Radial Coupling Method for Orthogonal Concentration within Planar Micro-Optic Solar Collectors

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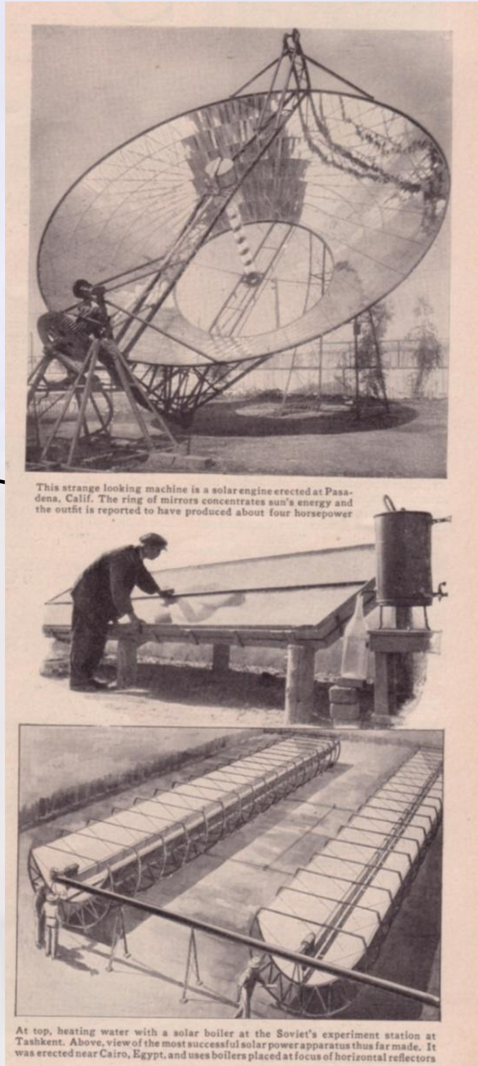
Photo: Kevin Walsh, OLR

Solar Collection: 80 years of progress

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)

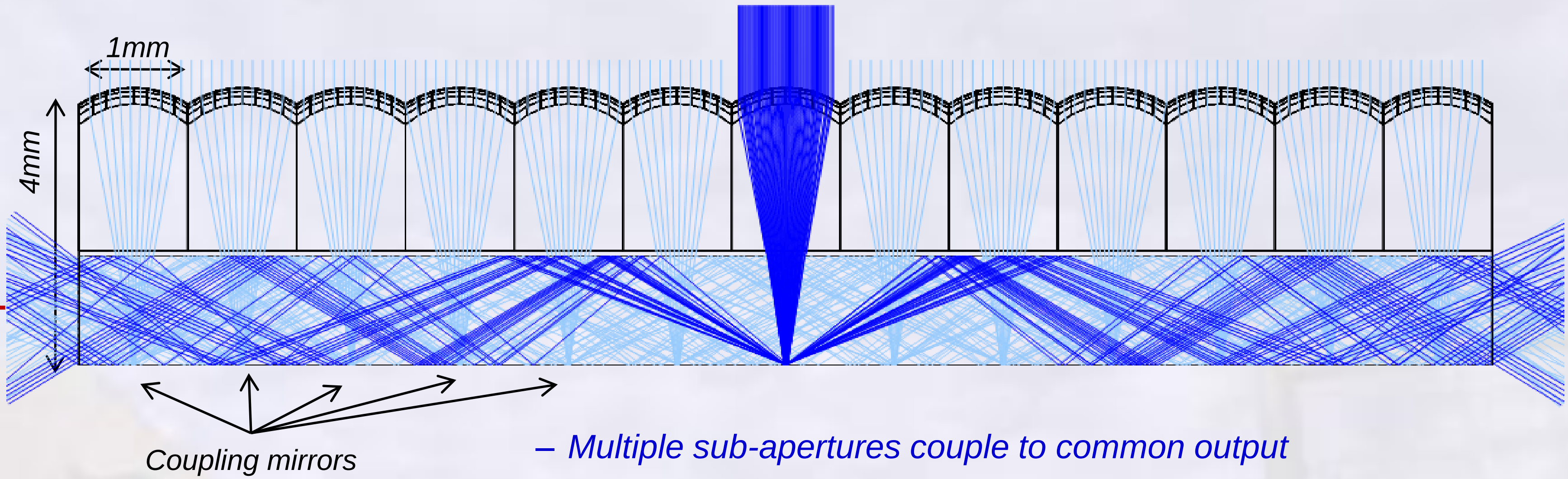


Panels
(fixed)

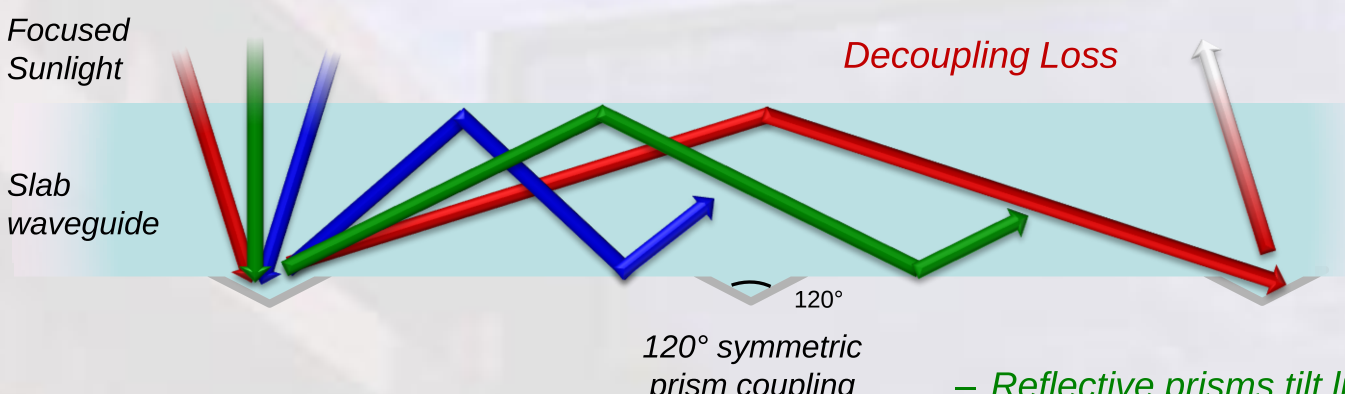

Troughs
(1-D tracking)


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

Planar Micro-Optic Concentration



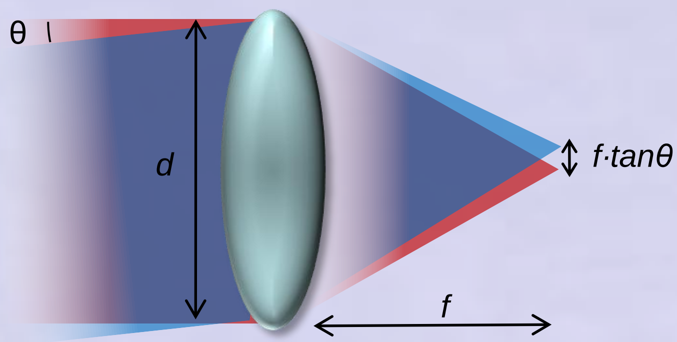
– *Multiple sub-apertures couple to common output*
– *Homogeneous output intensity*
– *Uniform thickness (roll-to-roll fabrication)*



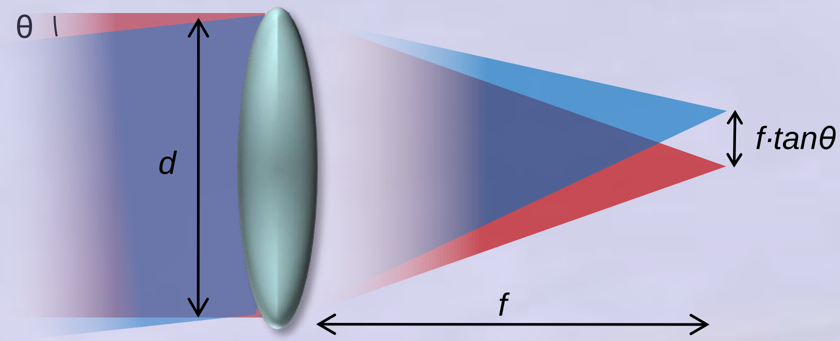
– *Reflective prisms tilt light to TIR*
– *Couplers occupy <<1% of waveguide surface*
– *Subsequent interaction decouples as loss*

Design Tradeoffs

Field Displacement: *Sun subtends ±0.25°*

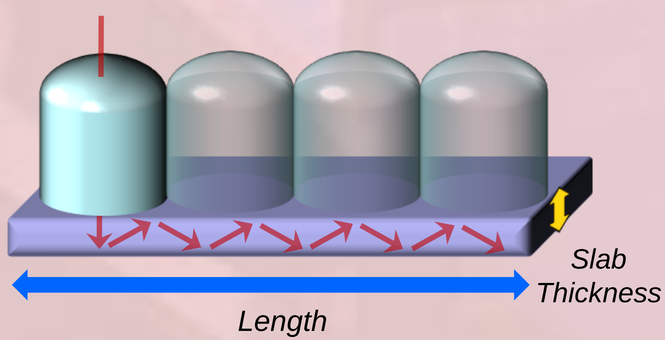


Short focal length → ***small coupling area***

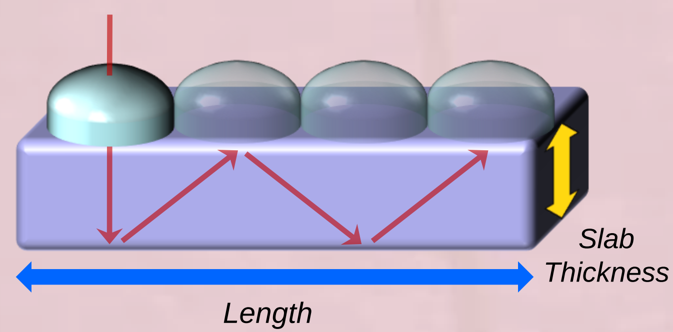


Long focal length → ***easier TIR condition***

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



Thin waveguide → ***high concentration***

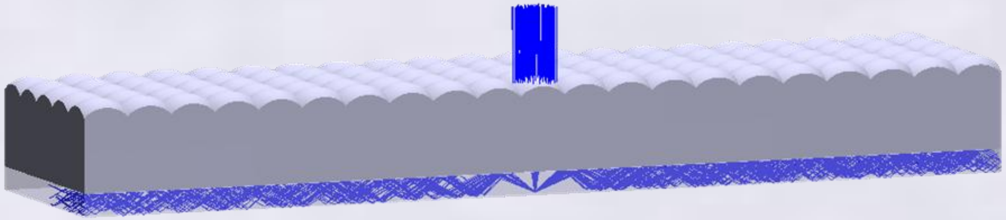


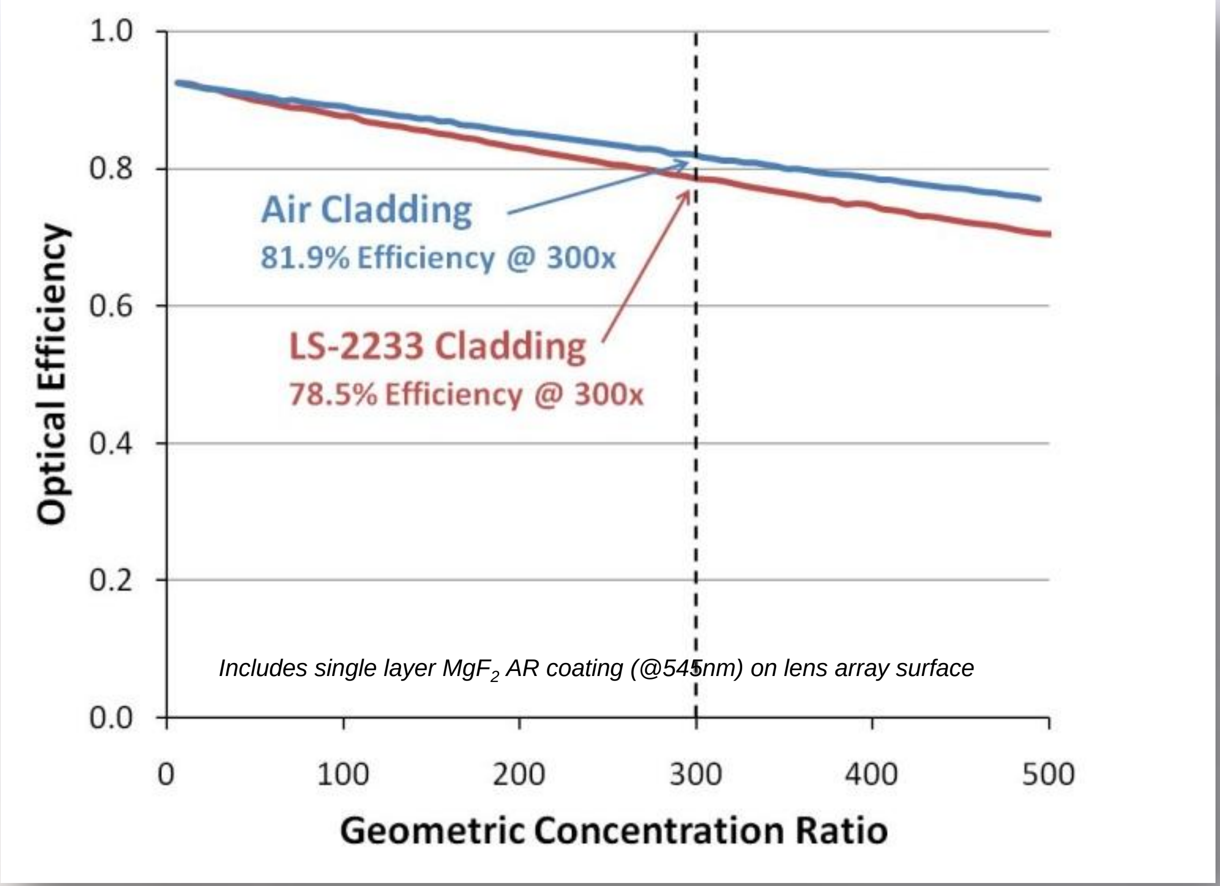
Thick waveguide → ***increased efficiency***

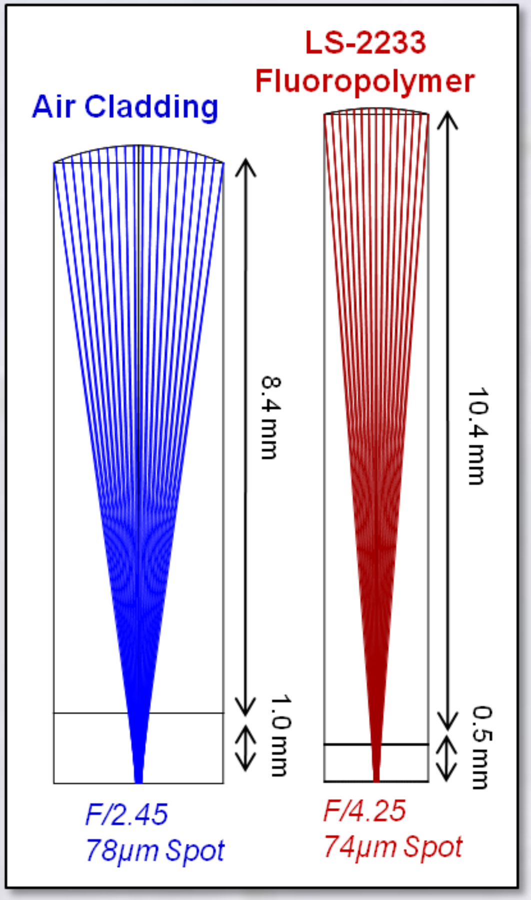
Optimized Designs

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

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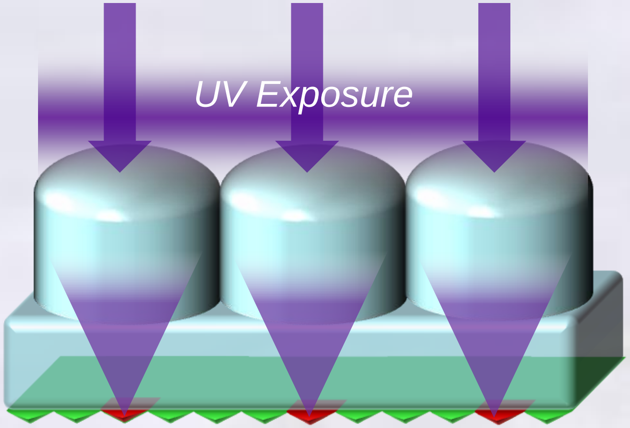
Critical Alignment Tolerance

- Lens focus must overlap with each coupling location
  - *<50μm lateral alignment tolerance*
  - *<0.01° (0.2mrad) rotational alignment*

Solution: Self-alignment

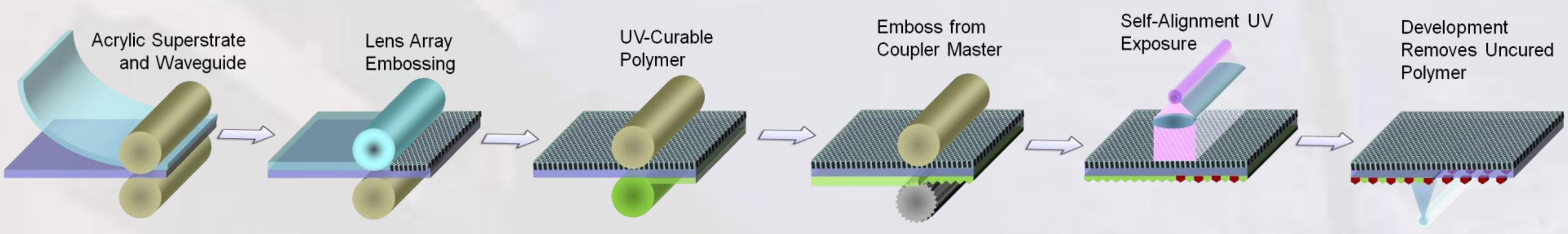
- Mold prism structure in UV-curable photopolymer
- Expose through lens array to define coupling regions
- Cured regions remain part of the final device



Coupling features made by exposure through lenses

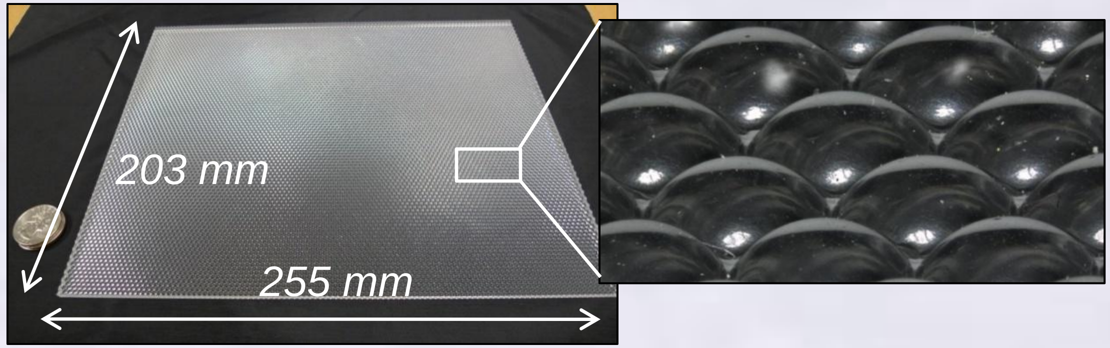
Low-cost manufacturing process

Continuous roll processing on flexible or rigid substrates



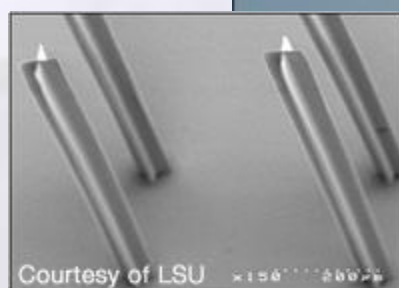
1st Generation Proof-of-Concept

- Lens Array: *Fresnel Technologies*
  - F/1.1 hexagonal lens array
  - UVT acrylic

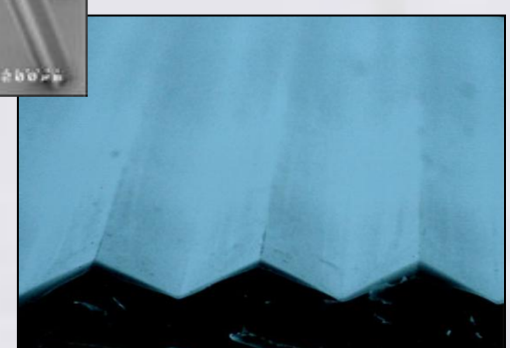


- Waveguide: *Fisher Scientific*
  - Microscope slide (75mm x 50mm)
  - BK7 float glass

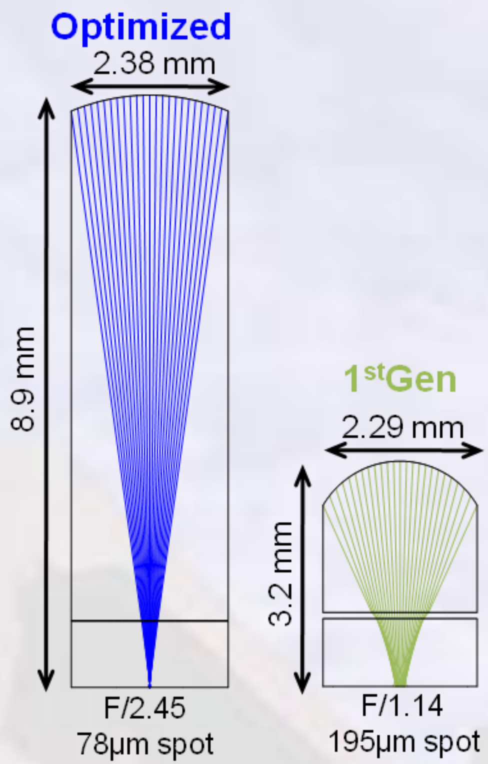
- Molding Polymer: *MicroChem Corp*
  - SU-8 Photoresist
  - Chemical and thermally resistant

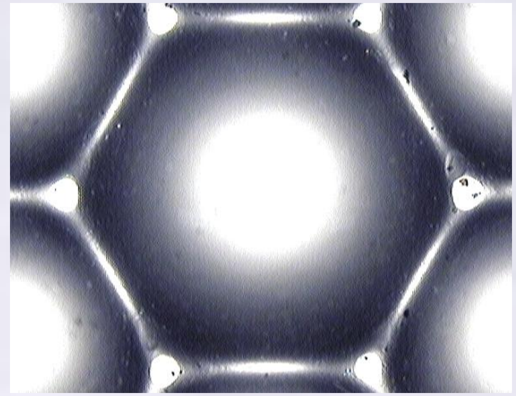


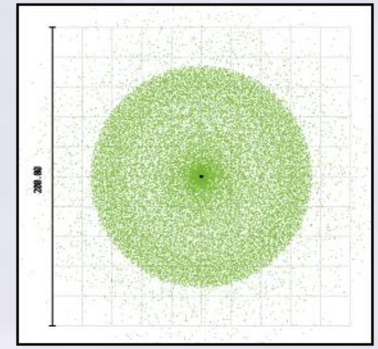
- Prism Mold: *Wavefront Technologies*
  - 120° symmetric prisms
  - 50µm period, 14.4µm deep



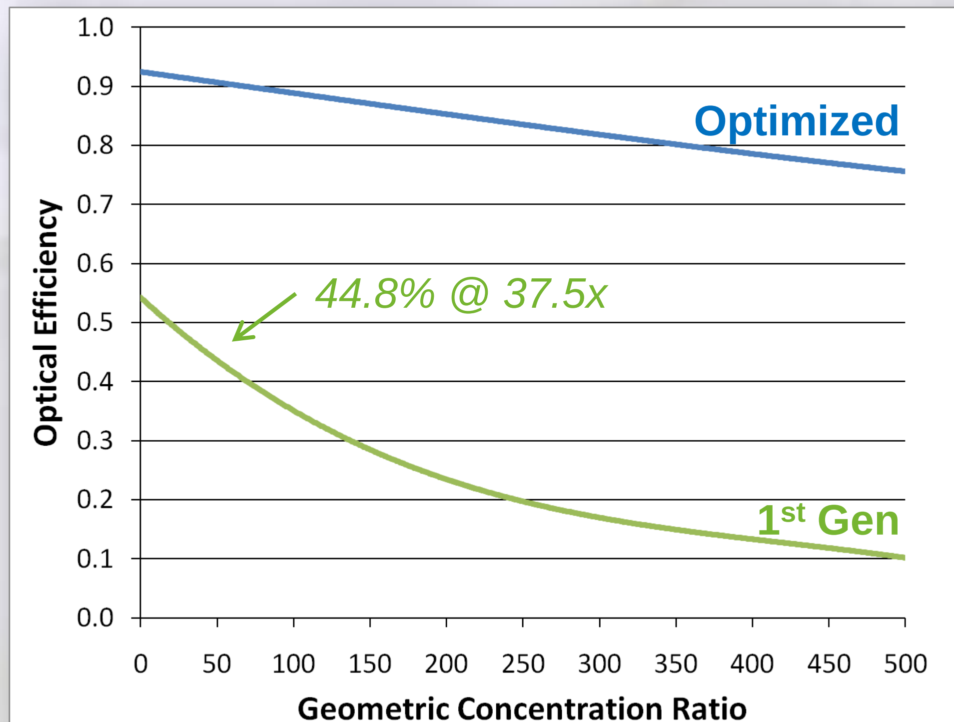
1st Generation System







160µm (On-axis)

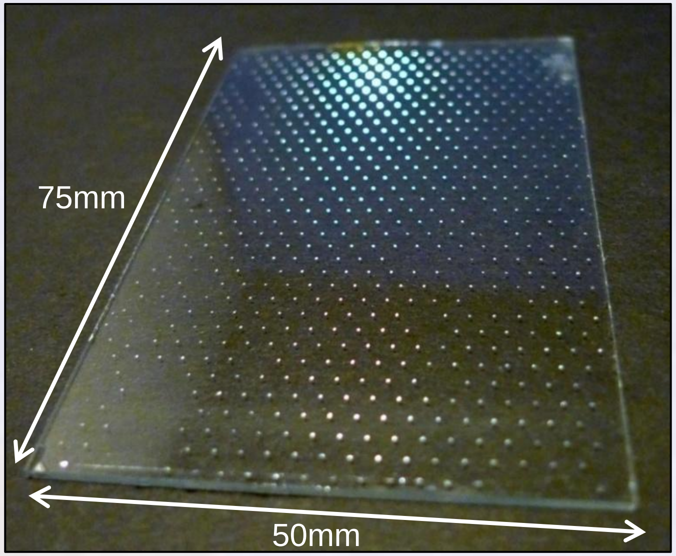


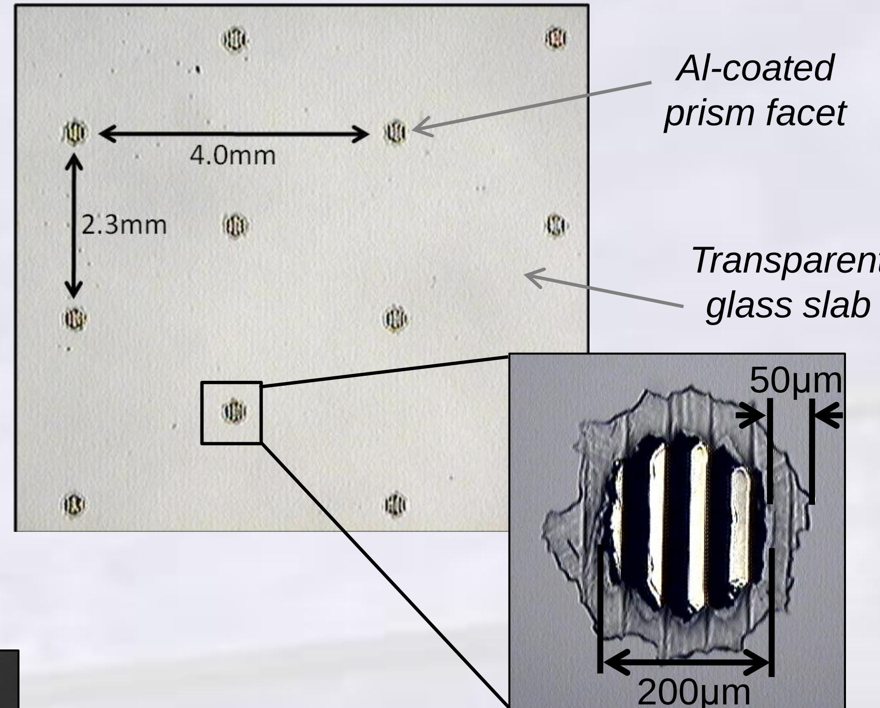
F/1.14 plano-convex lens array

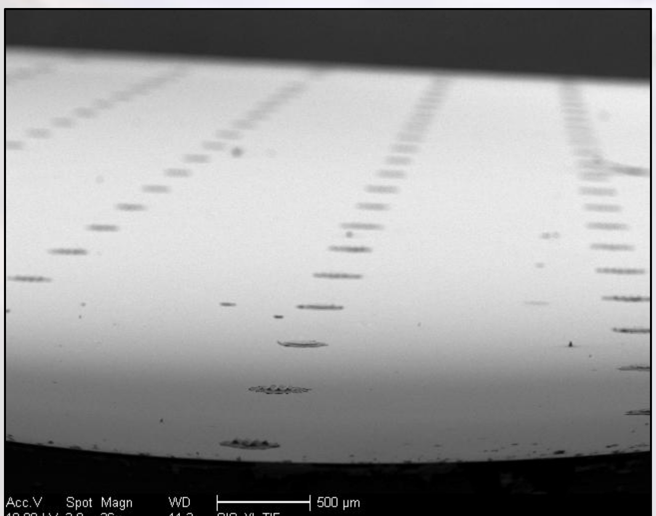
- Strong spherical aberration
- Gaps between elements

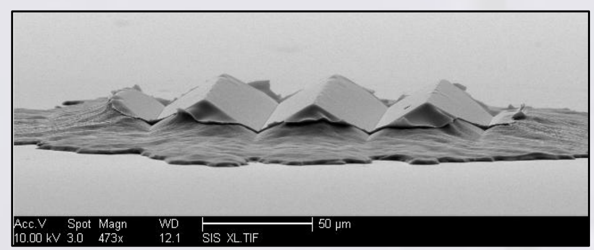
Predict low efficiency due to lens performance and fill-factor

Fabricated Couplers



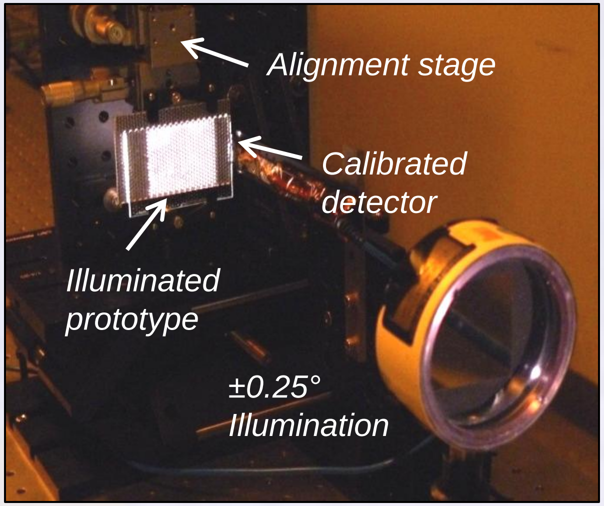






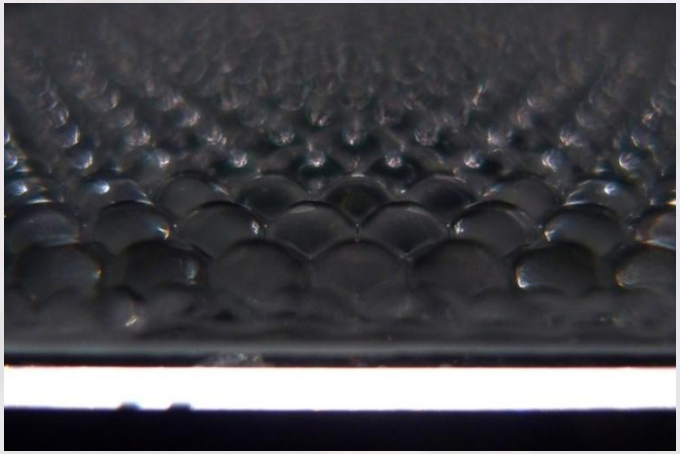
20µm Depth

1st Generation System Testing



37.5x concentration (2 outputs)

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



←Lens Array

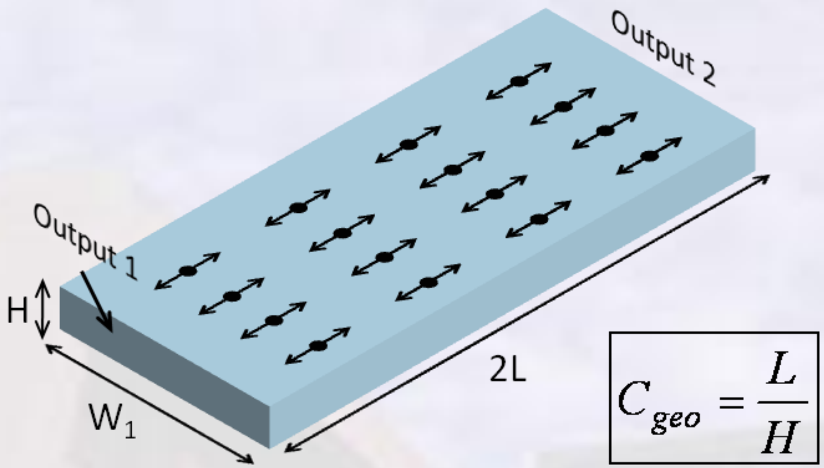
←Waveguide

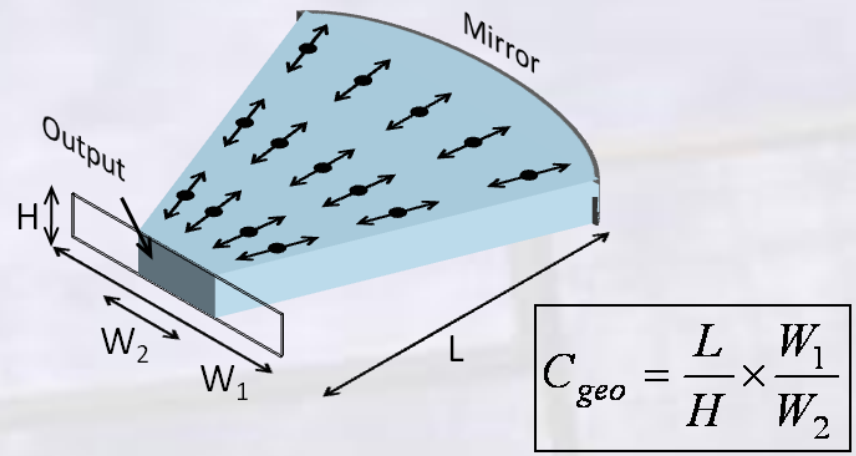
J. H. Karp, E. J. Tremblay and J. E. Ford, "Planar micro-optic solar concentrator," Optics Express, Vol. 18, Issue 2, 1122-1133 (2010).

TWO-DIMENSIONAL CONCENTRATION
(ORTHOGONAL CONCENTRATION)

Orthogonal Concentration

- Optical efficiency depends on geometric concentration
  - Long path lengths → additional decoupling and absorption losses
  - High concentration systems require long waveguides

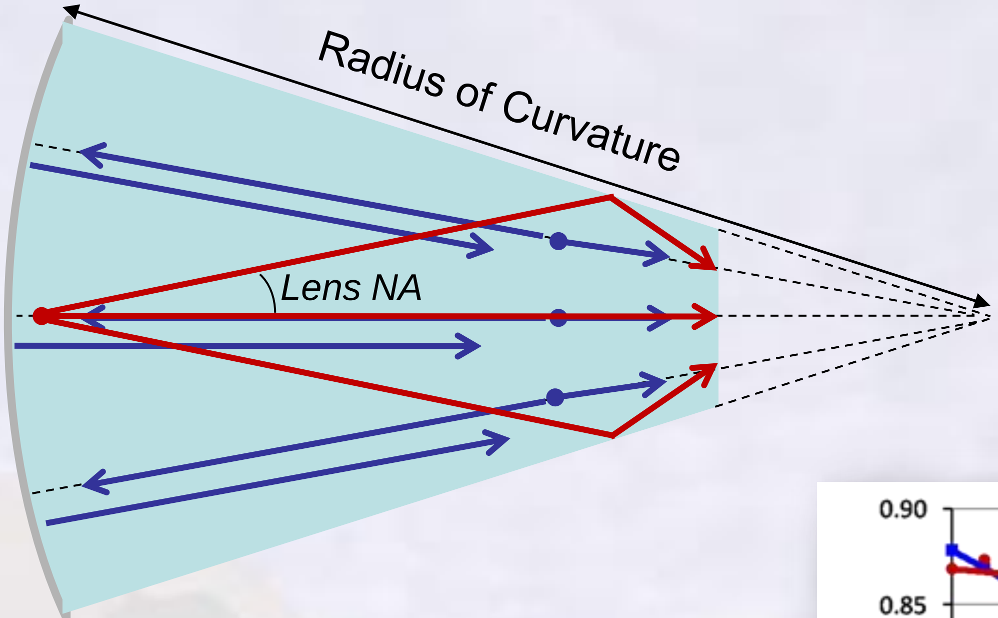




Radial coupling

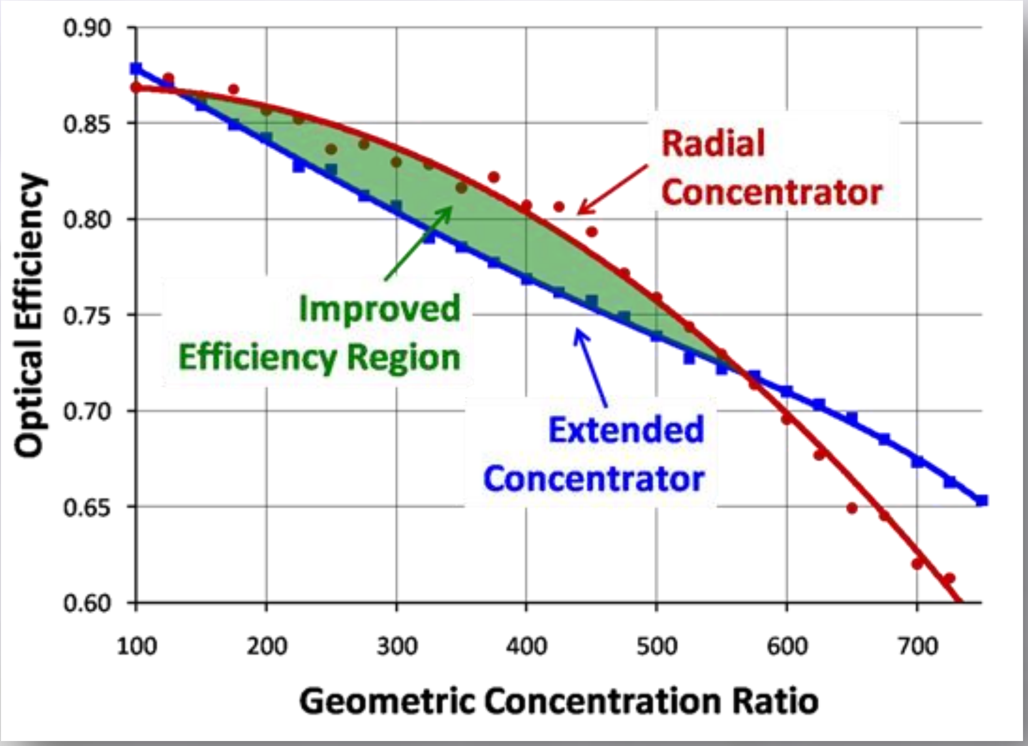
- **Orient couplers to direct light towards a limited output region**
- No change in optical path length → minimizes efficiency decrease
- Single output

Radial Concentration Performance



Back Reflector
- Mirror curvature lies normal to incident rays

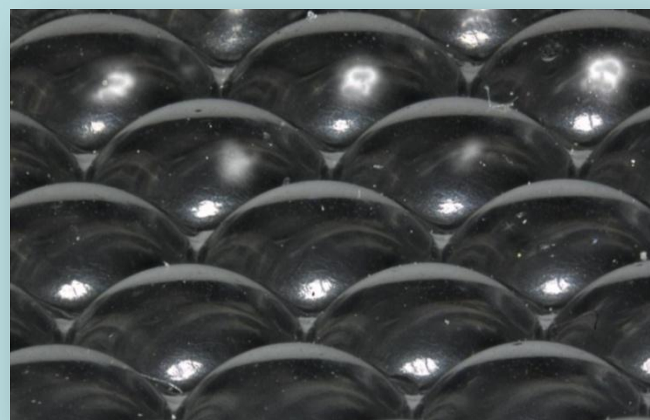
V-Trough
- Confines lens array divergence



Up to 5x concentration
- 20% less propagation loss
- Extra mirror reflection
  (reduced efficiency at low concentration)
- V-trough angle
  (light rejection from multiple reflections)

2nd Generation System

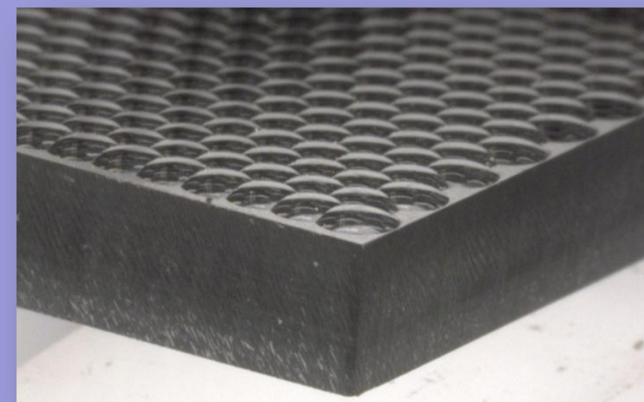
1st Generation Prototype



- F/1.1 plano-convex array
  - Spherical aberration
  - Gaps between lenses
- Coupler deformation

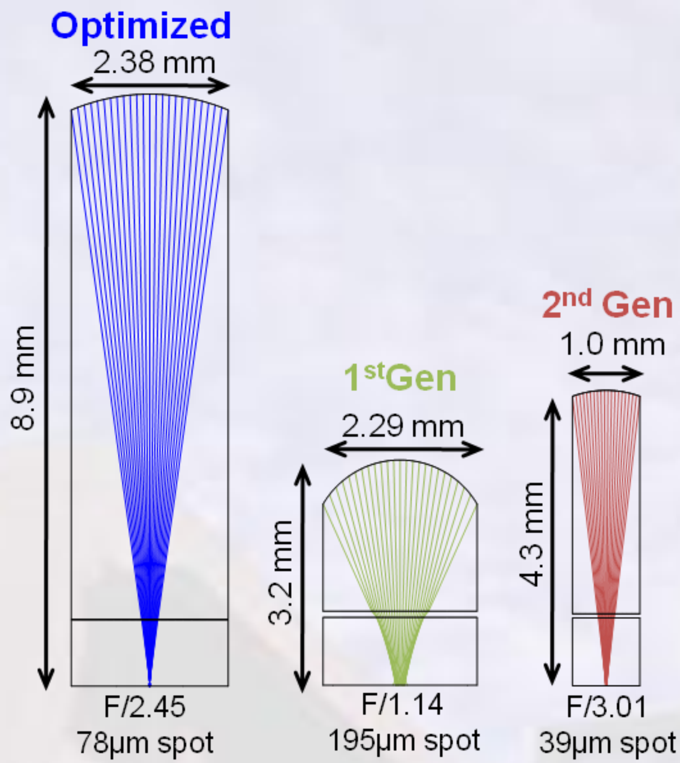
32.4% optical efficiency

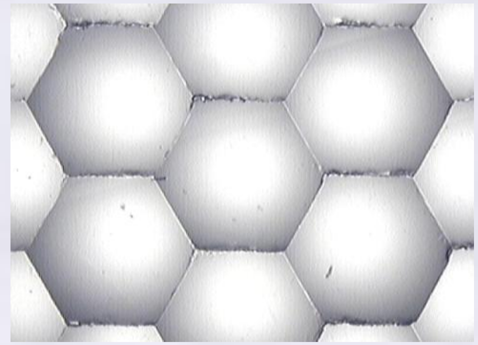
2nd Generation Prototype

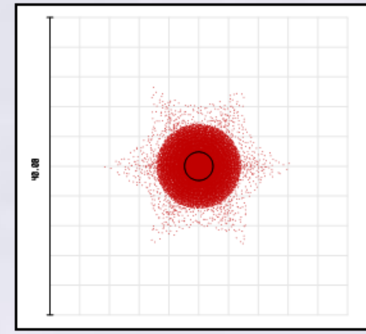


- F/3.01 plano-convex array
  - Near diffraction-limited
  - 100% fill-factor
- PDMS master mold
  - Porous to SU-8 solvent
  - Consistent molding

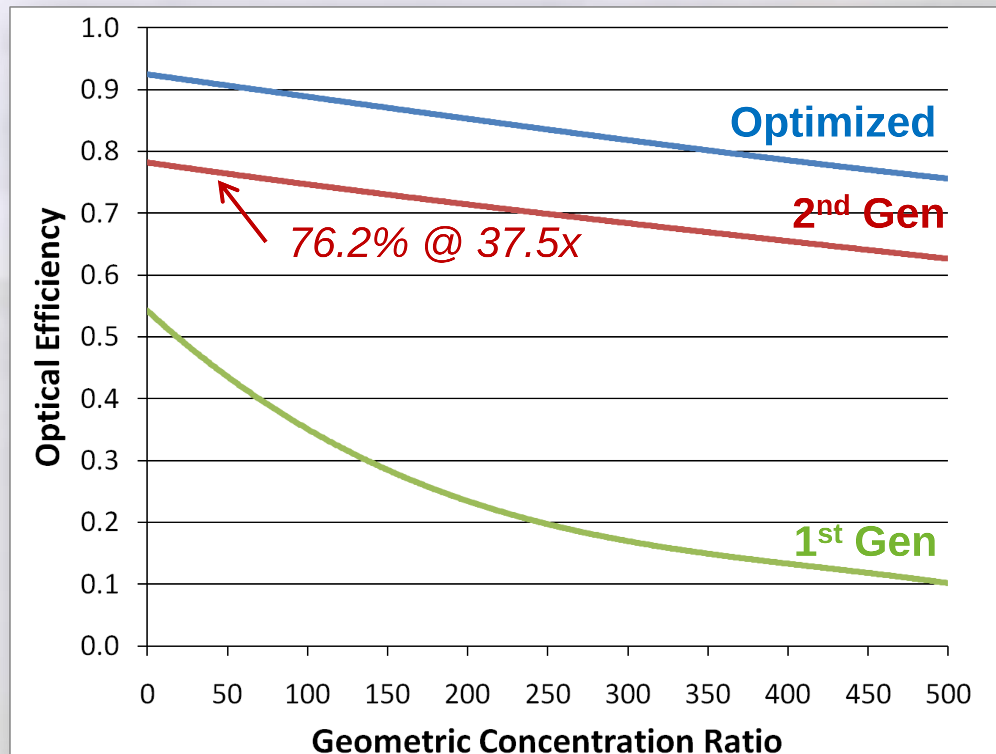
2^{nd} Generation Prototype





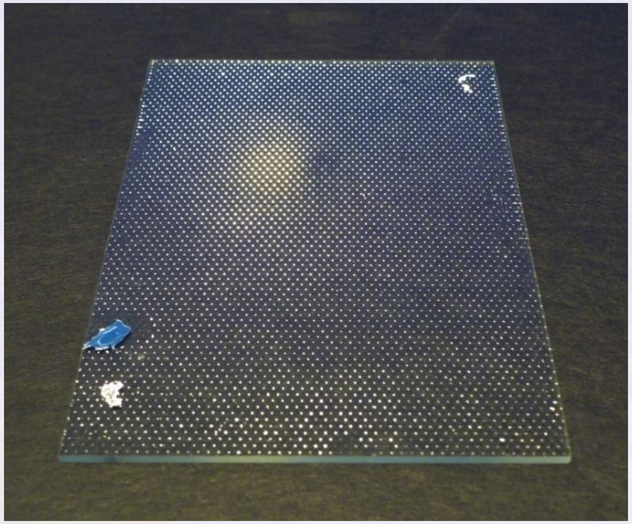


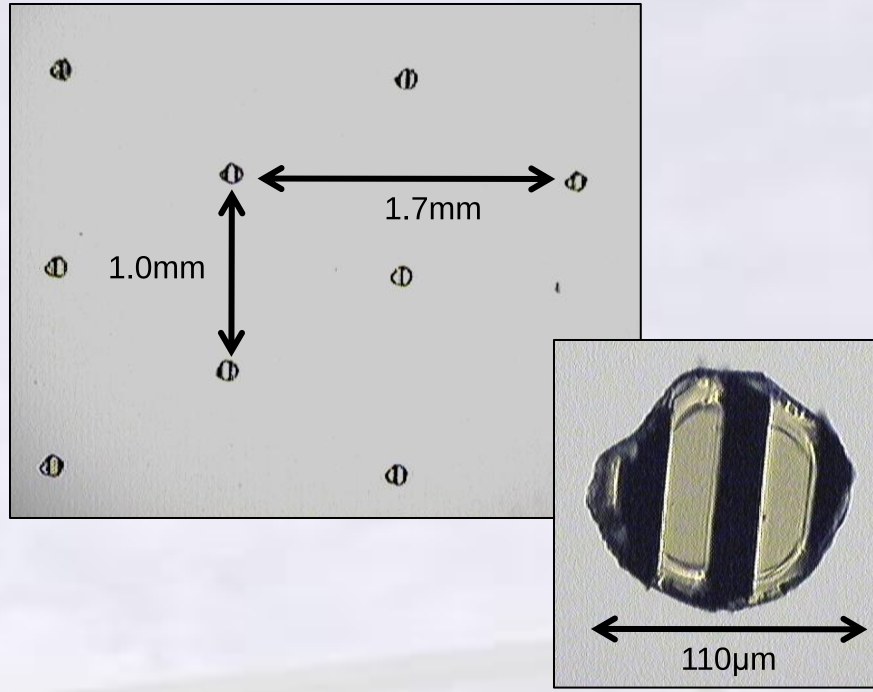
23µm (On-axis)



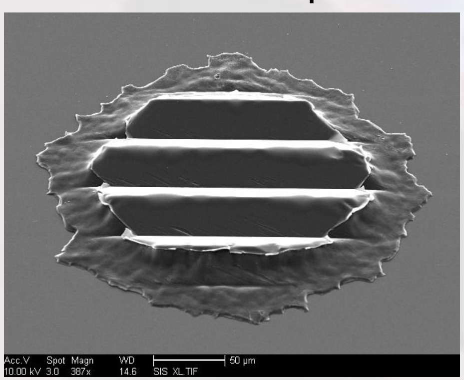
- F/3.01 plano-convex lens array
  - 1.0mm lens pitch
  - 39µm coupling regions (±0.25°)
- Comparable decoupling losses
  - No AR coatings

2^{nd} Generation Couplers

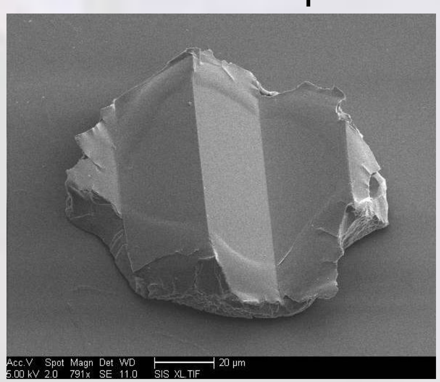




1st Gen Coupler

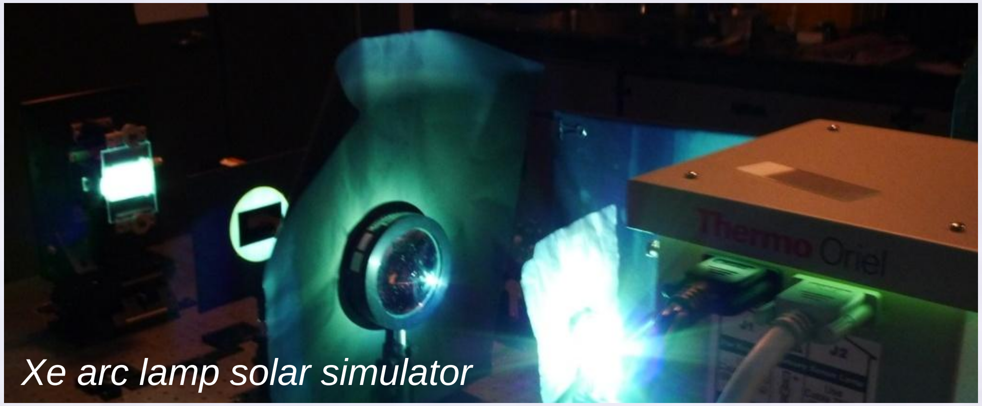


2nd Gen Coupler



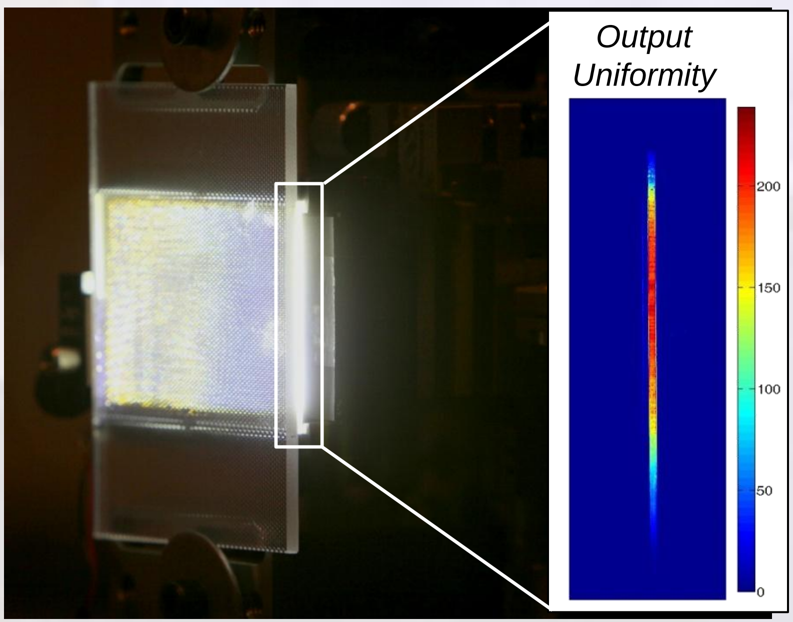
- Well-defined coupling regions
  - Less lens aberration
- **83% measured aluminum reflectivity**
  - 92% expected reflectivity

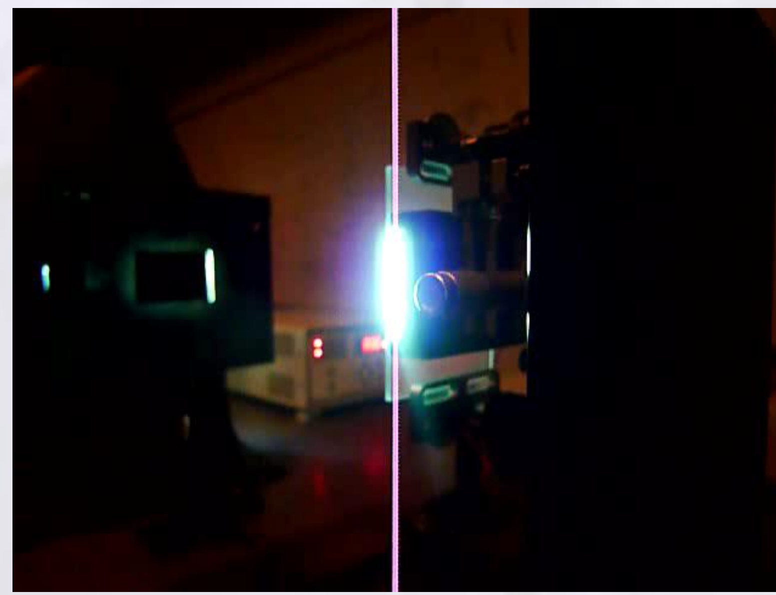
2nd Generation Prototype Performance


Xe arc lamp solar simulator

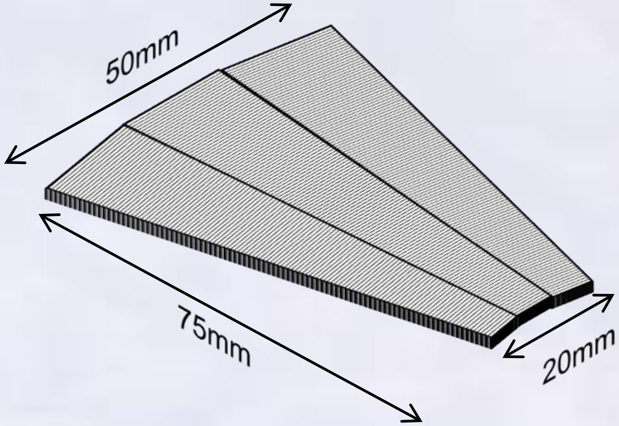
37.5x concentration (2 outputs)

- 76.2% Simulated efficiency
  - 65.6% (83% Al-coating)
- **52.3% Measured efficiency**
- ±0.38° angular acceptance



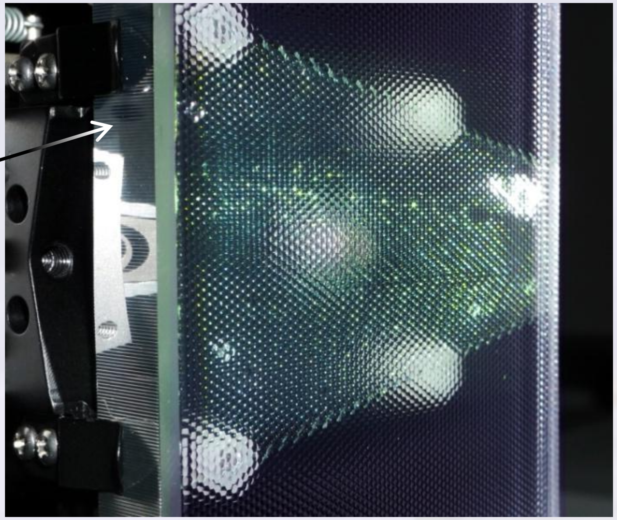

Video: Lateral alignment / misalignment effect

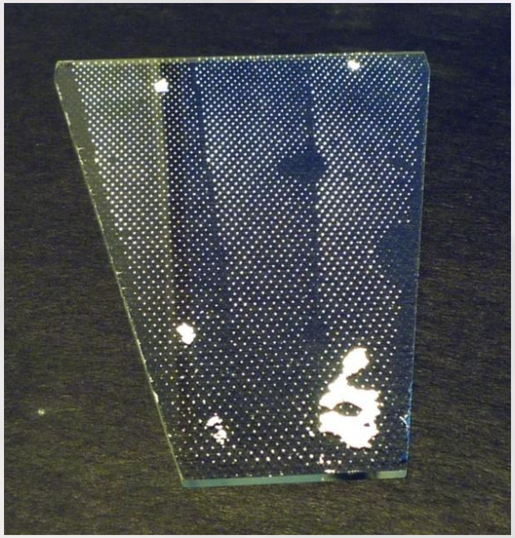
Radial Concentrator Prototype



- Approximate radial coupling with 3 segments
- 2.5x orthogonal concentration

Fresnel Mirror (backside)



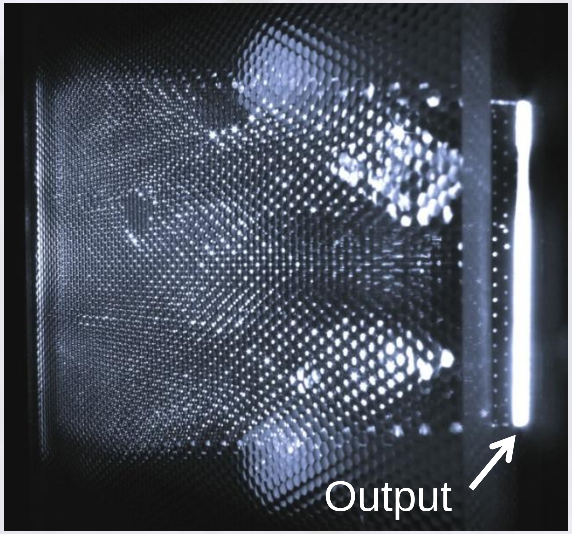


71x concentration

(1 output)

– 54.7% Simulated efficiency
  – 83% Al reflectivity

– **25.7% Measured efficiency**
  – Loss from residual metal



Efficiency Improvements

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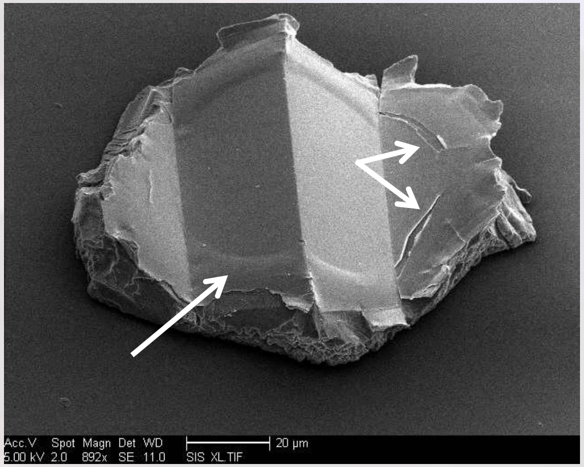
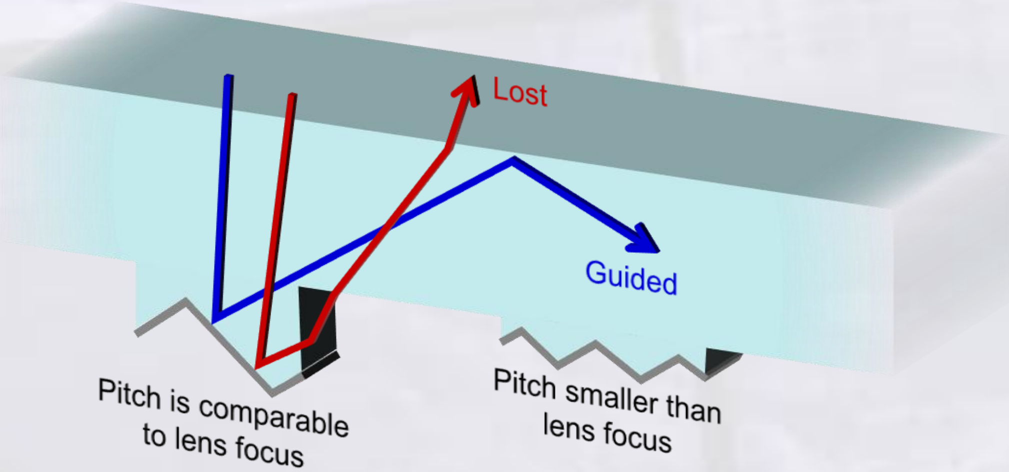
1. **Increase mirror reflectivity**
   - *Aluminum alloys, silver, dielectric*
2. **Improve liftoff process (eliminate unexposed regions)**
3. **Reflector adhesion – edges peel during development**
   - *Currently using central region of oversized couplers*
   - *Explore other photopolymers*
4. **Reduce prism pitch**
   - *Eliminate sidewall leakage*

Reflector Adhesion



Prism Pitch Losses



Summary and Future Directions

In Summary:

- Planar micro-optic concentration
  - Segmented primary aperture with fewer PV cells
  - Reduced optical volume
- Lithographic fabrication supports large-scale manufacture
  - Roll or batch processing (similar to flat-panel televisions)
- Orthogonal concentration through radial coupling
  - Increase concentration ratio without additional decoupling loss

Future Directions:

- Integrate prototype with multijunction PV cells
- Arc-shaped couplers for increased angular acceptance
- Planar micro-tracking
  - Lateral translation can collect off-axis sunlight

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Thank You

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