Efficient Direct Conversion of Sunlight to Coherent Light at High Average Power in Space


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NASA Institute for Advanced Concepts – Phase I Report
March 16, 2005
Outline

**Goal:** Optical Power Infrastructure in Earth-moon space

**Methodology:** Solar pumped solid state laser power oscillators most likely located primarily on the lunar surface combined with relay mirrors at L4 and L5 Lagrangian points

**Results:** Find an Optical Power Infrastructure providing needed power virtually anywhere virtually anytime is allowed by fundamental physical laws

**Conclusions:** Direct attention to maturation of four technical advances for transforming sunlight to coherent light that are required. Could be accomplished in time frame of exploration program.
Goal: Optical Power Infrastructure in Earth-moon space

> 100 kW power virtually anywhere and virtually anytime in Earth-moon space

Require high average power high coherence power laser oscillators
Supply power from lunar surface to spacecraft near Earth

Use of LaGrangian points provides access to regions that might otherwise be obstructed by Earth

Optical beams would normally not be visible in space

Image of optical power being beamed to spacecraft near Earth
Schematic and image of distribution of optical power to satellites in low Earth orbit and then to Earth’s atmosphere.

Non-military vs. military use

Array of remotely powered economical small satellites in LEO

e.g., atmospheric monitoring
Delivery of coherent power safely to Earth from space

Safety beam at low intensity surrounds power beam
Propagation distance vs. beam radius

Earth-moon distance

\[ D : 4 \sqrt{L \lambda / \pi} \]

Mirror diameter \( D \) (\( \lambda \sim 1 \) micron)

- 384 Mm
- 30 m

Examples:
- Liquid mirrors on moon

Legend:
- \( L \) (horizontal axis)
- \( \lambda \) (vertical axis)
Initial Findings

• Billions of terawatts of continuously renewed clean solar power are available in Earth-moon space as sunlight

• Sunlight cannot be usefully redistributed by linear optical systems

• Optical power in the form of coherent light (as lowest order Gaussian modes of free space) can be distributed virtually anytime virtually anywhere in Earth-moon space

The principal need is to transform sunlight into coherent light at high average power at reasonable efficiency in space
Transforming sunlight into coherent light at high average power in space requires four technical advances

1. **Concentrate** solar pump power to the saturation intensity of a useful laser transition in a gain volume approximating the lowest order Gaussian mode of a near confocal resonator

2. **Remove waste heat** from the gain volume in a manner that avoids unacceptable thermally induced optical distortion and stress

3. **Transfer the solar pump power efficiently and selectively** into the lowest order Gaussian mode of a near confocal resonator

4. **Transform temporally and spatially coherent light** beamed of Earth-moon distances at high efficiency, e.g. > 90%, into alternative, e.g. electrical power
#1: Concentrate needed solar pump power in required volume at ~ saturation intensity of laser transition, e.g. 10 kW/cm²

Spectrally filtered sunlight

Non-imaging concentrators

Tapered duct

Core doped with laser material

Design determined by optimizing concentration of pump power in most favorable geometry and dimensions using Advanced Systems Analysis Program (ASAP) (Hubble)
Selective absorption in central gain material doped region

Rays “bounce” in zigzag pattern, but are eventually absorbed with high probability in the gain material

Achieve integrated pump intensity substantially larger than intensity at the surface of the Sun
“Multiple suns” point of view

16 non-imaging concentrators each concentrate sunlight to maximum intensity at a plane

Each concentrator contributes power to gain medium comparable to conventional concentrator

3m length yields ~ 100 kW

> 80% of solar pump power is ~uniformly absorbed in the core region

End view

Sixteen times the effective intensity of one concentrator
Conventional optics for 8 collector concentrator

Collecting area for 8 concentrators is 200 m²
At 1 kg/m² mass is 200 kg

Estimate 4 kg/kW on basis of NASA optics Projections-comparable to nuclear projections

<1 metric ton for 200 kW output
#2: Remove heat from gain medium while avoiding thermally induced lensing and distortion

Heat removed **radially** using material having small thermo-optic coefficient and large thermal conductivity, e.g. diamond or undoped sapphire.

Heat removed **axially** from gain material having large thermo-optic coefficient, e.g. YAG.

Positive thermally induced lens is compensated by **negative** thermally induced lens.
#3: Need large cross sectional area, e.g., 1.5 cm radius, lowest order Gaussian mode of a near confocal resonator of practical dimensions

Double confocal paraboloidal resonator

Conventional lowest order Gaussian mode resonators would be kilometers long
#3. Double confocal paraboloidal resonator using Brewster angle gain elements

Provides **low loss** gain elements
#3 Double confocal paraboloidal resonator using Brewster angle gain elements

Energy brought in by solar pump photons must be transferred with high probability to lowest order Gaussian mode.

Selective transfer to the lowest order Gaussian mode requires selective loss introduced in the resonator.
Technical advances 1, 2, and 3 provide means of delivering optical power throughout Earth-moon space.
#4: Transform received optical power to alternative form, e.g., electrical, at high efficiency at receiving site. Requires matched coherent light.

\[ \eta \equiv (1 - \xi)[1 + \xi \ln \xi] \]

\[ \xi = \frac{kT}{h\nu} = 1 \]

Have neglected all sources of inefficiency except for thermal mechanisms.
Cost, income, specific power vs. year

- **Cost**
- **Income**
- **Specific Power**

<table>
<thead>
<tr>
<th>Years</th>
<th>Cost ($/kg)</th>
<th>Income ($/kg)</th>
<th>Specific Power (kW/kg)</th>
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<tbody>
<tr>
<td>2000</td>
<td>$10,000</td>
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<tr>
<td>2025</td>
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Current Experimental Results

Validates transient approach

532 nm pump

Experimentally measured temperature profile in Ti:sapphire as a function of time
## Plan of work

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<th>TASK</th>
<th>Experiment</th>
<th>Technical development</th>
<th>Analysis</th>
<th>Partner</th>
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<tr>
<td>1. Concentration of solar pump power</td>
<td>Laser for transient, heliostat for cw</td>
<td>Build concentrator elements</td>
<td>Measure power concentration</td>
<td>?</td>
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<td>2. Removal of heat with no distortion</td>
<td>Transient pump probe experiment</td>
<td>Nanostructured interfaces</td>
<td>Compare results and simulation</td>
<td>NRL, ANL</td>
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<tr>
<td>3. Large area resonator with selective excitation</td>
<td>Build scaled down resonator in our laser lab</td>
<td>Paraboloidal reflectors</td>
<td>Compare results and predictions</td>
<td>?</td>
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<tr>
<td>4. High efficiency optical to electrical</td>
<td>Perform experiments on NASA diodes</td>
<td>Sample diodes to be built</td>
<td>Compare results and theory</td>
<td>Entech, Inc</td>
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Issues:

1. Can transient measurements provide data adequate to evaluate high cw power?

Ans. Longest relevant time constants are $\sim 10 \text{ ms}$, so approach has scientific validity. Only way to perform meaningful experiments within current budget.
2. What is the case for scaling to high total power at reasonable cost?

Ans. The physical phenomena allow construction of small scale system that illustrates the key mechanisms.

Build small scale system and project the cost. The answers will be found in the maturing of the technologies.

No obvious reason cost will be a show stopper.
3. What would be the cost of robotic assembly in space?

Ans. We can make the system elements modular. The technology is similar to that of Project Lasso now being explored.
4. Sounds to good to be true.

Ans. Coherent light is different from conventional light. One may discover capabilities that were not fully anticipated.
Conclusions

1. An optical Power Infrastructure in Earth-moon space is allowed by fundamental physical laws.

2. There are four areas of technology maturation that are required to make such an infrastructure a possible.

3. The advances that are required are difficult, but are likely to yield to determined efforts.

4. The cost benefit analysis strongly recommends making the effort.
Special thanks to this years UAH laser and optics classes!

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