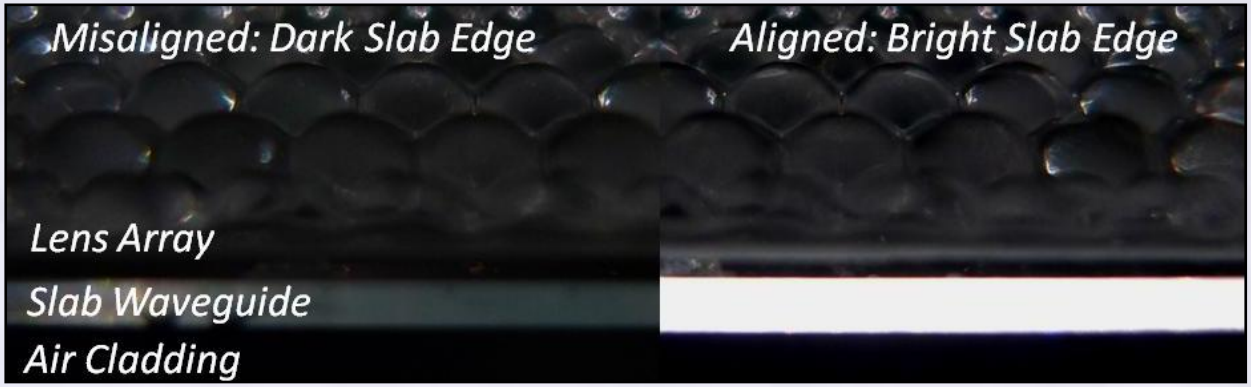


Trapped gas bubbles



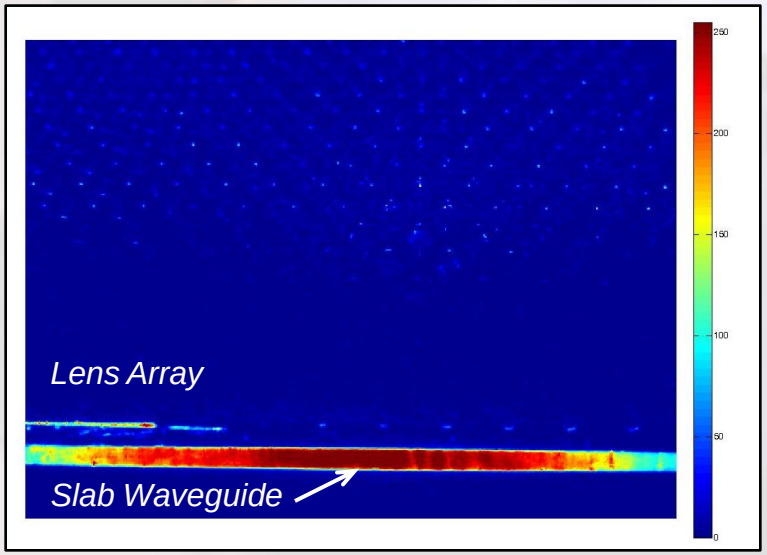


Uniformity and Alignment Tolerance



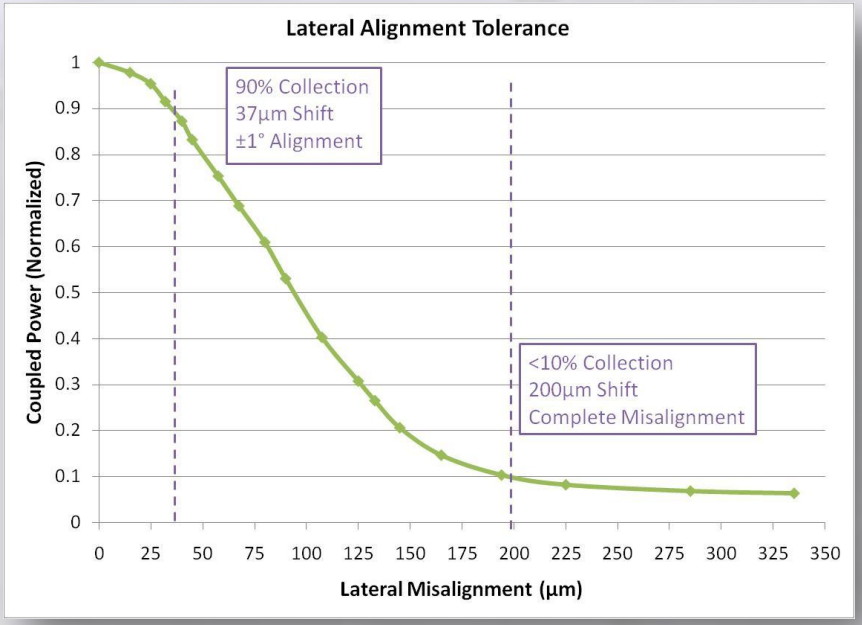
Beam Uniformity

- Finite width contributes to non-uniformity
- Uniformity increases with system size

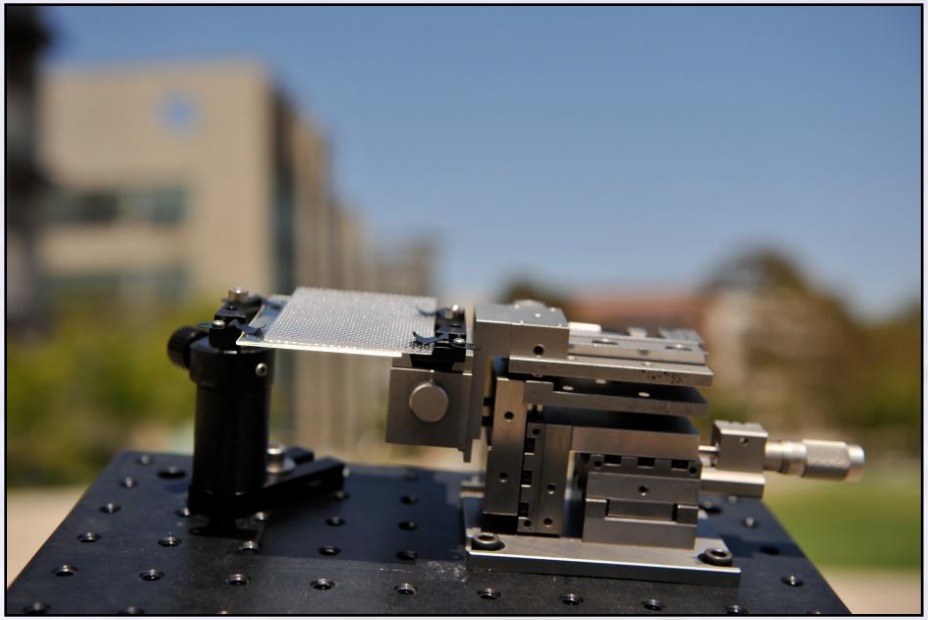


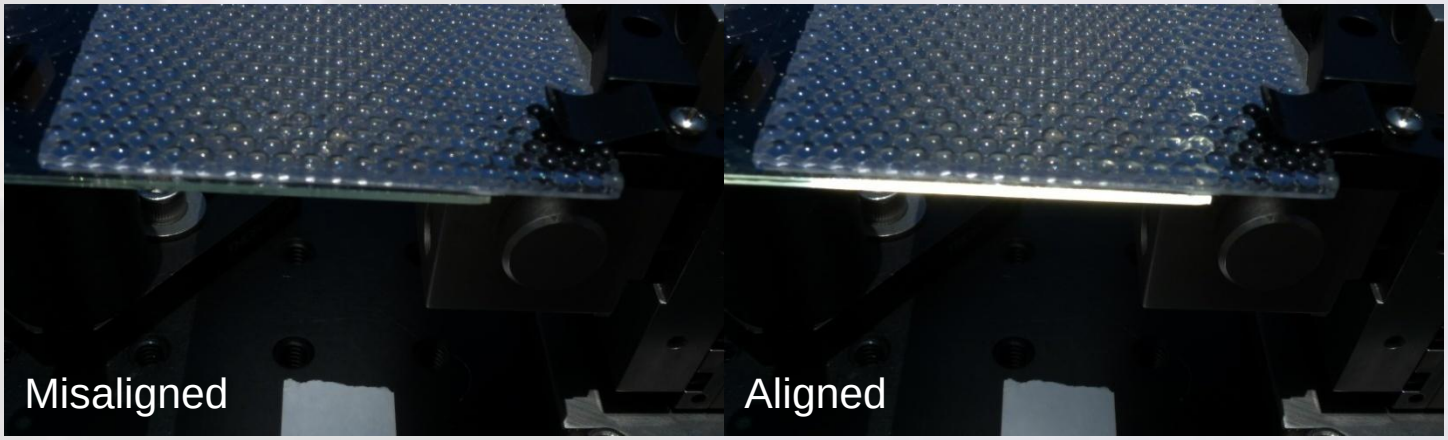
Lateral Alignment Tolerance

- 90% collection with 37µm shift (±1°)
- Alter UV source to add alignment tolerance



Solar Illumination Testing





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Thank You

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