LASER POWER TRANSMISSION

LASER IS ONLY FEASIBLE SYSTEM FOR LONG RANGE (> 1,000 KM) POWER TRANSMISSION IN SPACE.

LASER BEAM ACTS AS "SUPER CONDUCTOR" TO DELIVER HIGH GRADE POWER--NEAR ZERO ENTROPY.

MULTIMISSION SUPPORT POSSIBLE--ECONOMICAL.

LIGHT WEIGHT SYSTEMS IDENTIFIED--DIRECT SOLAR PUMPED LASERS AND LASER DIODE ARRAYS.

TRANSMITTER/RECEIVER SIZES vs RANGE

Graph showing transmitter/receiver sizes vs range, with different λ values and their corresponding systems.
LASERS AVAILABLE FOR LASER POWER TRANSMISSION

0 REQUIREMENTS

LASER POWER
> 10 MW ORBITAL MANEUVERING
> 1 GW EARTH-TO-ORBIT LAUNCHING (> 1 TON)
~ 1 MW OTHER MISSIONS

PHOTON FLUX
< 2 x 10^5 W/cm^2 CW
< 2 x 10^7 W/cm^2 PULSED (LSD PROP.)

WAVELENGTH
> 10 µm THROUGH ATMOSPHERE
~ 1 µm DEPENDS ON THE POWER RECEIVERS IN FREE SPACE

PULSE WIDTH
50 ns - 1 µs PLASMA GEN. AND HEATING

EFFICIENCY
HIGH TRANSMITTER AND RECEIVER

0 GROUND BASED WITH SPACE RELAY
FREE ELECTRON LASER (PULSED), CO_2 LASER (CW)
STATE-OF-THE-ARTS: MULTI-KILOWATT (CW), 500 kJ (PULSED)
SCALING-UP: POSSIBLE TO MULTI-MW LEVEL.

0 TECHNICAL ISSUES:
MANY ORDERS OF MAGNITUDE UP-SCALING NEEDED
ATMOSPHERIC INTERFERENCE

SPACEBORNE LASER OPTION SHOULD BE CONSIDERED

SPACE-BORNE LASERS FOR POWER TRANSMISSION

0 SOLAR POWERED LASERS

DIRECT SOLAR PUMPED LASERS
IODINE PHOTODISASSOCIATION LASER, IR PHOTODISASSOCIATION LASER
SOLID STATE LASERS (Nd^{3+}), LIQUID Nd^{5+} LASERS, DYE LASERS

INDIRECT SOLAR PUMPED LASERS
N_2-CO_2 BLACKBODY PUMPED LASER, CO BLACKBODY PUMPED LASER

SOLAR PHOTOVOLTAIC POWERED
ELECTRIC DISCHARGE LASERS (EXCIMER, COPPER, CO_2)
DIODE LASER ARRAYS/DIODE LASER PUMPED LASERS.

0 NUCLEAR POWERED LASERS

DIRECT NUCLEAR-PUMPED LASERS
HIGH EFFICIENCY ELECTRIC DISCHARGE LASERS OR DIODE LASERS
### SOLAR PHOTOVOLTAIC ELECTRICALLY PUMPED ONE MW LASER SYSTEMS

<table>
<thead>
<tr>
<th></th>
<th>Krf Excimer</th>
<th>Copper Vapor</th>
<th>Diode Array</th>
<th>CO₂</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laser Wavelength</strong></td>
<td>μm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.248</td>
<td>0.510</td>
<td>0.8</td>
<td>10.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.570</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Intrinsic Efficiency</strong></td>
<td>%</td>
<td>10</td>
<td>3</td>
<td>30</td>
<td>13.7</td>
</tr>
<tr>
<td><strong>Electric Efficiency</strong></td>
<td>%</td>
<td>2.5</td>
<td>1.4</td>
<td>30</td>
<td>5.5 WALL-PLUG EFF.</td>
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<tr>
<td></td>
<td></td>
<td>0.40</td>
<td>0.24</td>
<td>6.0</td>
<td>0.88</td>
</tr>
<tr>
<td><strong>Solar to Laser Efficiency</strong></td>
<td>%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Solar Power Collected</strong></td>
<td>MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>412</td>
<td>16.5</td>
<td>113.5</td>
<td></td>
</tr>
<tr>
<td><strong>Electric Power from PV Array</strong></td>
<td>MWₑ</td>
<td>50</td>
<td>82</td>
<td>3.3</td>
<td>22.7 20 PERCENT EFFICIENCY</td>
</tr>
<tr>
<td><strong>Solar Panel Area</strong></td>
<td>m²</td>
<td>185,185</td>
<td>305,185</td>
<td>12,318</td>
<td>84,444 1.55kW/m² AMU</td>
</tr>
<tr>
<td><strong>Thermal Radiated Power</strong></td>
<td>MW</td>
<td>49</td>
<td>81</td>
<td>2.5</td>
<td>21.7 OTHER THAN SOLAR ARRAY</td>
</tr>
<tr>
<td><strong>Radiator Temp./Area</strong></td>
<td>K/100m²</td>
<td>300/21.8</td>
<td>300/107</td>
<td>250/10.4</td>
<td>300/9.8</td>
</tr>
<tr>
<td></td>
<td>375/27.3</td>
<td>1770/0.057</td>
<td>409/10.8</td>
<td>289/10.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>326/19.1</td>
<td>107.057</td>
<td>10.4</td>
<td>20.8</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>63.2</td>
<td>107.057</td>
<td>10.4</td>
<td>20.8</td>
<td></td>
</tr>
</tbody>
</table>

### SOLAR PHOTOVOLTAIC PUMPED ONE MW LASER SYSTEMS

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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Electric Efficiency</strong></td>
<td>%</td>
<td>2.5</td>
<td>1.4</td>
<td>30</td>
<td>5.5 AFTER POWER CONDITIONING</td>
</tr>
<tr>
<td><strong>Electric Power</strong></td>
<td>MWₑ</td>
<td>50</td>
<td>82</td>
<td>3.3</td>
<td>22.7</td>
</tr>
<tr>
<td><strong>Solar Panel Area, Mass</strong></td>
<td>m²/kg</td>
<td>185,185</td>
<td>305,185</td>
<td>12,318</td>
<td>84,444 20% EFFICIENCY</td>
</tr>
<tr>
<td></td>
<td>166,666</td>
<td>273,333</td>
<td>11,000</td>
<td>76,000</td>
<td>300 W/kg (Ref. 1)</td>
</tr>
<tr>
<td><strong>Power Conditioner</strong></td>
<td>kg</td>
<td>88,000</td>
<td>144,320</td>
<td>5,808</td>
<td>40,120 1.76 kg/kW (Ref. 2)</td>
</tr>
<tr>
<td><strong>Thermal Power</strong></td>
<td>MW</td>
<td>49</td>
<td>81</td>
<td>2.3</td>
<td>21.7</td>
</tr>
<tr>
<td><strong>Radiator Area Mass</strong></td>
<td>m²/kg</td>
<td>63,200</td>
<td>107,057</td>
<td>10,400</td>
<td>20,600 2.7 kg/m² (Ref. 3)</td>
</tr>
<tr>
<td></td>
<td>170,660</td>
<td>289,054</td>
<td>28,080</td>
<td>55,620</td>
<td></td>
</tr>
<tr>
<td><strong>Total Mass</strong></td>
<td>kg</td>
<td>425,306</td>
<td>706,707</td>
<td>44,888</td>
<td>171,740 LASER CAVITY MASS NOT INCLUDED</td>
</tr>
</tbody>
</table>

2D LASER DIODE ARRAY

1D - Laser emission region

1291 diodes

0.71M

775 diodes

0.71M

250K heat sink

0.91mm

3mm

0.55mm

Not to scale

1MW LASER DIODE ARRAY SYSTEM

Earth radiation heat shield

Laser beam 1 MW

Laser diode radiator

Laser diode array

Solar array and radiator

3.3 MWe 13.2 MW

16.5 MW

111m

111m

111m

Sunlight

3.3 MWe
LASER DIODE ARRAY TECHNICAL ISSUES

ADVANTAGES:
0 HIGH SYSTEM EFFICIENCY (6%)
0 SMALL AND POTENTIALLY LEAST MASSIVE SYSTEM
0 NO LASANT FLOW REQUIRED
0 REASONABLE LASER WAVELENGTH
0 LASER DIODE ARRAY HAS GOOD POWER COUPLING TO SOLAR ARRAY
0 LOW WEIGHT/SIZE WASTE HEAT RADIATOR

DISADVANTAGES:
0 LOW TEMPERATURE LASER OPERATION REQUIRES LOW T RADIATOR AND HEAT REMOVAL SUBSYSTEM
0 VERY TEMPERATURE SENSITIVE
0 EFFECTS OF SPACE RADIATION MAY BE SEVERE

TECHNICAL ISSUES:
0 PHASE MATCHING ENTIRE LASER ARRAY NOT DEMONSTRATED
0 SCALING PRESENT 1-WATT SINGLE DIODES TO 1MW DIODE ARRAY
0 ARRAY COOLING WITH HEAT PIPES
0 ELECTRICAL DIODE LASER NETWORK

WEIGHT ESTIMATE OF DIODE PUMPED Nd YAG LASER SYSTEM

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode Laser Efficiency</td>
<td>30%</td>
</tr>
<tr>
<td>Pumping Efficiency</td>
<td>Nd:YAG Laser Output/Diode Laser Input</td>
</tr>
<tr>
<td>Electric Efficiency</td>
<td>10.5%</td>
</tr>
<tr>
<td>Solar Diode Laser Efficiency</td>
<td>6%</td>
</tr>
<tr>
<td>Overall System Efficiency</td>
<td>0.06 x 0.35 = 0.021 OR 2.1%</td>
</tr>
<tr>
<td>Solar Power Collected</td>
<td>1-MW/.021 = 48 MW</td>
</tr>
<tr>
<td>Electric Power</td>
<td>48 MW x .20 = 9.6 MWe</td>
</tr>
<tr>
<td></td>
<td>6.72 (thermal) + 2.88 MW (Laser)</td>
</tr>
<tr>
<td>Solar Panel Area</td>
<td>35,477 m²</td>
</tr>
<tr>
<td>Weight</td>
<td>32,000 kg</td>
</tr>
<tr>
<td>Power Conditioning</td>
<td>16,896 kg</td>
</tr>
<tr>
<td>Cooling Power</td>
<td>8.6 MW</td>
</tr>
<tr>
<td>Radiator Temperature</td>
<td>300 K/350 K</td>
</tr>
<tr>
<td>Area</td>
<td>18,770 m²</td>
</tr>
<tr>
<td>Weight</td>
<td>50,580 kg</td>
</tr>
<tr>
<td>Total Weight</td>
<td>99,576 kg</td>
</tr>
</tbody>
</table>

Compare: 44,888 kg for Diode Laser Array and 30,270 kg for Solar Iodine Laser
VARIOUS SOLAR PUMPED GAS LASERS

- Solar Pumped Lasers
  - Only Part of Solar Spectrum Utilized
    - Dissociative
    - Non-Dissociative Electronic Excitation e.g. Na₂
  - Whole Solar Spectrum Utilized to Heat A Cavity
    - Direct Black-Body Pumped Lasers (CO₂)
    - Gas-Dynamic Lasers, With Cooling of Media by Expansion

- Separate Absorber Hands Over Energy to Lasant Br₂·CO₂·He

- One Material Absorbs and Lases
  - X₂
  - XY (IBr)
  - RX C₃F₇₁
  - Premixed N₂·CO₂
  - Post Mixed N₂·CO₂

X = halogen, Y = different halogen atom
R = complex radical
CHARACTERISTICS OF IDEAL SOLAR PUMPED LASER

Good Solar Utilization
- AMO Solar spectrum
- Lasant absorption

High Quantum/Kinetic Efficiency
- Spontaneous Quenching
- Laser

Closed Cycle Operation of Lasant Fluid
- Solar
- R + I → R + I*
- R + I → RI
- Heat removal

Low Pumping Threshold
- Solar input
- 20k Solar constants max. con.
- 2.7 kW/cm²

IODINE LASER KINETICS

PUMP λ* ≈ 0.25 – 0.29 μm
LASER λ = 1.315 μm, η = 21%
ABSORPTION CROSS SECTIONS OF PERFLUOROALKYL IODIDES

SOLAR-PUMPED LASER EXPERIMENT

[Diagram of solar-pumped laser experiment showing components such as arc lamp, chopper, condenser, evaporator, and other parts involved in the experiment.]
PROGRESS IN SOLAR LASER POWER

10^6

10^4

10^2

10^0

10^-2

(LESS THAN SEC)

YEAR

10 80 82 84 86 88 90

Q-SW

CW

145
STATUS OF SOLAR-PUMPED IODINE LASER

0 KINETICS:
   LASER MEDIUM: C$_2$F$_7$I, C$_2$F$_9$I
   99 PERCENT RECYCLABLE
   PUMP BAND: 250-290 nm NUV
   INTRINSIC EFFICIENCY: 21 PERCENT
   EXCITATION MODE: PHOTODISSOCIATION TO I$^*$
   SOLAR-TO-LASER EFFICIENCY: 0.2 TO 0.6 PERCENT

0 SCALABILITY:
   PULSED POWER > 2 TW/2 KJ ACHIEVED (MARX-PLANCK INT.)
   CW > 15 W ACHIEVED (WITH SOLAR SIMULATOR)
   SCALING NO THEORETICAL LIMIT, 1 GW LEVEL POSSIBLE
   IMW SYSTEM STUDY COMPLETED

0 SOLAR-SIMULATOR PUMPED LASER EXPERIMENT:
   15 W CW, > 250 W PULSED (Q-SWITCHED)
   FLOW, SUBSONIC
   REP. PULSED MOPA UNDER DEVELOPMENT

0 R & D ISSUES:
   LARGE SOLAR UV COLLECTOR
   CHEMICAL REVERSIBILITY
   BEAM PROFILE CONTROL
   FLIGHT EXPERIMENT FOR THERMAL MANAGEMENT/BEAM TRANSMISSION

ONE MEGAWATT IODINE SOLAR PUMPED LASER POWER STATION

Lasant supply tanks  Solar collector

Transmission optics

Laser

Radiator 4 MW

Compressor turbine

1 MW

162 MW

157 MW

146
### ONE MW SOLAR IODINE LASER SYSTEM MASS

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector</td>
<td>14,800</td>
</tr>
<tr>
<td>Radiator</td>
<td>15,470</td>
</tr>
<tr>
<td>Total mass for collector and radiator</td>
<td>30,270</td>
</tr>
</tbody>
</table>

### OTHER SUBSYSTEMS:

- **LASER CAVITY**
  - Quartz Tube, kg: 1,860
  - Laser Cavity Optics, kg: 1,000
  - Laser Transmission Optics and Structure (27.5 m Diam.), kg: 24,000

- **GAS FLOW SYSTEM**
  - Compressor (2 Stage), kg: 12,700
  - Turbine, kg: 12,200
  - Ducts, kg: 3,000
  - r-C_6F_1 Storage Tanks (4 Empty Tanks), kg: 270

- **ATTITUDE CONTROL SYSTEM (CMG AND FUEL)**
  - CMG, kg: 2,000
  - 150 kg Fuel/YR, kg: 4,500

### FLOW AND THERMAL CYCLES OF ONE MW IODINE LASER

- **T_1** = 246 K
- **P_1** = 5.4 torr
- **V_1** = 63.1 m/s
- **M_1** = 0.8
- **A_1** = 4.08 m²

- **T_2** = 250 K
- **P_2** = 7.5 torr
- **V_2** = 10.3 m/s
- **M_2** = 0.13
- **A_2** = 18.3 m²

- **T_3** = 500 K
- **P_3** = 7.5 torr
- **V_3** = 20.7 m/s
- **M_3** = 0.184
- **A_3** = 18.3 m²

- **T_4** = 493 K
- **P_4** = 5.5 torr
- **V_4** = 89.2 m/s
- **M_4** = 0.8
- **A_4** = 5.72 m²

- **T_5** = 486 K
- **P_5** = 4.1 torr
- **V_5** = 83.4 m/s
- **M_5** = 0.75
- **A_5** = 8 m²

**Note:** The diagram illustrates the flow and thermal cycles for one MW solar iodine laser system, including the compressor, laser cavity, and radiator. The net work is 14.5 kW, and the 3.97 MW heat loss is noted.
LASER POWER CONVERSION SYSTEMS

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td>RECEIVER/PHOTOVOLTAIC/BATTERIES</td>
<td>34.0 %</td>
</tr>
<tr>
<td>RECEIVER/HEAT/BRAYTON/GENERATOR</td>
<td>34.2 %</td>
</tr>
<tr>
<td>RECEIVER/MHD GENERATOR</td>
<td>55.0 %</td>
</tr>
<tr>
<td>RECEIVER/PROPULSION (100 % THEORETICAL)</td>
<td>50.0 %</td>
</tr>
</tbody>
</table>

LASER POWER TRANSMISSION APPLICATIONS

- VERY LOW EARTH ORBIT SATELLITE -- DRAG REDUCTION
- OTV (LEO TO GEO) -- WEIGHT REDUCTION
- MARS -- SCIENTIFIC PROBES
- DEEP SPACE SATELLITE -- PRIME POWER SUPPLY
- SPACE PROCESSING/MANUFACTURING
MILESTONES

0 BEAM TRANSMISSION CHARACTERIZATION 5/88
0 TEST OF MOPA SYSTEM 12/88
0 OTHER GAS LASER ALTERNATIVES Na2, HoBr 12/88
0 Nd3+ LIQUID LASER EVALUATION 6/88
0 SOLID STATE LASER EVALUATION Nd3+: YAG, Nd3+: GSGG, Nd3+: YLF 3/88
0 PREFLIGHT EXPERIMENT GROUND TESTING 3/89
0 FLIGHT EXPERIMENT -- PLAN/DESIGN ?

SUMMARY AND CONCLUSION

0 SPACE-BORNE SOLAR-PUMPED LASER SYSTEMS ARE VIABLE OPTIONS FOR LASERS FOR FREE SPACE POWER TRANSMISSION. PRIME POWER SOURCE, SUN, IS FREE AND THE SYSTEM WITH 1.3-μM WAVELENGTH IS SUITABLE FOR TRANSMISSION OVER 1000 KM (LEO-GEO DISTANCE).

0 SOLAR-PUMPED IODINE LASER SYSTEM HAS SCALABILITY AND LIGHT WEIGHT (30 TONS/MW) SUITABLE FOR SPACE-BASED OPERATION.

0 DIODE LASER ARRAYS DRIVEN BY SOLAR PANELS OR SOLAR DYNAMIC GENERATORS COULD BE ANOTHER CANDIDATE FOR THE SPACE-BASED LASER SYSTEM IF BEAM PROFILE CONTROL FOR THE LONG DISTANCE TRANSMISSION IS POSSIBLE.

0 IODINE LASER PROGRAM PROGRESSED STEADILY SINCE 1980 AND FLIGHT EXPERIMENT PROPOSED FOR 1990'S.
REFERENCES


