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

Jason H. Karp, Eric J. Tremblay and Joseph E. Ford

Photonics Systems Integration Lab
University of California San Diego
Jacobs School of Engineering

August 4, 2009
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

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

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

**120° Symmetric Prism:**

- Symmetric coupling
- No blocking
- Repeatable structure

Focused rays from lens

Slab waveguide

Reflective facet

Guided Rays

TIR

Waveguide Decoupling (Primary Loss)

Other coupling points
System Layout

Geometric Concentration Ratio

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

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

Acrylic Superstrate and Waveguide

Emboss from Coupler Master

Self-Alignment UV Exposure

Development Removes Uncured Polymer

UV-Curable Polymer

 никто

8/5/2009

PHOTONIC SYSTEMS INTEGRATION LABORATORY – UCSD JACOBS SCHOOL OF ENGINEERING
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
**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

**Zemax Optimization: Efficiency vs Geometric Concentration**

- Air Cladding Design: 240x Flux 83.0% Efficiency 289x Geometric Ratio
- Fluoropolymer Design: 240x Flux 78.4% Efficiency 307x Geometric Ratio

Includes single layer MgF₂ AR coating (@545nm) on lens array surface
Broad Spectrum Performance

Optimized using 0.425-1.3μm illumination
- Accurate range of material models
- Minimum bandwidth for multi-junction PV cells

![Graph showing Zemax Optimization: Efficiency vs Wavelength](attachment:image.png)

- Air Cladding Design
  - 240x Flux
  - 83.0% Average Efficiency

- Fluoropolymer Design
  - 240x Flux
  - 78.4% Average Efficiency

Includes single layer MgF₂ AR coating (@545nm) on lens array surface
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

• 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
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
- Un-crosslinked SU-8
- Crosslinked SU-8
- Prism Mold
- Lens Array

**UV Exposure Source**
- Hg arc
- Uniform, collimated UV illumination
- Adjust beam divergence using the iris

Diagram: Diagram showing the steps of the fabrication process with labeled components.
Fabricated Couplers

- Transparent glass slab
- Al-coated prism facet
- 200 µm depth
- 2.3 mm separation
- 50 µm depth
- 75 mm and 50 mm dimensions
- 20 µm 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)

- Coupler Fabrication Yield
  - *Isolated instances*
  - Trapped gas bubbles
  - SU-8 solvent removal
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
This research is supported by the National Science Foundation Small Grants for Exploratory Research (SGER) program

Thank You

Email: jkarp@ucsd.edu

Website: psilab.ucsd.edu