Direct Conversion for Space Solar Power

Nicholas Boechler
gtg218s@mail.gatech.edu

Research Advisor: Prof. Komarath
Direct Conversion Concept

- Given broad/narrow band EM radiation source
  - Sun
  - Man made EM transmission
  - Other bodies: Jupiter, albedo from the Moon

- Absorb radiation and convert directly to lower narrowband frequency for re-emission

- Benefits:
  - Increased efficiency
  - Lower mass
  - Increased simplicity
Project Goals

- Study a number of options that might lead to direct conversion.
- Analyze technology that would warrant further exploration:
  - Aerospace systems applications?
  - Possible mass per unit power?
- Provide a justifiable estimate of mass per unit power of future direct conversion systems.
- Identify possible future applications that would benefit from direct conversion technology.
Current Technological Road Blocks to Space Solar Power Systems (1)

- Photovoltaic Technology
  - Old technology w/ low efficiency
  - Band gap
  - Direct current only – must re-oscillate
  - Relatively low specific power

<table>
<thead>
<tr>
<th>Solar Cell Performance</th>
<th>Thick Film</th>
<th>Thin Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>25-40%</td>
<td>10-20%</td>
</tr>
<tr>
<td>Specific Power (kW/kg)</td>
<td>0.05-.25</td>
<td>0.05-.25</td>
</tr>
<tr>
<td>Power Density (kW/m^2)</td>
<td>0.1-.4</td>
<td>0.1-.4</td>
</tr>
</tbody>
</table>

Solar Cell Performance [1,2,3,4,5]. Note: high estimate taken, usually not that good and decays w/ time.
Current Technological Road Blocks to Space Solar Power Systems (2)

- High Launch Costs
  - Importance of specific power

<table>
<thead>
<tr>
<th>Booster</th>
<th>2004 Cost ($ millions)</th>
<th>Payload to LEO (kg)</th>
<th>Payload Cost ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlas 5 551</td>
<td>125.1</td>
<td>20,050</td>
<td>6239.4</td>
</tr>
<tr>
<td>Delta 4 Heavy</td>
<td>193.4</td>
<td>25,800</td>
<td>7496.12</td>
</tr>
<tr>
<td>Space Shuttle</td>
<td>284</td>
<td>24,400</td>
<td>11639.3</td>
</tr>
<tr>
<td>Titan 4B</td>
<td>491.6</td>
<td>21,680</td>
<td>22675.3</td>
</tr>
</tbody>
</table>

Robel, M. [6]
Initial Direct Conversion Options

- Shocked Photonic Crystals [Joannopoulos 7,8,9]
- Signal Processing Solutions
- Optical Resonators [Iltchenko 10]
- Rapidly Ionizing Plasma [Ren 11]
- Solar Pumped Lasers and Masers [12,13]
- Optical Rectennae [14,15]
- Nanofabricated Antennae
Discounted Options (1)

Signal Processing Solutions

- Inefficient and some require a significant additional power source
- Tube, Cyclotron, Gyrotron type devices
  - Mechanical tolerances
  - Scaling problems
  - More difficult at higher frequencies
  - Low efficiency that degrades over time
  - Heavy
  - Impedance mismatching
  - Breakdown fields
  - Have not found any efficiencies over 60% and few near it
Discounted Options (2)

- Optical Resonator
  - Converts to amplified narrowband but does so inefficiently by rejecting non-resonant wavelengths

- Rapidly Ionizing Plasma [Ren 11] and Nanofabricated Antenna
  - Difficulty further developing viable concept
Discounted Options (3)

Optical Rectenna [1,2]

- Based of previous work of ITN Energy Systems and W.C. Brown
- Still very applicable technology, however it is surpassed by the possibility of focusing broadband radiation directly onto a medium
  - Estimated Efficiency = 85-100%:
  - Power Density = 1.165 kW/m^2 [W.C. Brown Microwave Rectenna]
  - Weight = .25 kg/m^2 [3]
  - Specific Power = 4.658 kW/kg
  - 1763% Increase in Specific Power over photovoltaics
Refined System Concepts

Near Term Concept
- Solar Pumped Maser

Long Term Concept
- Shocked Photonic Crystals
MASERs

MASER = Microwave Amplification by Stimulated Emission of Radiation

Naturally Occurring

- Detection of 183 GHz water vapor maser emission from interstellar and circumstellar sources [16]
  - Rotational transition of H2O
- 145 GHz Methanol maser
  - Collision excited [17]
Earth Atmosphere Absorption

CSO Zenith Transmission  Precipitable Water Vapor: 0.50 mm

Transmission (%)

Frequency (GHz)

http://www.islandone.org/LEOBiblio/microwave_transm.gif
MASER/LASER Examples

  - Solar pumped Nd/Cr:YAG ceramic laser
  - Demonstrated 38% efficiency

- Kiss, Z. J. “Sun Pumped Continuous Optical Maser” [19]
  - 1963
  - Shows same principle of solar pumped lasers can be applied to lower more convenient frequencies
Argument for Efficiency

- Use low density molecular vapor as in naturally occurring masers
  - Analogous to lasers
- Maser uses rotation-vibration transitions on the molecular level
  - Laser uses optical-electronic transitions on the subatomic level
  - 38% with a laser already proven – should be able to do better.
  - DARPA aiming for 50% with 1W CW laser
- Longer wavelengths – everything scaled up and easier to control
Parabolic Reflector

Solar sail type material for reflector

- 1-10 g/m^2 [20]
- May be heavier to prevent scatter – but will still be significantly lighter than traditional options
MASER System

Parabolic Reflector

Molecular Vapor Maser contained in near perfect-reflectivity casing

Beam Focusing Mechanism

Narrowband Microwave Emission
Problems/Considerations

\[ \eta_{\text{Total}} = \eta_{\text{Reflector}} \times \eta_{\text{Maser absorption}} \times \eta_{\text{Heat & Scattering}} \times \eta_{\text{Broadband Losses}} \times \eta_{\text{Emission}} \]

- Gas would have to be kept at uniform temperature for maximum efficiency
  - Balance between heating of radiation and cooling to the vacuum
  - Solar weather
- Unpredictability due to low density and possible high temperature
- Possible band gap – ie: portions of band perhaps ineffective towards transition
- Scattering/surface losses
MASER Calculations (1)

Maximum Power from Radiation into the Volume (as defined by desired Temperature)

\[ \alpha = \left[ \frac{\text{kW}}{\text{m}^3} \right] \]

Maximum Power Flux through the Surface of the Maser (as defined by Temperature at the interface and maintained uniformity)

\[ \beta = \left[ \frac{\text{kW}}{\text{m}^2} \right] \]

Reflector Specific Mass

\[ \pi = \left[ \frac{\text{kg}}{\text{m}^2} \right] \]

Maximum Focusing Ratio of Parabolic Reflector (Geometric Property, \[ \frac{A_{\text{Parabolic Reflector}}}{A_{\text{Maser Inlet}}} \])

\[ \phi = \text{[Unitless]} \]

P = Desired Power of the system
Specific Power = \( \frac{(1.37 \left[ \frac{kW}{m^2} \right] \text{Solar Radiation} \cdot \eta_{\text{Total}} \cdot (A_{\text{Parabolic Reflector}})}{(m_{\text{Structure}} + m_{\text{Vapor}} + m_{\text{Parabolic Reflector}})} \)

\( m_{\text{Structure}} \propto m_{\text{Vapor}} \)

\( m_{\text{Vapor}} = \frac{\rho_{\text{Vapor}} \cdot P}{\alpha} \)

\( m_{\text{Parabolic Reflector}} = A_{\text{Parabolic Reflector}} \cdot \pi \)

\( A_{\text{Parabolic Reflector}} = A_{\text{Maser Inlet}} \cdot \phi \)

\( A_{\text{Maser Inlet}} = \frac{P}{\beta} \)
Photonic Crystals

Through artificial geometry can create perfect waveguides and resonant cavities.

High to perfect theoretical efficiencies.

[Joannopoulos 7,8,9]
Doppler Shift and Photonic Crystals

- 2003 MIT
- Discovered that a non-relativistic reversed Doppler Shift in light occurs when light is reflected from a moving shock wave propagating through a photonic crystal
- Near 100% efficiency
- Proposed that a similar system be used in micro-electrical-mechanical devices. [7,8]
Simulation of frequency shift in photonic crystals from Joannopoulos J. [8]
**Shocked Photonic Crystal System**

- Solar sail type parabolic reflector
- “Shock like” modulation of the dielectric with separate power source
- Serially placed photonic crystals or single crystal with gradient geometry
  - Possible mismatch to geometry with large frequency shift over the course of the crystal
- Resulting pulsed transmission
Shocked Photonic Crystal System
Problems/Considerations

Creating a shock
- Physical shock too much energy
- “Shock like” modulation of the dielectric – still energy loss, but perhaps smaller
  - Need more information

Has not been physically tested – only simulations
- Initial efficiency probably low
- Depends greatly on nanotechnology
- Would have to limit unexpected internal scattering

Surface interface reflection and scattering still a problem

Heat over time

\[ \eta_{\text{Total}} = \eta_{\text{Reflector}} \times \eta_{\text{Maser absorption}} \times \eta_{\text{Heat & Scattering}} \times \eta_{\text{Broadband Losses}} \times \eta_{\text{Emission}} \times \eta_{\text{Efficiency Lost due to Generation of Dielectric Shock}} \]
Shock Photonic Crystal Calculations (1)

\[ \eta_{\text{Total without Dielectric Shock}} = \eta_{\text{Reflect}} \times \eta_{\text{Maser absorption}} \times \eta_{\text{Heat & Scattering}} \times \eta_{\text{Broadband Losses}} \times \eta_{\text{Emission}} \]

Maximum Power from Radiation into the Volume (as defined by desired Temperature):

\[ \alpha = \left[ \frac{\text{kW}}{\text{m}^3} \right] \]

Maximum Power Flux through the Surface of the Crystal (as defined by Temperature at the interface and maintained uniformity):

\[ \beta = \left[ \frac{\text{kW}}{\text{m}^2} \right] \]

Reflector Specific Mass:

\[ \pi = \left[ \frac{\text{kg}}{\text{m}^2} \right] \]

Maximum Focusing Ratio of Parabolic Reflector:

\[ \phi = \left[ \text{Unitless} \right] \]

\[ P = \text{Desired Power of the system} \]
Specific Power

\[
(1.37 \left[ \frac{kW}{m^2} \right] Solar \ Radiation) \times \eta_{Total - without \ Dielectric \ Shock} \times (A_{Parabolic \ Reflector} - A_{Shock \ Power \ Source}) = \frac{(m_{Structure} + m_{Crystal} + m_{Parabolic \ Reflector} + m_{Shocking \ Mechanism} + m_{Shock \ Power \ Source})}{\alpha}
\]

\[
m_{Structure} \propto m_{Crystal}
\]

\[
p_{Crystal} \times P
\]

\[
m_{Vapor} = \frac{p_{Crystal} \times P}{\alpha}
\]

\[
m_{Parabolic \ Reflector} = A_{Parabolic \ Reflector} \times \pi
\]

\[
A_{Parabolic \ Reflector} = A_{Crystal \ Inlet} \times \phi
\]

\[
P
\]

\[
A_{Maser \ Inlet} = \frac{P}{\beta}
\]
Applications (1)

- **Space Solar Power Grid**

  - **Improved Efficiency:** Based on calculations by Kulcinski [21], assuming a change of conversion efficiency from 15.7%, and 76.6% efficiency loss due to DC to RF conversion (don’t know where he got that number – should be lower)

    - Overall system efficiency from 7.81% to 64.9%

- **Distribution System:** no DC conversion between satellites
Electric Propulsion:

**Problems:** High mass per unit thrust, due to the power source and transmission system.

**Potential Systems:**

- **Ion Engines:** Ionize propellant particles such as xenon gas by EM radiation and accelerate them through an electric field.
Applications (3)

- **Magnetoplasma Engines and Mag Beam**: Heating neutral hydrogen gas into plasma using electric fields and contained by magnetic fields, the plasma then passes through an RF booster to further ionize the hydrogen plasma [22,23]

- **Solar Sail Hybrid Systems**: Solar sails are combined with electric propulsion systems to function as both a solar sail and reflector to power the electric propulsion system [24].

Magbeam from Winglee, R. [23]
Hybrid system from Landis, G. [24]
Benefits from Direct Conversion:

More Available Energy

- More energy can be gathered more efficiently
- Eliminate the need for an onboard power system
- Direct Conversion to Ionization Frequency
- Ultra Thin Solar Sail Possibilities

Hybrid
Future

Refine Estimates

Information Needed

- Flux and Power capacities of molecular vapors and crystal systems
- Temperature and density target for maser
- How fast heat can transfer through the various mediums – determines geometry
- Capacity of solar sail reflectors
- Shock like modulation of the dielectric
Bibliography

Thanks!

Research Advisor & Mentor: Dr. Komerath
  - Additional guidance on lasers/masers, photonic crystals, and other questions
    - Dr. Citrin (GT)
    - Dr. Kenney (GT)
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    - Dr. Marzwell (JPL)
    - Dr. Olds (GT & SpaceWorks Engineering Inc.)
    - Dr. Reed (Lawrence Livermore National Lab)

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