Beam control of Microwave Power Beam for a Solar Power Station/Satellite

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• Introduction of SPS
• Some merits of SPS
• Beam accuracy
• Beam control examples
Power From the Sun: Its Future

Peter E. Glaser

Science
Vol. 162
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Fig. 3. Concept for a satellite system for the generation of solar power.
NASA/DOE Reference Model (1978)
**TABLE VII**

CO$_2$ Emissions From Alternative Electric Power Generating Systems (G CO$_2$/kWh)

<table>
<thead>
<tr>
<th>Generating system</th>
<th>Operations</th>
<th>Construction</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS (baseline scenario)</td>
<td>0</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>SPS (breeder scenario)</td>
<td>0</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Coal$^b$</td>
<td>1,222</td>
<td>3</td>
<td>1,225</td>
</tr>
<tr>
<td>Oil$^b$</td>
<td>844</td>
<td>2</td>
<td>846</td>
</tr>
<tr>
<td>Liquefied Natural Gas (LNG)$^b$</td>
<td>629</td>
<td>2</td>
<td>631</td>
</tr>
<tr>
<td>Nuclear power$^b$</td>
<td>19</td>
<td>3</td>
<td>22</td>
</tr>
</tbody>
</table>

Comparison with Terrestrial Photovoltaics as a base load

• In order for the storage system to supply enough energy even after rainy days, the minimum insolation should be taken into account.

Let’s assume the insolation, say 2 kWh/m²/day. Then in order to obtain 24 kWh/m²/day, the necessary power for the rest of a day, 22 (=24-2) kWh/m²/day, must be stored. Full sun: 24 kWh/m²/day
Comparison with Terrestrial Photovoltaics as a base load

- If the storage efficiency is assumed to be 80%, the latter becomes $28 (=22/0.8)$ kWh/m$^2$/day.
- In order to store this power under the insolation of 2 kWh/m$^2$/day, the necessary solar cell area is 15 ($=(28+2)/2$) times of that of the full sun operation.

- Since 1 kW/m$^2$ can be obtained at full sun, we assume 24 kWh/m$^2$/day as base load power, which corresponds to 24 hour full sun per day. If the terrestrial system is used as a base load, the impact of introducing the storage system should be taken into account. The very large solar call area becomes necessary as shown below.
NASDA 2001 Model

JAXA 2004 Model
(Formation Flying)
Rectenna Site

POWER DENSITY is 23 mW/cm² at rectenna center

POWER DENSITY is 1 mW/cm² at rectenna edge

POWER DENSITY is 0.1 mW/cm² at rectenna site exclusion boundary

10 km east–west
13 km north–south
at 35° latitude

Safe level

Fig. 5. SPS microwave power density characteristics at a Reference System rectenna site.
### SPS Parameters

<table>
<thead>
<tr>
<th></th>
<th>5.8 GHz</th>
<th>2.45 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td>5.8 GHz</td>
<td>2.45 GHz</td>
</tr>
<tr>
<td><strong>Output Power</strong></td>
<td>1.3 GW</td>
<td>6.72 GW</td>
</tr>
<tr>
<td><strong>TX ANT diameter</strong></td>
<td>2.6 kmφ</td>
<td>1.93 kmφ</td>
</tr>
<tr>
<td><strong>Amplitude Taper</strong></td>
<td>10 dB Gaussian</td>
<td></td>
</tr>
<tr>
<td><strong>Max. power density</strong></td>
<td>63 mW/cm(^2)</td>
<td>114 mW/cm(^2)</td>
</tr>
<tr>
<td><strong>Min. power density</strong></td>
<td>6.3 mW/cm(^2)</td>
<td>11.4 mW/cm(^2)</td>
</tr>
<tr>
<td><strong>Antenna spacing</strong></td>
<td>0.75 λ (3.9cm)</td>
<td></td>
</tr>
<tr>
<td><strong>Output/antenna</strong></td>
<td>0.95 Wmax</td>
<td>6.1 Wmax</td>
</tr>
<tr>
<td><strong># of elements</strong></td>
<td>3,540 million</td>
<td>540 million</td>
</tr>
<tr>
<td><strong>RX ANT diameter</strong></td>
<td>2.0 kmφ</td>
<td>2.45 kmφ</td>
</tr>
<tr>
<td><strong>RX Max power density</strong></td>
<td>180 mW/cm(^2)</td>
<td>100 mW/cm(^2)</td>
</tr>
<tr>
<td><strong>Max. electric field</strong></td>
<td>823 V/m</td>
<td>614 V/m</td>
</tr>
<tr>
<td><strong>Collection efficiency</strong></td>
<td>96.5 %</td>
<td>96.2 %</td>
</tr>
</tbody>
</table>
For 250m on the ground, 
0.0002=2 \times 10^{-4^\circ}

\textbf{Random Error}

\[ \delta \theta^2 = \frac{12}{M} \delta \Phi^2 \]

\[ M = 5 \times 10^4 \quad \delta \Phi = 20 \]

\[ \therefore \delta \theta = 1.4 \times 10^{-6^\circ} \]

\( \delta \Phi \) Phase error

\( \delta \theta \) Direction error

\[ \phi = \left(2\pi d/\lambda\right)\sin \theta \]

Small Systematic Error \leftrightarrow Precise direction finding system
• Power beam should be send back to the direction of the pilot signal.
Software retrodirective system measures the direction of arrival (DOA) of a pilot signal by MUSIC etc. and sends the beam back to its direction. Flexible beam forming becomes possible.

Even power beams can be sent to multiple directions using spread spectrum pilot signals.
System Configuration

Pilot signal transmitter

Power Transmitting Signal (2.45GHz)

2.45GHz Antenna

Spectrum Spread Pilot Signal (⇒2.45GHz)

Phase Shifter

Down Converter

Phase Shifter

Down Converter

Phase Shifter

Down Converter

Phase Controlled Magnetron or FET AMP

Despread circuit (including MIXER)

A/D Converter

MIXER

A/D Converter

MIXER

A/D Converter

Computer
Effect of BEF and Soft Synchronization

Transmitting power is 10,000 times stronger than pilot power.
Direction Of Arrival Measurement by SS Pilot Signal

- Power Transmission Frequency: 2.45GHz
- Pilot signal
  - Center Frequency: 2.45GHz
  - Direct-Sequence Spread Spectrum
  - PN Code: M-series
    (Length=1023, 1.25Mcps)
- Pilot Signal Antenna: 2.25~2.6GHz Dipole
- T/R Antenna
  - 2.45GHz Circular MSA
  - 8 elements, 0.6λ spacing

\[ \theta = \sin^{-1}\left(\frac{x}{d}\right) \]

\[ = \sin^{-1}\left(\frac{\lambda}{360d}\phi\right) \]

\( \phi \): Phase Difference
Received intensity (power density) profiles at a rectenna site. 

**a** (Left) Array with 10-dB Gaussian power distribution, 

**b** (Right) Array with uniform excitation.
Study of beam forming by Phase-only Antenna pattern synthesis

Cooling problem ↔ amplitude taper
Genetic Algorithm

High efficiency
Low Sidelobe

Dual Beam
<table>
<thead>
<tr>
<th><strong>Frequency</strong></th>
<th>5.8GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of ant.</strong></td>
<td>$12 \times 12$ elements</td>
</tr>
<tr>
<td><strong>Antenna elements</strong></td>
<td>Circular polarized square patch</td>
</tr>
<tr>
<td><strong>Phase shifters</strong></td>
<td>4 bits per element (Resolution: $22.5^\circ$)</td>
</tr>
<tr>
<td><strong>Oscillator</strong></td>
<td>Semiconductor (FET)</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td>150W (9 units)</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>Approx. 10%</td>
</tr>
<tr>
<td><strong>Element spacing</strong></td>
<td>$0.6 \lambda \ (\sim 1.5 \lambda)$</td>
</tr>
<tr>
<td><strong>Sizes</strong></td>
<td>1.4m x 0.9m x 2.0m</td>
</tr>
</tbody>
</table>

(SPORTS 5.8 : Space POwer Radio Transmission System with 5.8GHz)
Optimized calculation and experiments

Experimental result (opt) at v=0[m], d=0.031[m]