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

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June 8, 2010
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**

\[ f \cdot \tan \theta \]

\[ d \]
Optimized Designs

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

**Fabrication process: Self-alignment**

**Critical Alignment Tolerance**
- Lens focus must overlap with each coupling location
  - $<50 \mu m$ lateral alignment tolerance
  - $<0.01^\circ$ (0.2 mrad) 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
1\textsuperscript{st} 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

Optimized

2.38 mm

F/2.45
39\,\mu m spot

1\textsuperscript{st} Gen
2.29 mm

F/1.14
120\,\mu m spot

190\,\mu m (±0.25°)

Optimized

44.8\% @ 37.5x

7/11/2010

Optical Efficiency

Geometric Concentration Ratio
Fabricated Couplers

- Transparent glass slab
- Al-coated prism facet

Dimensions:
- 75mm x 50mm
- 200μm Depth
- 50μm
- 200μm
1\textsuperscript{st} Generation System Testing

- 37.5x concentration (2 outputs)
  - 44.8\% Simulated efficiency
  - 32.4\% Measured efficiency
  - $\pm 1.0^\circ$ 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
- 44μm coupling regions (±0.25°)

Comparable decoupling losses
- No AR coatings

Optimized
- 2.38 mm

1st Gen
- 2.29 mm
- F/1.14
- 165μm spot
- 3.2 mm

2nd Gen
- 1.0 mm
- F/3.01
- 23μm spot
- 4.3 mm

[Graph showing optical efficiency vs. geometric concentration ratio]
- Optimized: 76.2% @ 37.5x
- 2nd Gen
- 1st Gen
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

Output Uniformity

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*
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
This research is supported by:

National Science Foundation (NSF), Small Grants for Exploratory Research (SGER) program

California Energy Commission (CEC), Energy Innovations Small Grant (EISG) program

Thank You

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