Micro-Optic Solar Concentration and Next-Generation Prototypes

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PHOTOVOLTAIC SPECIALISTS CONFERENCE
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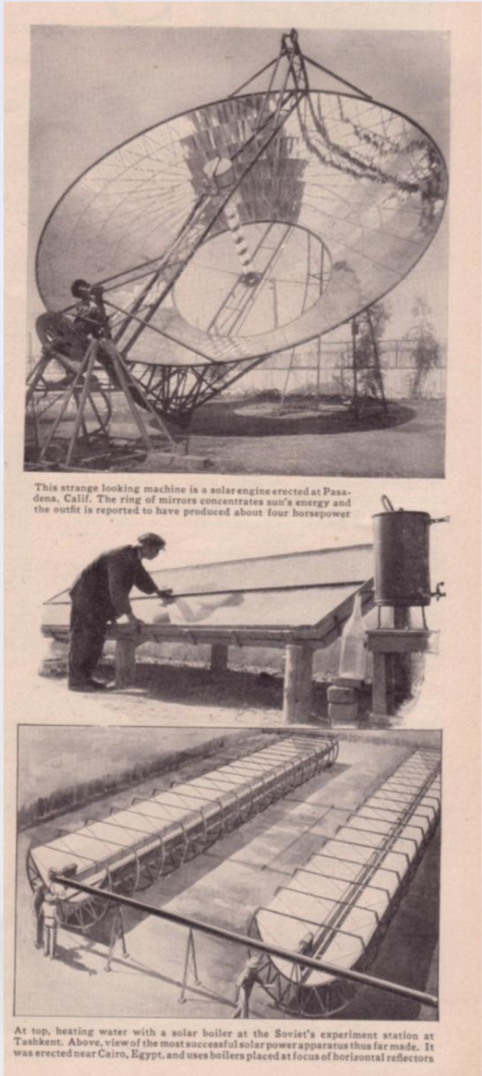
Photo: Kevin Walsh, OLR

Solar Collection: 80 years of progress

UCSD Photonics

1934 Issue of Popular Science


This strange looking machine is a solar engine erected at Pasadena, Calif. The ring of mirrors concentrates sun's energy and the outfit is reported to have produced about four horsepower

At top, heating water with a solar boiler at the Soviet's experiment station at Tashkent. Above, view of the most successful solar power apparatus thus far made. It was erected near Cairo, Egypt, and uses boilers placed at focus of horizontal reflectors

Imagers
(2-D tracking)



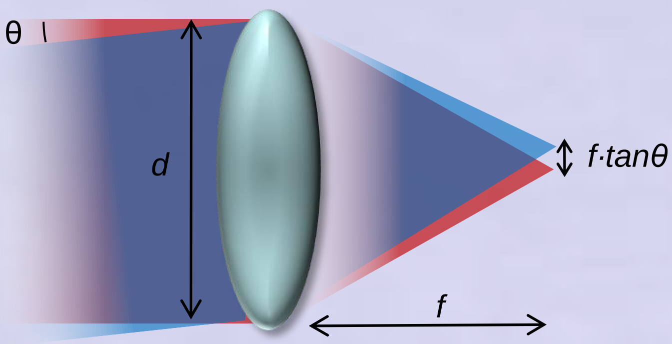
Panels
(fixed)


Troughs
(1-D tracking)

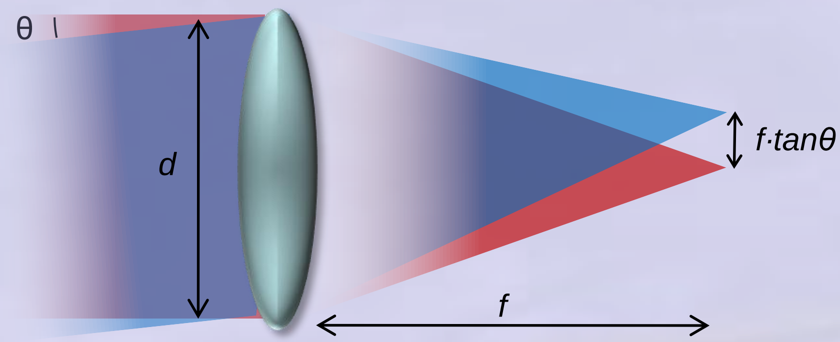

Rethink solar concentrator design to leverage large scale manufacturing techniques such as optical lithography and roll-to-roll processing

Design Tradeoffs

Field Displacement: *Sun subtends ±0.25°*



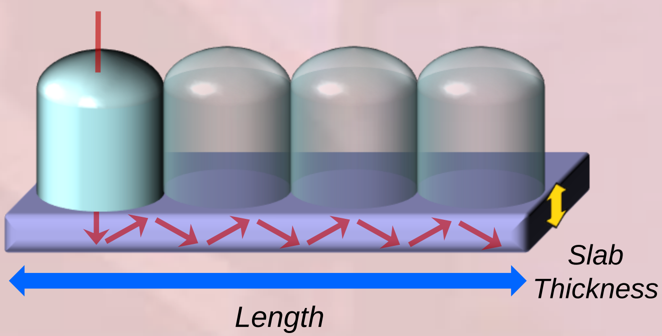
*Short focal length → **small coupling area***



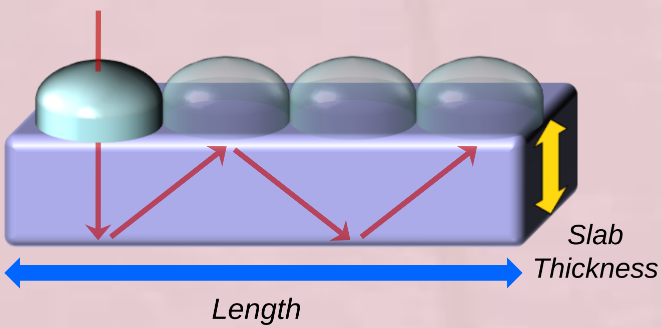
*Long focal length → **easier TIR condition***

Waveguide Thickness:

$$C_{flux} = \frac{\text{Slab Length}}{\text{2x Slab Thickness}} \text{ x Efficiency}$$



*Thin waveguide → **high concentration***



*Thick waveguide → **increased efficiency***

Planar Micro-Optic Concentration

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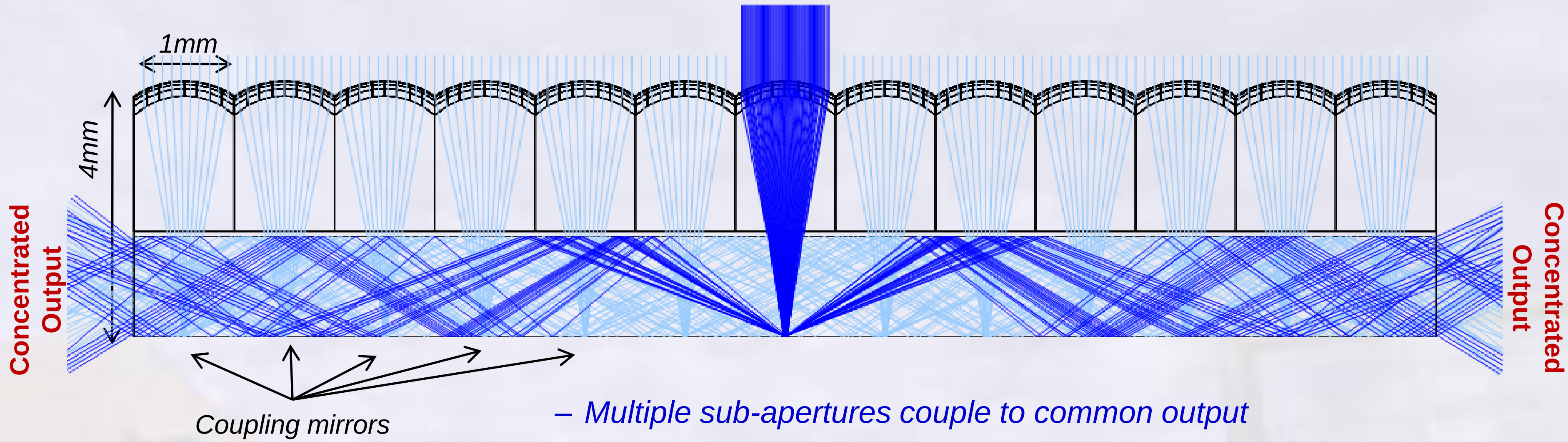
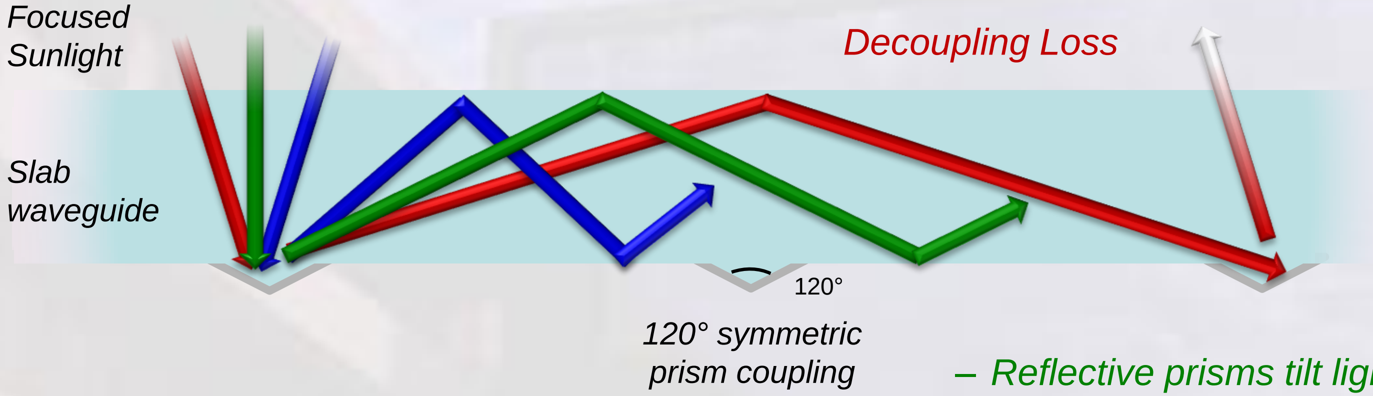


– Multiple sub-apertures couple to common output
– Homogeneous output intensity
– Uniform thickness (roll-to-roll fabrication)



– Reflective prisms tilt light to TIR
– Couplers occupy <<1% of waveguide surface
– Subsequent interaction decouples as loss

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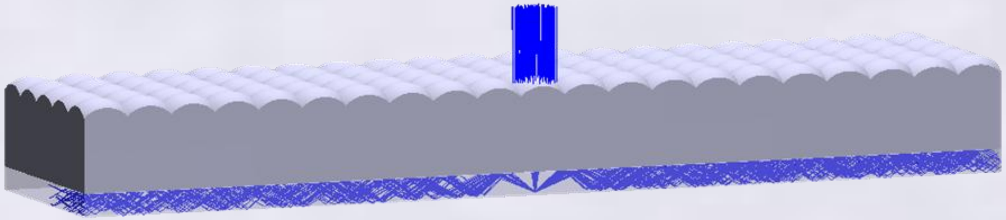
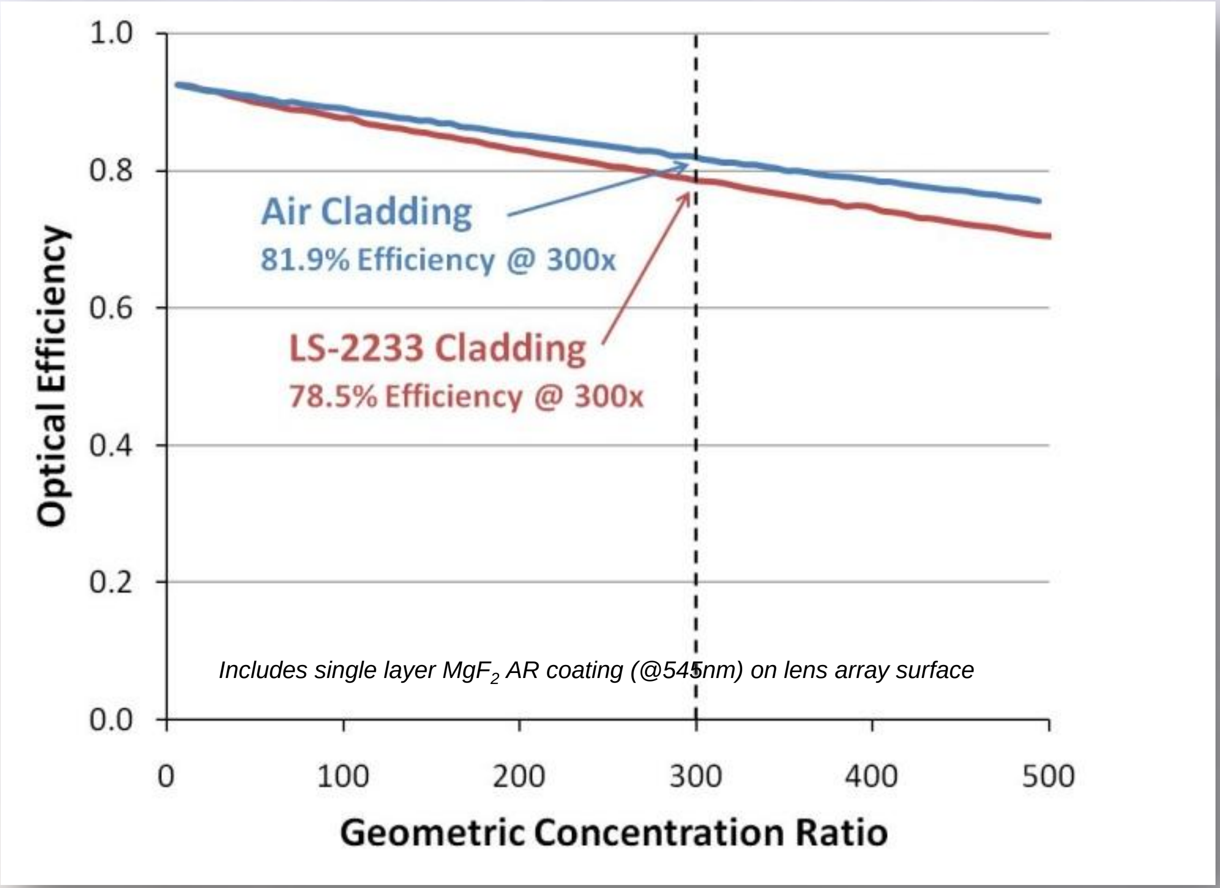
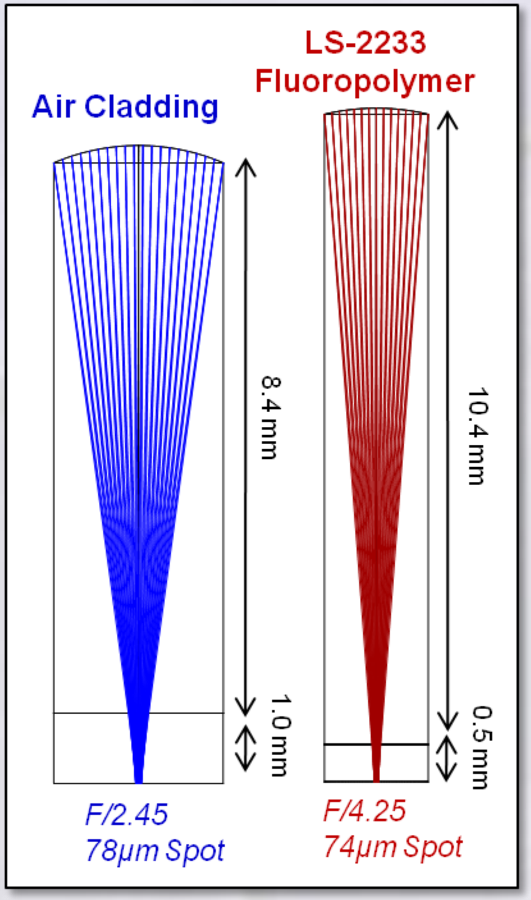
Optimized Designs

Zemax Non-Sequential Model
- Lens aberrations
- Polychromatic illumination
- Material dispersion
- Coatings and surface reflections





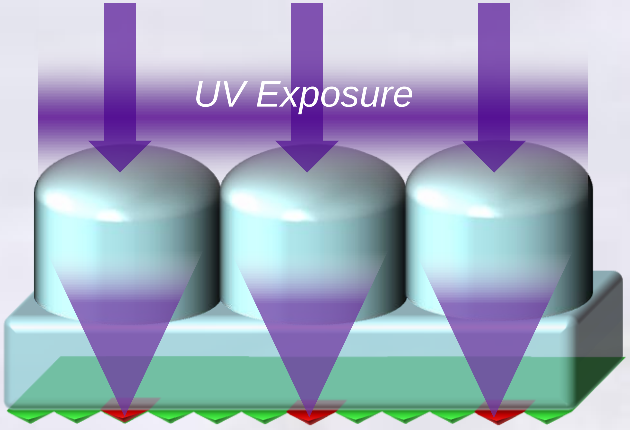


J. H. Karp, E. J. Tremblay and J. E. Ford, "Planar micro-optic solar concentrator," Optics Express, Vol. 18, Issue 2, 1122-1133 (2010).

Fabrication process: Self-alignment

Critical Alignment Tolerance

- Lens focus must overlap with each coupling location
  - *<10μm lateral alignment tolerance*
  - *<0.01° (0.2mrad) rotational alignment*



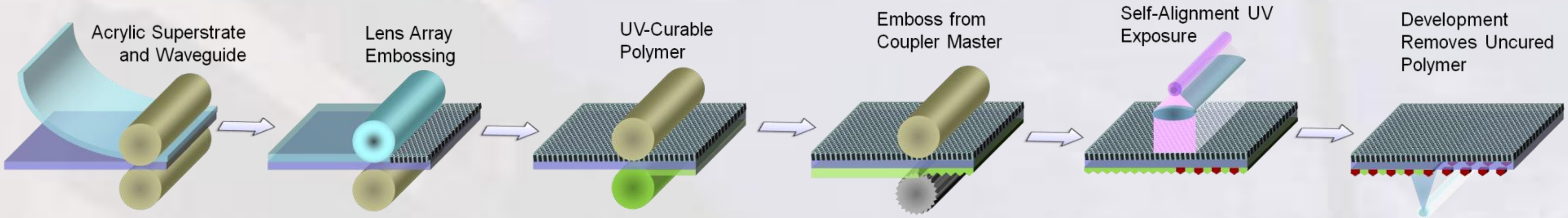
Coupling features created by exposing through lenses

Solution: Self-alignment

- Mold prism structure in UV-curable photopolymer
- Expose through lens array to cross-link localized prisms
- Cured regions remain part of the final device

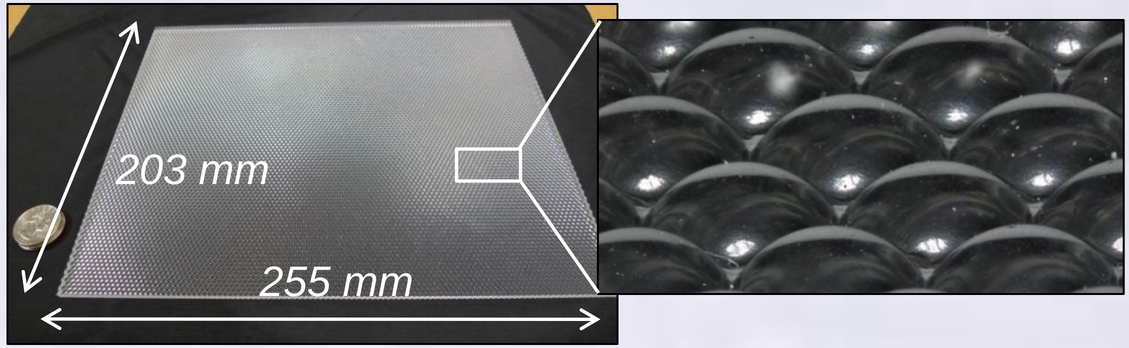
Low-cost manufacturing process

Continuous roll processing on flexible or rigid substrates



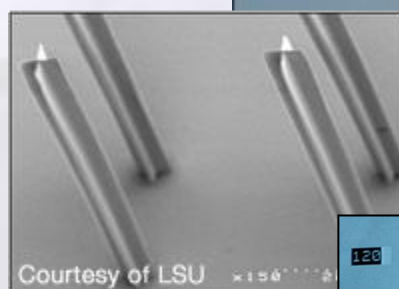
1st Generation Proof-of-Concept

- Lens Array: *Fresnel Technologies*
  - F/1.1 hexagonal lens array
  - UVT acrylic
  - *Strong Aberrations – Not Ideal*

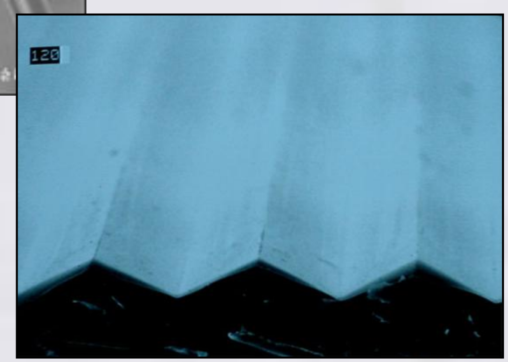


- Waveguide: *Fisher Scientific*
  - Microscope slide (75mm x 50mm)
  - BK7 float glass

- Molding Polymer: *MicroChem Corp*
  - SU-8 Photoresist
  - Chemical and thermally resistant

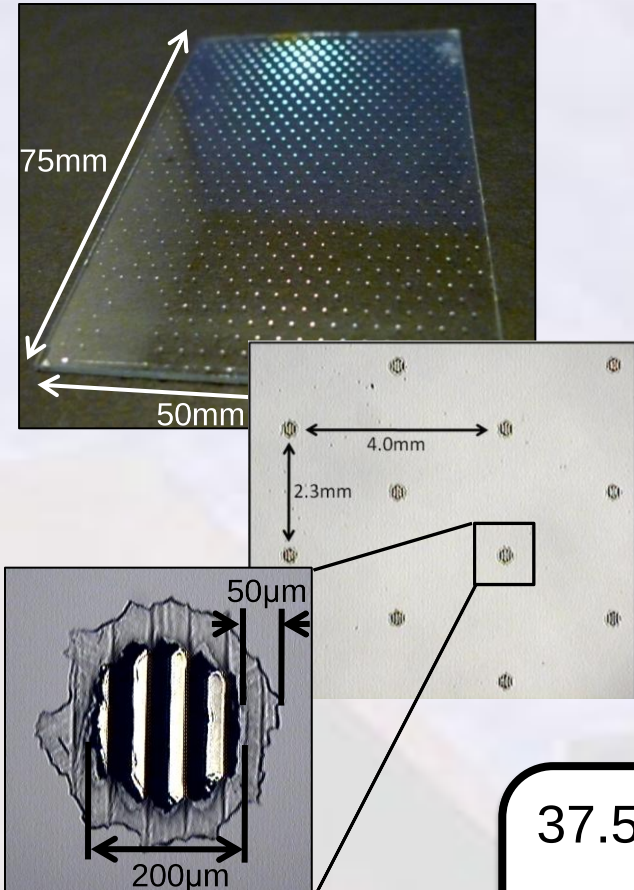


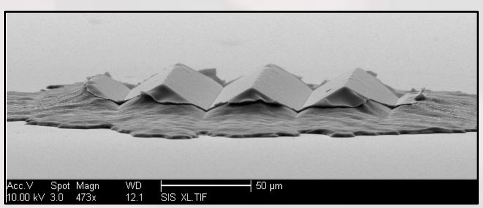
- Prism Mold: *Wavefront Technologies*
  - 120° symmetric prisms
  - 50μm period, 14.4μm deep



1st Generation Proof-of-Concept

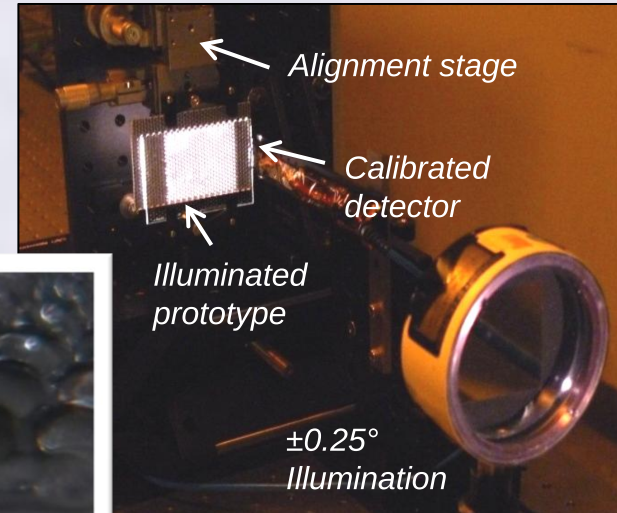
UCSD Photonics





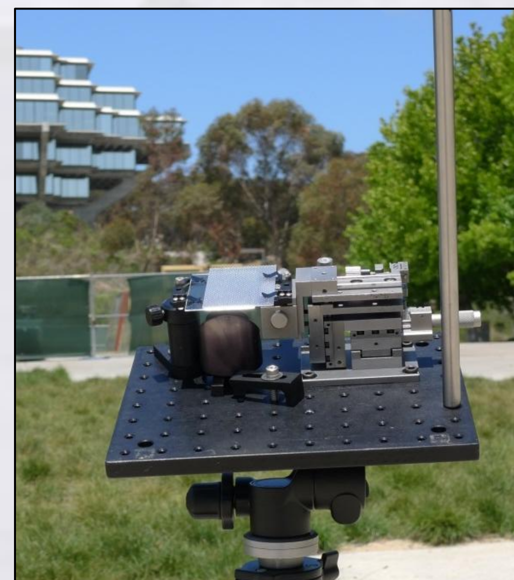
20µm Depth

Concentrator Edge - Aligned



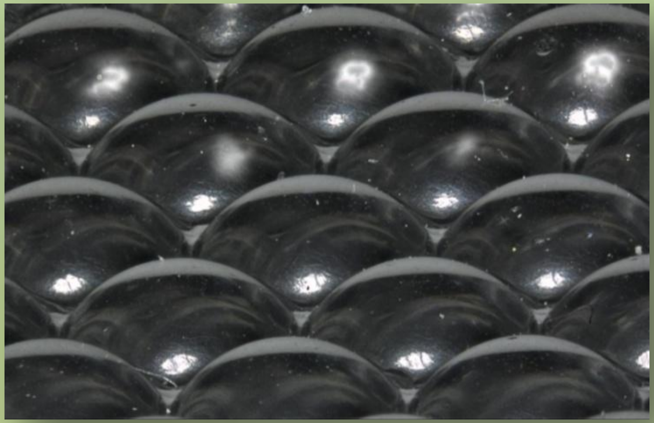
37.5x concentration (2 edges)

- 44.8% Simulated efficiency
- **32.4% Measured efficiency**
- **±1.0° Angular acceptance**



2^{nd} Generation Prototype

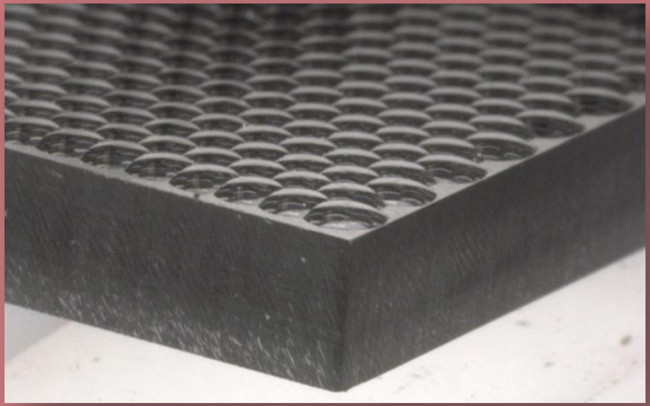
1^{st} Generation Prototype



- F/1.1 plano-convex array
  - Spherical aberration
  - Gaps between lenses
- Large couplers + Annulus

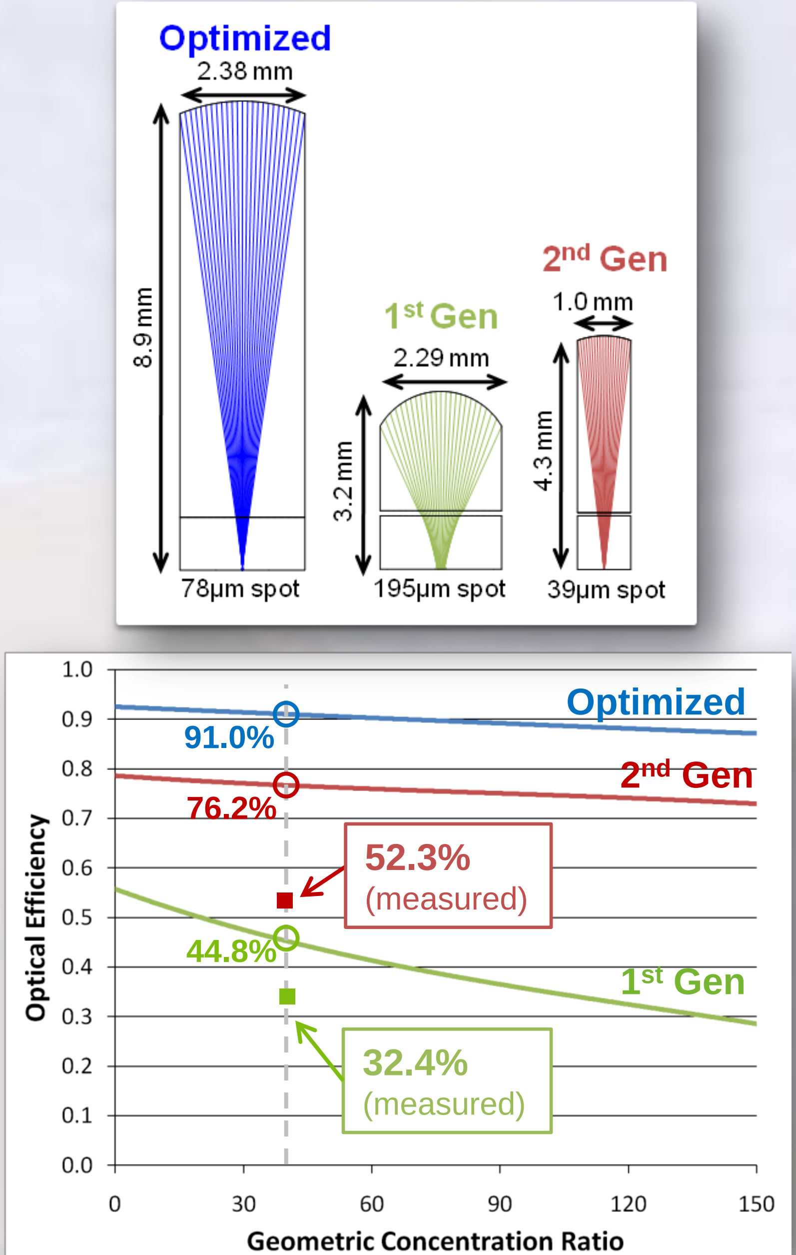
32.4% optical efficiency

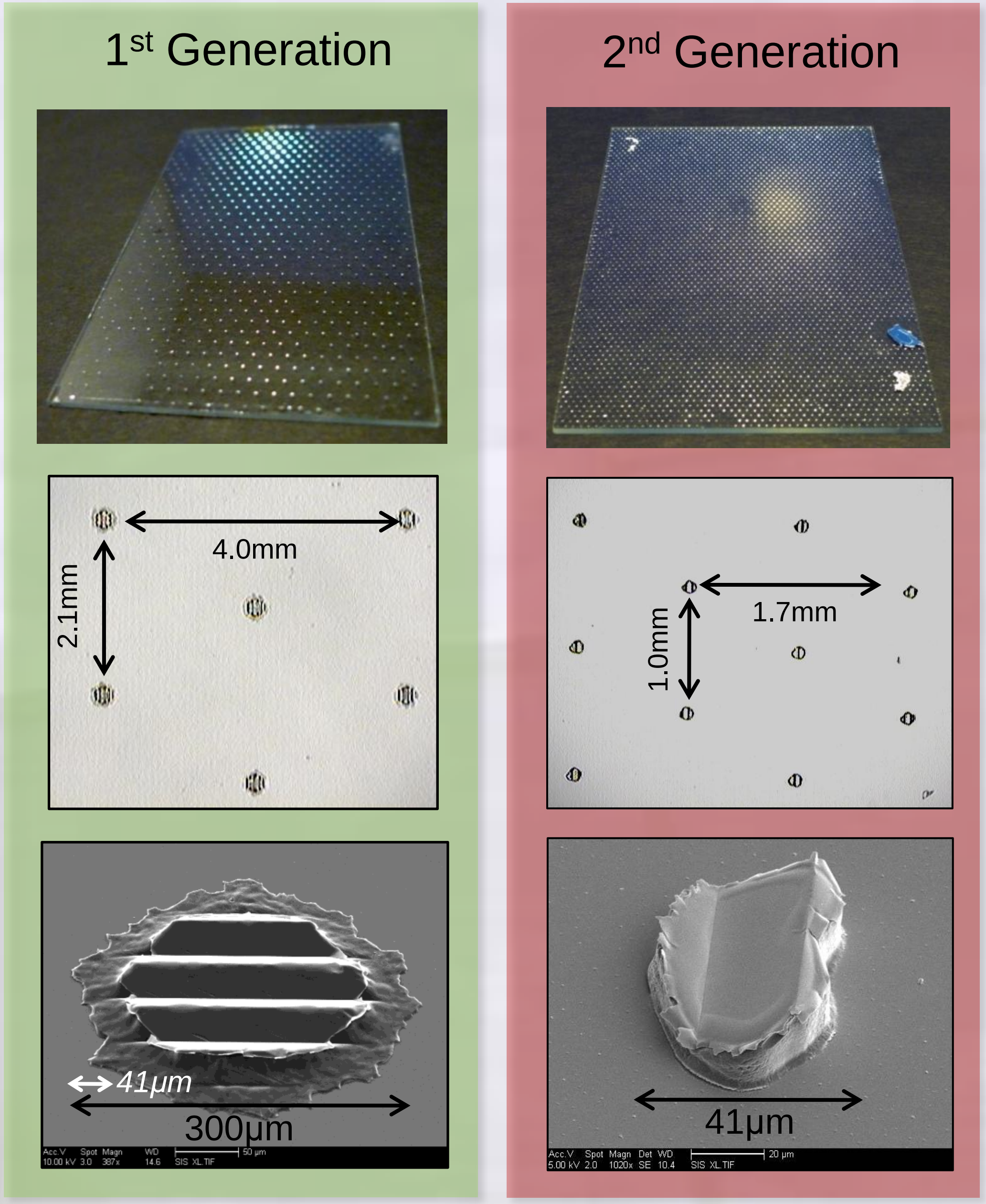
2^{nd} Generation Prototype



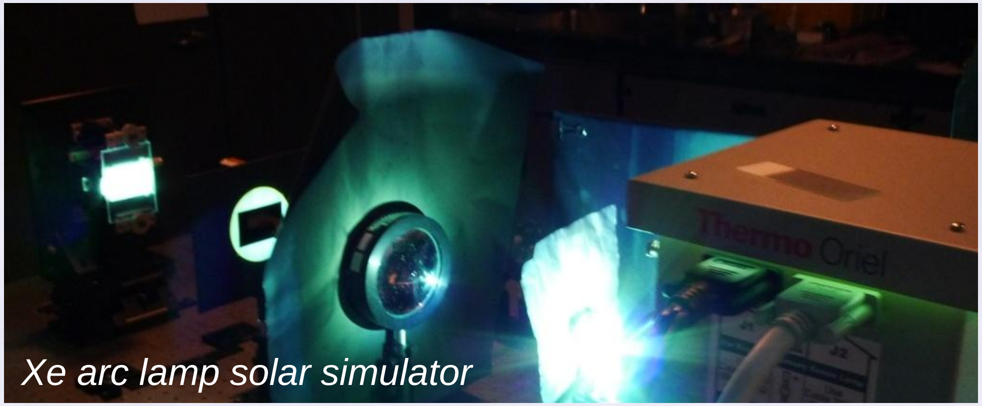
- F/3.01 plano-convex array
  - Near diffraction-limited
  - 100% fill-factor
- PDMS master mold
  - Consistent SU-8 molding

2nd Generation Prototype



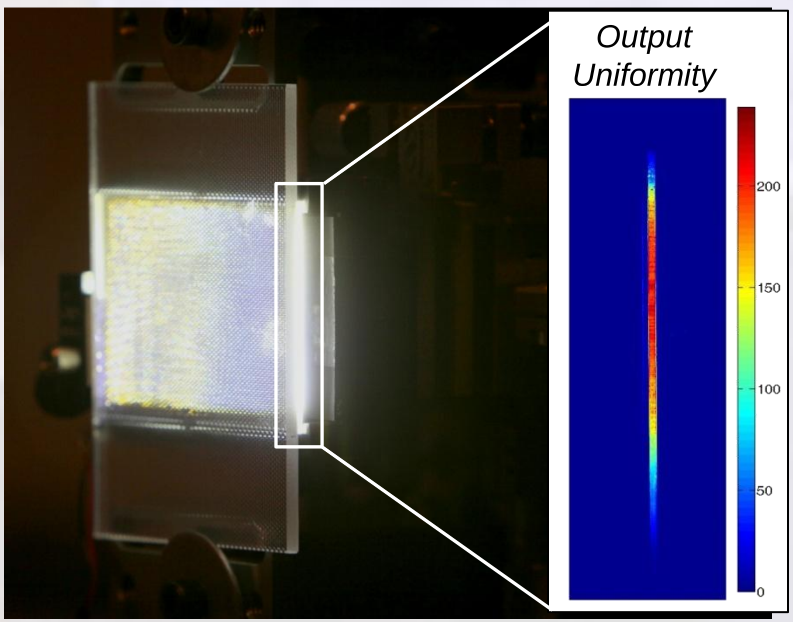


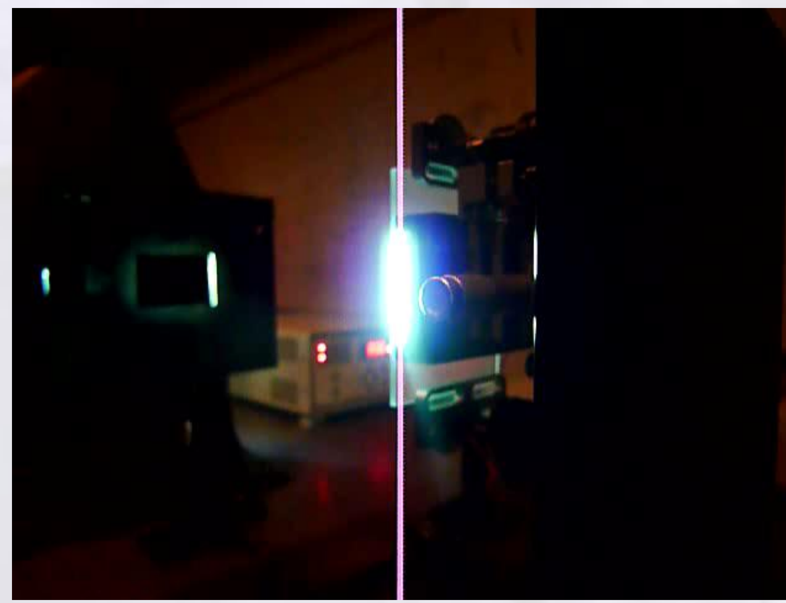
2nd Generation Prototype Performance


Xe arc lamp solar simulator

37.5x concentration (2 edges)

- 76.2% Simulated efficiency
- 65.6% with 83% reflective coupler
- **52.3% Measured efficiency**
- **±0.38° Angular acceptance**




Video: Lateral alignment / misalignment demonstration

NEXT-GENERATION CONCEPTS

- Secondary Coupling
- Orthogonal Concentration

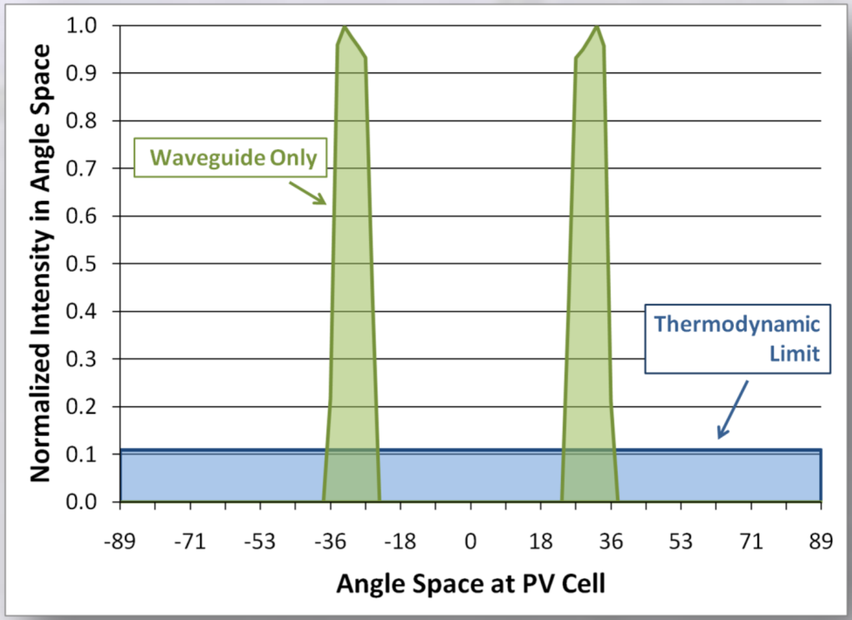
Secondary Coupler

Étendue: *entrance pupil x acceptance angle remains constant*

– Decrease output aperture → Increase output angles

Waveguide Output

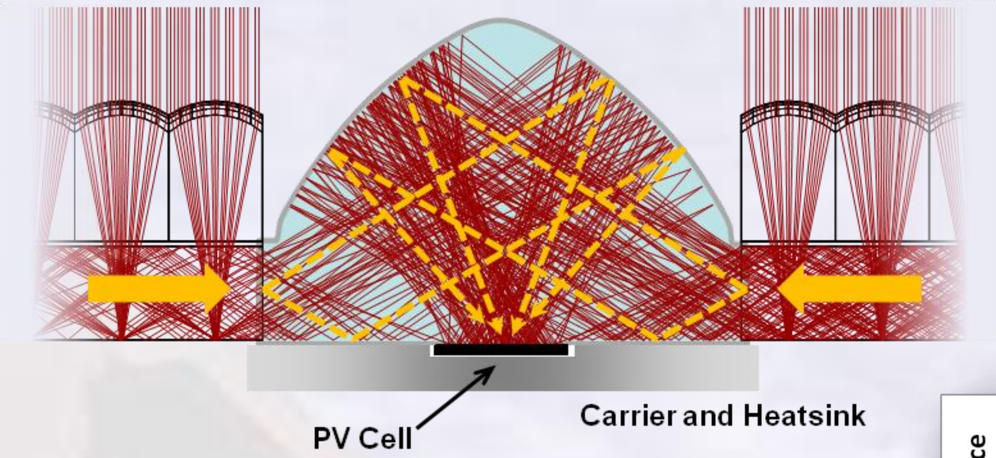
- Only lenses modify ray angles
  - Planar waveguide cannot further concentrate
- Lens divergence biased at ±30°
- Waveguide NA limits extreme ray angles



Secondary Coupler

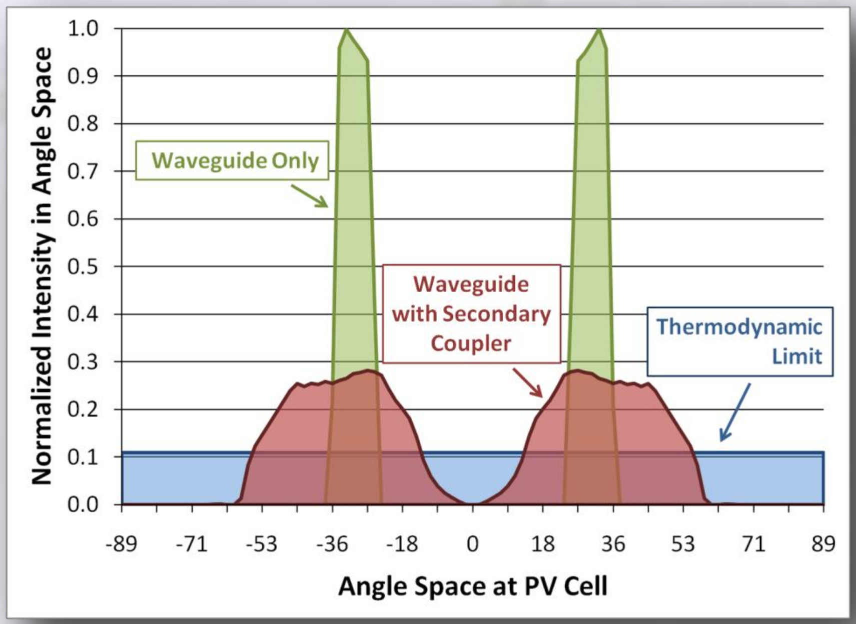
Étendue: *entrance pupil x acceptance angle remains constant*

– Increase output angles → Decrease output aperture



Secondary Coupler

- Opposing waveguide outputs
- PV cell placed below coupler

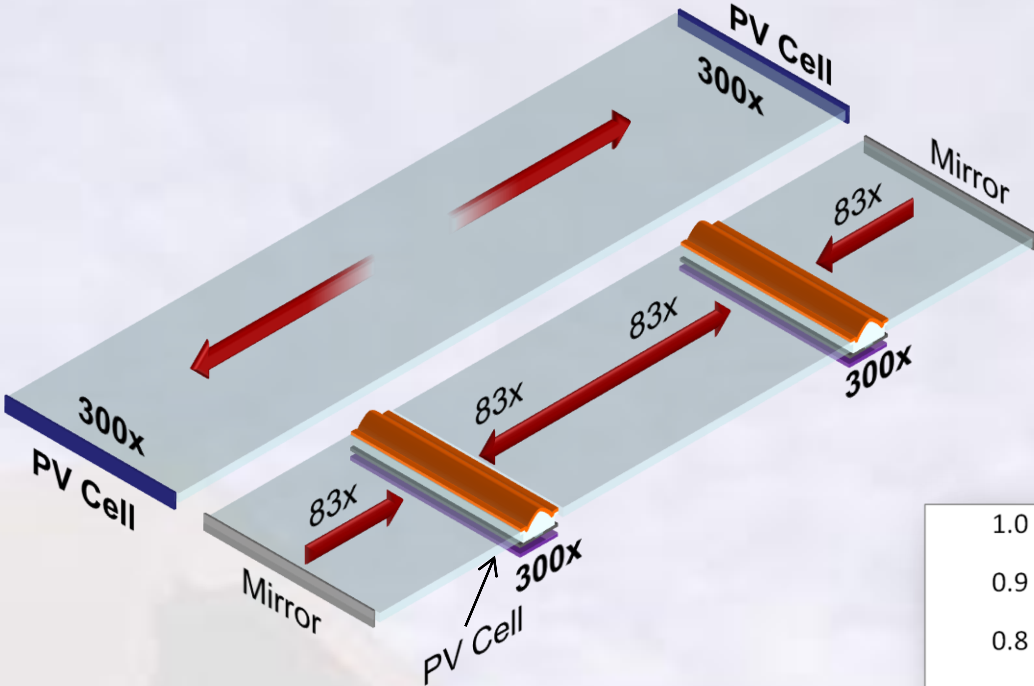


Increase Angular Spectrum

- Increased 'cone of light' at PV cell
- Reduced cell area

Provides 3.6x additional concentration

Concentration with Secondary Coupling



C_{geo} = *Waveguide Length / 2xThickness*

- Increase flux by extending length

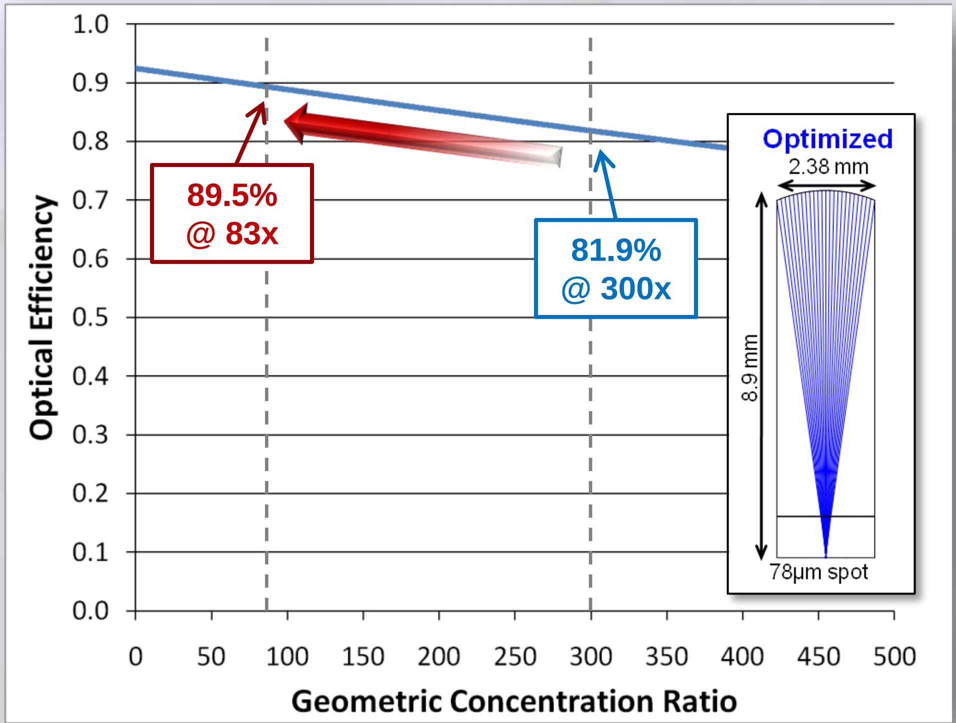
Reduce propagation losses

- Shorter waveguides + secondary coupler

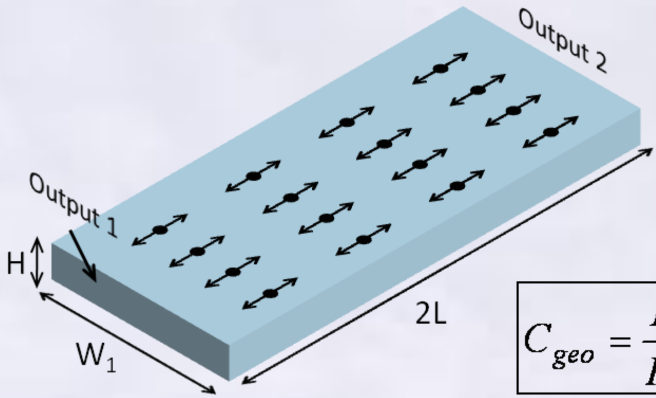
1) Waveguide: 89.5% @ 83x
2) Coupler: 98.0% @ 3.6x

Total efficiency: 87.7% at 300x

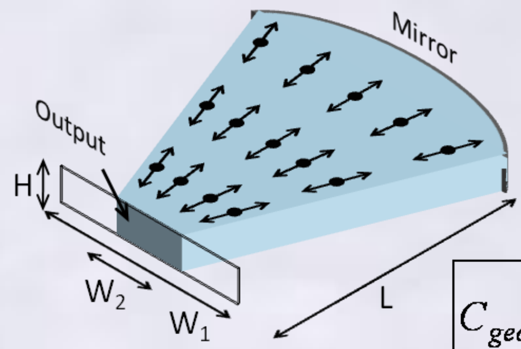
(81.9% without secondary coupling)



Orthogonal Concentration



$$C_{geo} = \frac{L}{H}$$



$$C_{geo} = \frac{L}{H} \times \frac{W_1}{W_2}$$

Radial prism orientation couples light towards limited output

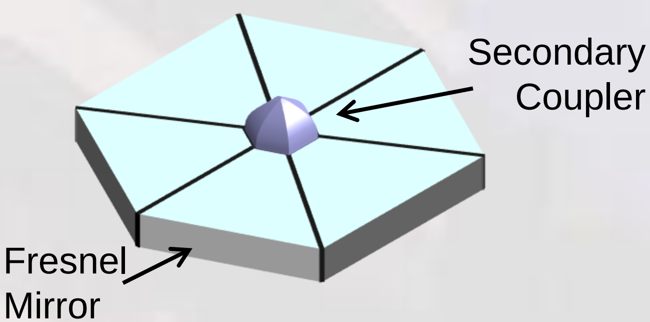
- No change in optical path length → 20% less propagation loss

Up to 5x additional concentration

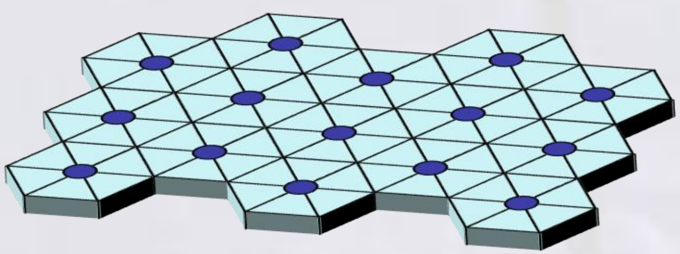
- Retroreflecting mirror + V-trough sidewalls

Secondary coupler enables high efficiency at >500x

Radial Concentrator Assembly



High Concentration Module

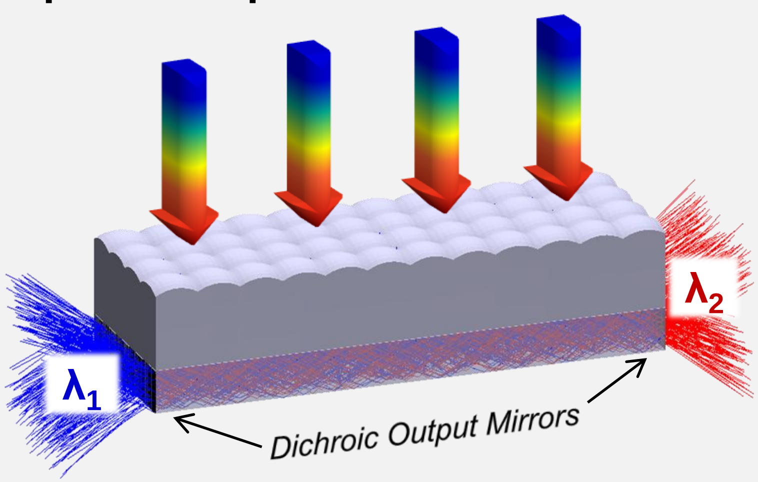


J. Karp, E. Tremblay, and J. Ford, "Radial Coupling Method for Orthogonal Concentration within Planar Micro-Optic Solar Collectors," Optics for Solar Energy, OSA, paper STuD2 (2010).

Summary and Future Directions

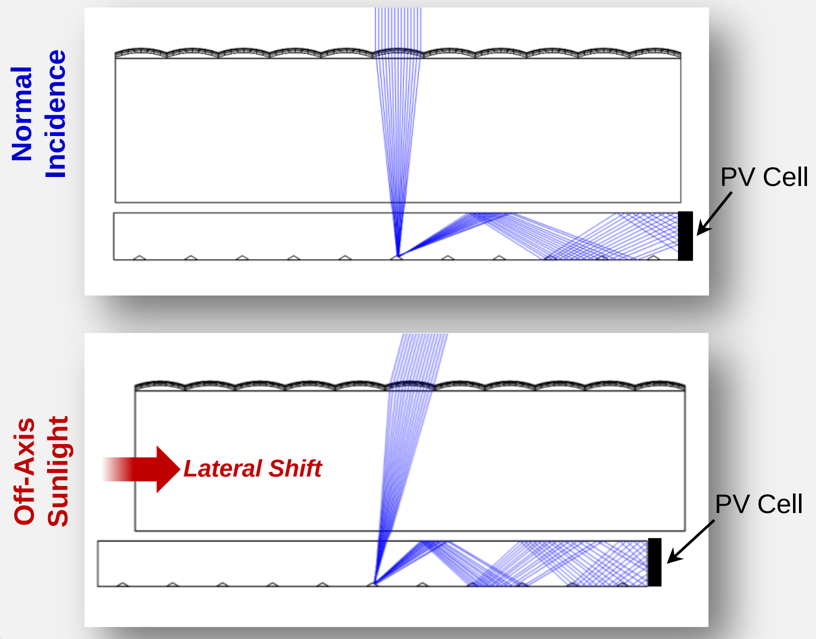
- Micro-optic concentration
  - *Lens array + Waveguide*
- High efficiency and high flux
  - *Demonstrated 52.3% efficiency*
  - *Potential 87.7% at 300x (w/ secondary)*

Spectral Separation

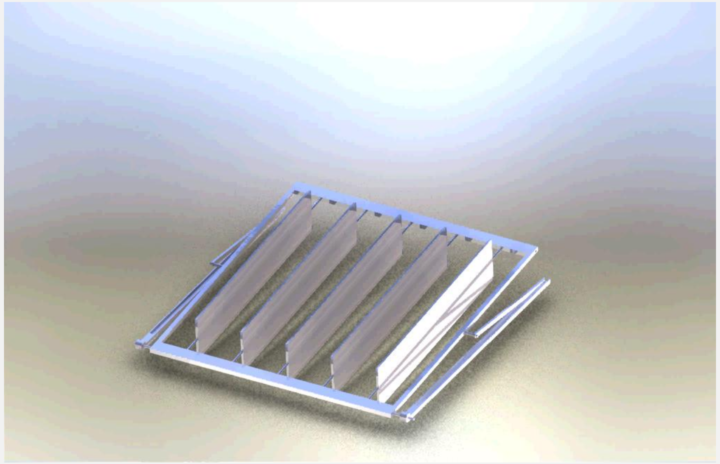


Tracking Methods

1) Lateral Micro-tracking



2) Tilt–Roll Platform



Animation created by Katherine Baker

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Thank You

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