Concentrating Solar Power: Progress and Trends

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UCSD

Triton SPIE/OSA
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Photo: Kevin Walsh, OLR

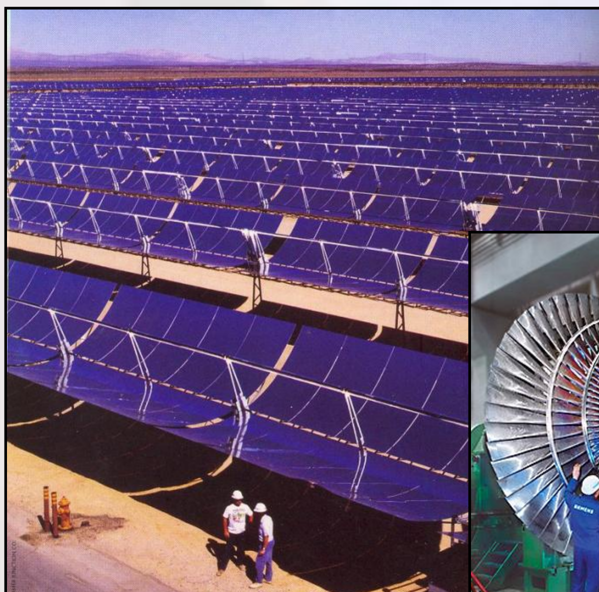
Outline

- **Introduction to Solar Power**
  - *Solar Thermal Power Generation*
  - *Photoelectric Effect and CPV*
- **Position of the Sun**
  - *Sun-Earth Geometry*
  - *Solar Tracking*
- **Concentrator Design**
  - *Nonimaging Optics*
  - *Low and High Concentration Examples*
- **CPV Trends and Research**
  - *Multijunction Solar Cell Efficiency*
  - *Test Installations*
  - *Research and Opportunities*

Thermal Vs. Photovoltaics

Concentrating Solar Power (CSP)

- Use sun's heat energy
  - Steam generation
  - Electricity via turbines
- Applications:
  - Utility grid power plants
  - Solar heating/lighting
  - Solar cooking



www.solaq.eu

Siemens Power Generation

Concentrating Photovoltaics (CPV)

- Use light photons
  - Photoelectric effect
  - Direct conversion to electricity
- Applications:
  - Utility grid power plants
  - Off-grid power generation
  - Small-scale power

www.slashphone.com

Batir Development

Concentrated Solar Power (CSP)

- Concentrate thermal radiation to generate steam
- Thermal storage medium
  - Water, iron ore, molten salt, liquid metal (sodium)
- Steam generators, turbines, sterling engines
  - ~12% solar-to-electric conversion efficiency

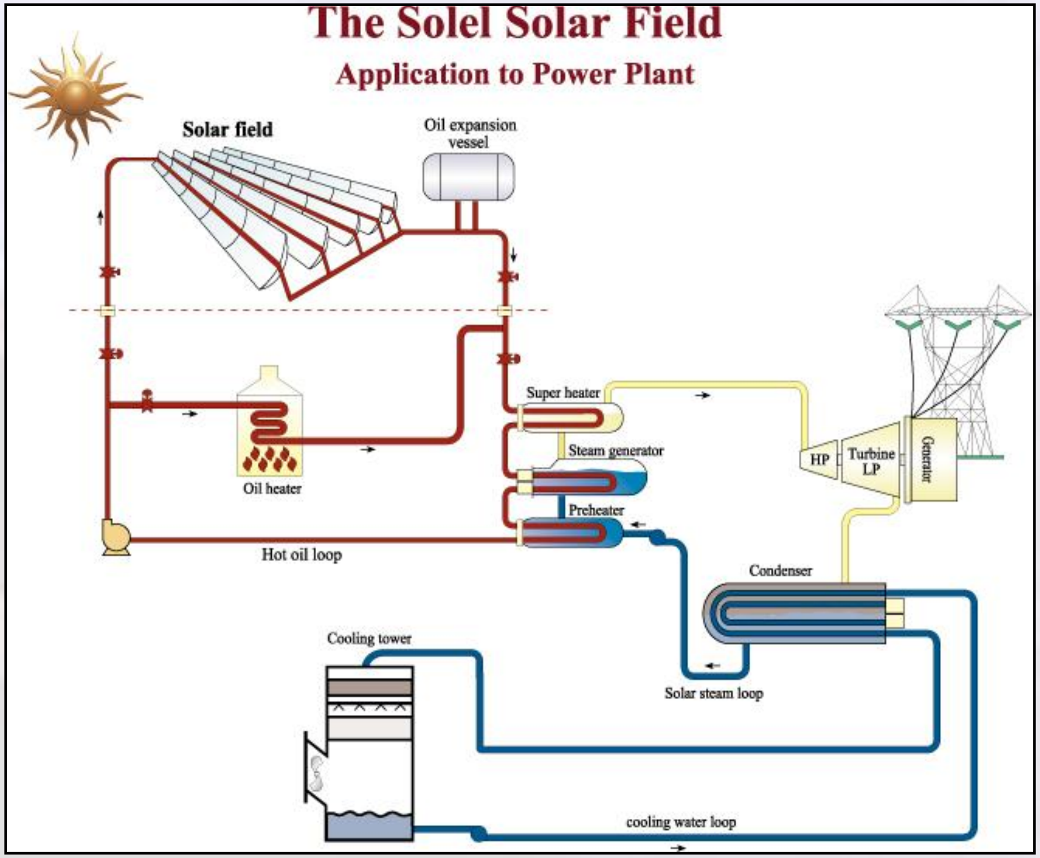
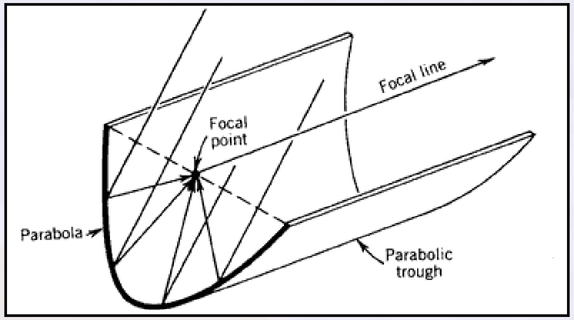


Diagram courtesy of: Solel Power Generation

CSP Technologies

- Parabolic Dish Installations
  - 1-dimensional line focus track East-West
  - 9 plants in California generating 354 MW



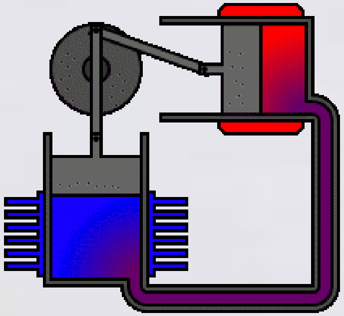
Powerfromthesun.net

Schott Solar

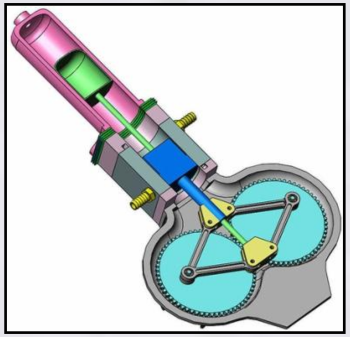
Solel Power Generation

Kennyjacob.net

- Sterling Engine
  - Convert heat directly into mechanical energy
  - Compress/expand gas within cylinders



By Richard Wheeler 2007



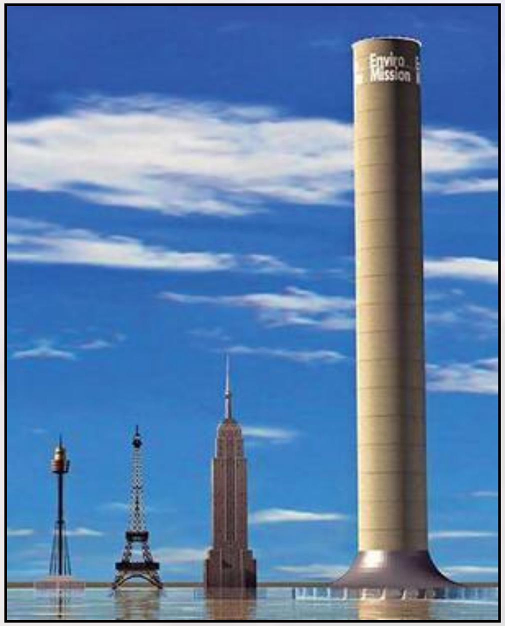
Nationmaster.com/sterling-engine

CSP Technologies

- Solar Tower
  - Heliostats reflect energy to central tower
  - Steam generation
  - Solar 2: Barstow, CA
  - PS10: Seville, Spain

Energy.ca.gov

Energiaspain.com

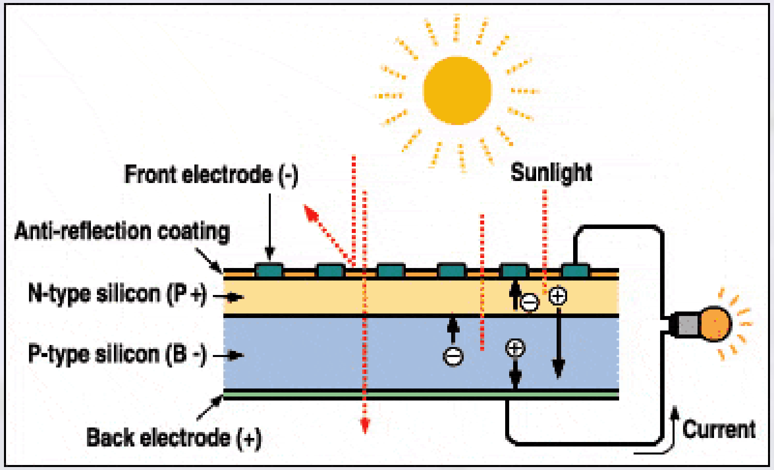


- Solar Updraft Tower *(concept only)*
  - Heat air to induce convection
  - Moving air drives turbines

Images courtesy of Enviromission.com

Photovolatic Power Generation

- *Photoelectric Effect (1902):*
  - *Photon energy is transferred to semiconductor lattice*
  - *Electrons excited into conduction band*
  - *Charge carriers move via drift (static E-field) or diffusion*
- Photons must span the material bandgap
  - Lower energy photons pass through cell
  - Excess energy dissipated as heat
- P-N junction creates E-field to move carriers to cell contacts
- Current generating device
  - >120mA at 1V



Girasolar.com.tr

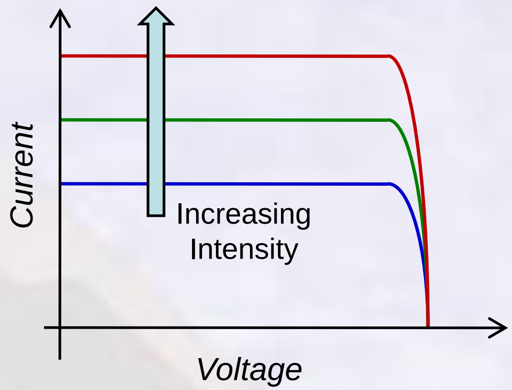
Day4 Energy

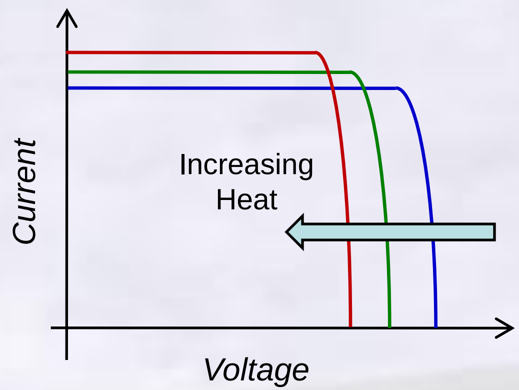
Energyoptions.biz

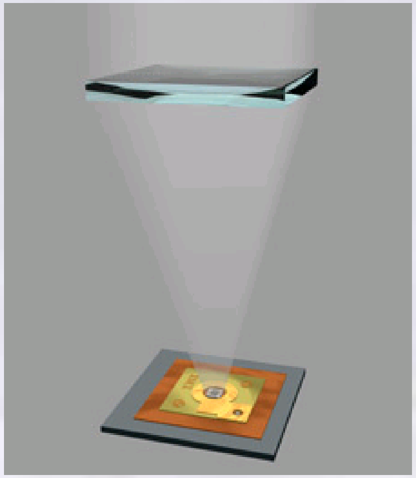
Cells are mounted in series to increase voltage and parallel to add current. Modules consist of 24-36 cells outputting upwards of 200W.

CPV Benefits

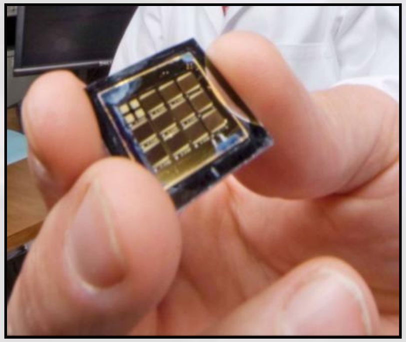
- Increased light intensity:
  - Increases photocurrent (additional photons)
  - Reduces open-circuit voltage (increased heat)
- Negligible real-world efficiency gain







Reuk.com.uk



Colorado Energy News

- CPV motivation: <u>reduce system cost</u>
- Replace expensive semiconductors with inexpensive lenses/mirrors
- Incorporate small-area, high-efficiency solar cells

Photovoltaic Technologies

UCSD Photonics

Type I: Crystalline Silicon

Photo courtesy of Kyocera

15-18% Efficiency

- Mono- or Polycrystalline
  - Crystalline Lattice
  - Indirect Bandgap
  - >100µm Thickness
- Direct and diffuse sunlight
- Suppliers:
  - Kyocera
  - Sharp
  - Mitsubishi

Type II: Thin Film

Photo courtesy of Global Solar

6-12% Efficiency

- 10µm Active Layer
  - Amorphous Silicon
  - CdTe, CdS, CIGS
  - Direct Bandgap
- Rigid or flexible substrate
- Suppliers:
  - First Solar
  - NanoSolar
  - Global Solar

Type III: Multijunction

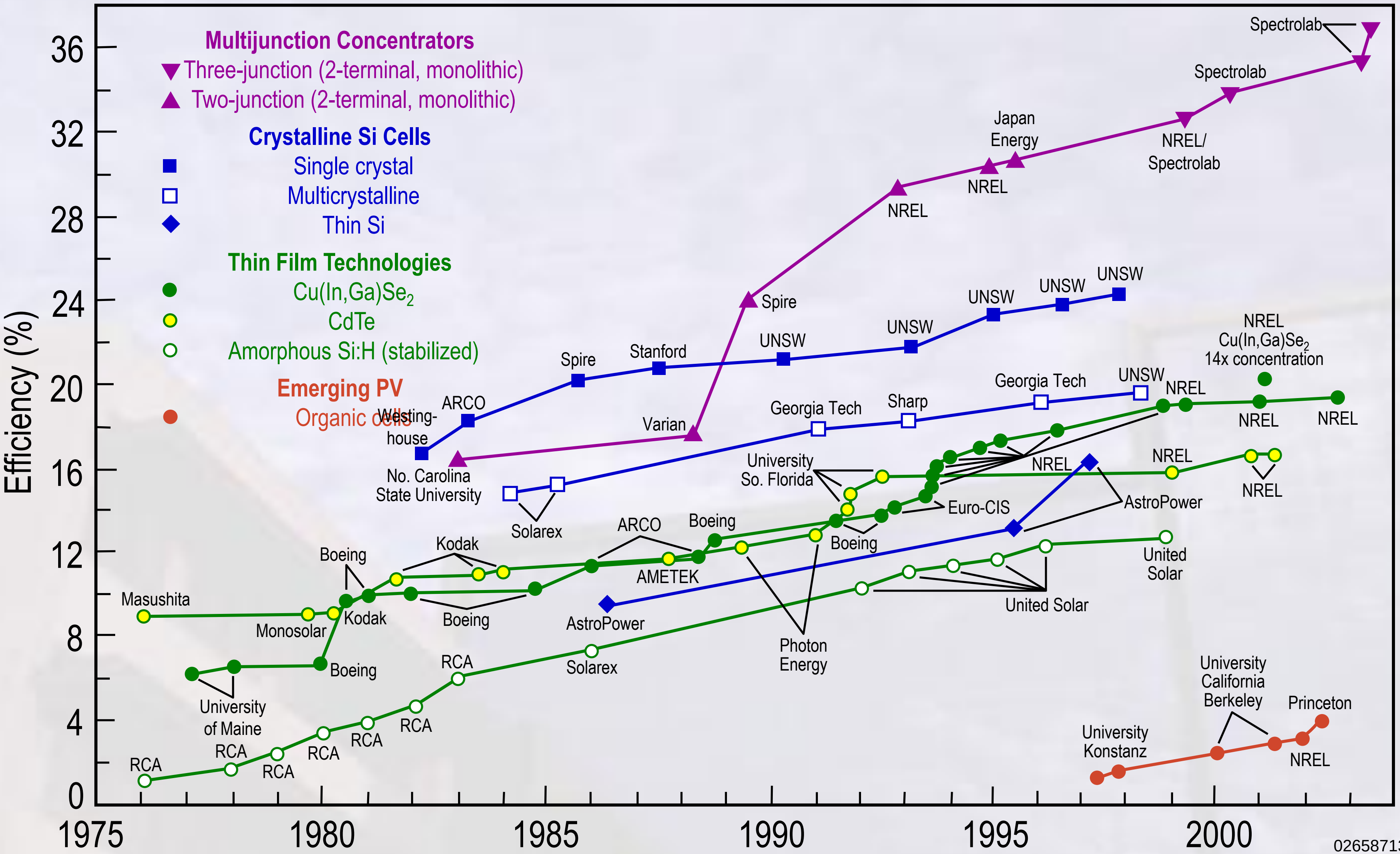
Photo courtesy of Spectrolab

>40% Efficiency

- 2- or more Bandgaps
  - Incresed spectral response
  - GaInP – GaInAs – Ge
- High material/fabrication costs
  - Small cell area
  - Flux Concentration
- Suppliers:
  - Spectrolab
  - Emcore

Best Research-Cell Efficiencies

UCSD Photonics



Source: Larry Kazmerski, Director of NREL

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UCSD Photonics

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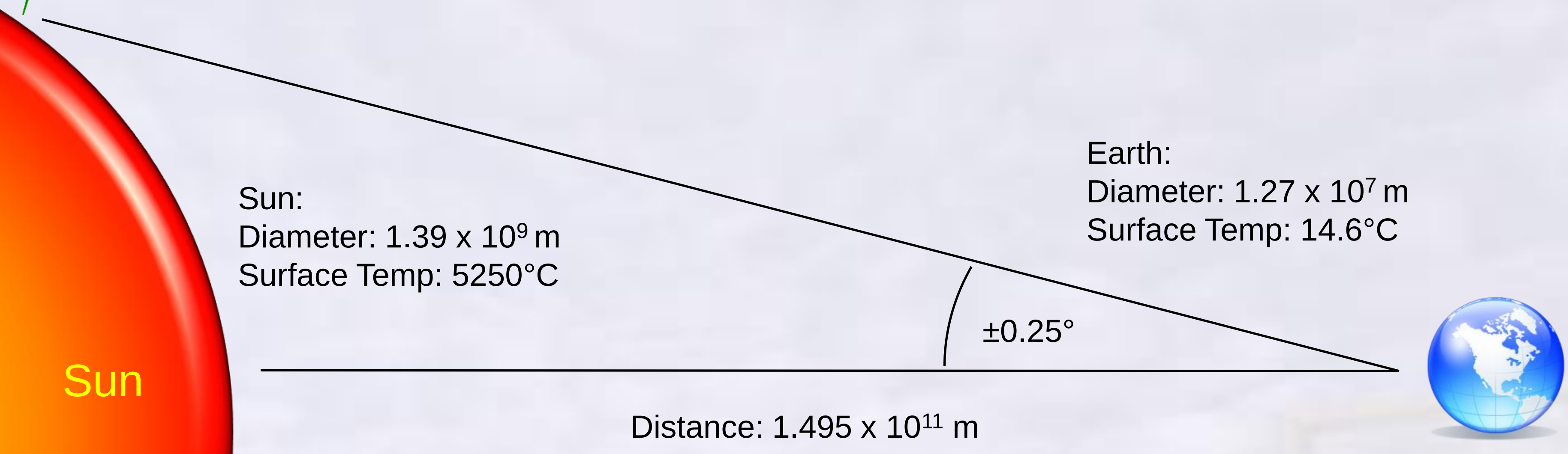
Sun-Earth Geometry



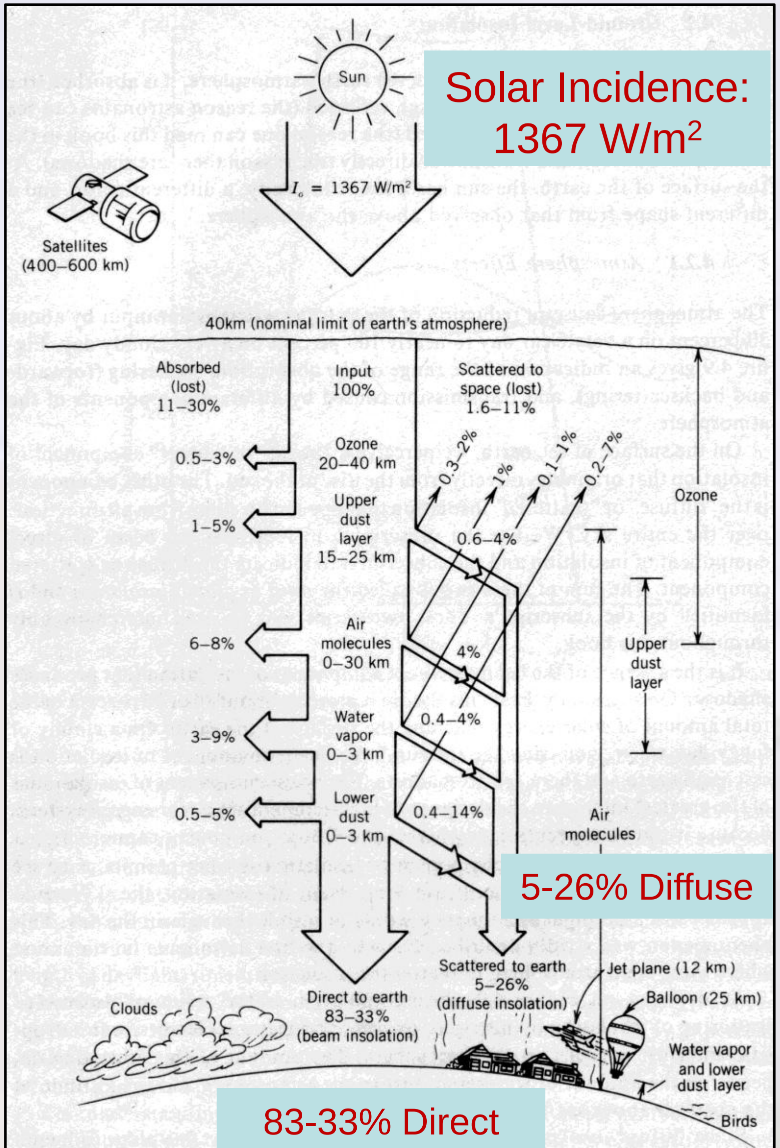
- Theoretical Limit of Concentration
- *2* *2nd Law of Thermodynamics: Heat generally cannot spontaneously flow from a material at lower temperature to a material at higher temperature*
  - *Receiver cannot exceed the temperature of the sun*

$$C_{2D} = \frac{Input \quad Area}{Cell \quad Area} = \frac{1}{\sin \ \theta_{sun}} = 213 \qquad C_{3D} = \frac{1}{\sin^{2} \ \theta_{sun}} = 45,300$$

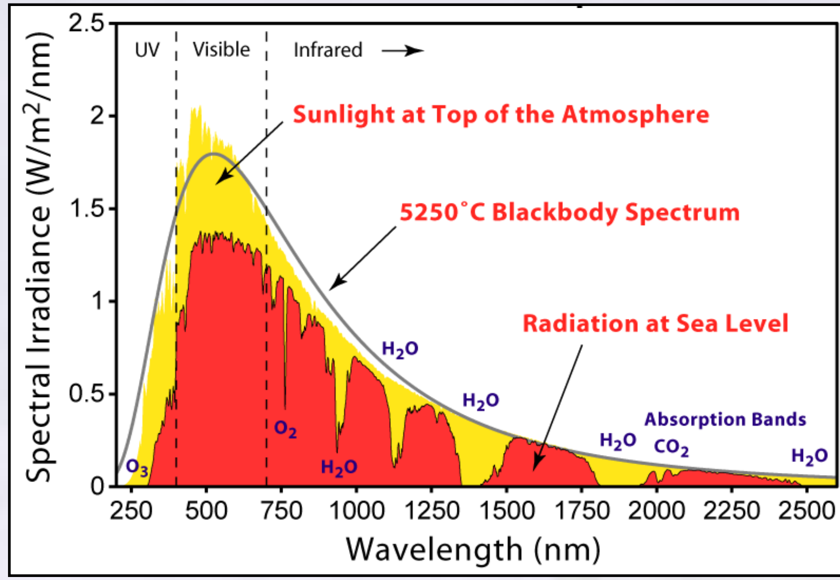
Note: Concentration ratio may be increased by placing the receiver within a dielectric

Solar Radiation

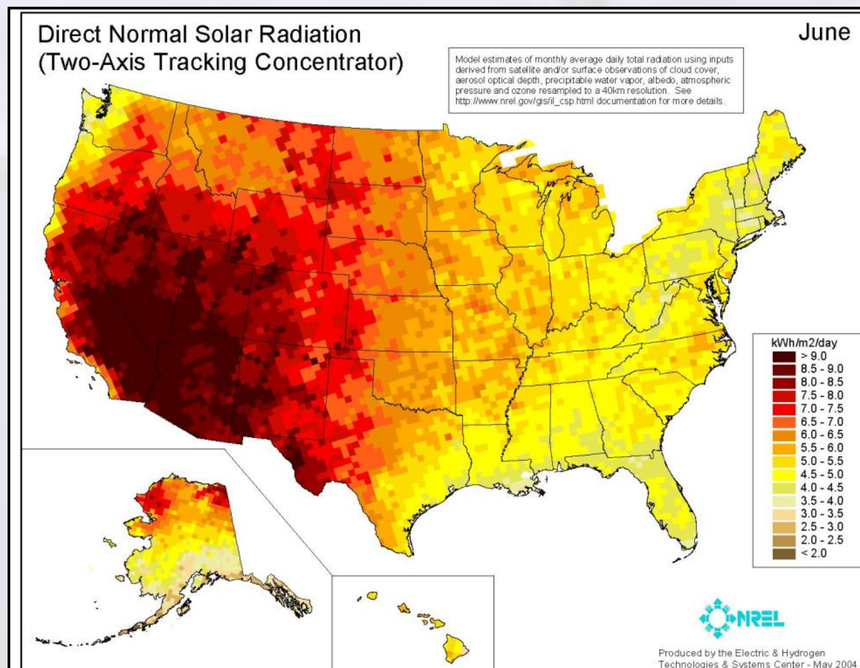
UCSD Photonics



W. Stine, Solar Energy Fundamentals, Wiley (1985)

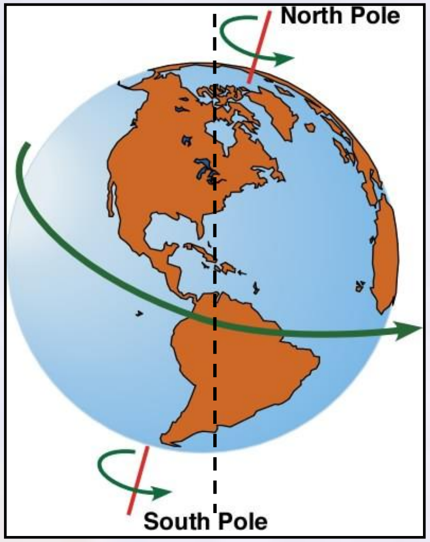


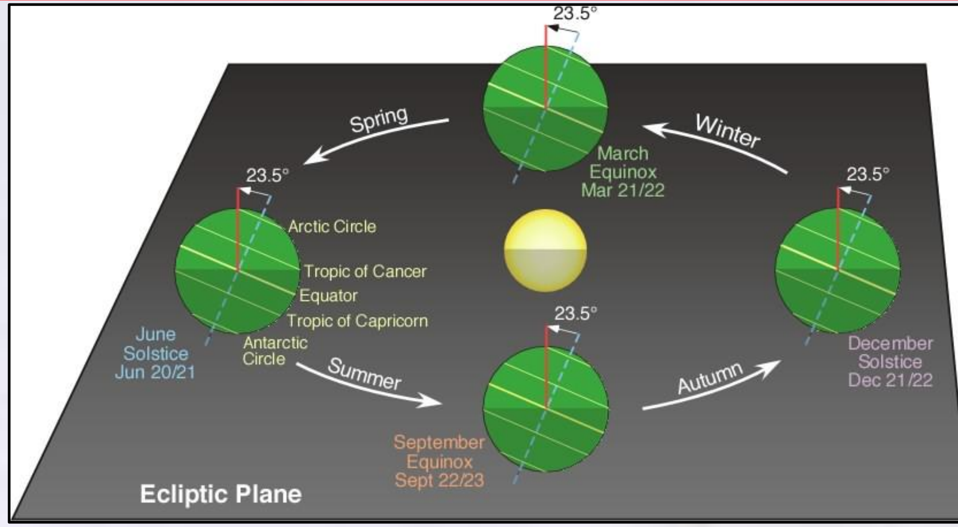
Globalwarmingart.com

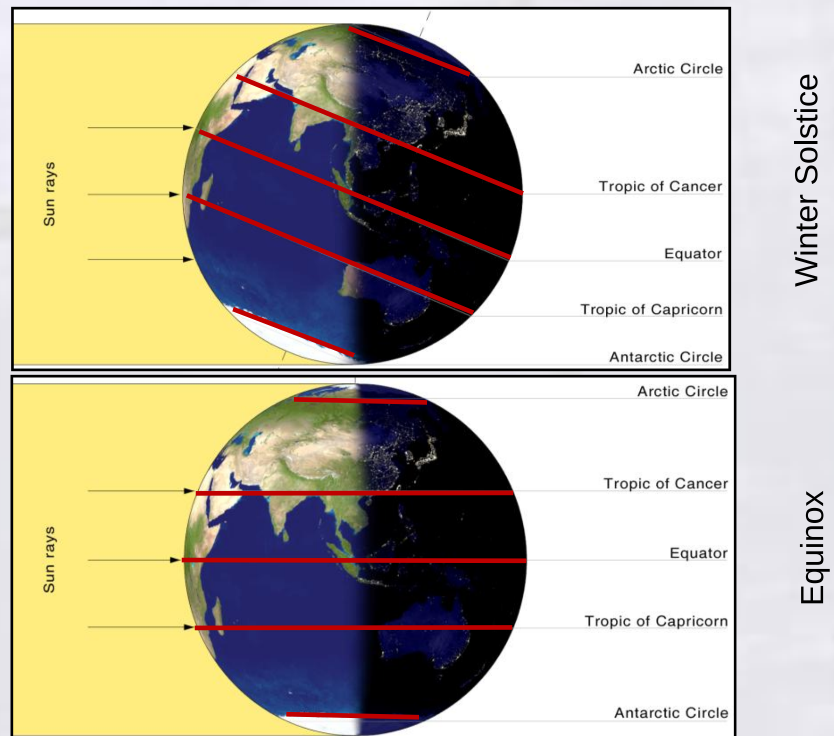


NREL.gov/gis/solar.html

Earth Motion





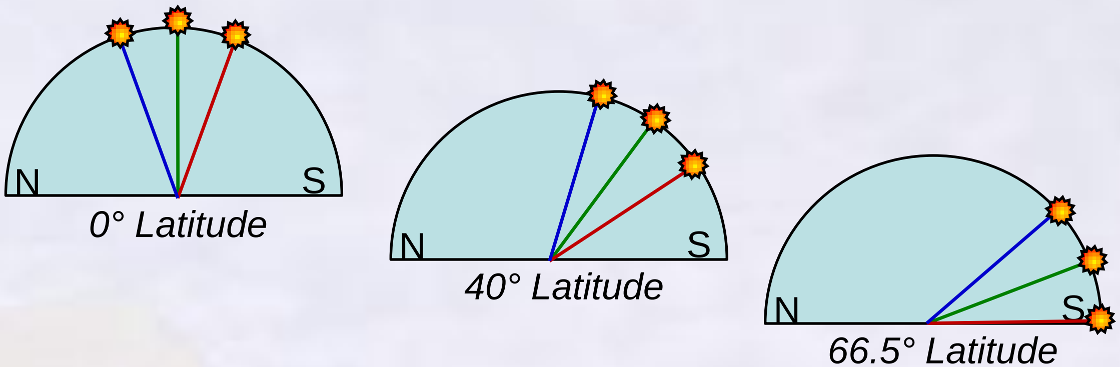


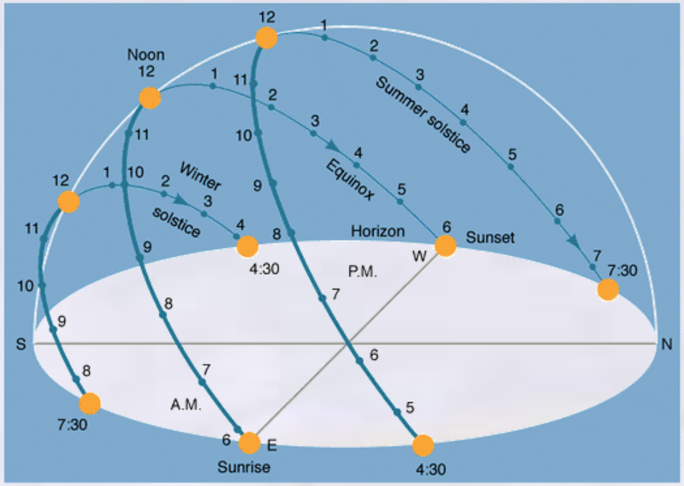
- 23.5° Declination angle
  - Accounts for seasonal variations
- Solstice: most oriented toward sun
  - Longest/Shortest days of the year
- Equinox: no tilt towards sun
  - Exactly 12hrs day/night
- Arctic Circle marks latitude (66.5°) for polar day/night (24 hrs)

Images courtesy of physicalgeometry.net

Solar Elevation

- Latitude determines solar elevation
- 47° seasonal elevation variation (±23.5°)

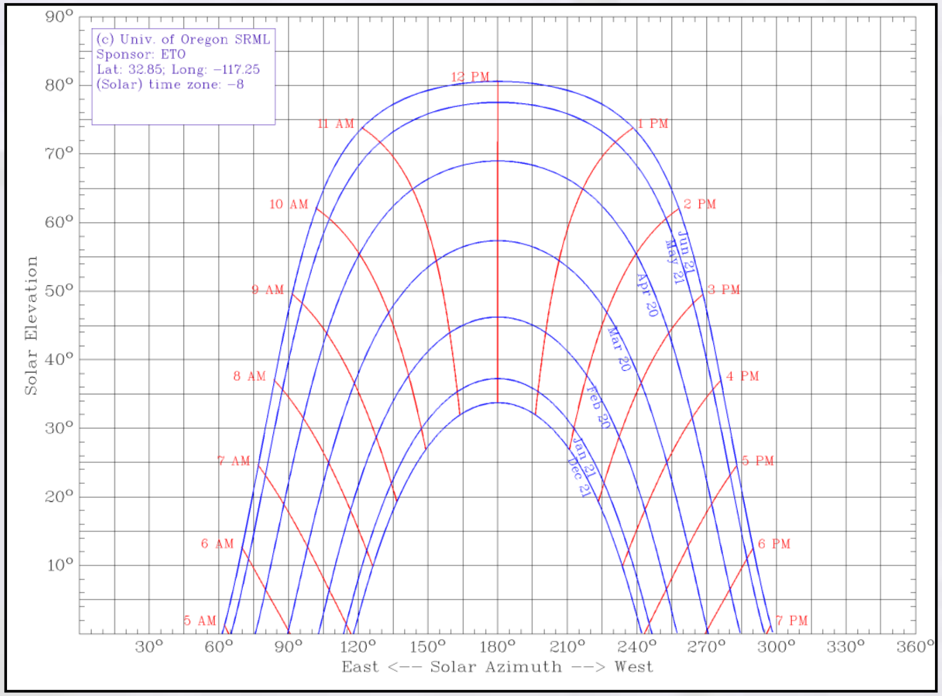




Sun Chart:

- Solar Azimuth vs Elevation
- Plots daily and seasonal variation
- Defines angles needed for tracking

Always orient fixed solar panels at:
(90° minus installation Latitude)



Sun Chart courtesy of University of Oregon, Solar Radiation Monitoring Lab

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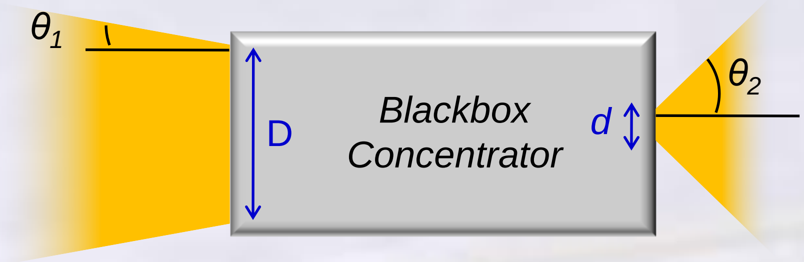
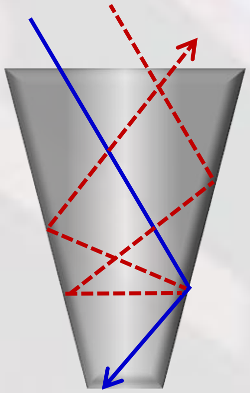
- Étendue: *product of entrance pupil and acceptance angle remains constant throughout all optical systems*
  - $D\theta_1 = d\theta_2$

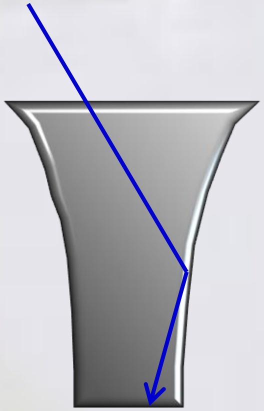


- Path length may not be maintained
- Minimum receiver size when $\theta_2 = 90^o$
  - aberration free *f/0.5* lens

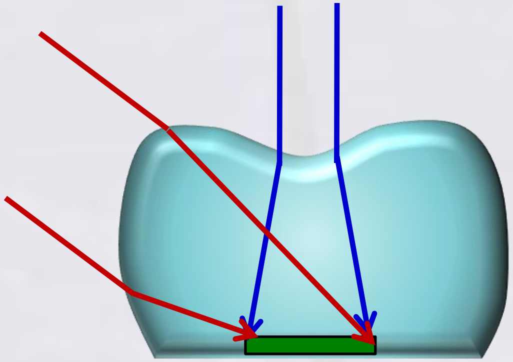
Cone Concentrator



Hyperbolic Trumpet



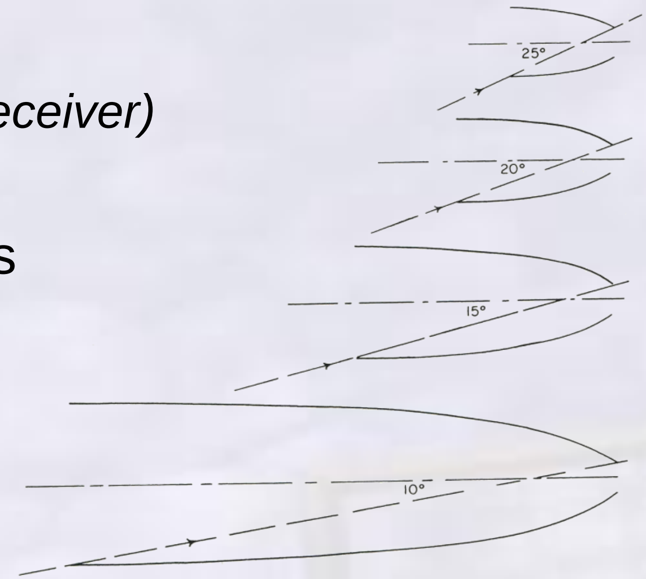
Free-form Optic

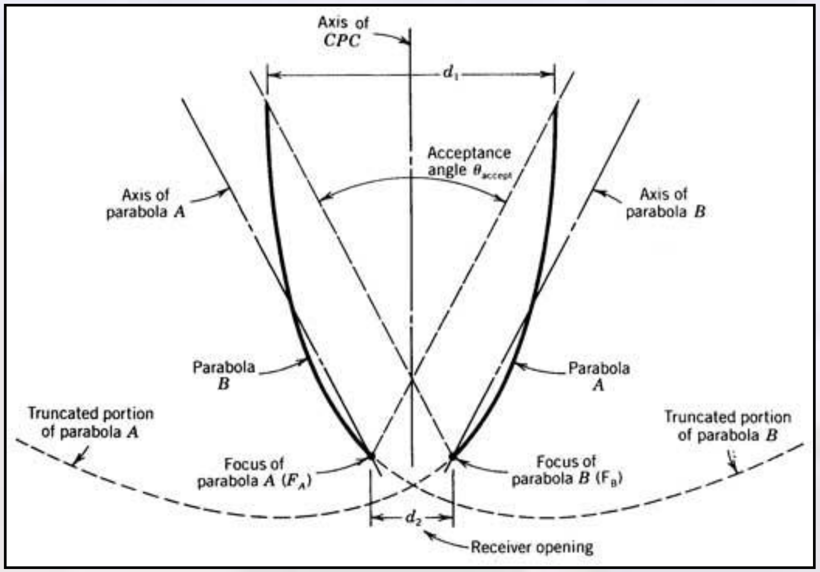


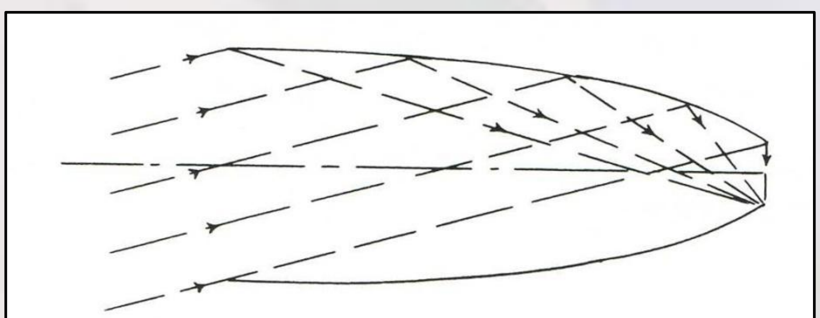
CPC: Compound Parabolic Concentrator

UCSD Photonics

- Achieves thermodynamic limit in 2D
- Very large aspect-ratio *(52m length for 1mm receiver)*
  - <5x concentration in practical installations
- Commonly used as secondary concentrators







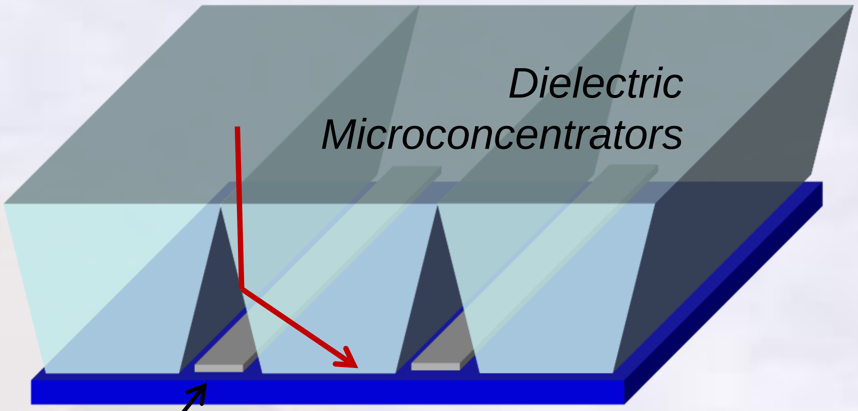
Lasergold.com

Winston, Minano & Benitez, Nonimaging Optics , Elsevier (2005)

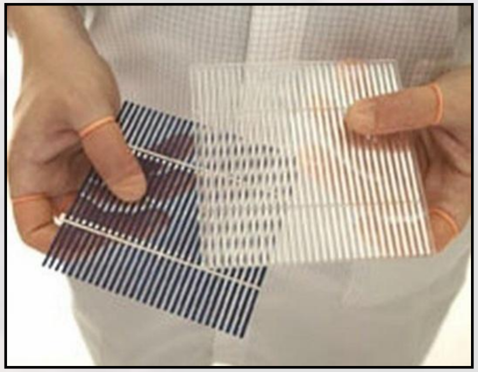
Paradigma.de

Fold Mirrors

- Inexpensive, planar reflective structures
- Minimize gap losses between cells/modules
- Low Concentration *(1.5-3x)*



www.zytech.es



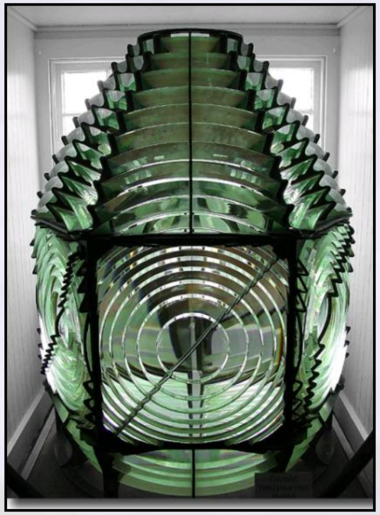
www.solaria.com

- *Solaria Corp. Fremont CA*
- *Zytech Solar, La Muela Spain*
- *Ben-Gurion University of the Negev, Israel*

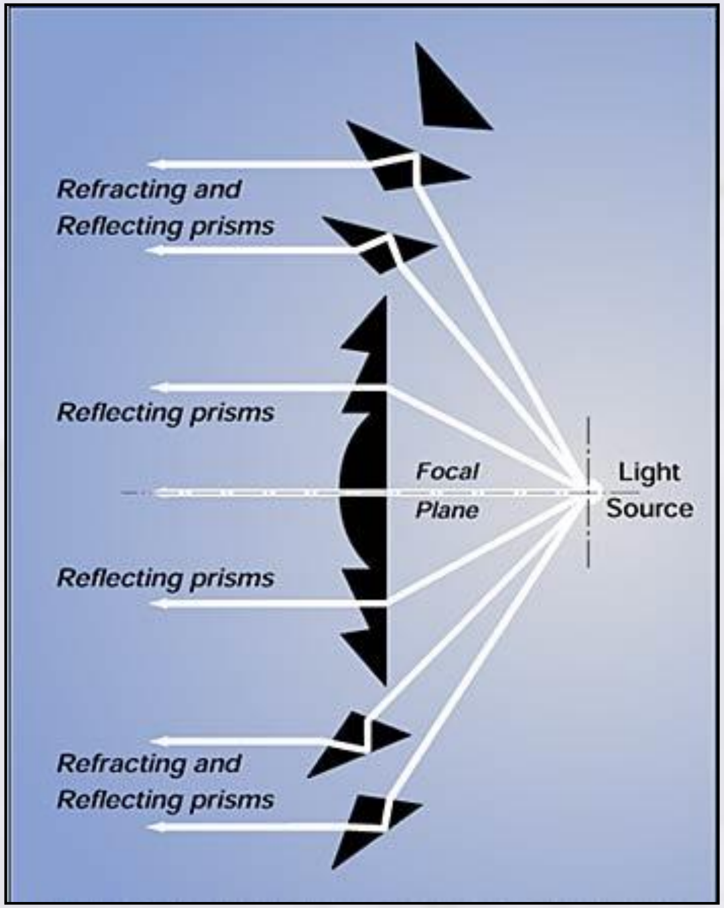
Nonimaging Fresnel Lens

UCSD Photonics

- Refractive facets in tandem with catadioptric prisms
  - Nonimaging due to unequal path lengths
  - Similar performance to reflective lenses without costly metallic coatings
- >1000x concentration
- Achieves very low *f/#*
  - Scattering losses
  - Prism blocking
  - Chromatic dispersion

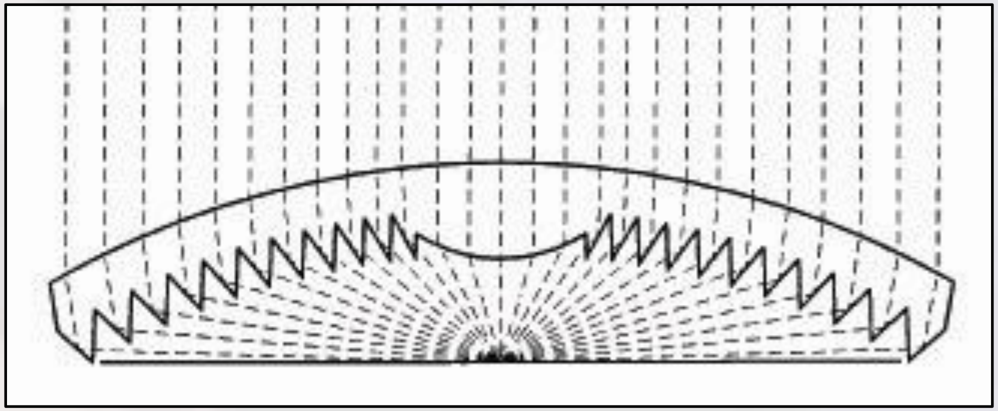


www.pbase.com



springpointlight.org

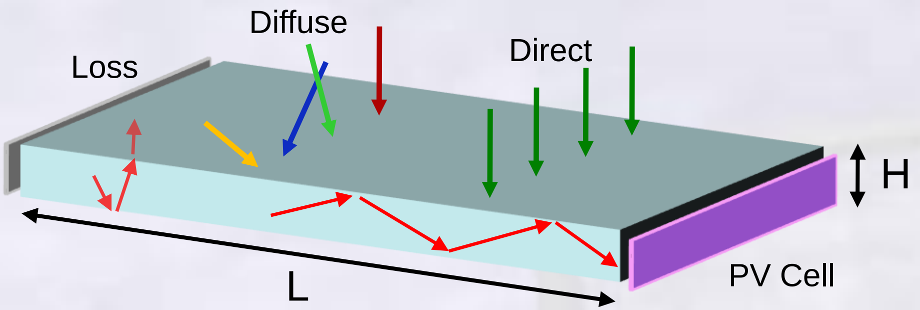
Nonimaging Fresnel Concentrator

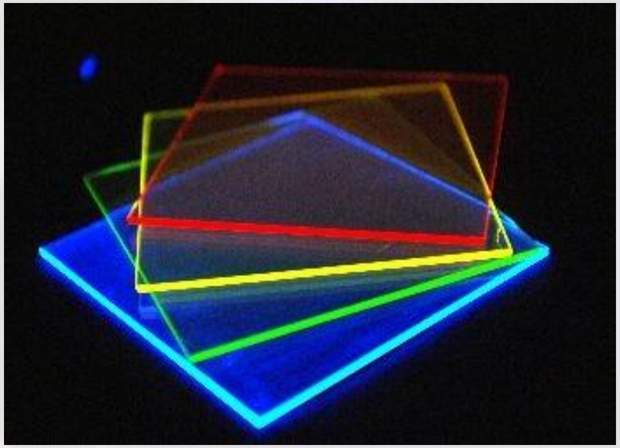


Fluorescent Solar Concentrator

UCSD Photonics

- Absorb solar radiation and reemit at longer wavelengths (Stoke's Shift)
- Embed guiding high-index slab with absorption medium
  - Fluorescent dye(s)
  - Quantum dots
- Collect guided light at slab edge
- Concentration = Length / Height
  - Energy loss from wavelength shift
  - Probability of reabsorption
  - Quantum efficiency
  - Loss due to omnidirectional reemission





www.renewableenergyworld.com

www.beseenonabike.com

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Multijunction Solar Cells

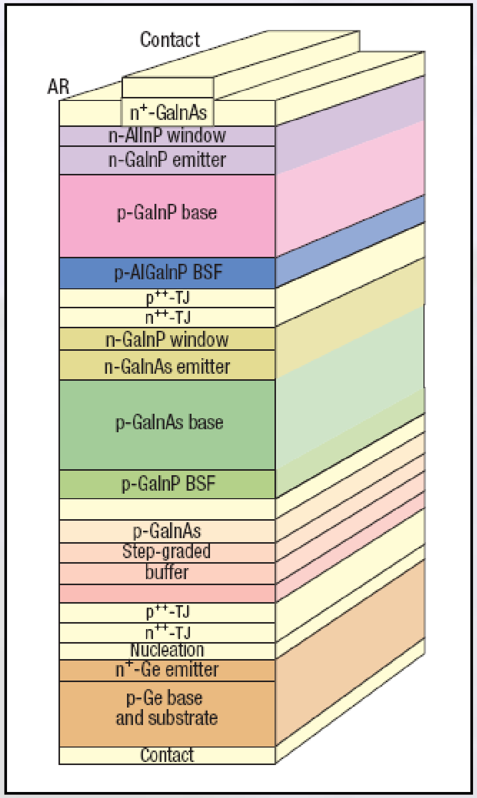
UCSD Photonics

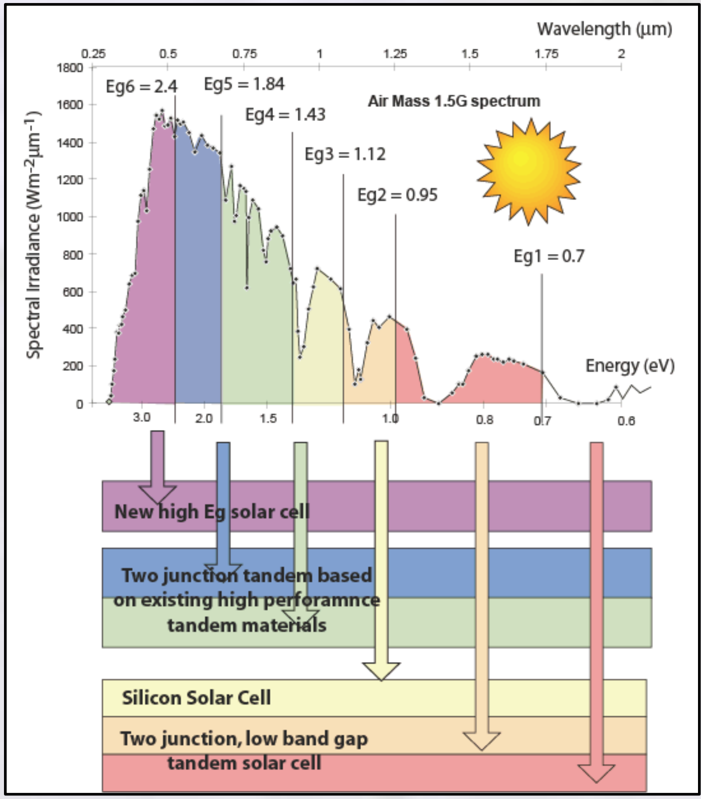
- Increase number of discrete bandgaps
  - Improves spectral response and efficiency
  - 4 and 6 junction solar cell research
- Material lattice mismatch – defects
  - Metamorphic PV cells provide buffer layers
- Research for high-energy UV photocells
  - AlGaInP (2.2eV)

www.nasa.gov

Spectrolab A Boeing Company

EMCORE





Barnett, A. et al., "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

R. King, "Multijunction Cells: Record Breakers," Nature Photonics, Vol 2, 284-286 (2008).

Solar Efficiency Records

- **40.7% @ 240x**: Spectrolab Inc. lattice-matched triple-junction (2006)
- **41.1% @ 454x**: Fraunhofer ISE metamorphic triple-junction (2009)
- Solar cell flash test:
  - Impulse from flash lamp (variable "concentration")
  - Does not account for heat or real concentrating optics
    - **4% efficiency loss per 10ºC**
    - **85% typical optical efficiency of concentrator**

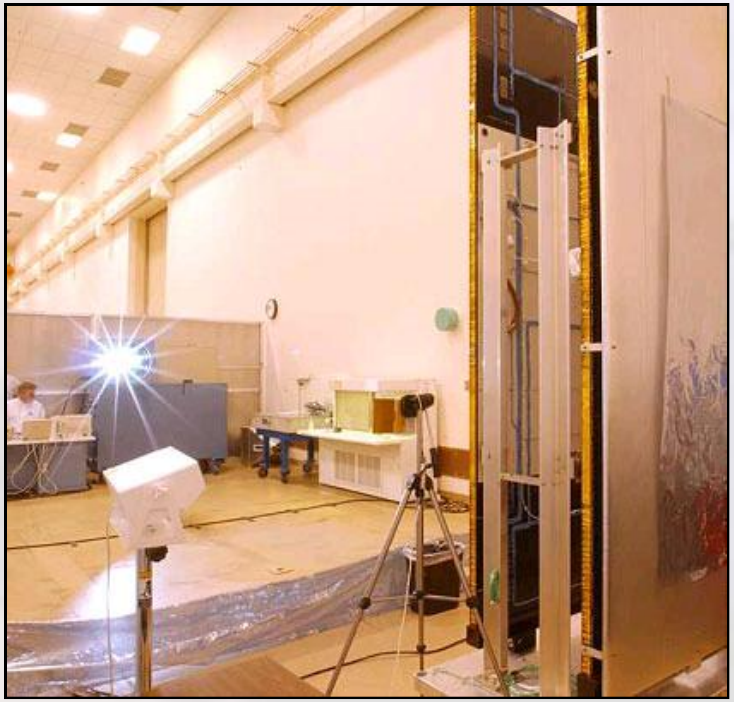
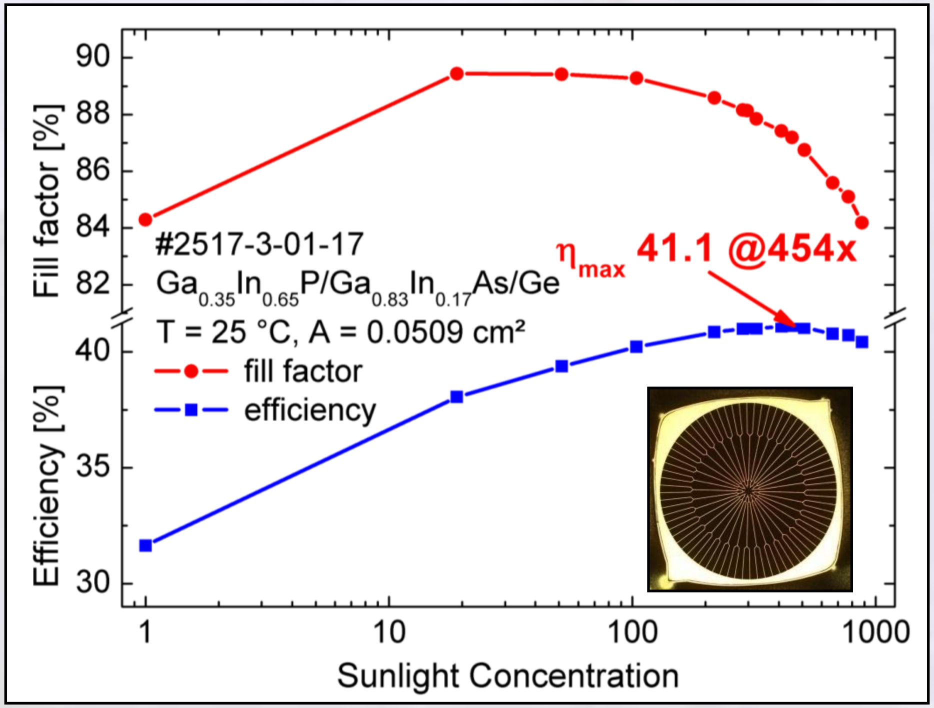
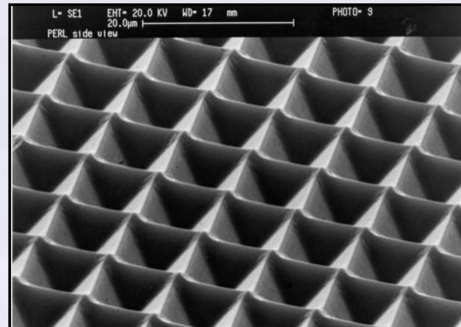


Image courtesy of NASA

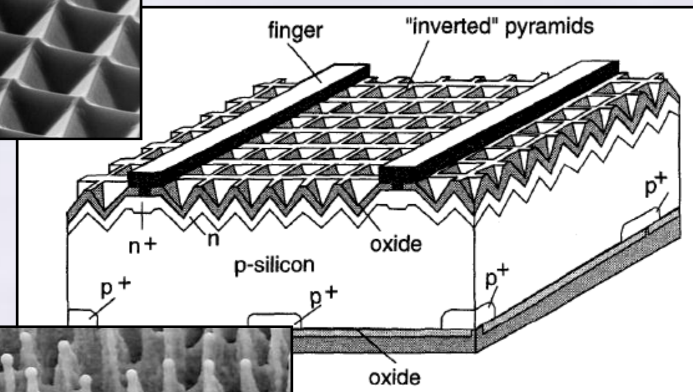


Fraunhofer Institute for Solar Energy Systems

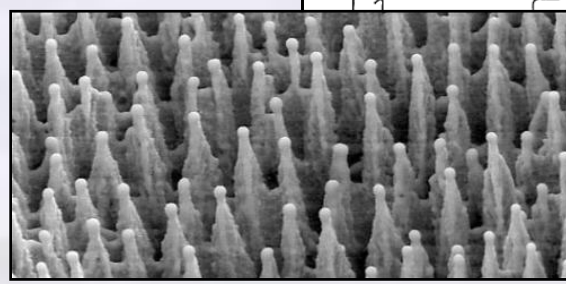
PV Cell Enhancement

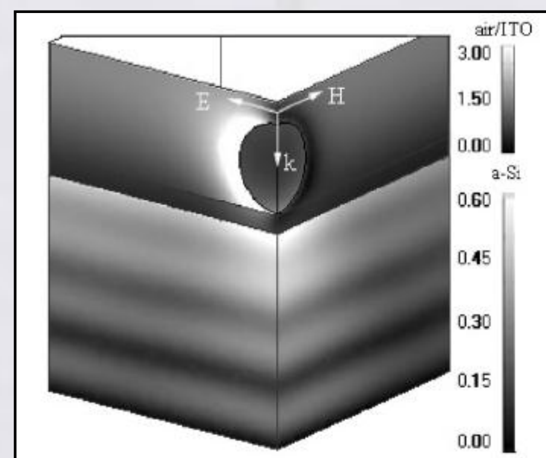


- Increase photon absorption
  - Extend photon lifetime



- Inverted-pyramid
  - Anisotropic chemical etch
- Black Silicon
  - Pulsed-laser etching
- Surface plasmon enhancement
  - Gold nanoparticles





Green, M.A., "High efficiency silicon solar cells," Optoelectronic and Microelectronic Materials And Devices Proceedings, 1996 Conference on , vol., no., pp.1-7, 8-11 Dec 1996

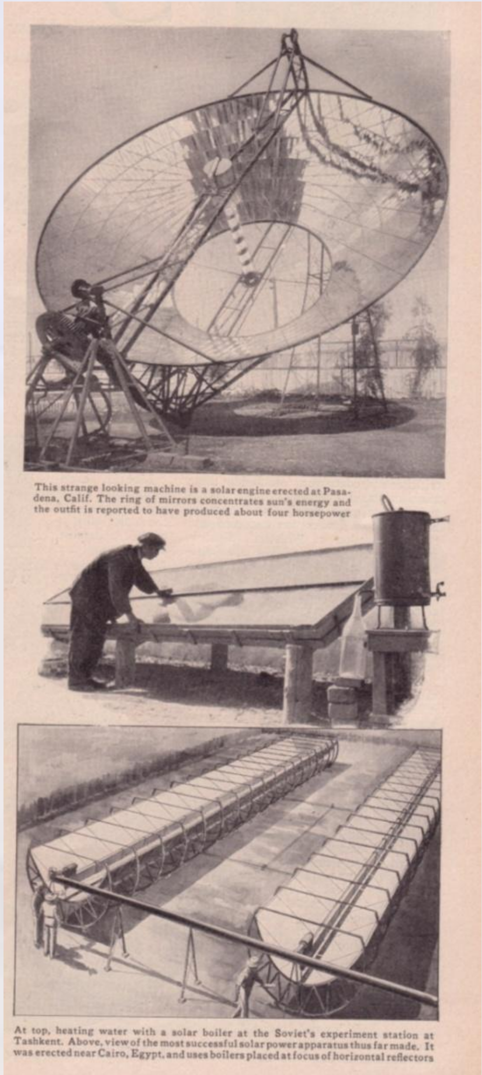
E. Mazur - SiOnyx

D. Derkacs, S. H. Lim, P. Matheu, W. Mar, and E. T. Yu, "Improved performance of amorphous silicon solar cells via scattering from surface plasmon polaritons in nearby metallic nanoparticles," Appl. Phys. Lett. 89, 093103 (2006)

80 years of Progress in Solar Concentrators

UCSD Photonics

3 types of solar-thermal concentrators featured in a 1934 issue of Popular Science Monthly



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

Tracking imagers

Fixed flat panels

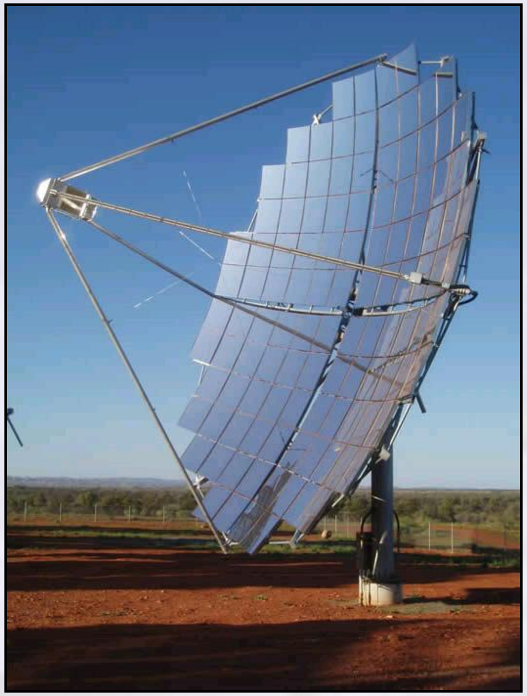
Parabolic troughs

Modern advances in photovoltaic technology prompt novel concentrator design

Solar Systems CS500

- 720kW installed since 2003
- 24% efficient silicon solar cells
- 30 parabolic dishes
  - 14m in diameter
- 500x concentration

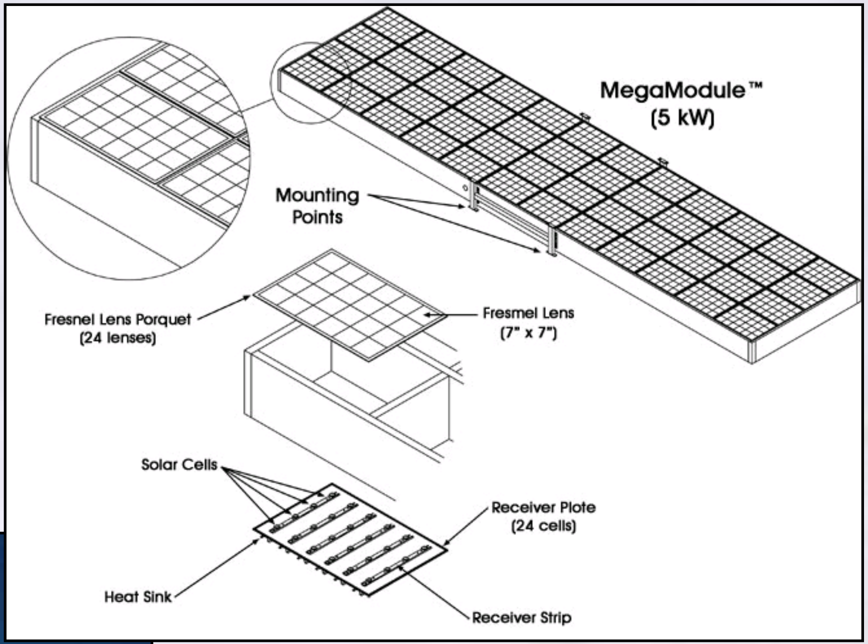
Installations:
Hermannsburg, Australia
Yuendumu , Australia
Lajamanu , Australia
Umuwa , Australia



Images courtesy of Solar Systems, Australia

Amonix APS Concentrating Module

- 570kW installed since 2000
  - 5kW "blocks" assembled together
- 3.7GW/hr produced to date
- 26.7% efficient silicon solar cells
- 500x 7"x7" acrylic fresnel lens



Installations:
Glendale, AZ
Prescott, AZ
Las Vegas, NV

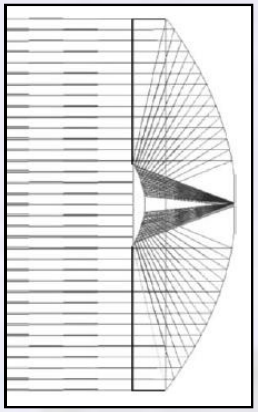
Images courtesy of Amonix

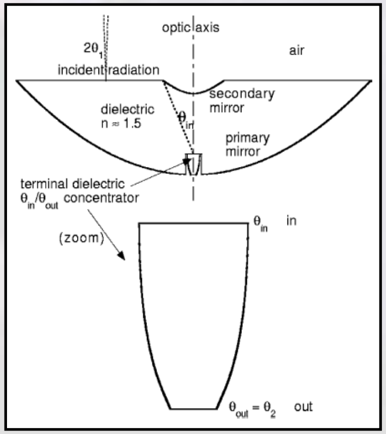
CPV Start-ups

SolFocus – Mountain View, CA

- CPV system
  - 500x Cassegrain telescope
  - Spectrolab 3-junction cells (38%)

Images courtesy of SolFocus

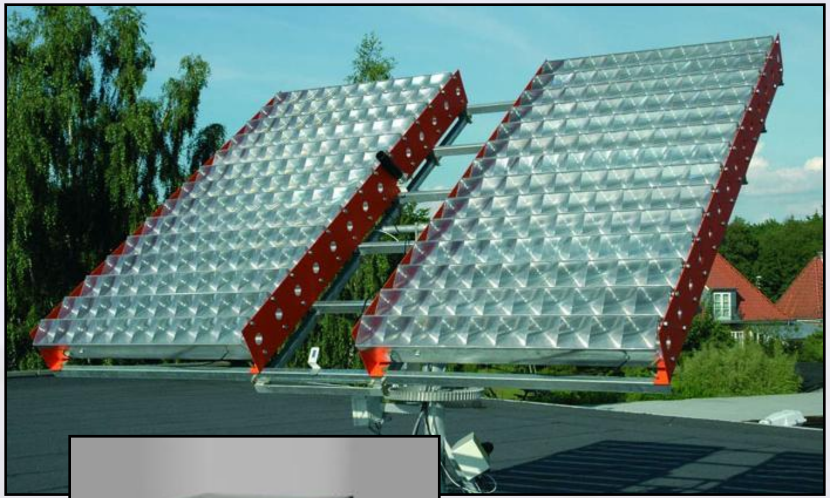


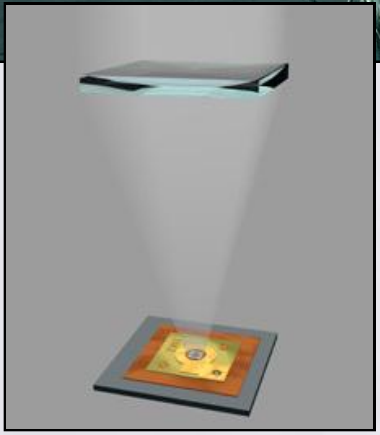


Installations:
Castilla La Marcha, Spain
Palo Alto, CA
Fremont, CA
Kailua Kona, HI

Concentrix Solar – Freiburg Germany

- FLATCON system
  - 500x silicon film fresnel lens on glass
  - Fraunhofer ISE 3-junction cells (36%)



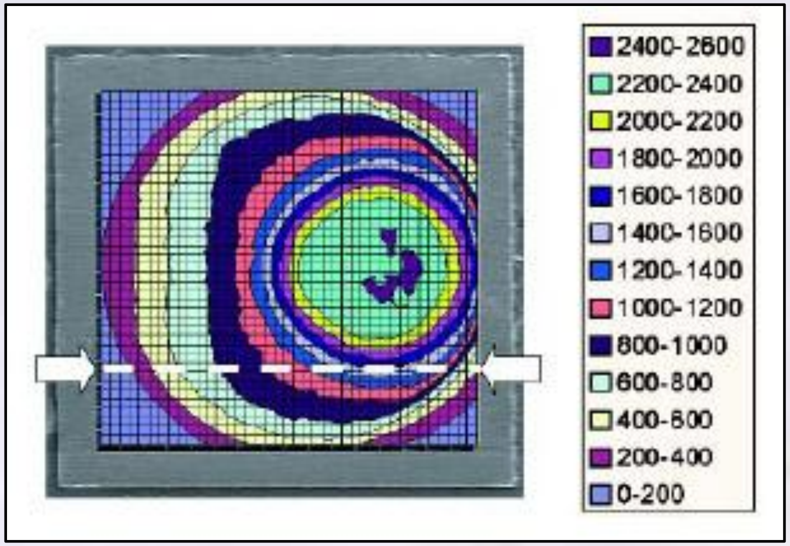


Images courtesy of Concentrix

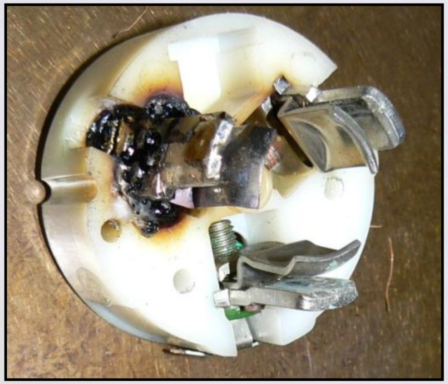
Installations:
Castilla La Marcha, Spain
Seville, Spain
Lorca, Spain

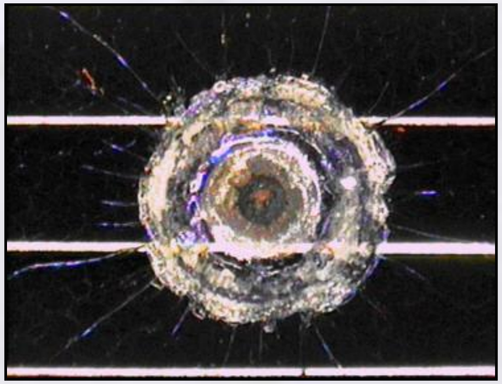
CPV Realiability

- Non-uniform illumination
  - Tunnel junctions
  - Localized heating
- Material durability
  - Life-time of mirror coatings
  - Plastic degradation
- Real-world test data
  - Failure mechanisms
  - Die-bonding
  - Wind loading
  - Impact resistance
  - Tracking / Misalignment



Luque & Andreev, Concentrator Photovoltaics, Springer (2007)





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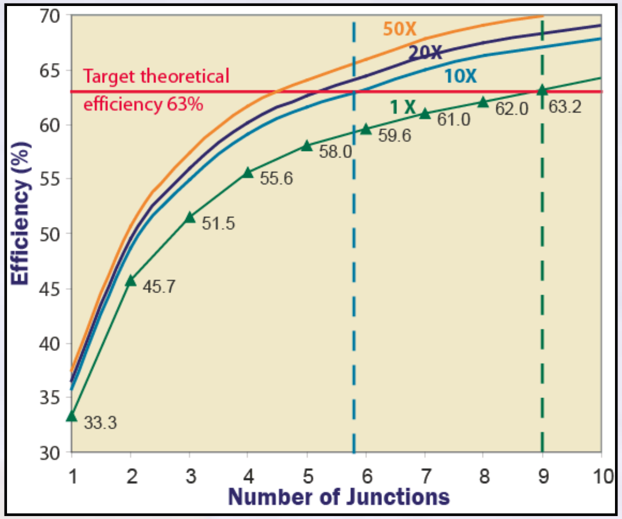
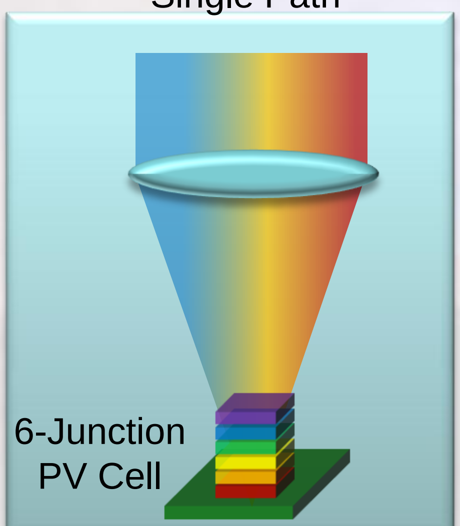
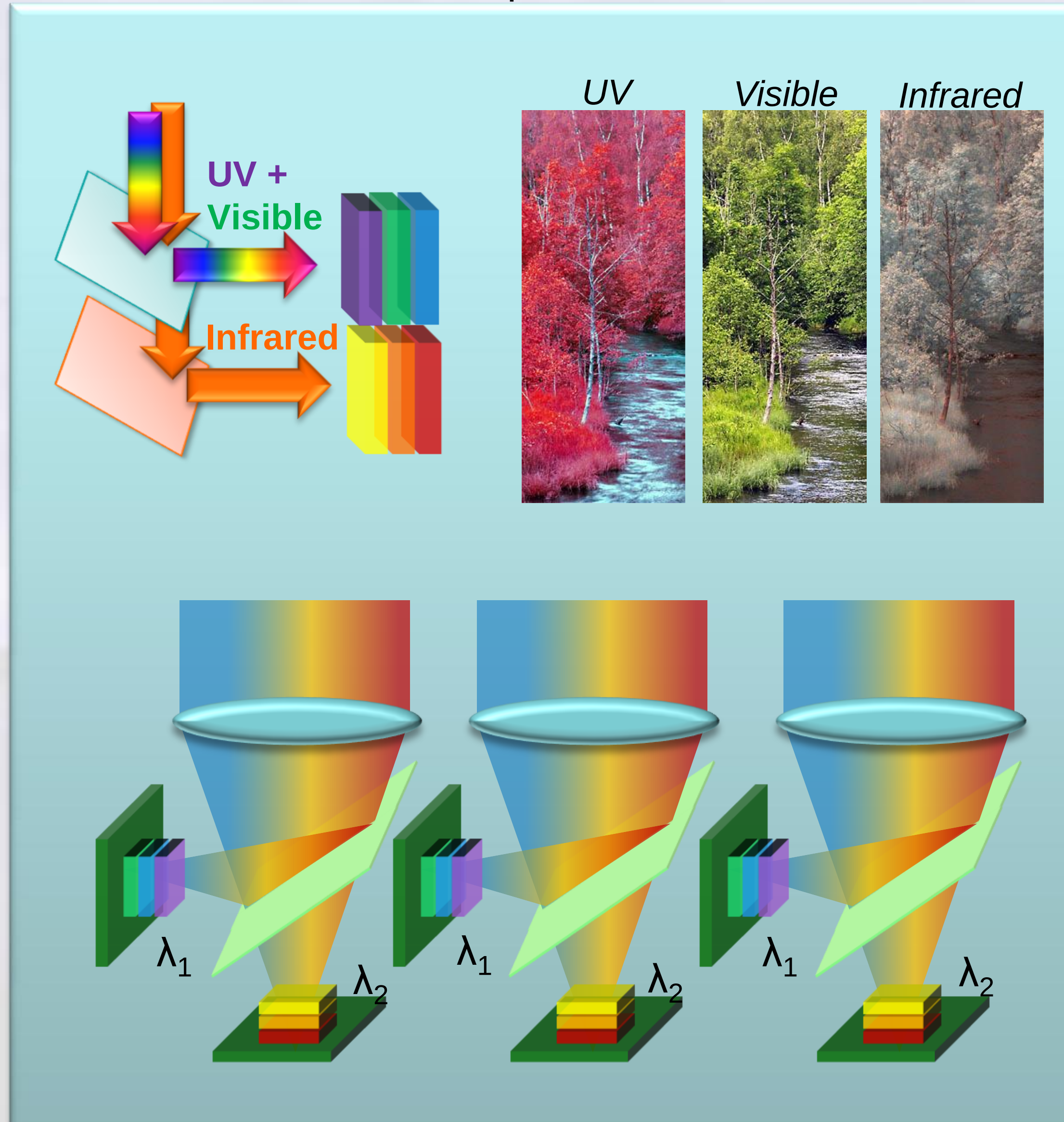
UCSD - Spectral Division



Single Path

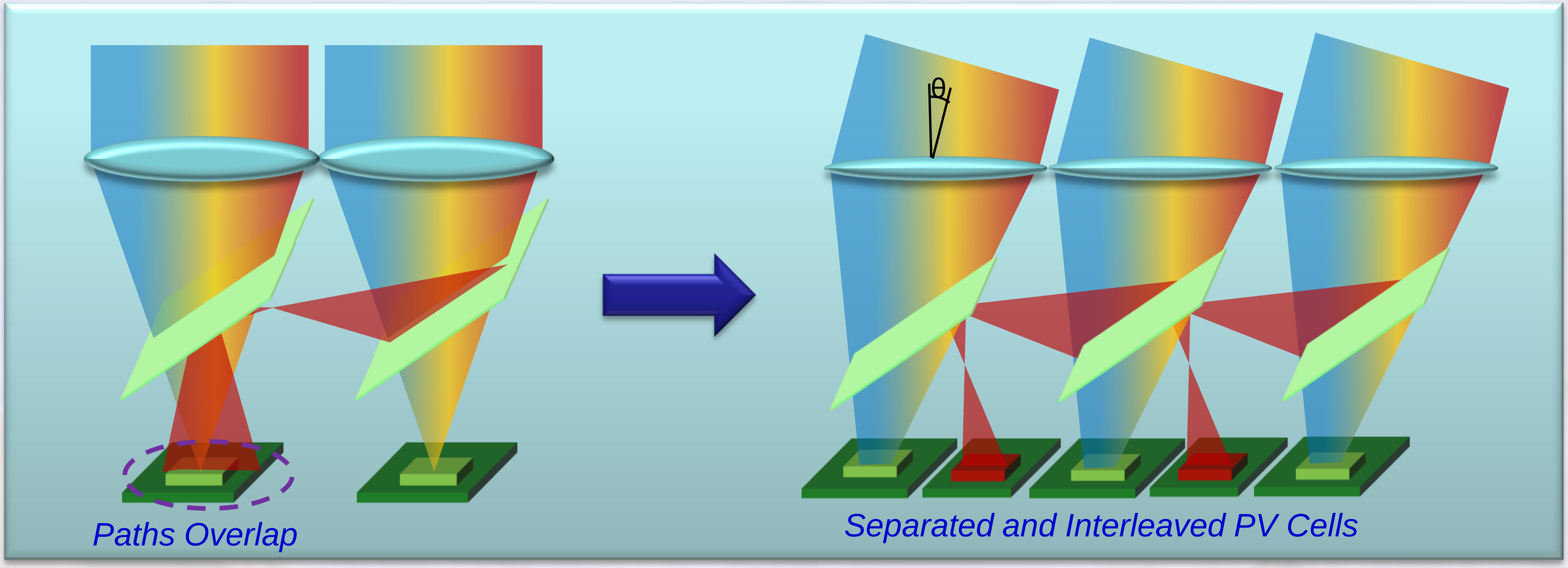


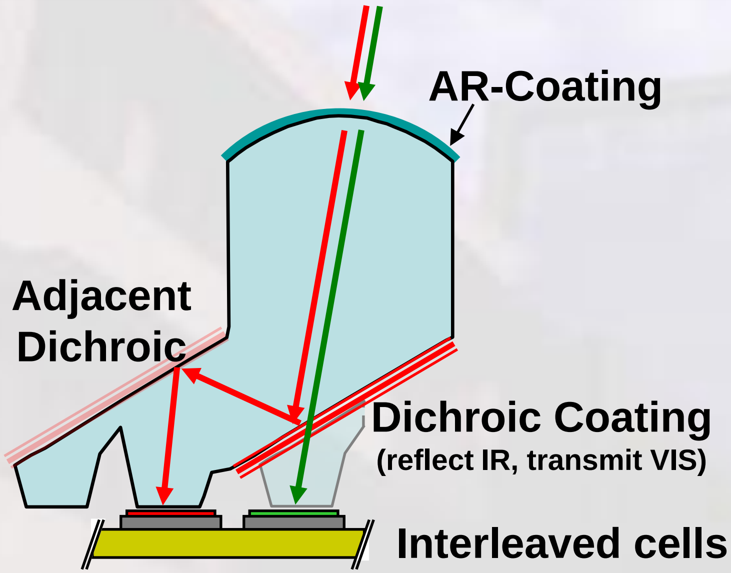
Dichroic Spectral Division



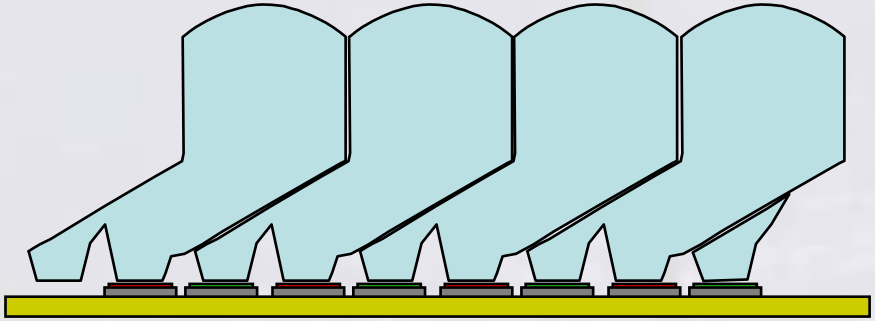
Barnett, A. et al., "50% Efficient Solar Cell Architectures and Designs," Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on , vol.2, no., pp.2560-2564, May 2006

Double-Reflection Geometry



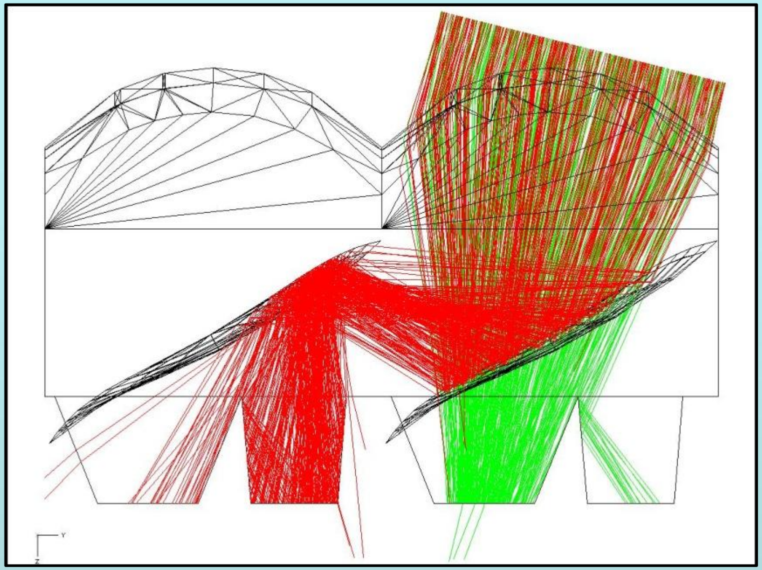


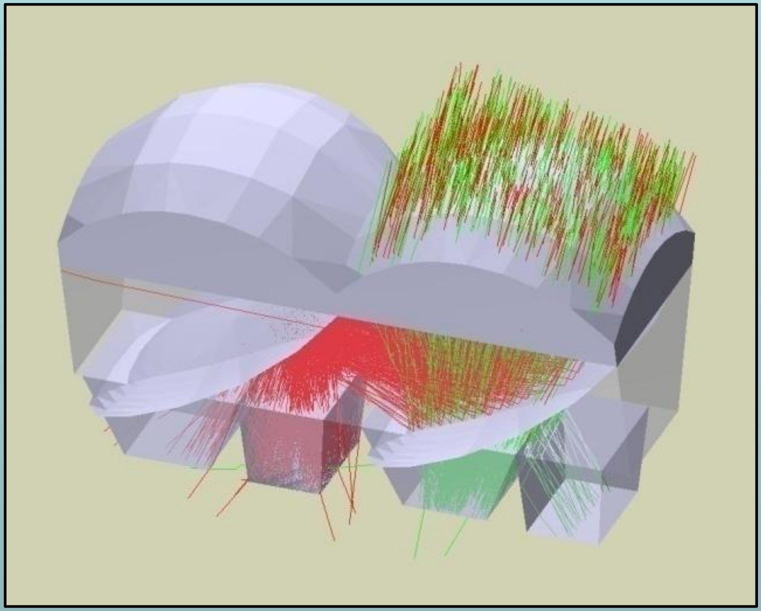
- Single micro-optic incorporates lens and dichroic
- Individual elements fit together to form an array

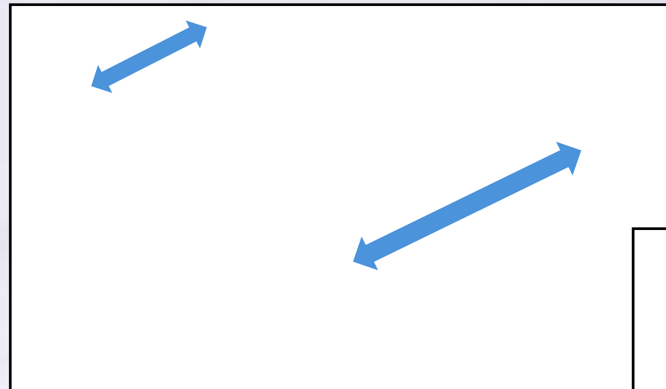


Non-sequential Design

UCSD Photonics







Freeform dichroic surface:

- Front and backside illumination
- Optimized “local” regions

Tapered Sidewalls:

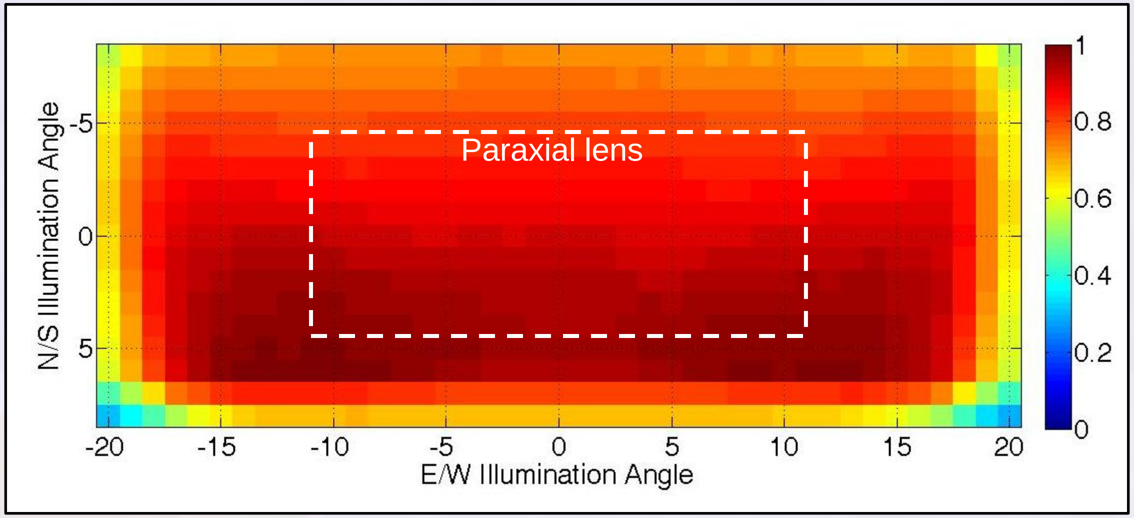
- TIR cone confines wide angles
- All planar surfaces

- <u>Zemax Non-sequentials:</u>
- Rays can: TIR, multiple ‘hits’, avoid objects, etc.
- Aspheric lens with intermediate focus
- Tapered exit apertures couples to PV cell
  - <45° exiting ray angles

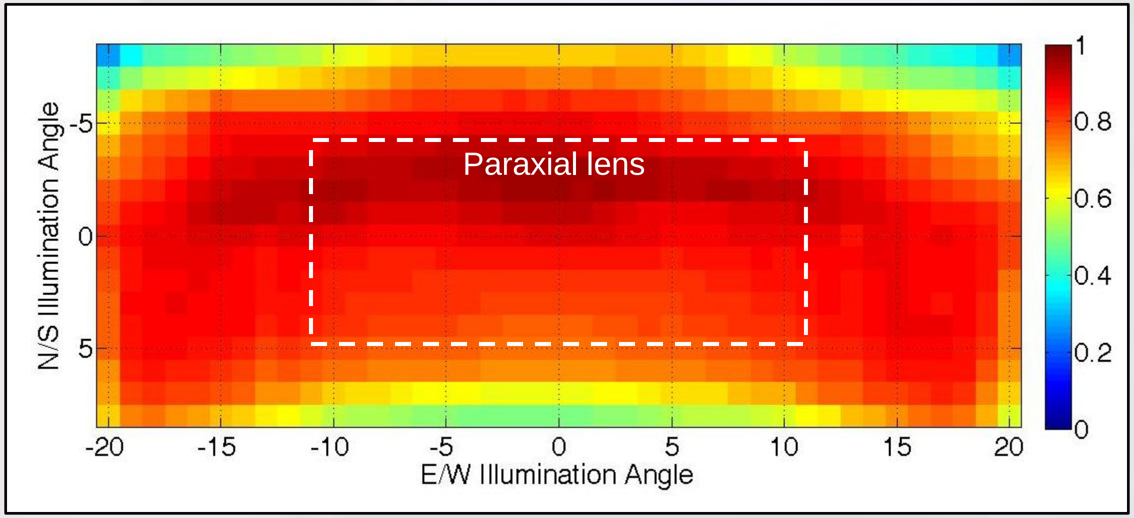
Angular Performance

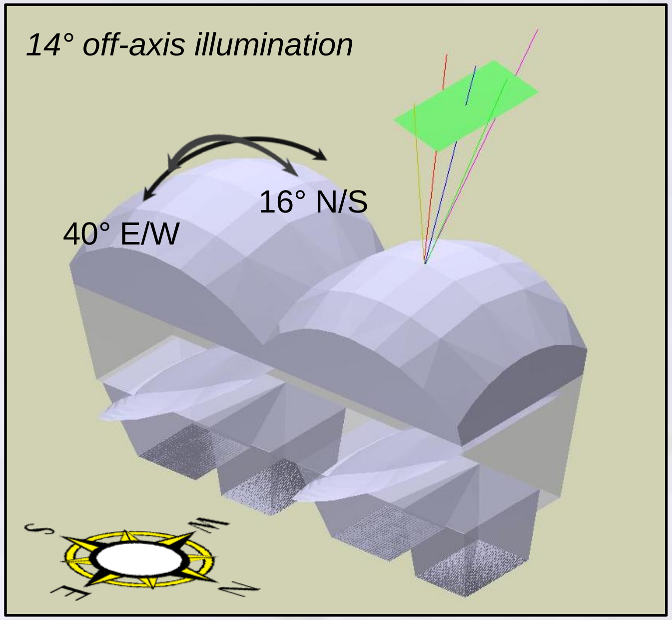
UCSD Photonics

Transmission Path: 87% Average Collection



Reflection Path: 84% Average Collection

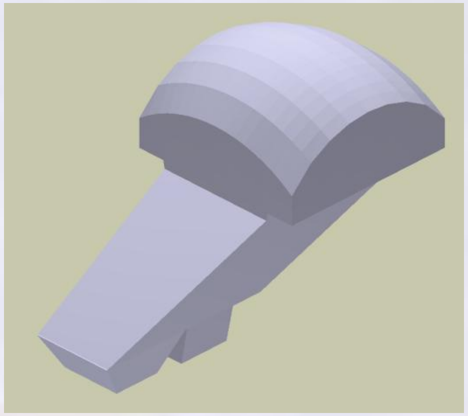




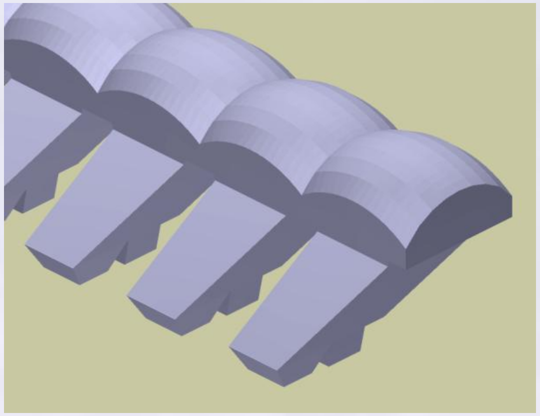
- Transmission:
  - 100% Peak, 87% Average
- Reflection:
  - 96% Peak, 84% Average
- Nonimaging sidewalls minimize ‘hot spots’ at PV cells
- Paraxial lens equivalent:
  - 22°x10° angular acceptance
  - 60% less light collection

Manufacturing Flow

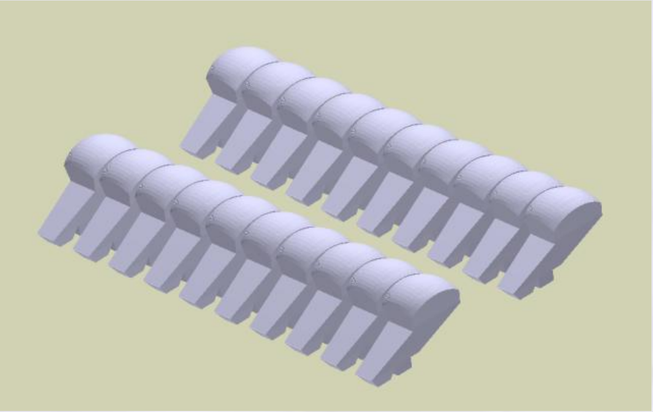
Diamond-Turned Master



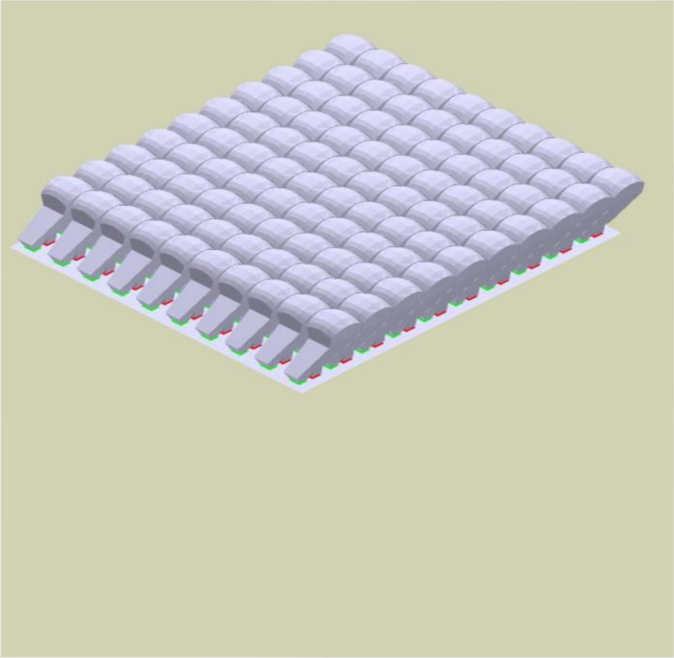
Molded 1D Array



Assemble with Index-matching Epoxy



Assembled PV Array



- Incorporate large number of energy bandgaps
- Spectral splitting simplifies multijunction fabrication
- Double-reflection geometry:
  - Improves packaging
  - Simplifies thermal management
- Single micro-optic designed for array concatenation
- Thin ‘sheet’ geometry reduces optical volume

Future Research Topics

Component Research

- III-V multijunction materials / fabrication
  - Device performance and reliability
- Concentrator miniaturization
  - Nonimaging / aspheric optics
  - Simplified fabrication and assembly (cost)

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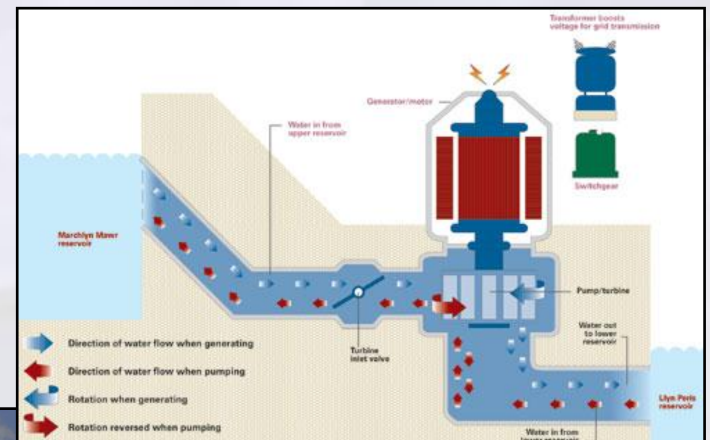

Mediawiki.middlebury.edu
pumped storage.jpg

Systems level research:

- Smart-Grid technology
  - Weather and demand monitoring
- Power transmission / distribution
- Solar energy storage:
  - Thermal storage (molten salt)
  - Pumped water
  - Batteries
- Hybrid power plants
  - CPV, Natural gas, coal

www.vnf.com

Thank You

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