Multiband Solar Concentrator using Transmissive Dichroic Beamsplitting

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Photo: Kevin Walsh, OLR

Presentation Outline

- Photovoltaic Technologies and Spectral Division
- Double-Reflection Dichroic Beamsplitting
- Optical Design and Process
- Simulated Performance
- Manufacturing Potential

Solar Concentration

- Concentrating Solar Thermal (CST)
  - Solar tower
  - Parabolic dish/trough

Photo courtesy of Schott

- Concentrator Photovoltaics (CPV)
  - Reflective telescope
  - Fresnel lens
  - Hybrid refractor/reflector

Photo courtesy of Solfocus

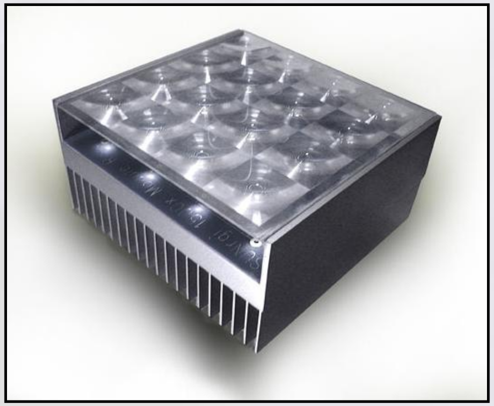


Photo courtesy of Sunrgi

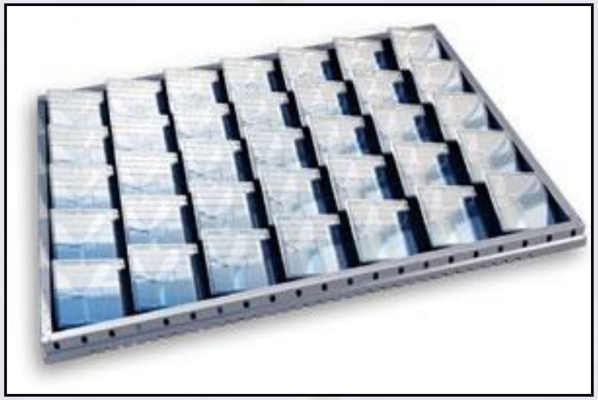


Photo courtesy of Soliant Energy

Photovoltaic Technologies

Crystalline Silicon

Photo courtesy of Kyocera

15-18% Efficiency

- Mono- or Polycrystalline
- Robust and reliable
- Direct and diffuse sunlight
- ~4$ / Watt
  - Kyocera
  - Sharp
  - Mitsubishi

Thin Film

Photo courtesy of Global Solar

6-12% Efficiency

- Amorphous Silicon
  - CdTe, CdS, CIGS
- Reduced material volume
- Rigid or flexible substrate
- Towards 1$ / Watt
  - First Solar
  - NanoSolar
  - Global Solar

Multijunction

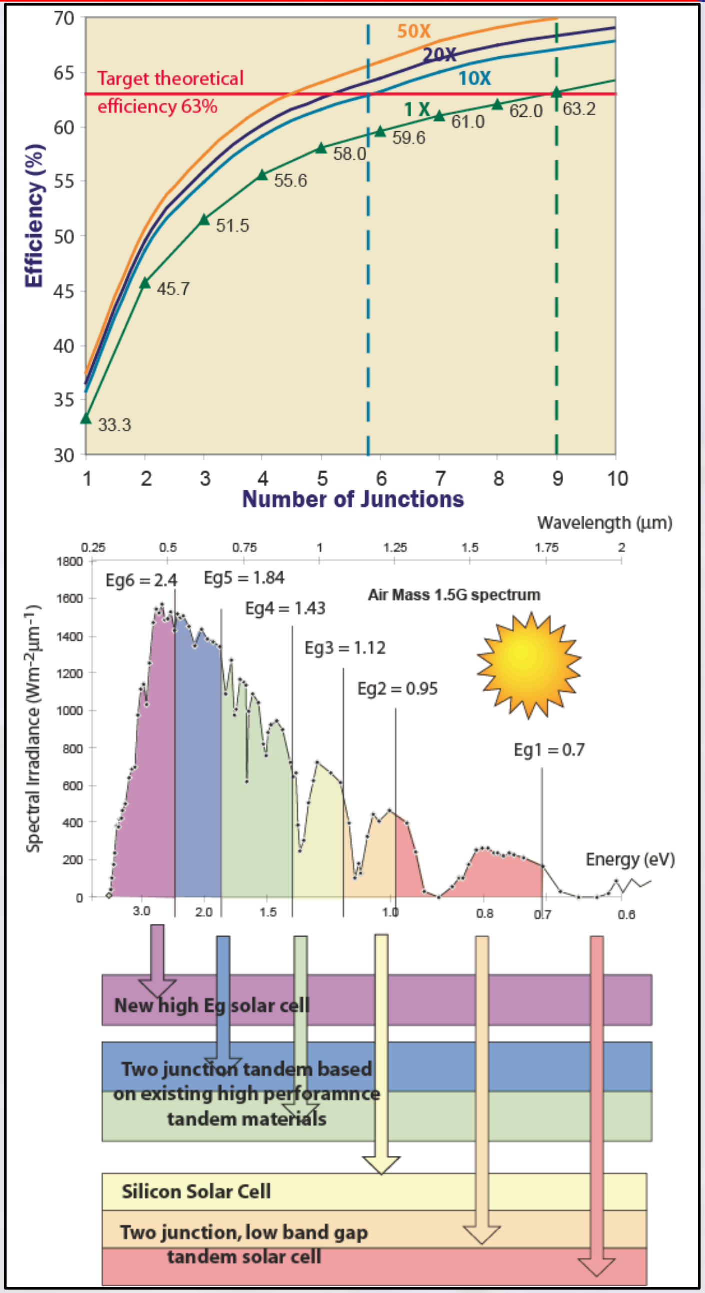
Photo courtesy of Spectrolab

>40% Efficiency

- GaInP – GaInAs – Ge
- High material/fabrication costs
- Flux concentration
  - Solar tracking
- System costs vs high efficiency
  - Spectrolab
  - Emcore

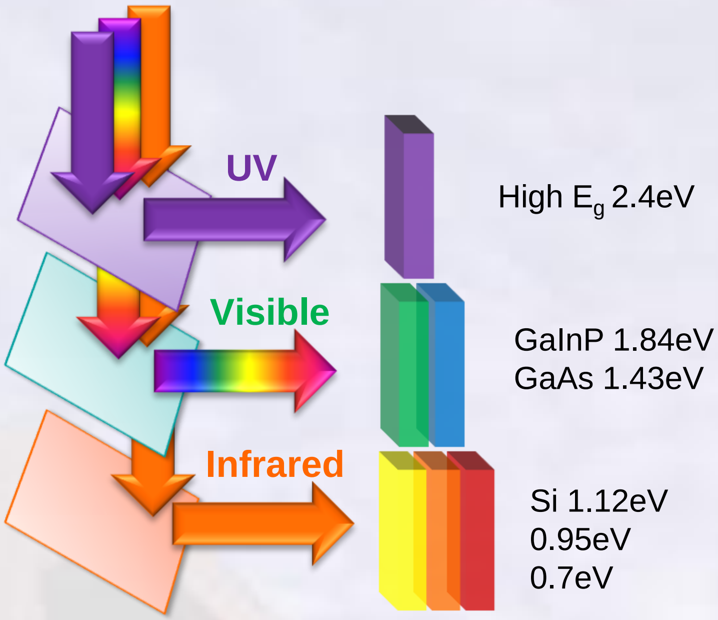
Towards 50% PV Efficiencies

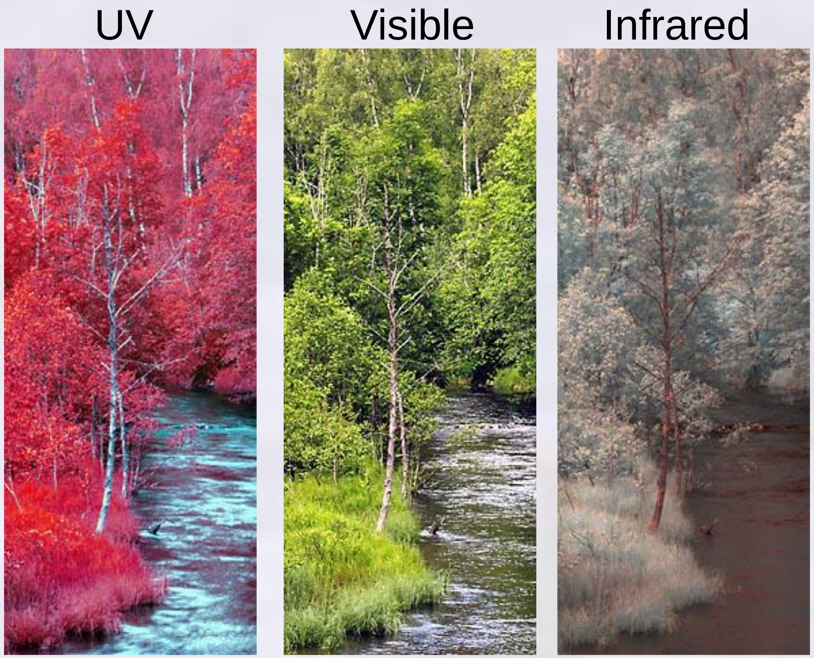
- Logarithmic efficiency increase with concentration
  - Largest gains with low concentration (10x)
  - Reduces required junctions from 9 to 6
- Spectrally separate incident light
  - Divide 6 junctions among multiple cells
  - Optimized bandgap materials
- Independent PV contacts
  - Avoid current matching issues
  - Flexible choice in materials
- Co-design optical, interconnect and solar cell designs to increase real-world performance



Barnett, A.; Honsberg, C.; Kirkpatrick, D.; Kurtz, S.; Moore, D.; Salzman, D.; Schwartz, R.; Gray, J.; Bowden, S.; Goossen, K.; Haney, M.; Aiken, D.; Wanlass, M.; Emery, K., "50% Efficient Solar Cell Architectures and Designs," Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on , vol.2, no., pp.2560-2564, May 2006

Spectral Splitting





Courtesy of Bjorn Rorslett, http://www.naturfotograf.com

- Spectral splitting using thin-film dielectric mirrors
  - Reflect specific bands/angles while passing others
  - Bands optimized for multijunction PV bandgaps
- Number of coating layers determine efficiency and cost
- <u>Existing dichroic designs exceed 90% optical efficiency</u>

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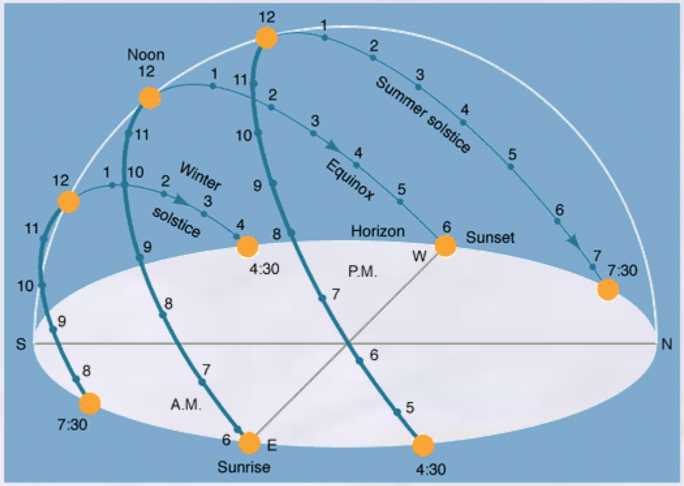
Design Targets

UCSD Photonics

- Optical Design Specifications:
  - Two-path spectral splitting
  - **40° (±20°) East-West angular acceptance**
  - **16° (±8°) North-South angular acceptance**
  - 10x geometric concentration
  - >90% peak optical efficiency
  - <20% roll-off at outer angles



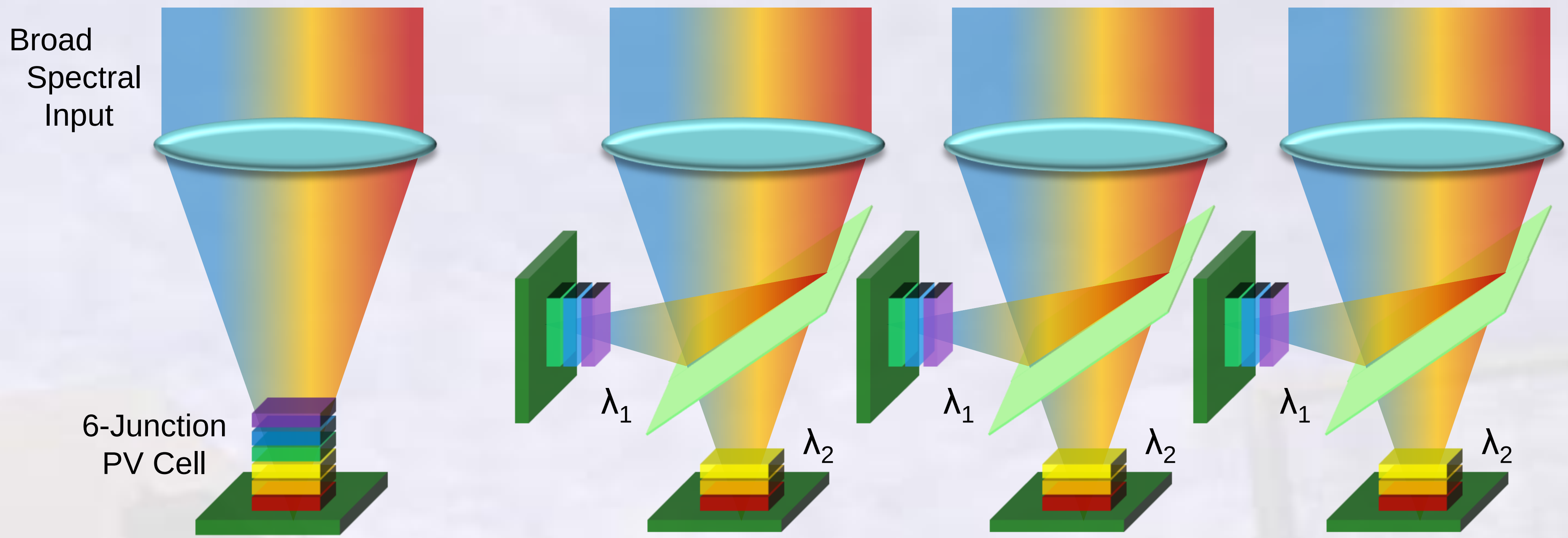
- Mechanical Requirements
  - **Minimize thickness → thin 'sheet'**
    - Small scale power generation
  - Modular array assembly
  - Support two-cell integration
  - Non-tracking due to wide angular acceptance

Photo courtesy of Solar Systems

Photo courtesy of pcpop.com and HTW electronics

DARPA MONTAGE MULTIPLE OPTICAL NON-REDUNDANT APERTURE GENERALIZED SENSORS

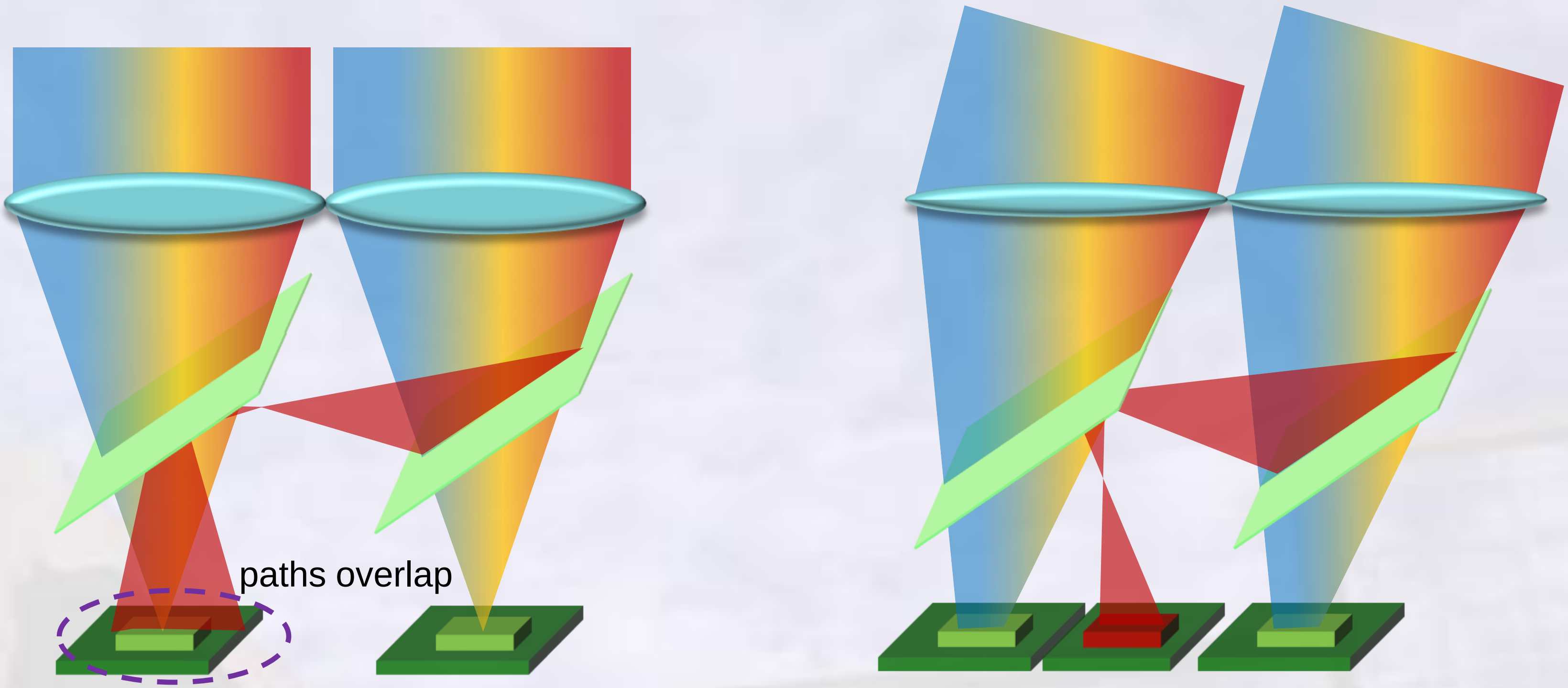
Arrayed Spectral Splitting



- Single path concentrator requires one 6-junction PV cell for 50% efficiency
  - Difficult construction and current matching
- Spectral splitting → lateral architecture with 2, triple-junction cells
- Orthogonal cells leads to costly packaging and poor thermal management
- Top cell creates optional third path

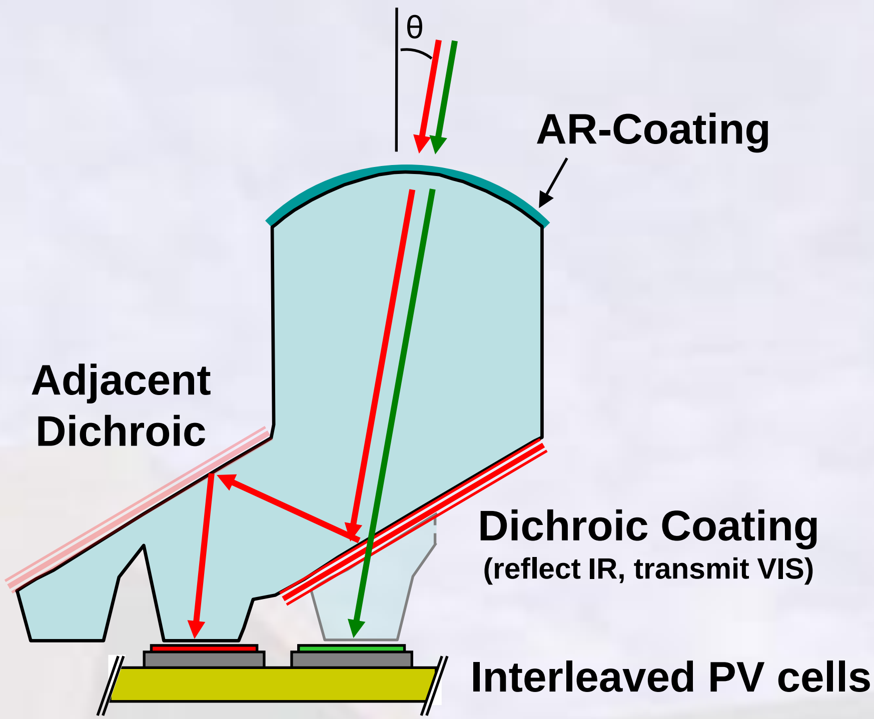
Goal: Design a dichroic concentrator with PV cells on a common substrate to promote array concatenation

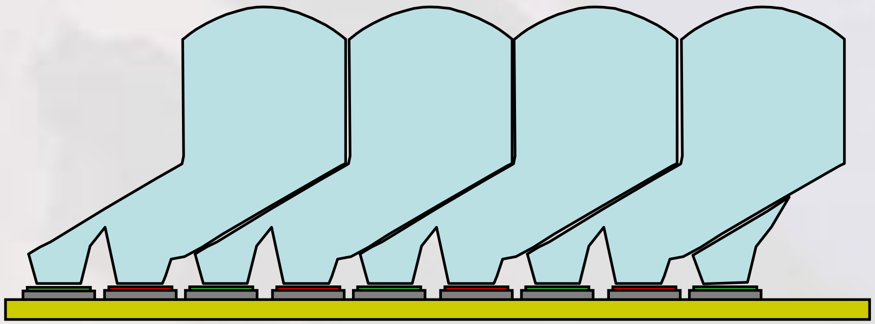
Double-Reflection Geometry



- Use two reflections to reorient second path
- PV cells must be laterally separated
  - Off-axis illumination
- Place lens focus between paths
  - Minimizes spot size for both paths

Micro-optic Design

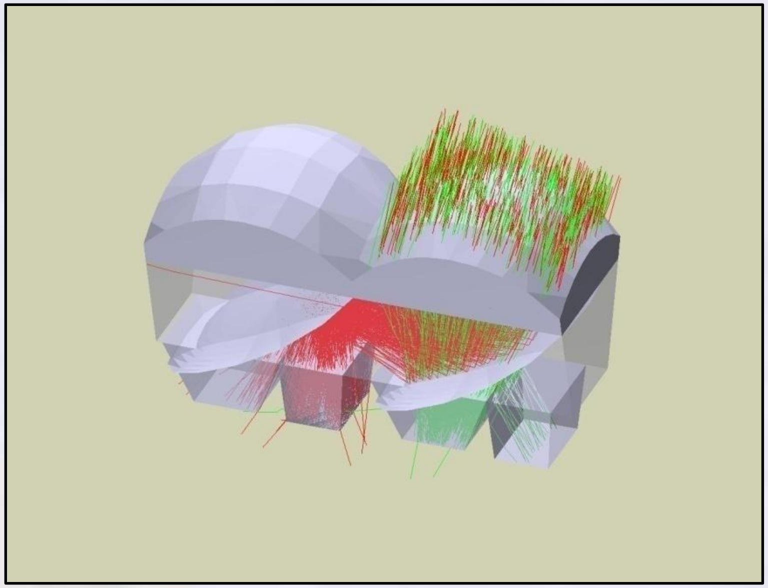


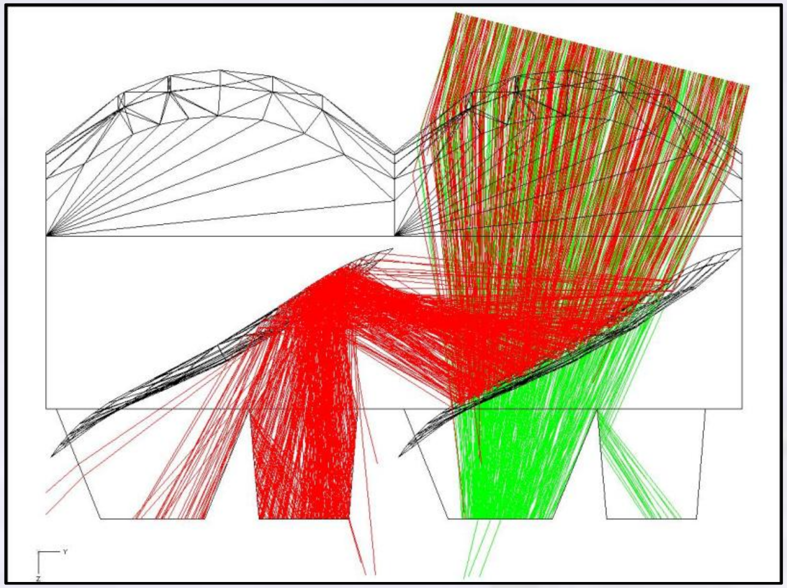


- Single micro-optic incorporates lens and dichroic reflector
  - 1-piece fabrication
  - Solid acrylic or glass component
  - Single antireflection (AR) coating
- Two PV-cells are interleaved on a common circuit board
- Individual elements fit together to form an array
  - Utilize adjacent mirror element

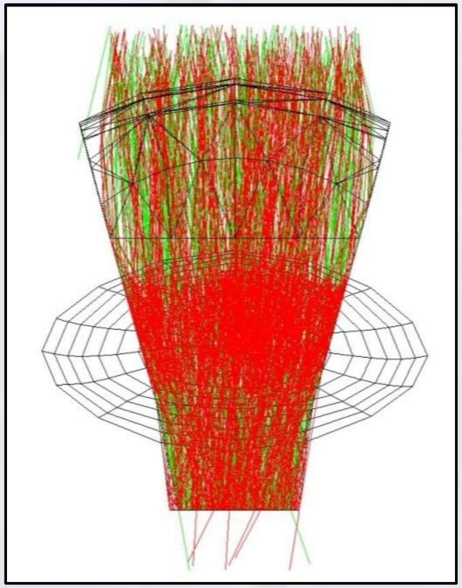
Non-sequential Design

UCSD Photonics

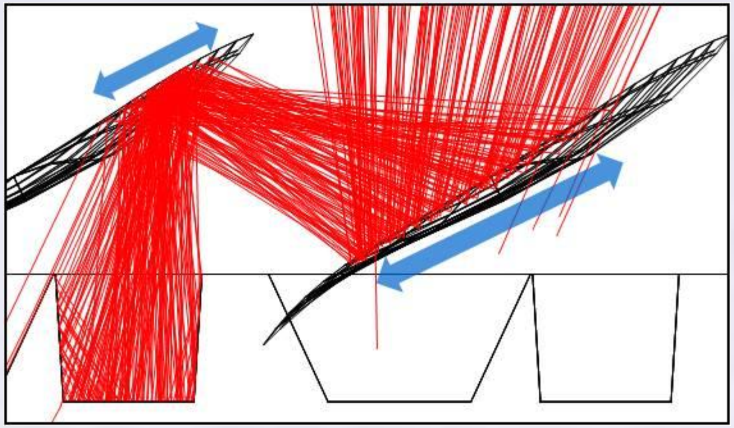




- Zemax Non-sequential: place 3D objects in global coordinate space for ray tracing
  - No assumptions regarding ray intercept order
  - Allows rays to: TIR, multiple 'hits', avoid objects, etc.
- Aspheric lens with intermediate focus
- Tapered exit apertures couples to PV cell
  - <45° exiting ray angles

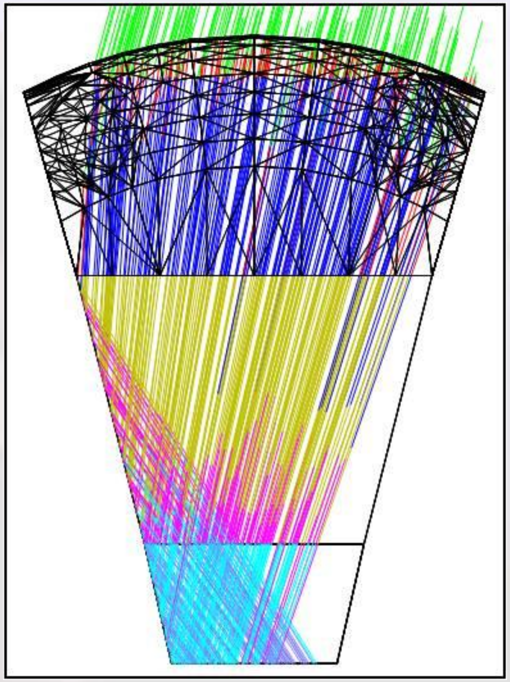


Design Features



Dichroic surface:

- Circular Zernike Polynomials
- Front and back surface illumination
- Specific regions optimized for each reflection
- Unique curvature aids in concentration

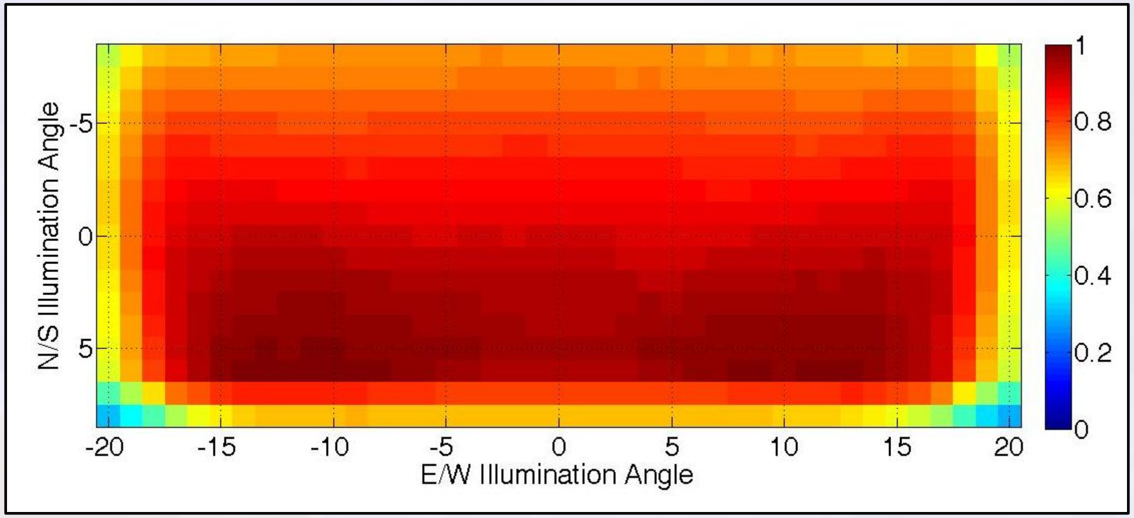


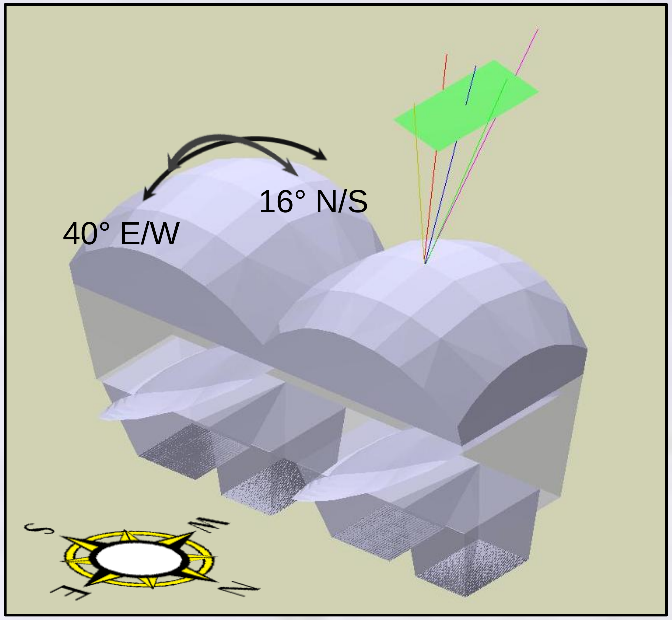
Reflecting Sidewalls:

- TIR cone confines wide angles
- All planar surfaces
- Exit tapers limit angular extent of output rays

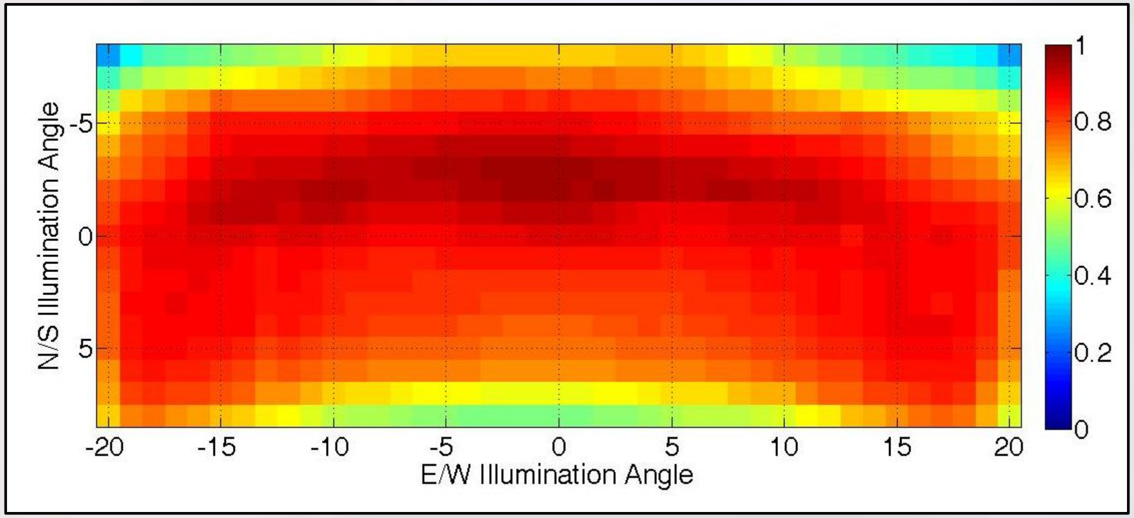
Angular Performance

Transmission Path: 87% Average Collection





Reflection Path: 84% Average Collection

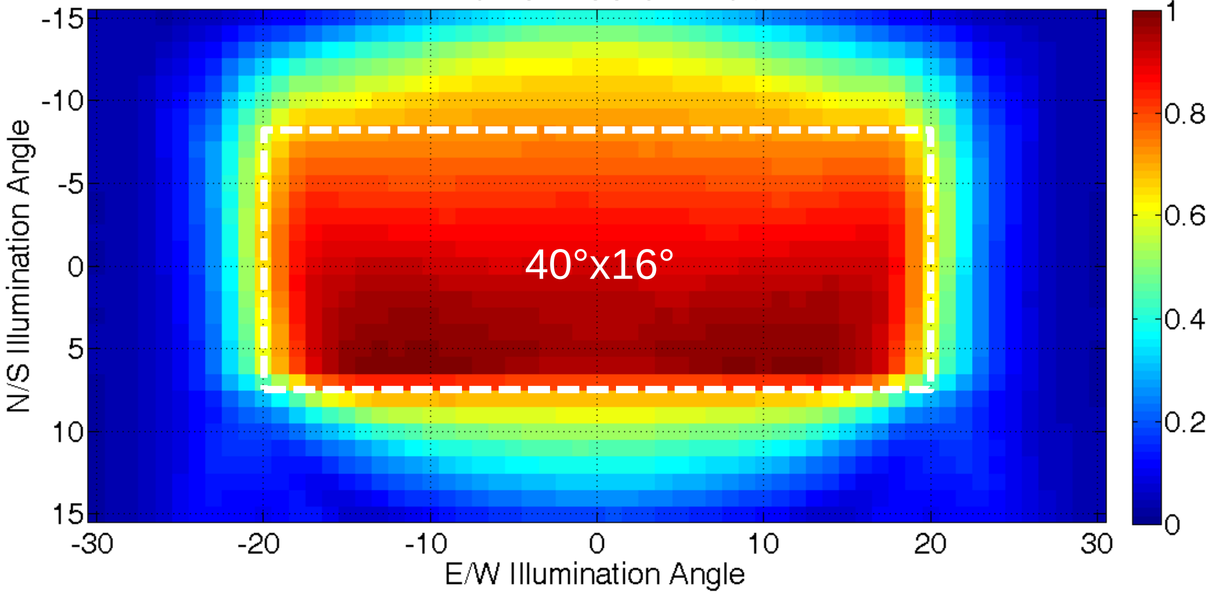


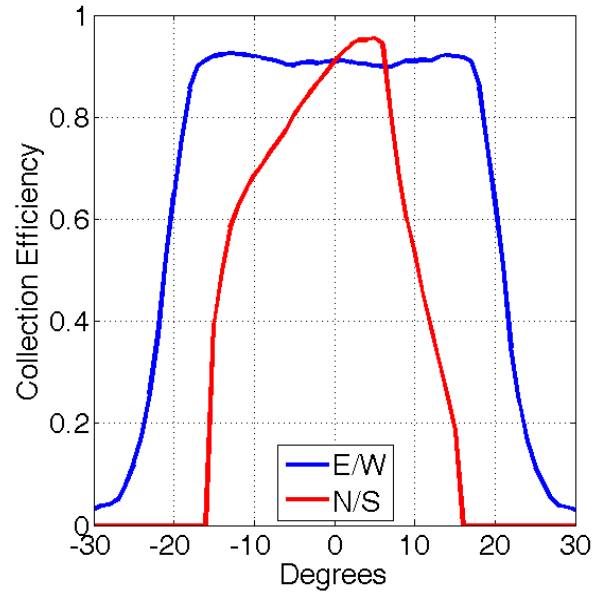
- 14° Off-axis illumination
- Transmission:
  - 100% Peak, 87% Average
- Reflection:
  - 96% Peak, 84% Average

Values do not include reflection/absorption losses

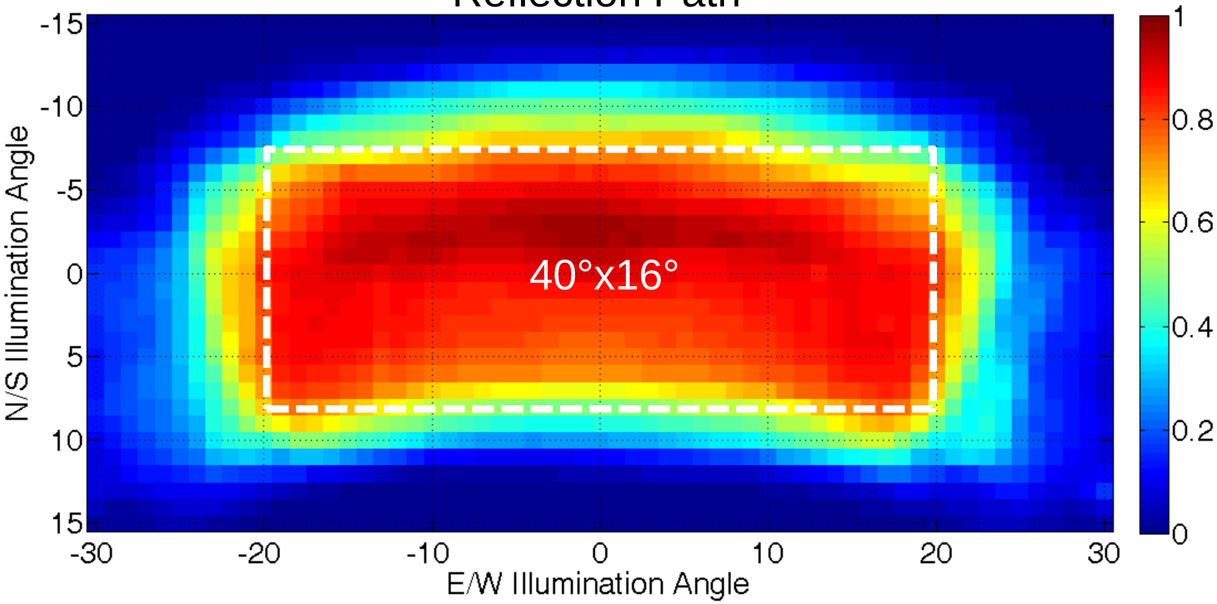
Expanded Angular Performance

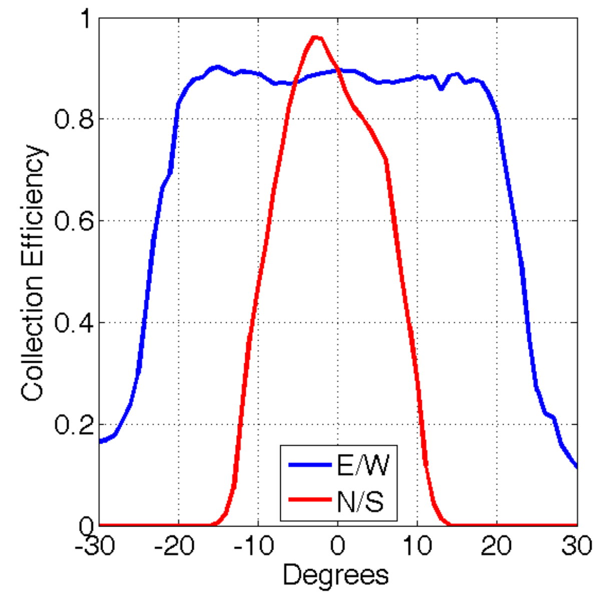
Transmission Path





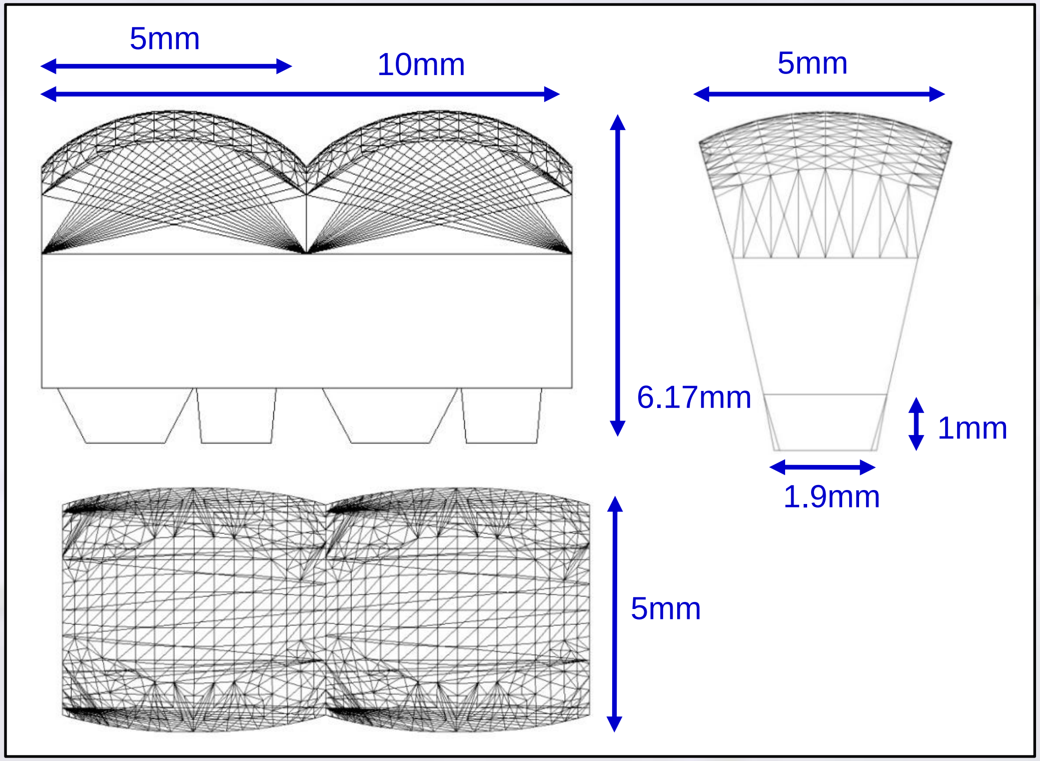
Reflection Path





Dimensions and Performance

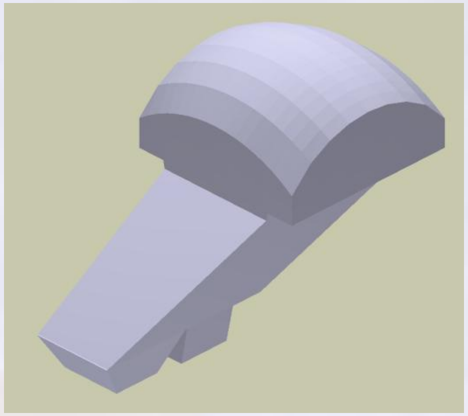
- Simulate using UV-transparent acrylic (n=1.491)
  - **Include material absorption**
  - Dichroic modeled as 'ideal' reflector
- Optical Efficiency:
  - **Transmission path: 82%**
    - 5% reduction in power collection
  - **Reflection path: 76%**
    - 8% reduction in power collection
- High-index materials may shorten optical track



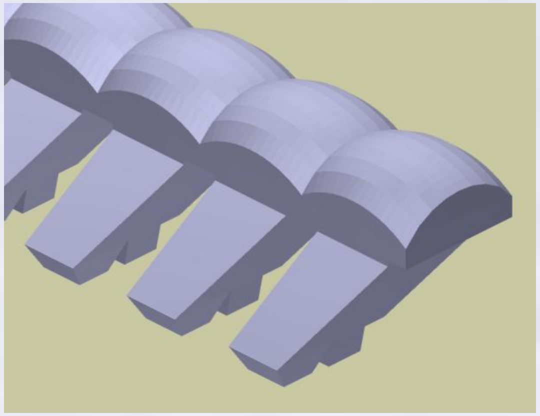
Entire optic can be scaled to any dimension

Potential for Manufacture

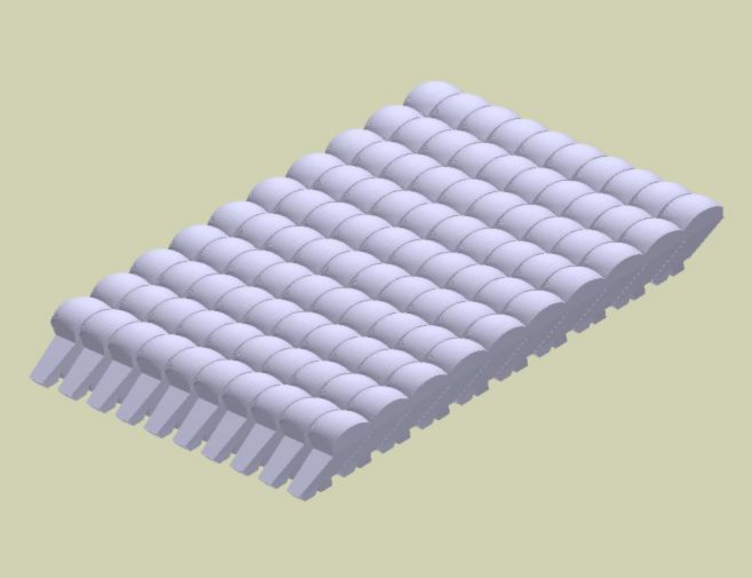
Diamond-Turned Master



Molded 1D Array



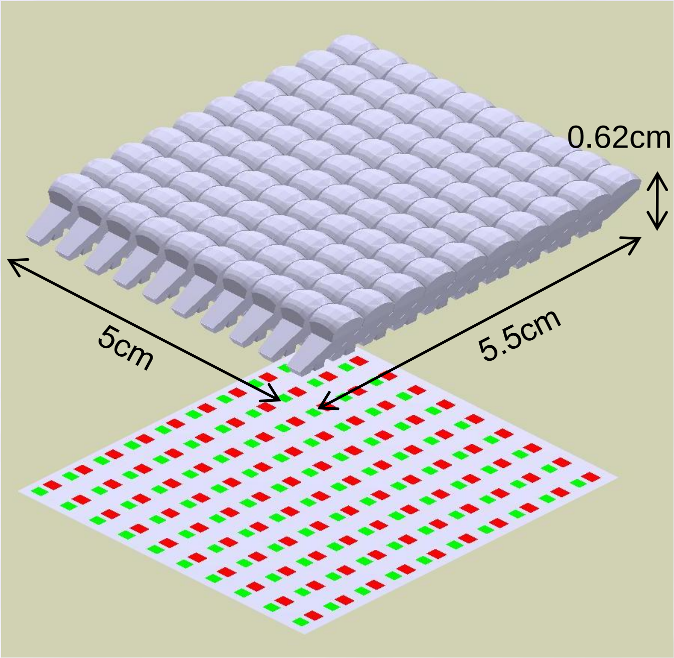
1D arrays connect into 2D collector

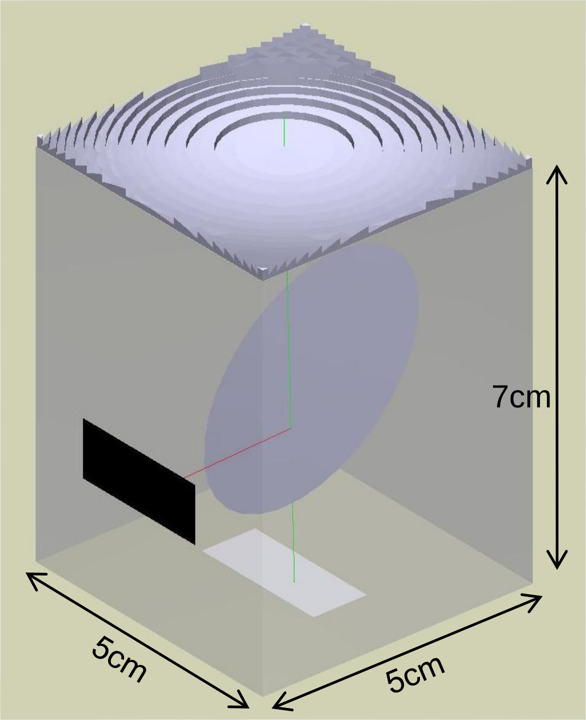


- Micro-optic diamond-turned master
  - Aspheric lens and Zernike reflector
- Replicate into 1-dimensional array
  - Glass or plastic molding technologies
- Apply AR and dichroic coatings
  - All other reflections are TIR
- Assemble into 2-dimensional arrays
  - Index-matching epoxy

Optical Volume

- 25cm^2 collection area
  - Same PV cell areas
- Total Volume:
  - **Micro-optic: 17cm^3**
  - **F/1.4 Fresnel: 175cm^3**
- Scale to cover large areas
  - Simple assembly
- Thin form-factor for portable power generation





- ***Spectral splitting increases photovoltaic response***
- ***Double-reflection improves packaging & thermal management***
- ***Single micro-optic designed for array manufacture***
- ***Thin 'sheet' geometry reduces optical volume***
- ***Next Step: Prototyping (permitting funding)***
- ***First of new 'sheet' concentrator designs***

Thank You

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