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

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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:**

\[ C_{\text{flux}} = \frac{\text{Slab Length}}{\text{Slab Thickness}} \times \text{Efficiency} \]

- Thin waveguide → **high concentration**
- Thick waveguide → **increased efficiency**
Zemax Non-Sequential Model
- Lens aberrations
- Polychromatic illumination
- Material dispersion
- Coatings and surface reflections

Includes single layer MgF$_2$ AR coating (@545nm) on lens array surface

UCSD Photonics

Fabrication process: Self-alignment

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

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

- 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

Al-coated prism facet

Transparent glass slab

75mm

50mm

2.3mm

4.0mm

50µm

200µm

20µm Depth
1st Generation System Testing

37.5x concentration (2 outputs)
- 44.8% Simulated efficiency
- 32.4% Measured efficiency
- ±1.0° angular acceptance

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
**2nd Generation Prototype**

- **F/3.01 plano-convex lens array**
  - 1.0mm lens pitch
  - 39μm coupling regions (±0.25°)

Comparative decoupling losses
- No AR coatings

**Optimized**
- 2.38 mm

**1stGen**
- 2.29 mm
- F/2.45
  - 78μm spot

**2nd Gen**
- 1.0 mm
- F/1.14
  - 195μm spot
- F/3.01
  - 39μm spot

**23μm (On-axis)**

**Optimized**
- 76.2% @ 37.5x

**2nd Gen**

**1st Gen**

**Geometric Concentration Ratio**

**Optical Efficiency**
2nd Generation Couplers

- Well-defined coupling regions
  - Less lens aberration
- 83% measured aluminum reflectivity
  - 92% expected reflectivity
2nd Generation Prototype Performance

37.5x concentration (2 outputs)
- 76.2% Simulated efficiency
  - 65.6% (83% Al-coating)
- 52.3% Measured efficiency
- ±0.38° angular acceptance

Xe arc lamp solar simulator

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

Output
Efficiency Improvements

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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