HOLOGRAPHIC SOLAR CONCENTRATOR FOR RESIDENTIAL & COMMERCIAL SOLAR POWER SYSTEMS

• Motivation for improving solar concentration systems
• Types of concentrators systems
• Holographic concentrators
• Prototypes and current research

Jose Castro, Deming Zhang, Ray Kostuk
Photonics System Laboratory
Electrical and Computer Engineering
University of Arizona
Motivation

Sun power received on the earth = 174 PW
World Average Power = 15 - 17 TW (2009)
US Average Power = 3.5 - 4TW

\[
\frac{(250 \times 1600m)^2 \times 6\text{KWh/m}^2}{24h} = 4\text{TW}
\]

Sources:
- Nathan S. Lewis, California Institute of Technology
- DOE 2009 Annual Energy Outlook Early Release Overview
- Software Program METEONORM by MetoTest
Motivation

Cost of PV System ready to Use Grid Connected 8.5 $/W (2006)
PV Cell % 58%

Sources:
Motivation

<table>
<thead>
<tr>
<th>KY</th>
<th>FL</th>
<th>CA</th>
<th>NY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 (0.8)</td>
<td>1.6 (1.8)</td>
<td>2.7</td>
<td>2.9 (3.9)</td>
</tr>
</tbody>
</table>

Sources:
- Nathan S. Lewis, California Institute of Technology
- DOE 2009 Annual Energy Outlook Early Release Overview
- Software Program METEONORM by MetoTest
Motivation

Cost of Power Solar

\[
\text{Cost of Power Solar} = \frac{\text{Cost} [\$/m^2]}{\text{Efficiency} [%] \times 1000 \text{W/m}^2}
\]

Sources:
Sun illumination

\[ \alpha_s \text{ solar azimuth} \]
\[ \gamma_s \text{ solar elevation from horizon} \]
\[ \alpha \text{ azimuth of PV generator} \]
\[ \beta \text{ tilt angle of PV generator} \]
Sun illumination

\[ AM = \text{Air Mass} \approx \frac{1}{\cos(\gamma)} \]

Spectrum
Solar Illumination

Components of the Solar Illumination

Scattering in the Atmosphere

Diffuse Radiation

Diffuse and Direct Radiation

Global Radiation

Absorption by Clouds and Pollutants

Direct Normal Radiation

Diffuse Radiation

Albedo

Sun trajectories

Seasonal variation angle

Daily variation angle

[Graph showing seasonal and daily variation angles with a timeline and degree scale.]
Concentration Systems

General considerations for the design:

• Concentration level, acceptance angle, optical efficiency, irradiance uniformity
• Geometry or form factor, installation, lifetime, cost.

\[
\text{Maximum Concentration} = \frac{\text{refractive index of concentrator}}{\sin(\text{angular field of view}/2)}
\]
Holographic Concentrators
Conceptual Design

Seasonal Variation

Daily Variation

Grating Planes

Sun

HPC Module

PV Cell
Hologram fabrication Setup and Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulation</th>
<th>Sensitivity (J/cm²)</th>
<th>Resolution (line pairs/mm)</th>
<th>Thickness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photographic emulsion</td>
<td>Absorption or phase</td>
<td>~5 × 10⁻⁵</td>
<td>~5000</td>
<td>&lt;17</td>
</tr>
<tr>
<td>Dichromated gelatin</td>
<td>Phase</td>
<td>~7 × 10⁻²</td>
<td>&gt;3000</td>
<td>12</td>
</tr>
<tr>
<td>Photoresist</td>
<td>Phase</td>
<td>~1 × 10⁻²</td>
<td>~1000</td>
<td>&gt;1</td>
</tr>
<tr>
<td>Photopolymer</td>
<td>Phase</td>
<td>~1 × 10⁻²</td>
<td>3000</td>
<td>3–150</td>
</tr>
<tr>
<td>Photoplastic</td>
<td>Phase</td>
<td>~5 × 10⁻³</td>
<td>&gt;4000</td>
<td>1–3</td>
</tr>
<tr>
<td>Photochromic</td>
<td>Absorption</td>
<td>~2</td>
<td>&gt;2000</td>
<td>100–1000</td>
</tr>
<tr>
<td>Photorefractive</td>
<td>Phase</td>
<td>~3</td>
<td>&gt;1000</td>
<td>5000</td>
</tr>
</tbody>
</table>

Diagram of hologram fabrication setup.
Holograms

Sources:
Plots from faculty.ksu.edu.sa/azeer/Documents/534%20PHYS/LN10_s.pdf

Diffraction Efficiency = \frac{\text{Power Diffracted}}{\text{(Power Intensity in the glass)}}
Holographic Solar Concentrators (HSC)

Advantages

- Ideal for small factor **planar** Solar concentrators
- Potential market niche for low concentration ratios (<4X)
- Holograms perform concentration at desired regions of solar spectrum.
- Rejection of infrared illumination reduce heating of solar cells.
- Collect diffuse radiation components and albedo
- Proved fabrication technology.

Sources:
*Figure from www.prismsolar.com*
Holographic Solar Concentrator Prototypes

![Diagram showing the holographic solar concentrator prototypes with layers labeled A, B, and n1, n2, n3, and PV cell within a DH/2 DH/2 DH/2 structure. The bottom layer consists of glass or plastic with DH and PV cell labeled.]
Design Considerations

- Strength and angular bandwidth

![Graph showing DE vs θ for different wavelengths (0.5um, 0.6um, 0.7um, 0.8um).]
Design Considerations

• Crosstalk and Double Pass coupling
Design Considerations

- Layout: Maximize the amount and uniformity of the illumination at the PV Cell
Diffraction Efficiency as a function of angles and Wavelengths

$\theta = \text{Zenith angle}$

$\psi = 0 \text{ degrees}$

Fringes parallel to $x$ axis

Diffraction Efficiency

Wavelength [um]

$\theta$, [deg.]
Diffraction Efficiency as a function of angles and Wavelengths

$\theta$ = Zenith angle

$\psi$ = Azimuth angle

$\psi$ = 90 deg.

Fringes parallel to X axis

Diffraction Efficiency

$\theta$ deg.

500 1000

Wavelength
Energy gain

A- Seasonal trajectory
B- Daily trajectory
θ=zenith angle
Ψ=azimuth angle
β=tilt angle around the x axis

Grating Plane

PV Cell

Hologram Comp.

Relative Power [A.U.]

Time [hr]
Annual energy collection factor variation for and hologram with an area = $\frac{1}{2}$ of PV area

$\delta =$ Sun declination angle
Optimized annual energy collection

Days 1 & 355

Days 51 & 300

Days 100 & 250

Days 150 & 190

δ = Sun declination angle
Optimized annual energy collection

Energy collection factor vs day

\[ \delta = \text{Sun declination angle} \]
Applications for Spectrum Splitting and Concentration

Fig. 5.1: Tandem cell concepts: (a) spectrum splitting; (b) cell stacking.

SOURCE:
- Planning and Installing Photovoltaic systems, EcoFIS 2005 ISBN 1-84407-131-6
Applications for Spectrum Splitting and Concentration

Chirped Holograms
Spectrum Splitting + Concentration using Holographic Concentrators
Conclusions

• Concentrator with small form factors can be produced.
• Market niche for low concentration ratios (<4X) where tracking is not required
• Larger concentration ratios are allowed but require single axis tracking
• Holograms perform concentration at desired regions of solar spectrum.
• Rejection of infrared illumination reduce heating of solar cells.
• Collect diffuse radiation components and albedo
• Research to improve the energy collection efficiency in progress.